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UNCERTAINTY EVALUATION USING LAW OF PROPAGATION AND MONTE CARLO SIMULATION METHODS WITH THE AUTORFPOWER MEASUREMENT SOFTWARE

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Highlights

- The Law of Propagation (LoP) and Monte Carlo Simulation (MCS) uncertainty calculation methods were briefly discussed.
- The details of the AutoRFPower software were presented, which was developed for performing LoP and MCS uncertainty calculations in automatic RF power measurement tasks.
- Measurement and uncertainty calculation results obtained using the AutoRFPower software were presented.
- A comparison was made between the uncertainty calculation results from the AutoRFPower software and those from a commercial uncertainty calculation simulation tool (Oracle Crystal Ball).
- The uncertainty calculation capabilities of the developed AutoRFPower software were validated.

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ABSTRACT: RF power measurement is essential in RF and microwave metrology. For reliable and accurate power measurement, automatic measurement is preferred. A software application in C#, named AutoRFPower, was developed for automatic RF power measurement and uncertainty calculations at this study. According to the GUM document, this application is enhanced for uncertainty calculations by utilizing the Law of Propagation method and the Monte Carlo Simulation method. Trial measurements were performed at different RF power levels and frequencies between 50 MHz and 18 GHz using the AutoRFPower software. Law of Propagation and Monte Carlo Simulation uncertainty calculations were carried out by AutoRFPower based on the trial measurements and by the Oracle Crystal Ball simulation application. All measurements and their uncertainty calculations were compared with each other, and this study validated the uncertainty calculation of AutoRFPower. In addition, it was observed that in the Monte Carlo Simulation, uncertainty calculation results were non-symmetrical normal distribution, contrary to the assumption of symmetrical normal distribution according to the Low of Propagation method. Moreover, it has been observed that the statistical distribution of uncertainty changes depending on the dominant component of the parameters in the model function used for the uncertainty calculation with the Monte Carlo Simulation method.

Keywords: *Auto RF Power Measurement, Law of Propagation Method, Monte Carlo Simulation Method, Uncertainty Calculation*

1. INTRODUCTION

RF power measurement is a vital topic at the RF and microwave metrology laboratory. To have reliable power measurement, operator mistakes should be decreased. To minimize those mistakes, the use of automatic measurement software is preferred.

Although it is crucial to carry out such good, successive measurements at RF and Microwave metrology, it is also essential to calculate the uncertainty of the measurement correctly according to the "Guide to the Expression of Uncertainty in Measurement (GUM)" document [1, 2]. Law of Propagation (LoP) and Monte Carlo Simulation (MCS) methods are used to evaluate measurement uncertainties in GUM [3, 4].

The LoP method is based on the central limit theory. It calculates uncertainty with all input parameters that contribute to uncertainty calculation having normal distribution, or those should be transformed from other distributions such as rectangular, triangular, and u-shape to normal distribution. The input

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parameters that do not have normal distribution are assumed as symmetrical normal distribution when transformed into a normal distribution from their actual distributions. If the uncertainty component has rectangular, triangle, and u-shape distributions, it should be divided into $\sqrt{3}$, $\sqrt{6}$, and $\sqrt{2}$ for normal distribution transfer, respectively. This assumption causes the calculated uncertainty of the LoP method to have a balanced normal distribution. Combined uncertainty can be calculated using Equation (1) for the LoP method [1, 2].

$$u\,(k=1) = \sqrt{\sum_{i=1}^{n} c_i^2 . u_i^2} \tag{1}$$

where $u(k{=}1)$ is the combined uncertainty with coverage factor one (68 % reliability), c_i is the sensitivity coefficient of each uncertainty component in the model function ($f\,(.)$) and u_i is the uncertainty value of each component in the model function The c_i can be calculated with partial derivative of the model function of the considered uncertainty component $(\partial f(.)/\partial i)$, and u_i is a related uncertainty which has normal distribution. Figure 1 shows the visualization of the calculation flow of the LoP method uncertainty.

