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ESTIMATION OF THE UNCERTAINTY OF MEASUREMENT IN A TWO-CHANNEL SYSTEM FOR TESTS ON THE INTENSITY OF INFRARED RADIATION

Key words

Uncertainty of measurement, infrared radiation, infrared detector.

Abstract

Execution of long-term tests on infrared radiation waves requires the use of a stable transceiver circuit for infrared radiation. The unit developed by the authors of this paper is an example of possible instruments that can be used in such tests. The system is composed of a stabilized supply source for a transceiver circuit and a programmed temperature change option for output signals. The tests were carried out for a two-channel radiation transceiver with *860* and *950 nm* wavelengths. The results obtained were analysed and their expanded uncertainties were determined for a *99%* level of confidence, based on the assumed uncertainty budgets. Standard uncertainties were determined using calculation methods type A and B.

After verification, the developed stand can be used to test infrared radiation for two wavelengths. It can also find application in the design of bigger control systems, where it can play the role of a measurement module. The examples of

such applications include, inter alia, tests on the transmission and reflection of the infrared light.

Introduction

The result of measurement for any physical quantity differs from its actual value. Therefore, the full measurement result is given together with the uncertainty of the estimate. Measurement uncertainty can be caused by a number of the following factors [1]:

- Incomplete definition of the measured value;
- Imperfect execution of the definition of the measured value;
- Unrepresentative sampling;
- Incomplete knowledge of environmental influence on the measurement, or imperfect measurement of environmental conditions;
- Subjective errors in readings;
- Finite resolution or instrument excitability threshold;
- Inaccurate values assigned to calibrators and reference materials;
- Inaccurate constants and other parameters obtained from an external source, and used in data processing procedures;
- Approximations and simplified assumptions inherent in the method and the measurement procedure; and,
- Changes of values during observations of the value measured in repeated seemingly identical conditions.

After eliminating the known systematic errors, the standard uncertainty of an estimate can be determined with two methods, i.e. "Type A" and "Type B" methods [2]. The Type A evaluation method is based on statistical analysis in which Gaussian and t-Student distributions are used for, respectively, a large number of measurements and few measurements. Determination of uncertainty using the Type A evaluation method requires the calculation of an arithmetic mean for an "n" number of measurements "x_k" with the following dependency:

$$\mathrm{x}_{sr} = \frac{1}{n}\sum_{k=1}^{n} x_k \tag{1}$$

Since measurements of value "x" differ, as a results of, e.g. interactions or changes in entry values, one needs to calculate a positive square root from the estimated standard experimental deviation of the set of measured results *($\sigma(x_k)$)* that characterizes the deviation of "x" from mean value "x_{sr}". The standard experimental deviation is described with the following formula:

$$\sigma(x_k) = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x_k - x_{sr})^2} \tag{2}$$

The calculation of standard experimental deviation enables the determination of the standard experimental deviation of the mean value obtained from the following dependency:

$$u_A(x_{sr}) = \frac{\sigma(x_k)}{\sqrt{n}} \tag{3}$$

The result of this estimated standard experimental deviation of the mean value is called the "Type A standard uncertainty."

The Type B method uses a pool of information available [2], with which changes of input value "*x*" can be determined, and which are fixed and unknown in the experiment. This information may include the following:

- Previous measurement data;
- Experience and knowledge of phenomena and properties of relevant materials and instruments;
- Manufacturer's specifications;
- Data from calibration and certification; and,
- Uncertainties assigned to reference data taken from handbooks.

The use of analogue measuring instruments for the determination of the measured value is always connected with the introduction of certain limitations to measurement precision that are determined by a maximum permissible error Δ_{gr}, which is based on which the standard uncertainty $u(x_i)$ of the result of a measurement conducted with a measuring instrument is calculated. Proper juxtaposition of standard uncertainties forms a complex standard uncertainty $u_c(y)$. Determination of the complex standard uncertainty stems from the correlation or the lack of a correlation of input values affecting the result of the measurement. When these values are not correlated, it can be assumed that complex standard uncertainty $u_c(y)$ is a positive square root from the complex variance, expressed with the following dependency [1]:

$$u_c^2(y) = \sum_{k=1}^{n} \left(\frac{\partial f}{\partial x_k} \right)^2 u^2(x_k) \tag{4}$$

When input values are correlated, the variance is expressed with the following equation [1]:

$$u_c^2(y) = \sum_{k=1}^{n} \left(\frac{\partial f}{\partial x_k} \right)^2 u^2(x_k) + \sum_{\substack{i=1 \\ k=1}}^{n} \frac{\partial f}{\partial x_k} \frac{\partial f}{\partial x_i} u(x_k, x_i) \tag{5}$$

Where $u(x_k, x_i)$ is the covariance estimate connected with "x_k" and "x_i".

