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# Evaluation of measurement uncertainty when calibrating power analyzers of high-frequency signals in coaxial paths

S. Shevkun[1], M. Dobroliubova[2], E. Lapko[3]

[1] State Enterprise "All-Ukrainian State Scientific and Production Centre for Standardization, Metrology, Certification and Protection of Consumer" (SE "Ukrmetrteststandard"), Metrologichna Str., 4, 03143, Kyiv, Ukraine
shevkun@ukrcsm.kiev.ua
[2] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Peremogy Ave., 37, 03056, Kyiv, Ukraine
m.dobroliubova@ukr.net
[3] Village council of Chabany, Mashynobudivnykiv Str., 4, 08162, Chabany, Ukraine
elapko@ukr.net

**Abstract**

Implementation of modern requirements for the quality and stability of radio communications, including the required data rate in industrial and atmospheric jamming, is impossible without accurate measurements of signal power at the output of transmitting devices in the transmitter-antenna section. Such measurements are performed using power analyzers that measure both incident and reflected waves. These parameters allow calculating the standing wave ratio, which makes it possible to ensure optimal coordination of the transmitter with antenna, the required power modes and the efficiency of the transmitter as a whole.

The paper presents main results of the research on the evaluation of measurement uncertainty when calibrating of the analyzers of the throughput power of high-frequency signals in coaxial paths.

The structural scheme and equations (model) of measurements, and features of calculating uncertainty budget are described. The basic principles for obtaining continuous calibration results in the whole range of measurements are revealed. An example of presenting calibration results in graphical form is given.

The content of quantitative and qualitative indicators of corrections that must be taken into account during calibration to achieve the highest accuracy of measurements is revealed. It is expedient to use practical results of researches on calibration of throughput power meters in many areas connected with telecommunications and transmission of radio signals.

**Keywords:** power analyzer; power meter; calibration; measurement uncertainty; uncertainty budget; measurement range.

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**Introduction**

BIRD Power Analyzers 5000, Anritsu ML2495A and similar devices are used to measure the power of radio frequency signals. Thanks to them, it is possible to measure the power of both incident and reflected waves simultaneously, which makes it also possible to calculate the coefficient of standing wave in automatic mode [1]. The standing wave ratio affects the efficiency of the "transmission line – load" system, the maximum value of the power transmitted by a communication line, as well as the generator operation mode. These parameters are determined to ensure the quality and stability of communication, including the required data transfer rate in conditions of industrial, atmospheric interference, etc. Measurements of signal power and calculations of the standing wave ratio are performed in the following cases:

- initial commissioning, during which the transmitter is coordinated with an antenna;
- optimization of transmitter network and modes of their operation;
- ensuring sanitary standards of radiation in the coverage area.

High-frequency signal power measurements are used in the following areas of science and technology: telecommunications; analog and digital radio broadcasting; air, land and sea transport; defense; the sphere of communal services; safety and security; fire protection; navigation, radar, telematics, etc. The power of high-frequency signals is measured during the development and operation of the following communication facilities: universal mobile telecommunication systems of 2G (GSM), 3G (UMTS) and 4G, GPRS packet data systems, EDGE high-speed data transmission systems, high-speed packet data systems HSDPA, Bluetooth wireless data transmission system, Tetra digital tracking radio communication system, APCO / P25 citizen safety communications,


Fig. 1. Power meters and power sensors of high-frequency signals in coaxial paths

DMR digital mobile radio communication and MOTOTRBO time-based digital radio communication, Trunking concept radio communication systems with access to a wide range of users, communication systems with multiple code (CDMA, WCDMA) and time (TDMA) distribution, LMR high-reliability communication systems, GPS global navigation satellite transmission stations and others, transmitters of radar stations for various purposes and radio actions, paging, WiMAX long-distance radio systems, WLAN and Wi-Fi wireless LAN, etc. Measurements of the power of high-frequency signals, as a rule, are carried out at the output of transmitting devices of communication systems. The means of measuring the power of high-frequency signals include many such devices as analyzers and power meters, wattmeters, antenna testers and antenna analyzers. They differ in frequency and dynamic ranges, application conditions (laboratory devices and portable devices for field operation), as well as construction technology (analog and digital) (Fig. 1). The general metrological characteristics of the specified measuring equipment are as follows: the range of the measured power of radio signals is from – 67 dBm to + 60 dBm, frequency range is from 0 Hz to 110 GHz, accuracy of measurements is from ± 0.15 % to ± 7 %. The reliability and accuracy of power measurements is ensured by calibrating these measuring instruments.