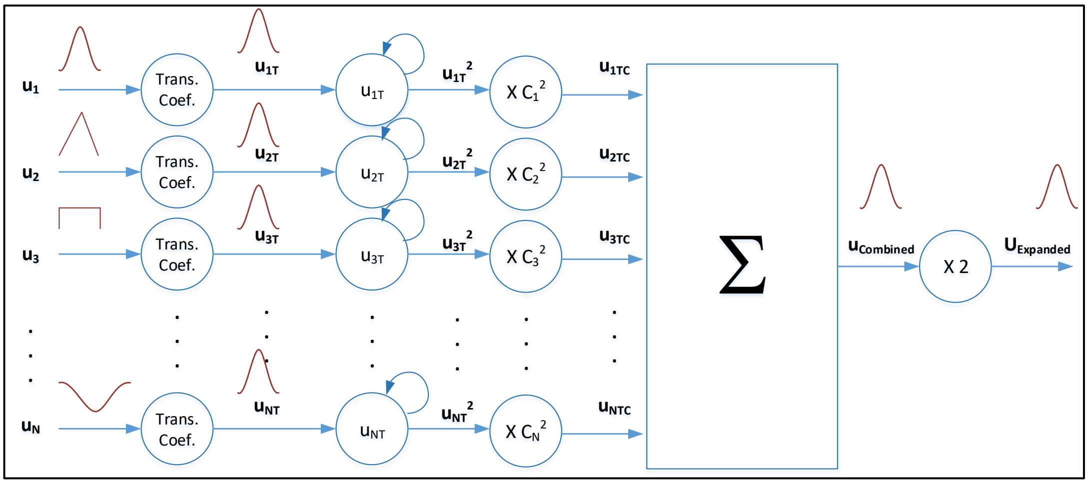

Figure 1. Uncertainty calculation flow chart of the LoP method

The MCS method is an analytical method used before and still in calculating measurement uncertainties. The MCS method is generally not preferred if LoP can be used because it is difficult to take many repetitive measurements such as 10^5 times or more [5-10]. Many repetitive measurements can be impossible for each uncertainty component. To simulate the real measurement, all the input parameters for uncertainty calculation is generated by randomized at least 10^5 times before uncertainty calculation. There is no symmetrical normal distribution transformation in the MCS method, and the input component's distribution effect can be seen in the combined uncertainty in the MCS method. The uncertainty calculation flow chart is given in Figure 2 for the MCS method in this study.

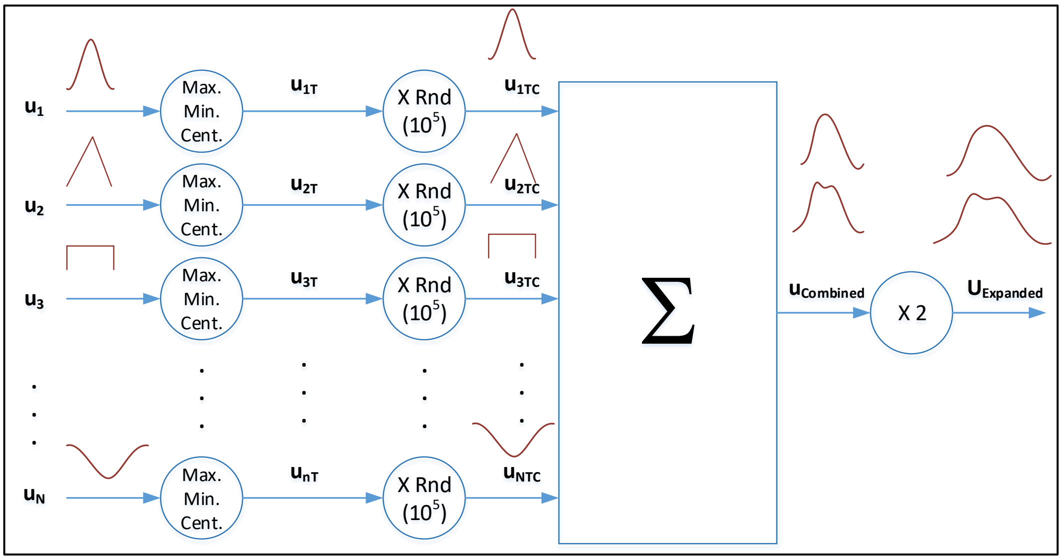

Figure 2. Uncertainty calculation flow chart of the MCS Method

Uncertainty calculation needs to be improved in the LoP method due to the normal distribution transformation of all parameters. The LoP method might have deficiencies when the model function has non-linear input parameters.