Determination of the complex standard uncertainty helps one to obtain expanded uncertainty U [2]. This value is equal to the complex standard uncertainty multiplied by the coefficient of expansion “*k*,” that is selected, depending on the required level of confidence:

$$U = ku_c(y) \tag{6}$$

The outcome of the measurement with the determined expanded uncertainty is presented in the following form:

$$Y = y \pm U \tag{7}$$

The analysis of the calculation of uncertainty presented above is recommended by the guide GUM [1]. This analysis aimed at the estimation of uncertainty in the measurement of infrared radiation (IR) in two independent channels and with different radiation wavelength.

1. Description of the test stand

The two-channel test stand developed by the authors for infrared radiation measurements is composed of a system of a photo emitter and a system of a photo detector (Fig. 1). In the first of them, a stabilized current source, a photo emitter (i.e. the electroluminescent diode for infrared radiation), a transistor switch, and a generator controlling its work can be found [3]. The output waveforms of the generator are programmed by the PLC based on the PWM modulation.

The system of the photo emitter is responsible for the creation of the modulated light of infrared radiation. It also helps in ensuring a stable level of intensity of the infrared source (Channel 1 – CQY37N; Channel 2 – VSLY3850), in the range of nominal work parameters supplied by the manufacturer [4].

The photo detector unit, on the other hand, is composed of a stabilized supply source, a voltage source, a photo detector (phototransistor), and the voltage measurement unit. The aim of the photo detector system is to detect the intensity of the infrared radiation.

It can be assumed that, when leaving the phototransistor, the current is directly proportional to the intensity of the light, at the constant voltage of polarization of the semiconductor junction, and that it is a measure of the intensity of infrared radiation for a wavelength tested. Measurement of the current in the photo detector unit is conducted using an indirect method in which a voltage value is measured on a resistor with a constant and known value of resistance.

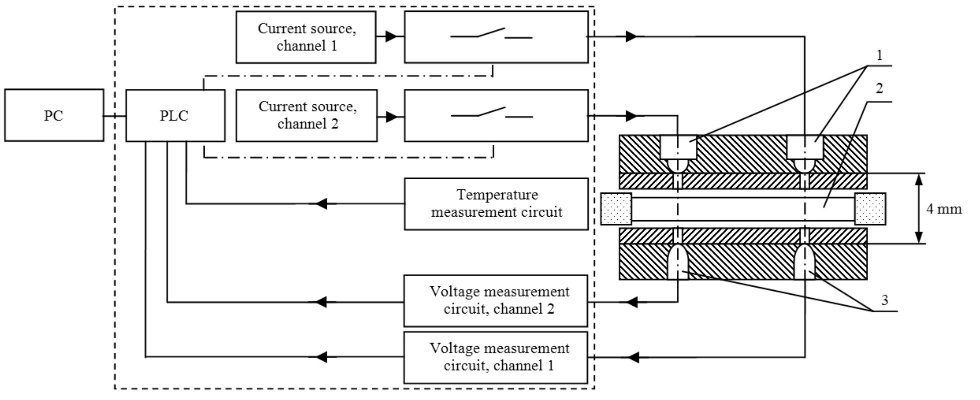


Fig. 1. Schematic of the two-channel test stand for infrared radiation measurements. 1 – photo emitters, 2 – reference material (*10%* Densitometric Screen S/N012; Eclipse Laboratories Inc.), 3 – photo detectors

2. Estimation of uncertainty in radiation measurement

The authors carried out long-term tests on IR intensity with a two-channel stand, during which the values of the current were recorded by the photo detector, and a programmed temperature of current indications was corrected. For results obtained in this way, uncertainties were estimated using Type A and Type B methods. The Type A method was used to determine standard experimental deviation of the mean from $n = 87501$ verification measurements of current intensity I_{1W} and I_{2W} sampled at *(3 s)* intervals. Average arithmetic values I_{1Wsr} and I_{2Wsr} were estimated from "*n*" measurements based on dependency (1), their standard deviations $\sigma(I_{1W})$ and $\sigma(I_{2W})$ were determined according to dependency (2), and standard uncertainties Type A (average standard deviations) $u_A(I_{1W})$ and $u_A(I_{2W})$ were estimated based on dependency (3). These results are presented in Table 1.

