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Examples of uncertainty calculations in thermographic measurements

Streszczenie. *We współczesnej metrologii istnieją dwie główne teorie - teoria błędów pomiarowych i teoria niepewności pomiaru. Celem niniejszego artykułu jest przedstawienie praktycznych przykładów estymacji rozszerzonej niepewności standardowej i jej składników występujących w bezdotykowych pomiarach temperatury dokonywanych za pomocą kamer termowizyjnych. W niniejszej pracy przedstawiono wyniki obliczeń dla najbardziej typowych warunków występujących w praktyce. W każdym przykładzie obliczono 95% poziom ufności. Umożliwiło to uniwersalną ocenę dokładności zgodnie z wytycznymi podanymi przez międzynarodowe organizacje metrologiczne.* ***Przykłady obliczeń niepewności przy pomiarach termograficznych***

Abstract*. In the contemporary metrological sciences there are two main theories - the theory of measurement errors and the measurement uncertainty theory. The purpose of this paper is to show the examples of estimation of the combined standard uncertainty and its components occurred in the non-contact temperature measurements made by means the infrared cameras. In this work the calculations conducted at the most common conditions existed in practical situations were presented. In each example the 95% coverage interval was calculated. It enabled the universal accuracy assessment in accordance with the guidelines of the international metrological organizations.*

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Słowa kluczowe: niepewności pomiarów termograficznych, termografia w podczerwieni, termowizja, bezstykowy pomiar temperatury.
Keywords: uncertainties in thermographic measurements, infrared thermography, thermovision, non-contact temperature measurements.

Introduction

1.1. Analysis of the measurements accuracy in the presence of the random interactions

In this work the static model of thermographic measurement is presented. The static model (i.e. the model in which a detector integration time is long enough compared with a time constant of infrared detector) can be expressed as a function of five input variables:

$$T_{ob} = f(\varepsilon, T_0, T_{atm}, \omega, d) \tag{1}$$

where: T_{ob} – object temperature (K), ε – band emissivity of the object surface, T_o – ambient temperature (K), T_{atm} – temperature of atmosphere (K), ω – relative humidity, d – camera-to-object distance (m).

In equation (1) the model of the atmosphere transmission can be calculated using a complex approximated functions delivered by a FLIR company [7]. Then, the model of atmospheric transmission can be described as the following simplified formula:

$$P_{atm} = f(\omega, d, T_{atm}) \tag{2}$$

where: P_{atm} – an atmospheric transmission coefficient.

In practice, the measurement uncertainty can be defined as [4]:

$$u(x_i) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x-\overline{x})^2} \tag{3}$$

where: x_i – a result of a single measurement, N – the number of measurements.

Additionally, when we will assume a lack of the correlations between the input variables of measurement model, we can define the combined standard uncertainty, as a positive value of the square root from the combined variance, described as:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \tag{4}$$

where $f(x_1, x_2, \ldots, x_n)$ is a measurement model.

The expanded uncertainty define the limits of the coverage interval at the given level of confidence, the most commonly at 95%. The expanded uncertainty can be expressed as the following equation:

$$U = k u_c(y) \tag{5}$$

where: k – the expansion coefficient.

Unfortunately, in most cases, the probability distribution of the output variable of measurement model remains unknown. Therefore, the Joint Committee for Guides in Metrology (JCGM) developed the document [4], in which, the method of the propagation of distributions is featured.

This method allows for correct estimation of accuracy including the following cases:

- the partial derivatives are countless,
- the probability distribution of the output variable is not Gaussian,
- the measurement model is strongly nonlinear.

The evaluation of the measurement uncertainty with the method for the propagation of distributions can be divided into the following stages [4]:

- define of the measurand (the output quantity of the measurement),
- define of the input variables of the measurement model,
- define of the input variables of the measurement model,
- design of the measurement model,
- determination of the probability distributions of input variables,
- evaluation of the probability distribution of the output variable (measurand),
- estimation of the statistical parameters of the probability distribution of the output variable (e.g. 95% coverage interval).

1.2. The software used in the numerical calculations of the accuracy

In the examples of the numerical calculations presented below, the programs created in the MATLAB environment were used. The basic functions of the software are [1]:

- generating of the random variable realizations with the parameters and distributions defined by the user,
- reading of the calibration parameters and the reference values from the Agema File Format files,
- simulation of the data processing algorithm based on the mathematical model of the infrared camera measurement,
- estimation of the combined standard uncertainty and its components,
- estimation of the 95% coverage intervals,

- graphical presentation of the simulation results.