A software tool, called AutoRFPower, was developed on the C# platform with the collaboration of TUBITAK, SPARK, and METU [11, 12]. In this study, LoP and MCS methods calculated the uncertainties of the measurements taken using the enhanced automatic RF power measurement software (AutoRFPower). Also, the uncertainty calculation capabilities of the AutoRFPower software were validated. For validation, firstly, the uncertainty values calculated numerically according to the LoP method were compared with the uncertainty values produced by the AutoRFPower software, and the MCS uncertainty ability of the software was compared with the results of commercially available MCS software. This study compared and discussed all uncertainties calculated with the developed software and simulator.

2. MEASUREMENT BY AUTORFPOWER SOFTWARE AND UNCERTAINTY CALCULATION TECHNIQUES

An RF signal generator, a power sensor, and a power meter are used in a simple RF power measurement setup as shown in Figure 3. An attenuator is preferred for high power measurement with low power sensor and an adapter is preferred for adapting the different connectorized RF connectors in Figure 3. Depending on the measurement frequencies and RF power levels, various power sensors, such as thermocouples, semiconductor diodes, and thermistors, can be used as RF power sensors [13, 14]. In order to measure wide frequency range and wide power range, it is necessary to use an automatic measurement system.

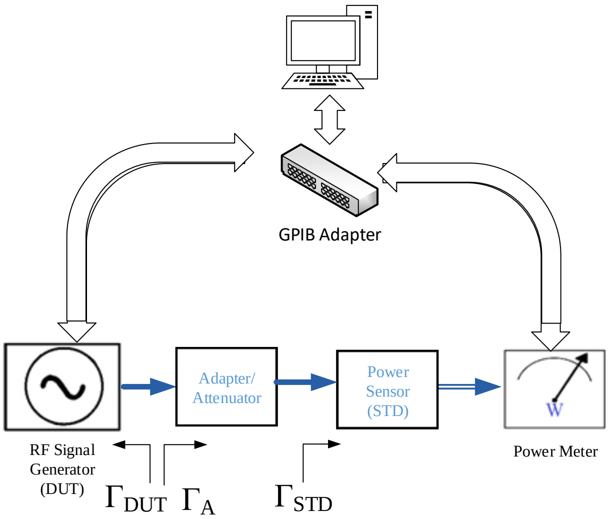

Figure 3. Automatic RF power measurement setup

For measuring RF power automatically, developed software is necessary to control the operations of the computer and the measurement system. In order to communicate with the computer and measurement devices, an interface bus should be used. As shown in Figure 3, the General Propose Interface Bus (GPIB) adapter and its protocol are used to communicate with the computer and the other measurement devices used for automatic RF power measurement [15].

The power value read by the power meters in RF power measurement systems cannot directly show the power given by RF signal sources due to impedance mismatches with non-ideal connectors and power sensor losses. Considering the losses and impedance mismatches in the RF power measurement system, it is necessary to calculate the actual RF power value of the RF signal source by writing a model function. The model function for the actual RF power of the signal generator is given with Equation (2) for the setup given at Figure 3.

$$P_{DUT} = \frac{P_{READ}}{CF_{STD}} \cdot \left|\frac{1}{S_{21A}}\right|^2 \cdot M \tag{2}$$

where;

P_{DUT} : Actual RF Power of Device Under Test (DUT) RF signal generator,
P_{READ} : Average RF power reading from power meter,
CF_{STD} : Calibration Factor of Standard (STD) power sensor,
S_{21A} : Forward transmission coefficient of the attenuator (complex),
M : Impedance mismatch due to the non-ideal RF connectors, it can be calculated with Equation (3),

$$M = |1 - \Gamma_A \cdot \Gamma_{DUT}|^2 \tag{3}$$

where;

Γ_A : Equivalent reflection coefficient of the input port of attenuator(s) shown in Figure 3 (complex). Γ_A is the reflection coefficient of the STD power sensor input (Γ_{STD}), if attenuator is not placed on the setup,
Γ_{DUT} : Complex reflection coefficient of DUT signal generator shown in Figure 3.