The power analyzer should be understood as a power meter equipped with a power sensor (Fig. 2). Calibration of power analyzers by direct comparison can have four options depending on the standard equipment, as well as on the measured power: throughput or absorbed. Below is a summary of main features of these options.

When calibrating throughput power analyzers, the following can be used as a standard:

1) standard signal generator as a measure of power;

2) standard absorbed power analyzer connected in series with a calibrated analyzer.

When calibrating absorbed power analyzers, the following can be used as a standard:

1) standard signal generator as a measure of power;

2) standard absorbed power analyzer included to replace the calibrated analyzer.

The article analyses and describes the method of calibrating throughput power analyzers using a standard power analyzer connected in series.

The problem in carrying out the calibration of throughput power analyzers is the absence in modern scientific literature of a specific and detailed description of calibration methods in the full range of measured power values that would meet the requirements of [2].

The purpose of the article is to present the results of the development of a methodology for calibrating throughput power analyzers of high-frequency signals in the full range of measurements from 30 to 60 dBm and the frequency range from 2 MHz to 2.7 GHz.

**The result of research**

It is proposed to consider methods for calibrating radio signal throughput power analyzers using digital signal power meter Bird 5000-EX, which is used in a set with Bird 5014 Directional RF Power Sensor (Fig. 1). The metrological characteristics of Bird Model 5000-EX Power Meter and Wideband Bird 5014 Directional RF Power Sensor are given in [1, 3]. Rohde & Schwarz NRP Standard Power Meter equipped with Rohde & Schwarz NRP-Z Power Sensors, HAMEG HM8134 RF-Synthesizer and R&S BBA150 Broadband amplifier are used to implement the measurement scheme. The metrological characteristics of HAMEG HM8134 RF-Synthesizer, the Rohde & Schwarz NRP Standard Power Meter (Fig. 1) and Rohde & Schwarz NRP-Z

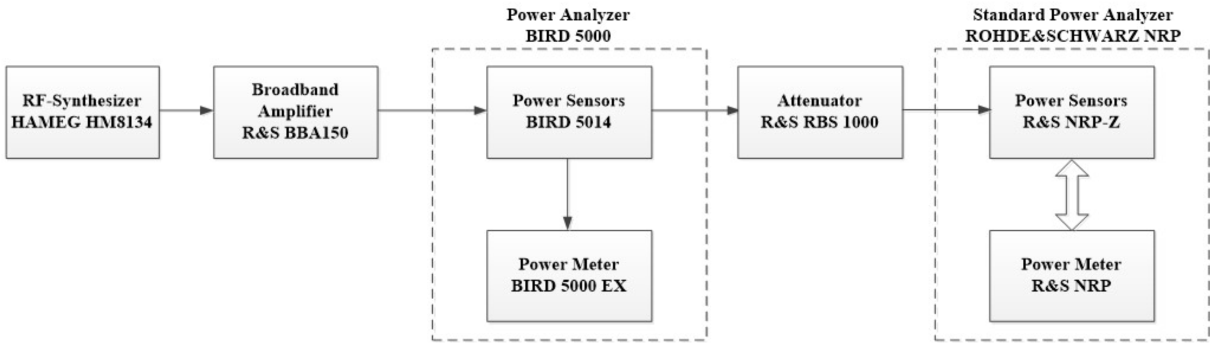


Fig. 2. Measurement scheme during the calibration of a throughput power analyzer

Power Sensors are given in [4–6]. Rohde & Schwarz NRP Standard Power Analyzer has a line of power sensors with a variety of frequency and dynamic ranges.

The scheme of measurements during the calibration of the throughput power analyzer is shown in Fig. 2.

HAMEG HM8134 RF-Synthesizer generates signals that are fed through Rohde & Schwarz BBA150 Broadband amplifier to Bird 5014 Directional RF Power Sensor from Bird 5000 Power Analyzer. From one output of Bird 5014 Directional RF Power Sensor, the signal is fed to Bird 5000-EX Power Meter, and from the other to Rohde & Schwarz NRP-Z Power Sensor. The signal power is measured simultaneously using Rohde & Schwarz NRP Standard Power Analyzer and the calibrated Bird 5000-EX Power Analyzer. Thus, the calibration is carried out by a direct comparison.