The screenshot of main window of the program used in the above-mentioned calculations is presented in Fig. 1. The source code of this software was attached to the work [1].

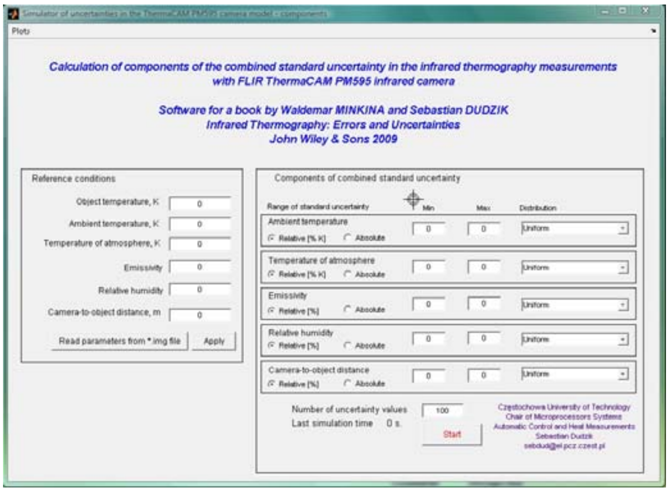

Figure 1: The main window screenshot of the program used for the calculations of the components of combined standard uncertainty in the measurements with the FLIR ThermaCAM PM595 infrared camera

2. Exemplary numerical calculations of the components of combined standard uncertainty in temperature measurements carried out with the FLIR infrared cameras

2.1. Components of the relative standard uncertainty associated with the object emissivity

Example 1

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.4. Calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the object emissivity ε_{ob}, assuming that T_{ob} = 303 K (30 ^{o}C), if we know that the relative standard uncertainty $u(\varepsilon_{ob})$ = 10%. The estimates of the remaining input variables of the model (1) should be assumed according to the table 1.

Table 1: The values of the input variables of the model (1) assumed for the calculations of the accuracy

ε	T_o [K]	T_{atm} [K]	ω	*d* [m]
0.4; 0.9	293	293	0.5	1

To solve the problem, the above mentioned program was used. The simulation results (i.e. the components of the combined standard uncertainty associated with the object emissivity ε_{ob}) were presented in Fig. 2. The value of component of the relative combined standard uncertainty associated with the object emissivity, for the relative standard uncertainty of the object emissivity $u(\varepsilon_{ob})$ = 10% and value of object emissvity $\square_{ob}$ = 0.4, can be read from Fig. 2. For the object temperature T_{ob} = 303 K (30 ^{o}C), it is equal to $u(T_{ob}) \approx$ 0.4%.

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.6. Calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the object emissivity ε_{ob}, assuming that T_{ob} = 323 K (50 ^{o}C), if we know that the relative standard uncertainty $u(\varepsilon_{ob})$ = 15%. The estimates of the remaining input variables of the model (1) should be assumed according to the table 1.

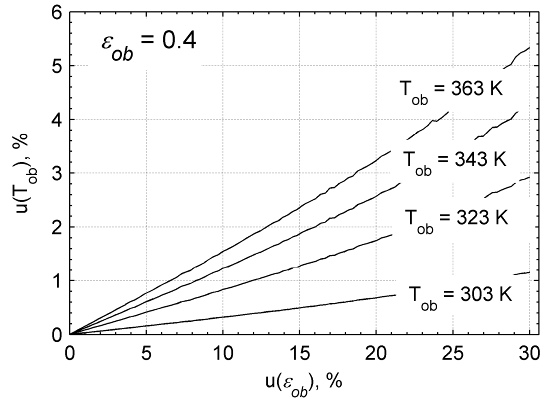

Figure 2: Component of the relative combined standard uncertainty associated with emissivity ε_{ob} (results of simulations for data collected in table 1)

Example 2

To solve the problem, the above mentioned program was used. The simulation results (i.e. the components of the combined standard uncertainty associated with the object emissivity ε_{ob}) were presented in Fig. 3. The value of component of the relative combined standard uncertainty associated with the object emissivity, for the relative standard uncertainty of the object emissivity $u(\varepsilon_{ob})$ = 15% and value of object emissivity ε_{ob} = 0.6, can be read from Fig. 3. For the object temperature T_{ob} = 323 K (50 ^{o}C), it is equal to $u(T_{ob}) \approx$ 1.3%.