In this study, different RF power and frequency range measurements were tried with the AutoRFPower software, and the uncertainty calculation capabilities of the software were validated.

For the first experiment, the technical specifications of the power meter, the power sensor, and the RF signal source used in this measurement setup are given in Table 1.

Table 1. The equipment used in the measurement setup

Equipment	Model	Measurement Range
Power Meter	N1914A	-70 dBm -+44 dBm
Power Sensor	E4413A	50 MHz – 26.5 GHz
Signal Generator	E8257D	250 kHz – 40 GHz
10 dB Attenuator	8491B	10 MHz – 18 GHz

Measurements were performed by the measurement setup at the frequencies of 50 MHz, 1000 MHz, 5000 MHz, 10000 MHz, 15000 MHz and 18000 MHz, and at power levels of 0 dBm and 5 dBm. While taking the measurements by the developed software at the different frequencies and power levels, they were also successively recorded manually by the operator for software validation.

The actual RF power value (P_{DUT}) was calculated by taking into account the calibration factor of the power sensor, the forward transmission coefficient of the attenuator, and the complex equivalent reflection coefficient of the input port of the attenuator and also that of the DUT signal generator using the Equation (2).

Two different RF power values can be calculated depending on whether the DUT signal generator's reflection coefficient (Γ_{DUT}) is vectorial or only magnitude. If the Γ_{DUT} is known as vectorial (Case 1), the impedance mismatch is calculated by using Equation (3). In order to calculate the impedance mismatch numerically Equation (4) can be used as well. Mismatch uncertainty calculation has normal distribution when Equation (4) is used.

$$M = 1 + |\Gamma_A|^2 + |\Gamma_{DUT}|^2 - 2.|\Gamma_A|.|\Gamma_{DUT}|.cos(\Theta_A + \Theta_{DUT}) \quad (4)$$

If only the magnitude of Γ_{DUT} is known (Case 2), the impedance mismatch (M) is assumed to be 1 (one). In this situation, the uncertainty of the impedance mismatch can be calculated using the magnitude of the reflection coefficient of the signal generator and the magnitude of the reflection coefficient of the power sensor. The magnitude of the reflection coefficient of the signal generator can be obtained by using the standing wave ratio of the signal generator, which is given into the data sheets of the signal generator. This mismatch uncertainty has a U-shaped distribution. In order to calculate the power uncertainty, the uncertainty of the mismatch, which has a U-shaped distribution, should be transformed into a normal distribution by dividing it by $\sqrt{2}$.

In this study, the measurement results taken by the AutoRFPower software and calculated actual powers are given in Table 2. The P_{DUT} values were calculated for both impedance mismatch calculation cases. The vectorial reflection coefficient measurement of the signal generator is so tricky. Most laboratories do not prefer the vectorial reflection coefficient measurement, and they like to use the standing wave ratio of the manufacturer in the manufacturer data sheets. The complex reflection coefficient of the signal generator was not measured in this study. A calibrated attenuator was connected to the output port of the signal generator. In order to check the AutoRFPower software's uncertainty calculation capability for this study at Case 1, the output reflection coefficient of the attenuator was accepted that the complex reflection coefficient of the signal generator. Impedance mismatch error was calculated by the output reflection coefficient of the attenuator (in complex) and the reflection coefficient of the DUT PS (in complex). Calculated P_{DUT} values are given for two different power levels as 0 dBm and 5 dBm and Case 1 and Case 2 in Figure 4 and Figure 5, respectively.

The reading powers (P_{READ}) differ from the calculated actual power (P_{DUT}) in Figure 4 and Figure 5. The P_{READ} contains the power sensor losses and the impedance mismatch errors. In order to eliminate these errors using Equation (2), P_{DUT} was obtained as a difference from P_{READ}. There is a slight difference between the calculated P_{DUT} for Case 1 and the calculated P_{DUT} for Case 2. These differences come from the different impedance mismatch calculations as given above.