In the measurement range above 45 dBm, before applying the signal to Rohde & Schwarz NRP-Z Power Sensor, it must be attenuated by 20 dB using Rohde & Schwarz RBS 1000 Attenuator [7].

According to the measurement scheme, based on the approaches described in [2], the measurement model has the form of the following equation (1)

$$\begin{aligned}\Delta W_x &= W_x - \left(W_s - \Delta W_s\right) + \Delta W_{\beta con} + \Delta W_{\beta x} + \Delta W_{\gamma s} + \\ &+ \Delta W_{ts} + \Delta W_{tx} + \Delta W_{ds} + \Delta W_{dx} - \Delta W_{att} + \Delta W_l + \\ &+ \Delta W_{\gamma att} + \Delta W_h + \Delta W_{cr} + \Delta W_{tatt} + \Delta W_{lerr},\end{aligned} \tag{1}$$

where $\Delta W_x$ is the deviation of the readings of the calibrated Bird 5000 Power Analyzer from the reference value; $W_x$ is the value measured by the calibrated Bird 5000 Power Analyzer, which is estimated by averaging 10 readings on the screen of Bird 5000-EX Power Meter; $W_s$ is the value measured by Rohde & Schwarz NRP Standard Power Analyzer, which is estimated by averaging 10 readings on the screen of R&S NRP meter; $\Delta W_s$ is the deviation of the readings of Rohde & Schwarz NRP Standard Power Analyzer from the reference value specified in the calibration certifi-cate for this point in the range; $\Delta W_{\beta con}$ is the correction of a mismatch in the electrical connector between Bird 5014 Directional RF Power Sensor and Rohde & Schwarz NRP-Z Power Sensor; $\Delta W_{\beta x}$ is the correction of operating attenuation of signal in Bird 5014 Directional RF Power Sensor; $\Delta W_{\gamma s}$ is the drift correction of Rohde & Schwarz NRP Standard Power Meter since its last calibration; $\Delta W_{ts}$ is the correction of temperature dependence of Rohde & Schwarz NRP-Z Power Sensor; $\Delta W_{tx}$ is the correction of temperature dependence of Bird 5014 Directional RF Power Sensor; $\Delta W_{ds}$ is the correction of the discreteness of the indicator readings of R&S NRP Standard Power Meter; $\Delta W_{dx}$ is the correction of the discreteness of the indicator readings of Bird 5000-EX Power Meter; $\Delta W_{att}$ is the attenuation in Rohde & Schwarz RBS 1000 Attenuator from the calibration certificate; $\Delta W_l$ is the correction of signal attenuation in the cable between Bird 5000-EX Power Meter and Rohde & Schwarz RBS 1000; $\Delta W_{\gamma att}$ is the drift correction of Rohde & Schwarz RBS 1000 since its last calibration; $\Delta W_h$ is the correction of heating losses of the measurement circuit elements; $\Delta W_{cr}$ is the correction of parasitic losses due to the variability of the consistency parameters when connecting the elements of the measurement circuit; $\Delta W_{tatt}$ is the correction of temperature dependence of Rohde & Schwarz RBS 1000 Attenuator; $\Delta W_{lerr}$ is the correction of nonlinearity of the measuring system.

Based on the measurement model, we obtain the uncertainty budget [8, 9] when calibrating the throughput power analyzer at the frequency of 900 MHz at the point of 50 dBm, an example of which is presented in Table 1. The numerical values of the quantities and their uncertainties are obtained experimentally and theoretically by calculation and analysis of the reference data.

The calibration result at the specified measurement point is as follows:

$$\begin{aligned}&\Delta W_x\left(900\ \text{MHz}, 50\ \text{dBm}\right) = \\ &= \left(0.595 \pm 0.029\right)\text{dB},\ p = 0.95.\end{aligned} \tag{2}$$

Particular attention should be paid to the correctness of mathematical operations with logarithmic units.

It should be noted that calibration of throughput power analyzers must be performed over the entire range of power values. This calibration is performed at several points in the range.