Example 3

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.9. Calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the object emissivity ε_{ob}, assuming that T_{ob} = 363 K (90 ^{o}C), if we know that the relative standard uncertainty $u(\varepsilon_{ob})$ = 20%. The estimates of the remaining input variables of the model (1) should be assumed in accordance with the table 1. The component of the relative combined standard uncertainty associated with the object emissivity ε_{ob} were presented in Fig. 4. They were obtained from simulations conducted for data from table 1. As you can see in Fig. 4, the value of the component of relative combined standard uncertainty for $u(\varepsilon_{ob})$ = 20%, ε_{ob} = 0.9 and T_{ob} = 363 K (90 ^{o}C), equals to $u(T_{ob}) \approx$ 1.3%.

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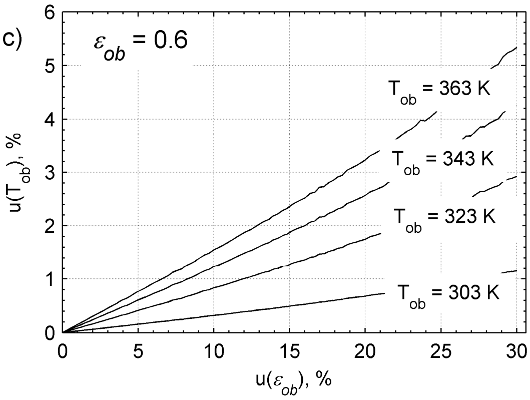

Figure 3: Component of the relative combined standard uncertainty associated with emissivity ε_{ob} (results of simulations for data collected in table 1

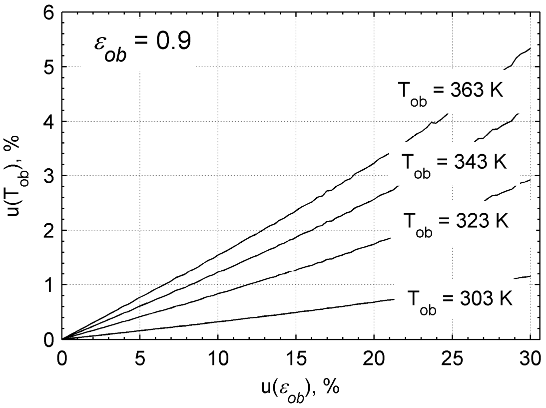

Figure 4: Component of the relative combined standard uncertainty associated with emissivity ε_{ob} (results of simulations for data collected in table 1

2.2. Components of the relative standard uncertainty associated with the ambient temperature

Example 4

In the example the emissivity of the investigated object was equal to ε_{ob} = 0.4. We should calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the ambient temperature T_o, assuming that T_{ob} = 303 K (30 ^oC), if we know that the relative standard uncertainty $u(T_o)$ = 0.5%. The values of the remaining input variables of the model 1 should be assumed according to the table 1. As above, the simulations with data from table 1 were carried out. The component of the relative combined standard uncertainty associated with the ambient temperature T_o obtained from the simulations were presented in Fig. 5. The value of the component of the relative combined standard uncertainty associated with the ambient temperature T_o, for the relative standard uncertainty of the ambient temperature $u(T_o)$ = 0.5%, and the object emissvity ε_{ob} = 0.4 can be read from Fig. 5. For the object temperature T_{ob} = 303 K (30 ^oC), the value of the component $u(T_{ob}) \approx 0.75\%$.

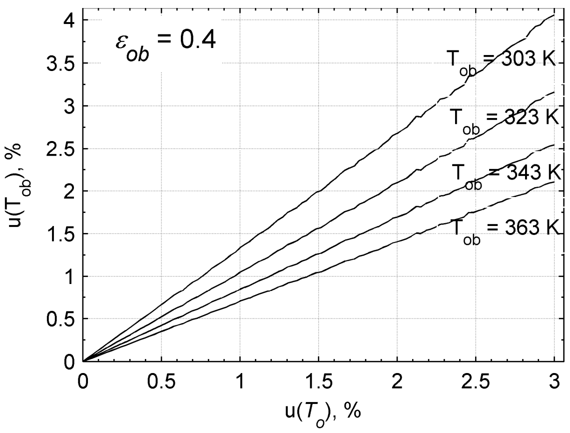

Figure 5: Component of the relative combined standard uncertainty associated with the ambient temperature T_o (results of simulations for data collected in table 1