Table 2. Calculated RF power values according to the mismatch calculation cases

Freq. (MHz)	Applied Power from Signal Generator (DUT) (dBm)	Reading Power P_{READ} (mW)	CF_{STD}	S_{21A} (Linear Magnitude)	Calculated Power P_{DUT} (mW) @ Case 1	Calculated Power P_{DUT} (mW) @ Case 2
50	0	0.092038	1.0000	0.3184366	0.98725	0.98580
1000	0	0.090822	0.9816	0.3176025	1.00163	1.00024
5000	0	0.080260	0.9592	0.3157301	0.93193	0.92623
10000	0	0.076380	0.9365	0.3132852	0.89847	0.90027
15000	0	0.071097	0.9210	0.3113364	0.88172	0.87236
18000	0	0.068634	0.9150	0.3108678	0.83852	0.82781
50	5	0.294230	1.0000	0.3184366	3.15470	3.15143
1000	5	0.288524	0.9816	0.3176025	3.18116	3.17756
5000	5	0.254833	0.9592	0.3157301	2.95980	2.94086
10000	5	0.242381	0.9365	0.3132852	2.85191	2.85686
15000	5	0.227139	0.9210	0.3113364	2.81639	2.78701
18000	5	0.220456	0.9150	0.3108678	2.69217	2.65898

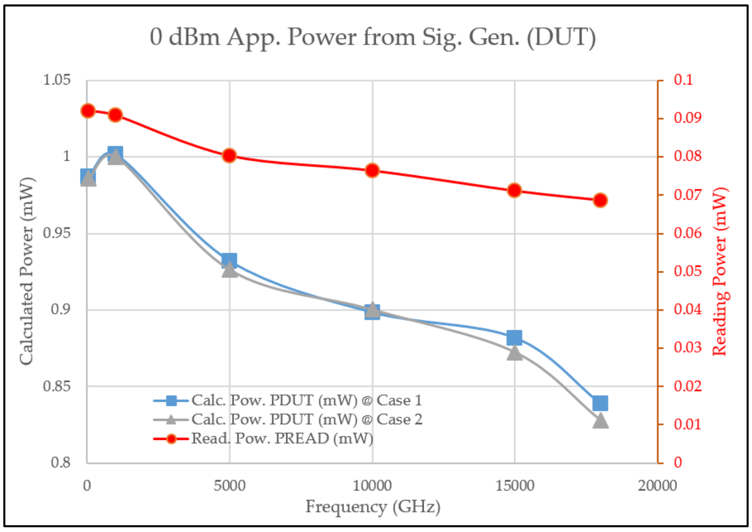

Figure 4. 0 dBm calculated DUT output powers for Case 1 and Case 2

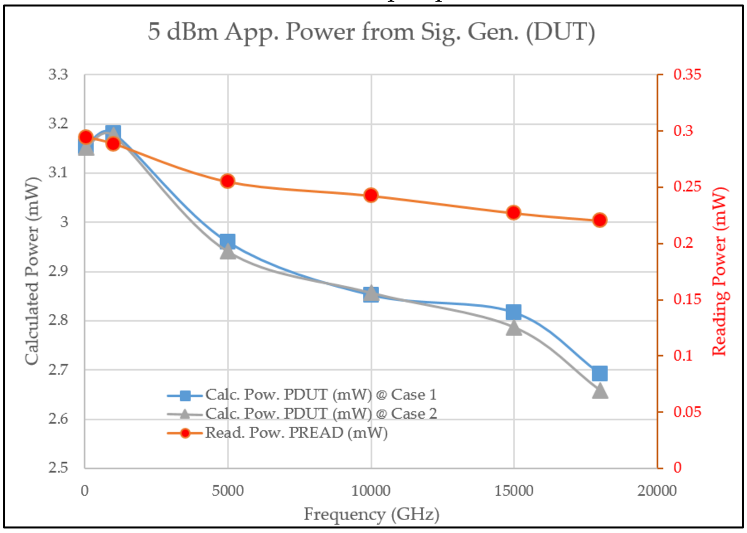

Figure 5. 5 dBm calculated DUT output powers for Case 1 and Case 2

3. COMPARISON OF UNCERTAINTY EVALUATION METHODS

To calculate uncertainty with the AutoRFPower software, two uncertainty calculation codes, implementing the LoP and MCS methods, were included in the software.