Table 1

Uncertainty budget when calibrating the throughput power analyzer at 900 MHz at 40 dBm

| Quantity $x_i$ | Estimate $x_i$ | Standard uncertainty, $u(x_i)$ in dB | Probability distribution | Method of evaluation (A, B) | Sensitivity coefficient, $c_i$ | Uncertainty contribution, $u_i(y)$ in dB |
|---|---|---|---|---|---|---|
| $W_x$ | 50.053 dBm | 2.10E-03 | normal | A | 1 | 2.10E-03 |
| $W_s$ | 30.463 dBm | 1.55E-03 | normal | A | –1 | –1.55E-03 |
| $\Delta W_s$ | –0.024 dB | 1.10E-03 | normal | B | 1 | 1.10E-03 |
| $\Delta W_{\beta con}$ | 0.41 dB | 1.40E-03 | U-shaped | B | 1 | 1.40E-03 |
| $\Delta W_{\beta x}$ | 0.17 dB | 4.30E-03 | normal | B | 1 | 4.30E-03 |
| $\Delta W_{\gamma s}$ | –0.014 dB | 3.80E-03 | normal | B | 1 | 3.80E-03 |
| $\Delta W_{ts}$ | 0 dB | 7.50E-03 | normal | B | 1 | 7.50E-03 |
| $\Delta W_{tx}$ | 0 dB | 1.00E-02 | normal | B | 1 | 1.00E-02 |
| $\Delta W_{ds}$ | 0 dB | 2.89E-03 | rectang | B | 1 | 2.89E-03 |
| $\Delta W_{dx}$ | 0 dB | 2.89E-03 | rectang | B | 1 | 2.89E-03 |
| $\Delta W_{att}$ | 20.014 dB | 1.20E-03 | normal | B | –1 | –1.20E-03 |
| $\Delta W_l$ | 0.44 dB | 1.30E-03 | U-shaped | B | 1 | 9.19E-04 |
| $\Delta W_{\gamma att}$ | 0.011 dB | 1.00E-03 | normal | B | 1 | 1.00E-03 |
| $\Delta W_h$ | 0.011 dB | 1.00E-03 | normal | B | 1 | 1.00E-03 |
| $\Delta W_{cr}$ | 0.015 dB | 1.10E-03 | U-shaped | B | 1 | 7.78E-04 |
| $\Delta W_{tatt}$ | 0 dB | 1.80E-03 | normal | B | 1 | 1.80E-03 |
| $\Delta W_{lerr}$ | 0 dB | 1.00E-04 | normal | B | 1 | 1.00E-04 |
| $\Delta W_x$ | 0.595 dB | Combined standard uncertainty | | | | 1.493E-02 |
| | | Effective degrees of freedom | | | $n_{eff} > 200$ | $k = 2$ |
| | | Expanded uncertainty ($p \geq 95\%$) | | | | 2.987E-02 |

Fig. 3 shows an example where calibration is performed at 7 points in the measurement range from 30 dBm to 60 dBm within the interval of 5 dBm. At these points, a calibration result similar to (2) is obtained.

To obtain a calibration curve (calibration diagram), an approximation of the tabular data $\Delta W_x$ should be applied. For this purpose, appropriate software is used, which allows obtaining calibration results in the form of a set of numerical values, an equation (polynomial) for constructing a continuous graph, which shows the dependence of the deviation $\Delta W_x$ from the point of the power range at which measurements are made.

As a result of experimental studies, it was revealed that obtaining the most accurate calibration diagram, which gives the smallest distance to the points of the calibration results with the highest smoothness of the calibration curve and provides approximation using polynomials of the $5^{th}$ and $6^{th}$ orders. When using polynomials of the $5^{th}$ order, the value of the reliability of the approximation $R^2$ is 0.9963 and 0.996, and when using polynomials of the $6^{th}$ order – $R^2$ is 1, i.e. the error of the approximation is close to zero and equal to zero, respectively. Therefore, as the order of the polynomial decreases, the approximation error also increases.

Similarly, a calibration curve is obtained for the uncertainty assigned to each point in the measurement range.

It is better to give the result of the calibration in a graphical form using a calibration curve (Fig. 3), which will make it more convenient to make necessary corrections when performing measurements by users.