The Type B method was used to estimate standard measurement uncertainty for a phototransistor (SFH309FA) [5], for a light-voltage converter circuit, and a 12-bit A/C converter of the PLC. Additionally, the precision of measurements of IR intensity depended on the distance between the photo emitters and the photo detectors.

Table 1. Comparison of average arithmetic values, standard deviations, and standard uncertainties of the current measurements I_{1W} and I_{2W}

I_{1Wsr} [mA]	I_{2Wsr} [mA]	$\sigma(I_{1W})$ [mA]	$\sigma(I_{2W})$ [mA]	$u_A(I_{1W})$ [mA]	$u_A(I_{2W})$ [mA]
0.7935	0.7027	0.0257	0.0423	0.00009	0.00014

The temperature range of the light-voltage converter assumed was between *13* to *26°C*, where the phototransistor had stable, linear characteristics. Therefore, the precision of the measurement was mainly influenced by the precision of the resistor of the light-voltage converter and the precision of the A/C converter. The maximum permissible error of the applied resistor with nominal resistance of *330 Ω* and a tolerance of ± *1%* was $\Delta_{gr}R = 3.3\ \Omega$, while the maximum permissible error of the A/C converter ($\Delta_{gr}U$) was determined on the basis of catalogue data for the A/C module (TM2AMM6HT) of the PLC [6]. The manufacturer assumed a measurement error of *1%* and the resolution of the converter $LSB = 2.5\ mV$. The average indication of the measured voltage on the measurement resistor was, for the first measurement channel, $\bar{U}_{1K} = 395.6\ mV$, and for the second channel, $\bar{U}_{2K} = 336.5\ mV$. Since current intensity was estimated with indirect measurements, the size of the measured current was determined as a function of other directly measured quantities. Using Ohm's law, the authors estimated dependencies between mean current values measured in two measurement channels:

$$\bar{I}_{1K} = \frac{\bar{U}_{1K}}{R} = 1.199mA \tag{8}$$

$$\bar{I}_{2K} = \frac{\bar{U}_{2}}{R} = 1.020mA \tag{9}$$

Then, the maximum permissible errors were estimated in the following manner:

$$\Delta_{gr}U_{1K} = \frac{a \cdot \bar{U}_{1K}}{100} + n \cdot LSB = 0.0065V \tag{10}$$

$$\Delta_{gr}U_{2K} = \frac{a \cdot \bar{U}_{2K}}{100} + n \cdot LSB = 0.0059V \tag{11}$$

The LM35DZ temperature sensor with the measurement range from *0* to *100ºC* and precision *±0.9ºC* [7] was used for the measurement of temperature. Sensor maximum permissible error was estimated ($\Delta_{gr}T = 0.9ºC$), and the following temperature correction functions were assumed for the two measurement channels used: $I_{1WK} = -0.0081T+0.833$ for Channel 1, and $I_{2WK} = -0.0131T+0.775$ for Channel 2.

The error resulting from the changes in the distance between the photo emitter and photo detector was insignificant due to the application of a stiff frame for both photo elements; therefore, it was not taken into consideration at the time of uncertainty estimation (its value was below *2%* of the share in the complex standard uncertainty [8]).

Standard uncertainties were determined based on maximum permissible errors and considering rectangular probability distribution [9], and received the following values:

$$u_B(R) = \frac{\Delta_{gr} R}{\sqrt{3}} = 1.91\Omega \tag{12}$$

$$u_B(T) = \frac{\Delta_{gr} T}{\sqrt{3}} = 0.52°C \tag{13}$$

$$u_B(U_{1K}) = \frac{\Delta_{gr} U_{1K}}{\sqrt{3}} = 0.0037V \tag{14}$$

$$u_B(U_{2K}) = \frac{\Delta_{gr} U_{2K}}{\sqrt{3}} = 0.0034V \tag{15}$$

Using the law of propagation of uncertainty [1], the authors determined the complex uncertainty for measurements of correlated functions $I_{1K}(T)$ and $I_{2K}(T)$.