Combined uncertainties were calculated using Equation (1) and Equation (5) for LoP and MCS methods, respectively at this study.

$$u\,(k=1) = \sqrt{\sum_{i=1}^{n} u_{Ri}^{2}} \tag{5}$$

where *u(k=1)* is the combined uncertainty with coverage factor one (68 % reliability), and u_{Ri} is the uncertainty value of each component in the model function randomly generated and u_{Ri} has different distribution.

Four uncertainty calculations given below were performed in this study.

1. According to the GUM LoP method, the first uncertainty calculation was done using manual measurement data and the MS Excel application.
2. The Oracle Crystal Ball application calculated the second uncertainty using the MCS method (OMm).
3. The third uncertainty calculation was made by AutoRFPower software. AutoRFPower can calculate the uncertainty using the GUM LoP method (ALm).
4. The fourth uncertainty calculation was made by AutoRFPower software alone. The AutoRFPower software can also calculate the uncertainty using the GUM MCS method (AMm).

For four uncertainty calculations, the same RF power measurement data were used for Case 1 and Case 2 determined in this study.

Uncertainty components and their statistical distributions are given below;

- u_{PREAD} – uncertainty of repeated power measurement, Gaussian
- u_{PMacc} – uncertainty of accuracy of the power meter, rectangular
- u_{PMres} – uncertainty of resolution of the power meter, rectangular
- u_{CFSTD}- uncertainty of CF of the STD PS, Gaussian
- u_{S21A}- uncertainty of the forward transmission coefficient of attenuator, Gaussian
- $u_{|\Gamma_A|}$- uncertainty of the magnitude of Γ_A, Gaussian
- $u_{|\Gamma_{DUT}|}$- uncertainty of the magnitude of Γ_{DUT}, Gaussian
- u_{Θ_A}- uncertainty of the phase of Γ_A, Gaussian
- $u_{\Theta_{DUT}}$- uncertainty of the phase of Γ_{DUT}, Gaussian
- u_M- uncertainty of the impedance mismatch of connector where Γ_{DUT} is known as magnitude, U shape

In order to validate the LoP uncertainty calculation of AutoRFPower, manually calculated LoP uncertainty by using MS Excel and AutoRFPower LoP uncertainty calculation (ALm) were compared. There was a good agreement at the level of 10^{-4} differences. This difference is an acceptable value that the ALm could be used as a reference for comparisons.

In order to compare the uncertainty calculations at the first step in this study, ALm uncertainty were compared with AMm uncertainty. ALm uncertainty calculations, which were validated with MS Excel manual calculation, were used as a reference value for comparison.

In the second step of comparison, OMm uncertainty was compared with ALm uncertainty using the same measurement data. Calculated uncertainty values were given in Table 3 and Table 4 according to the cases with coverage factor two (95 %). Uncertainty differences from the reference uncertainty were given in Table 5. In this study, only the difference between the calculated uncertainties were given as evaluation method for comparison results.

Table 3. Calculated uncertainties according to the LoP and MCM with developed software and MC simulator application for Case 1

Frequency (MHz)	Calculated Power PDUT (mW) Case 1	ALm Unc. of Calculated Power (mW) Case 1	AMm Unc. of Calculated Power (mW) Case 1	OMm Unc. of Calculated Power (mW) Case 1
50	0.98725	0.01202	0.01203	0.01204
1000	1.00163	0.01243	0.01245	0.01243
5000	0.93193	0.01478	0.01481	0.01480
10000	0.89847	0.01426	0.01424	0.01427
15000	0.88172	0.03200	0.03201	0.03207
18000	0.83852	0.02267	0.02271	0.02268
50	3.15470	0.03837	0.03836	0.03843
1000	3.18116	0.03943	0.03938	0.03931
5000	2.95980	0.04689	0.04703	0.04683
10000	2.85191	0.04520	0.04520	0.04520
15000	2.81639	0.10220	0.10232	0.10215
18000	2.69217	0.07277	0.07276	0.07278

Table 4. Calculated uncertainties according to the LoP and MCM with developed software and MC simulator application for Case 2