Example 5

In this example the emissivity of the investigated object was equal to ε_{ob} = 0.6. We should calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the ambient temperature T_o, assuming that T_{ob} = 323 K (50 ^oC), if we know that the relative standard uncertainty $u(T_o)$ = 1.5%. The values of the remaining input variables of the model 1 should be assumed according to the table 1. As above, the simulations with data from table 1 were carried out. The component of the relative combined standard uncertainty associated with the ambient temperature T_o obtained from the simulations were presented in Fig. 6. The value of the component of the relative combined standard uncertainty associated with the ambient temperature T_o, for the relative standard uncertainty of the ambient temperature $u(T_o)$ = 1.5%, and the object emissivity ε_{ob} = 0.6 can be read from Fig. 6. For the object temperature T_{ob} = 323 K (50 ^oC), the value of the component $u(T_{ob}) \approx 0.75\%$.

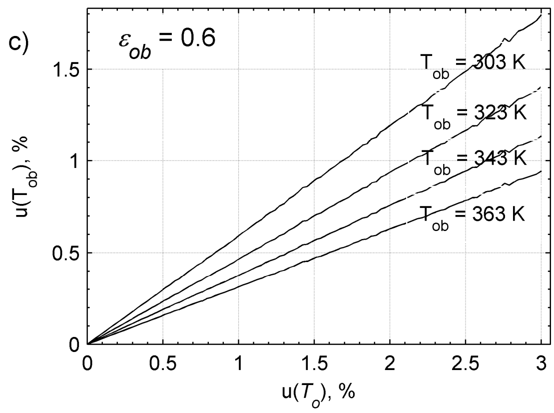

Figure 6: Component of the relative combined standard uncertainty associated with the ambient temperature T_o (results of simulations for data collected in table 1

Example 6

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.9. Calculate the uncertainty component associated with the ambient temperature T_o, assuming that T_{ob} = 323 K (50 ^oC), if we know that the relative standard uncertainty $u(T_o)$ = 2.0%. The values of the remaining input variables of the model (1) should be assumed according to the table 1. The task was resolved using the simulations and data from table 1. The components of the combined standard uncertainty associated with the ambient temperature T_o obtained from the simulations were presented in Fig. 7. The value of the component of the relative combined standard uncertainty associated with the ambient temperature T_o, for the relative standard uncertainty of the ambient temperature $u(T_o)$ = 2.0%, and the object emissivity ε_{ob} = 0.9 can be read from Fig. 7. For the object temperature T_{ob} = 323 K (50 ^oC), the value of the component $u(T_{ob}) \approx 0.11\%$.

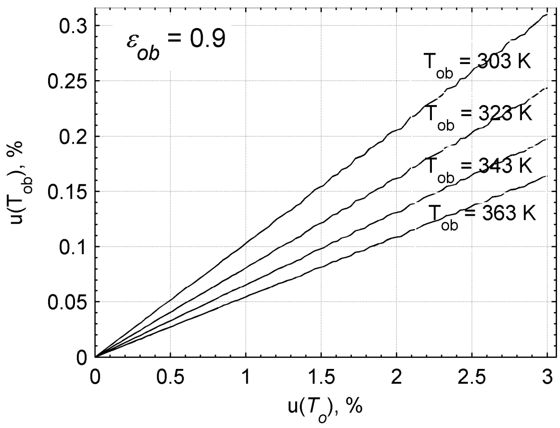

Figure 7: Component of the relative combined standard uncertainty associated with the ambient temperature T_o (results of simulations for data collected in table 1

2.3. Components of the relative standard uncertainty associated with the camera-to-object distance

Example 7

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.4. Calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the camera-to-object distance d, assuming that T_{ob} = 303 K (30 ^{o}C), if we know that the relative standard uncertainty $u(d)$ = 10%. The values of the remaining input variables of the model (1) should be assumed according to the table 1. To solve the task from this example, the simulations with data from table 1 were carried out. The component of the relative combined standard uncertainty associated with the camera-to-object distance d obtained from the simulations were presented in Fig. 8. The value of the component of the relative combined standard uncertainty associated with the camera-to-object distance d, for the relative standard uncertainty of the camera-to-object distance $u(d)$ = 10%, and the object emissivity ε_{ob} = 0.4 can be read from Fig. 8. For the object temperature T_{ob} = 303 K (30 ^{o}C), the value of the component $u(T_{ob}) \approx 0.0010\%$.