Covariance associated with estimates of voltage and resistance input values was considered to be insignificant, hence complex uncertainty of measurement took the following form:

$$u(I_{1K}) = \sqrt{\left(\frac{\partial I_{1K}}{\partial U_{1K}}\right)^2 \cdot u_B^2(U_{1K}) + \left(\frac{\partial I_{1K}}{\partial R}\right)^2 \cdot u_B^2(R) + \left(\frac{\partial I_{1WK}}{\partial T}\right)^2 \cdot u_B^2(T) + u_A^2(I_{1W})} = 0.014mA \tag{16}$$

$$u(I_{2K}) = \sqrt{\left(\frac{\partial I_{2K}}{\partial U_{2K}}\right)^2 \cdot u_B^2(U_{2K}) + \left(\frac{\partial I_{2K}}{\partial R}\right)^2 \cdot u_B^2(R) + \left(\frac{\partial I_{2WK}}{\partial T}\right)^2 \cdot u_B^2(T) + u_A^2(I_{2W})} = 0.014mA \tag{17}$$

Because most values measured could be found near the centre of the range of variation, and the conditions of the Central Limit Theorem were met, the authors assumed normal distribution as a model of the input value probability distribution [2]. Therefore, expanded uncertainties were estimated for the *99%* level of confidence and the coefficient of expansion $k_p = 2.576$ [1]. The values obtained are the following:

$$U(I_{1K}) = k_p \cdot u(I_{1K}) = 0.036mA \tag{18}$$

$$U(I_{2K}) = k_p \cdot u(I_{2K}) = 0.036mA \tag{19}$$

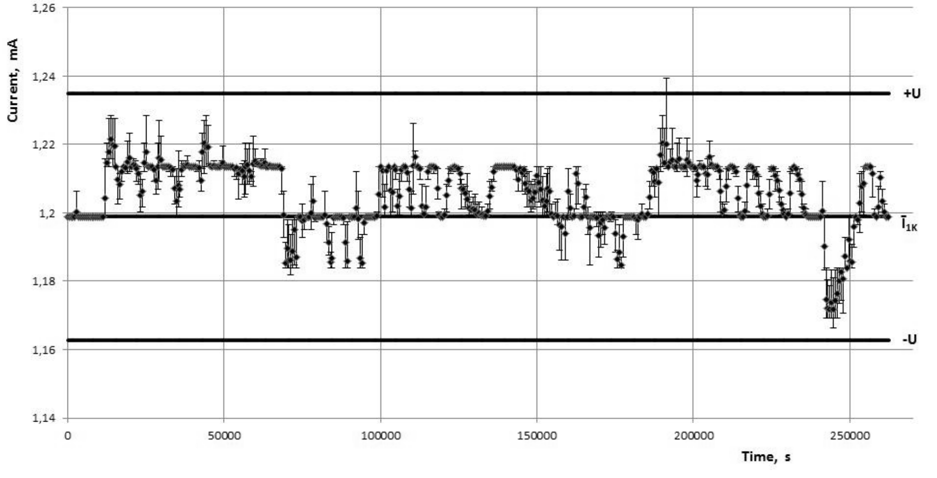
The value of the IR current intensity measured in two channels and its expanded uncertainties are as follows:

$$I_{1K} = \bar{I}_{1K} \pm U(I_{1K}) = 1.199 \pm 0.036 mA \quad (20)$$

$$I_{2K} = \bar{I}_{2K} \pm U(I_{2K}) = 1.020 \pm 0.036 mA \quad (21)$$

Figure 2 presents the mean values of the IR current intensity measured in two channels and their expanded uncertainties together with the set of measurement data.

a)



b)