Frequency (MHz)	Calculated Power PDUT (mW) Case 2	ALm Unc. of Calculated Power (mW) Case 2	AMm Unc. of Calculated Power (mW) Case 2	OMm Unc. of Calculated Power (mW) Case 2
50	0.98580	0.01206	0.01209	0.01209
1000	1.00024	0.01412	0.01411	0.01413
5000	0.92623	0.03606	0.03619	0.03610
10000	0.90027	0.02156	0.02159	0.02159
15000	0.87236	0.06486	0.06500	0.06488
18000	0.82781	0.09185	0.09188	0.09193
50	3.15143	0.03851	0.03845	0.03856
1000	3.17756	0.04481	0.04473	0.04470
5000	2.94086	0.11449	0.11445	0.11458
10000	2.85686	0.06840	0.06853	0.06844
15000	2.78701	0.20720	0.20712	0.20749
18000	2.65898	0.29503	0.29472	0.29510

Table 5. Calculated uncertainty differences from reference uncertainty

Frequency (MHz)	AMm-ALm @ Case 1	OMm-ALm @ Case 1	AMm-ALm @ Case 2	OMm-ALm @ Case 2
50	0.00001	0.00002	0.00003	0.00003
1000	0.00002	-0.00000	-0.00001	0.00001
5000	0.00003	0.00002	0.00013	0.00004
10000	-0.00002	0.00001	0.00003	0.00003
15000	0.00001	0.00007	0.00014	0.00002
18000	0.00004	0.00001	0.00003	0.00008
50	-0.00001	0.00006	-0.00006	0.00005
1000	-0.00005	-0.00012	-0.00008	-0.00011
5000	0.00014	-0.00006	-0.00004	0.00009
10000	-0.00000	-0.00000	0.00013	0.00004
15000	0.00012	-0.00005	-0.00008	0.00029
18000	-0.00001	0.00001	0.00003	0.00003

The uncertainties calculated with the MCS method using the uncertainty calculation module of the AutoRFPower software, were plotted for each frequency. Some selected graphics are given in Figures 6-7 for Case 1 and Case 2, respectively. It has been seen in the graphics that the uncertainties obtained by the MCS method calculation do not have a homogeneous normal distribution. Non-homogenous normal distribution can be seen using the triangles drawn in the figures, where the triangles are symmetrical, but the top corners of the triangles are not at the top of the histograms. In order to obtain the homogeneous normal distribution, more than 10^5 times power measurement should be performed instead of the generated randomized power values from 10 times power measurement.