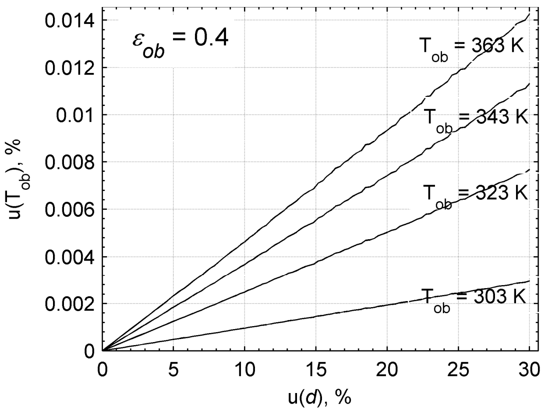

Figure 8: Component of the relative combined standard uncertainty associated with camera-to-object-distance d (results of simulations for data collected in table 1

Example 8

The temperature was measured using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.6. Calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the camera-to-object distance d, assuming that T_{ob} = 323 K (50 ^{o}C), if we know that the relative standard uncertainty $u(d)$ = 15%. The values of the remaining input variables of the model (1) should be assumed according to the table 1. To solve the task from this example, the simulations with data from table 1 were carried out. The component of the relative combined standard uncertainty associated with the camera-to-object distance d obtained from the simulations were presented in Fig. 9. The value of the component of the relative combined standard uncertainty associated with the camera-to-object distance d, for the relative standard uncertainty of the camera-to-object distance $u(d)$=15%, and the object emissivity ε_{ob} = 0.6 can be read from Fig. 9. For the object temperature T_{ob} = 323 K (50 ^{o}C), the value of the component $u(T_{ob}) \approx 0.0038\%$.

Example 9

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.9. Calculate the component of the relative combined standard uncertainty $u(T_{ob})$, associated with the camera-to-object distance d, assuming that T_{ob} = 363 K (90 ^{o}C), if we know that the relative standard uncertainty $u(d)$ = 20%. The task from the example was resolved using the simulations with model (1) and data from table 1. The component of the relative combined standard uncertainty associated with the camera-to-object distance d obtained from the simulations were presented in Fig. 10. The value of the component of the relative combined standard uncertainty associated with the camera-to-object distance d, for the relative standard uncertainty of the camera-to-object distance $u(d)$ = 20% and the object emissivity ε_{ob} = 0.9 can be read from Fig. 10. For the object temperature T_{ob} = 363 K (90 ^{o}C), the value of the component $u(T_{ob}) \approx 0{,}0095\%$.

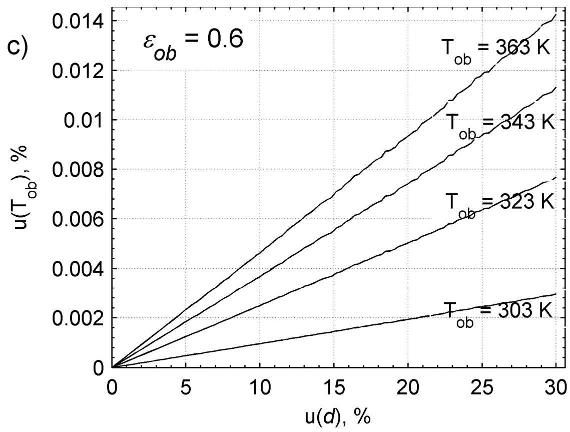

Figure 9: Component of the relative combined standard uncertainty associated with camera-to-object-distance d (results of simulations for data collected in table 1

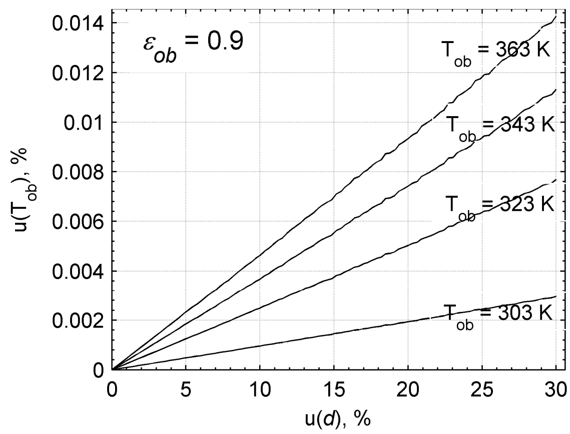

Figure 10: Component of the relative combined standard uncertainty associated with camera-to-object-distance d (results of simulations for data collected in table 1)