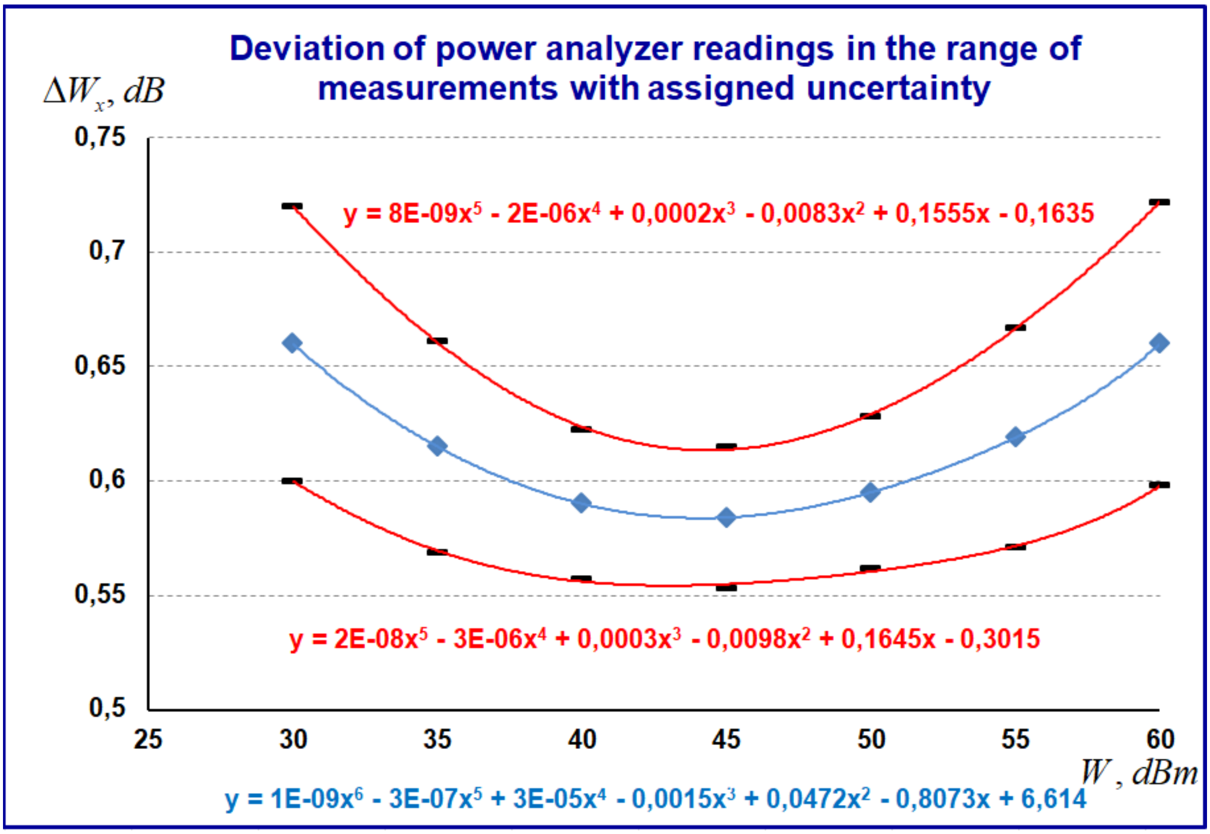


Fig. 3. Graphical way of presenting calibration results (a calibration curve)

In the case when the calibration result (deviation and associated uncertainty) needs to be calculated more accurately, it is advisable to use the mathematical expressions of the polynomials obtained during the approximation (the equation in Fig. 3).

Throughput power analyzers must be calibrated at the frequency at which the user will measure the signal power. If there are several such frequencies, calibration should be performed at all frequencies separately. The standard power analyzer must be calibrated at all required points in the dynamic and frequency ranges with the appropriate metrological traceability. In the absence of a reference generator and amplifier with necessary signal parameters (power, modulation type, duty cycle, coding, etc.), it is advisable to carry out calibration at the customer's facilities.

**Conclusion**

1. The developed methodology allows to evaluate uncertainty of measurements during the calibration of throughput power analyzers of high frequency signals in the full range.

2. To calibrate power analyzers over the full range of values, it is necessary to measure and calculate measurement uncertainty at several points in the range.

3. To obtain continuous calibration results of power analyzers in the measurement range, it is necessary to approximate the calibration results at individual points using the polynomials of the 6$^{th}$ and 5$^{th}$ order.

4. It is convenient to present the calibration result (deviation and associated uncertainty) in a graphical form (calibration curve), which will ensure that all the necessary corrections are made when performing power measurements by users.

5. In the case when the calibration result should be calculated more accurately, it is advisable to use the mathematical expressions of the polynomials obtained during the approximation.