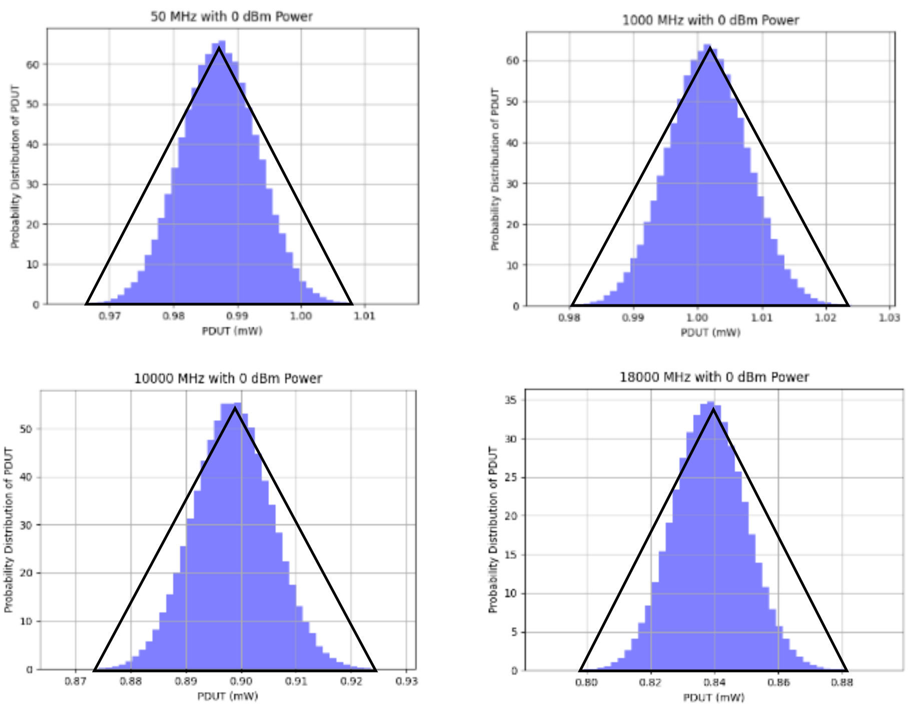

Figure 6. MCS Uncertainty values for Case 1 @ 0 dBm and different frequencies

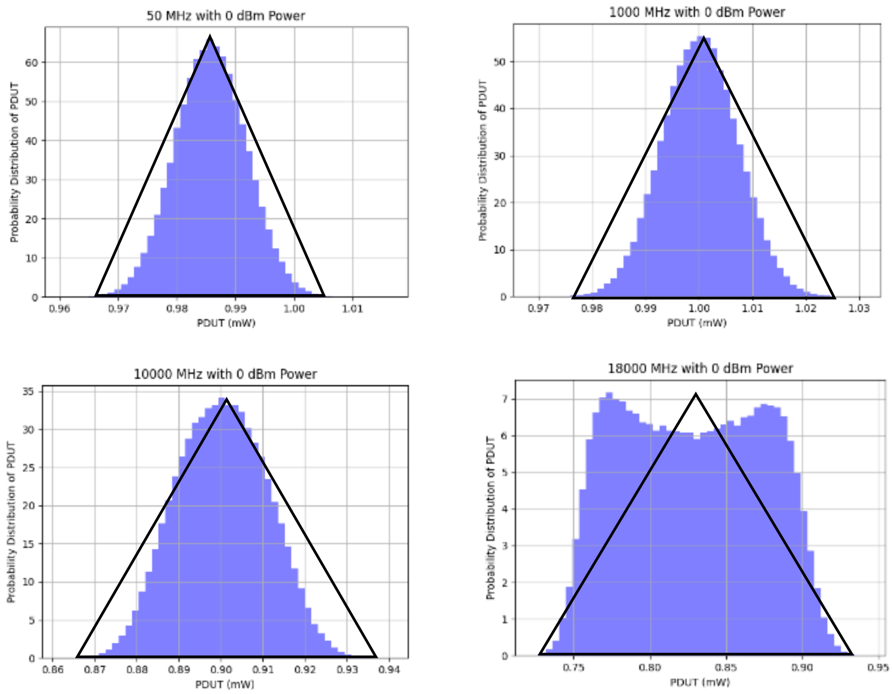

Figure 7. MCS Uncertainty values for Case 2 @ 0 dBm and different frequencies

4. CONCLUSION

This study validated the measurement results of the AutoRFPower software and uncertainty calculation results carried out by AutoRFPower according to the LoP and MCS methods. The AutoRFPower software was being tested with this study, and it will be available from SPARK (www.sparkmeasure.com). In addition, OMm uncertainties and AMm and ALm uncertainties calculated with AutoRFPower were compared.

In comparisons, it was observed that there was a 10^{-4} level difference between the LoP and the MCS method uncertainties.

When the uncertainty calculation results of the AutoRFPower software were compared with the OCB uncertainty results, it was observed the uncertainties obtained by MCS were the same as the OCB uncertainties. Moreover, it was noticed that the uncertainties evaluated according to the MCS method had a non-symmetrical normal distribution, contrary to the assumption of symmetrical normal distribution according to LoP GUM. On the other hand, in the uncertainty calculation by using the MSC method, it has been observed that the statistical distribution of the uncertainty changes depending on the dominant component of the parameters in the model function used for the uncertainty calculation.

AutoRFPower software was initially developed for the Keysight, Agilent, and HP brand mark devices. This software is being improved in other European-funded research projects by other National Metrology Institutes and designated institutes such as NSAI (Ireland), CMI (Chezh Republic), Trescal (Denmark), IMBiH (Bosnia & Herzegovina), and SIQ (Slovenia). Additional measurement devices are being added to the software in an ongoing European-funded project. AutoRFPower software can calculate the ALm and AMm uncertainty with the new brand devices by new users in future.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Credit Authorship Contribution Statement

CRediT (Contributor Roles Taxonomy) was introduced with the intention of recognizing individual author contributions, reducing authorship disputes and facilitating collaboration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

There is no any data from a data repository.

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