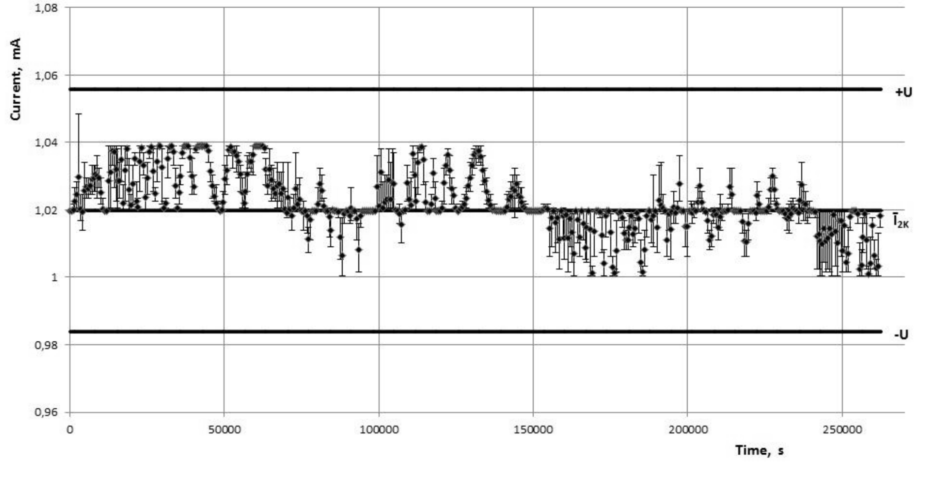


Fig. 2. Graphs of measurement data of the IR current with their expanded uncertainties. a) the data collected for the measurement channel 1, b) the data collected for the measurement channel 2

The waveforms of measurement data presented confirm the correctness of the adopted model of input value probability distribution, because these values are mainly concentrated around the centre of the variation range.

The verification of the measurement system and analysis of measurement uncertainty allowed further indications of areas of the most measurement discrepancies. These points overlap with the areas of extreme temperature functions, where the derivative of the temperature function changes its sign.

Summary

The study on the transceiver circuit for infrared radiation focused on the determination of dependencies between current intensity of the IR, and time, and temperature. The tests allowed the authors to determine operational characteristics of the transceiver circuits for two wavelengths of infrared radiation, *860* and *950 nm*. The investigations were carried out using a *10%* transmittance filter by Eclipse Laboratories Inc. (*10%* Densitometric Screen S/N012). In the system developed, the values of the current of the photo detector circuit were recorded. Additionally, a programmed temperature correction system was implemented, which enabled procurement of stable readings in the temperature range from *13* to *26°C*. Verification of the stand during long-term tests allowed the authors to obtain positive results, because current output waveforms for two measurement channels were time and temperature stable.

For each result obtained, expanded measurement uncertainties were estimated for a *99%* level of confidence. This enabled the procurement of the following results for current intensities: *1.199 ±0.036 mA* for Channel 1, and *1.020 ±0.036 mA* for Channel 2.

The estimation of current measurement uncertainties enabled the selection of the least favourable conditions of operation, which were defined as a moment when the derivative of the temperature function changes its sign. It is the source of the greatest interferences of a measurement signal.

The developed algorithms of IR intensity measurement allow the reduction of these interferences and help in obtaining a temperature stable output signal.

As verified, the developed two-channel transceiver system for infrared radiation can be used in the systems for infrared transmission or the reflection of elastic materials [10, 11] and tests on light transmission of biological and chemical samples [12].

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Szacowanie niepewności pomiarowej dwukanałowego układu do badania natężenia promieniowania podczerwonego

Słowa kluczowe

Niepewność pomiaru, promieniowanie podczerwone, detektor podczerwieni.

Streszczenie

Realizacja długookresowych badań monochromatycznej fali promieniowania podczerwonego wymaga stabilnego układu nadawczo-odbiorczego. Jednym z rozwiązań jest opracowany taki układ, w którym obok stabilizowanych źródeł zasilania toru nadawczego i odbiorczego zastosowano programową stabilizację

temperaturową jego sygnałów wyjściowych. Przedmiotem badań był dwukanałowy układ nadawczo-odbiorczy promieniowania o długościach fal *860* i *950 nm*. Wyniki przeprowadzonych badań układu poddano analizie i na podstawie oszacowanych budżetów niepewności wyznaczono ich rozszerzone niepewności o *99%* poziomie ufności. Niepewności standardowe wyznaczono z oszacowań metodami typu A i B. Zweryfikowane stanowisko pomiarowe do badania promieniowania podczerwonego o dwóch długościach fal, można wykorzystywać w większych systemach sterowania, w których układ ten pełniłby rolę jednego z modułów pomiarowych. Przykładem takich aplikacji mogą być systemy do badania przepuszczalności lub odbicia światła podczerwonego.