# Оцінювання невизначеності вимірювань під час калібрування аналізаторів потужності сигналів високих частот у коаксіальних трактах

С.М. Шевкун [1], М.В. Добролюбова [2], Є.В. Лапко [3]

[1] *Державне підприємство "Всеукраїнський державний науково-виробничий центр стандартизації, метрології, сертифікації та захисту прав споживачів" (ДП "Укрметртестстандарт"), вул. Метрологічна, 4, 03143, Київ, Україна*
*shevkun@ukrcsm.kiev.ua*
[2] *Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського", пр. Перемоги, 37, 03056, Київ, Україна*
*m.dobroliubova@ukr.net*
[3] *Чабанівська селищна рада, вул. Машинобудівників, 4, 08162, смт Чабани, Україна*
*elapko@ukr.net*

**Анотація**

Реалізація сучасних вимог до якості та стійкості радіозв'язку, в тому числі необхідної швидкості передавання даних в умовах індустріальних і атмосферних завад, неможлива без точних вимірювань потужності сигналів на виході передавальних пристроїв на ділянці передавач-антена. Такі вимірювання виконуються за допомогою аналізаторів потужності, які здійснюють вимірювання як падаючої, так і відбитої хвилі. Зазначені параметри дозволяють розраховувати коефіцієнт стоячої хвилі, що надає можливість забезпечити оптимальне узгодження передавача з антеною, необхідні енергетичні режими та коефіцієнт корисної дії передавача в цілому.

Для забезпечення точності та достовірності вимірювань аналізатори потужності потребують періодичного калібрування. Під час калібрування необхідно враховувати умови навколишнього середовища, в яких експлуатується аналізатор потужності, а також характеристики сигналу (вид модуляції, скважність, кодування тощо), для вимірювання потужності якого він призначений.

У роботі наведено основні результати досліджень щодо оцінки невизначеності при калібруванні аналізаторів прохідної потужності сигналів високих частот. Описано структурну схему та рівняння вимірювань, а також особливості розрахунку бюджету невизначеності при калібруванні. Розкрито основні принципи щодо отримання безперервних результатів калібрування в усьому діапазоні вимірювань за допомогою апроксимації з використанням поліному п'ятого та шостого порядку. Наведено приклад подання результатів калібрування у графічній формі.

Розкрито зміст кількісних та якісних показників поправок, які необхідно враховувати під час калібрування для досягнення найвищої точності вимірювань. Практичні результати досліджень доцільно використовувати при калібруванні вимірювачів прохідної потужності у багатьох галузях, пов`язаних із телекомунікаціями та передаванням радіосигналів.

**Ключові слова:** аналізатор потужності; вимірювач потужності; калібрування; невизначеність вимірювань; бюджет невизначеності; діапазон вимірювань.

# Оценивание неопределенности измерений при калибровке анализаторов мощности сигналов высоких частот в коаксиальных трактах

С.М. Шевкун [1], М.В. Добролюбова [2], Е.В. Лапко [3]

[1] *Государственное предприятие "Всеукраинский государственный научно-производственный центр стандартизации, метрологии, сертификации и защиты прав потребителей" (ГП "Укрметртестстандарт"), ул. Метрологическая, 4, 03143, Киев, Украина*
*shevkun@ukrcsm.kiev.ua*
[2] *Национальный технический университет Украины "Киевский политехнический институт имени Игоря Сикорского", пр. Победы, 37, 03056, Киев, Украина*
*m.dobroliubova@ukr.net*
[3] *Чабановский сельский совет, ул. Машиностроителей, 4, 08162, пгт Чабаны, Украина*
*elapko@ukr.net*

**Аннотация**

Реализация современных требований к качеству и устойчивости радиосвязи невозможна без точных измерений мощности сигналов передающих устройств на участке передатчик-антенна. Такие измерения производятся

с помощью анализаторов мощности, осуществляющих измерение как падающей, так и отраженной волны, что позволяет рассчитывать коэффициент стоячей волны для обеспечения оптимального согласования передатчика с антенной, необходимых энергетических режимов и коэффициента полезного действия передатчика в целом.

В работе представлены результаты исследований по оценке неопределенности при калибровке анализаторов проходной мощности сигналов высоких частот в коаксиальных трактах. Описаны структурная схема, уравнение измерений, расчет бюджета неопределенности при калибровке. Раскрыты принципы получения непрерывных результатов калибровки во всем диапазоне измерений. Приведен пример представления результатов калибровки в графической форме. Раскрыты количественные и качественные показатели поправок для достижения наивысшей точности измерений.

**Ключевые слова:** анализатор мощности; измеритель мощности; калибровка; неопределенность измерений; бюджет неопределенности; диапазон измерений.

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