3. Exemplary numerical calculations of the combined standard uncertainty and 95% coverage interval in temperature measurements carried out with the FLIR infrared cameras

Example 10

Temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.4. Calculate the combined standard uncertainty $u_c(T_{ob})$ and evaluate the 95% coverage interval $I_{95\%}$ assuming that the object temperature T_{ob} = 323 K (50 ^{o}C). The values of the input variables of the model (1) should be assumed according to the table 2. The standard uncertainties of the input variables of the model (1) should be assumed according to the table 3.

Table 2: The values of the input variables of the model (1) assumed for the calculations of the combined standard uncertainty

ε	T_o [K]	T_{atm} [K]	ω	d [m]
0.4; 0.9	293	293	0.5	10

Table 3: Standard uncertainties of the input variables of the model assumed for the calculations of the combined standard uncertainty

$u(\varepsilon_{ob})$ [%]	$u(T_o)$ [%]	$u(T_{atm})$ [%]	$u(\omega)$ [%]	$u(d)$ [%]
10	10	10	10	10

To solve this problem, the simulations using data from tables 2 and 3 were carried out. The calculations were made with the program for simulations of the combined standard uncertainty. The screenshot of the program is presented in Fig. 11. The normalized histogram of the probability density function $g(T_{ob})$ of output variable T_{ob} of model (1) is presented in Fig. 12. The ends of the 95% coverage interval are marked by vertical lines. The function $g(T_{ob})$ was evaluated with the method for the propagation of distributions and Monte Carlo simulations described in detail in [4]. In simulations the uniform distributions of the input variables were assumed. The value of the combined standard uncertainty $u_c(T_{ob})$ of the object temperature for the input variable estimates collected in table 2 and the standard uncertainties collected in table 3, was equal to $u_c(T_{ob})$ = 11 K (3.4% of the expected value).

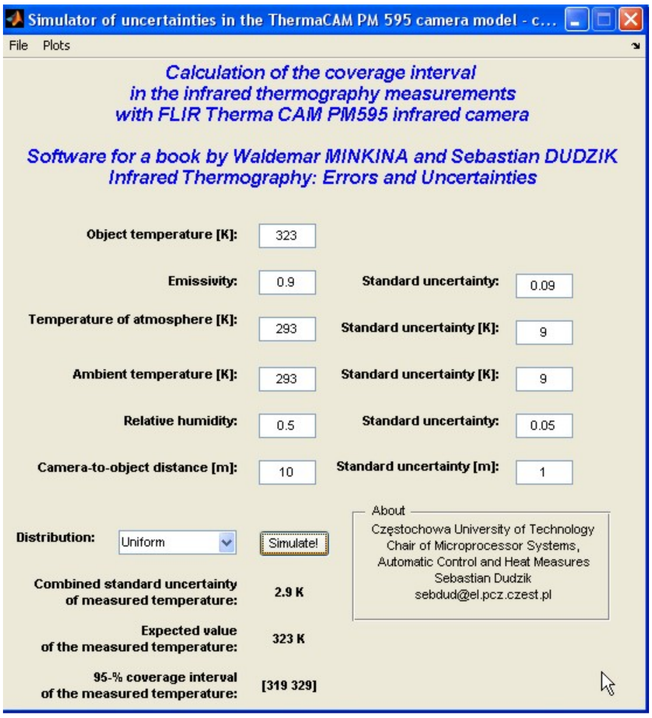

Figure 11: The main window screen shot of the program used for the calculations of the combined standard uncertainty in the temperature measurements with the FLIR ThermaCAM PM595 infrared camera

Calculations were carried out for ε_{ob} = 0.4 and T_{ob} = 323 K (50 ^{o}C). The width of the 95% coverage interval for data from this example can be read from Fig. 12. The shortest width is equal to 39 K. The limits of the 95% coverage intervals read from Fig. 12 is $I_{95\%}$ = [302, 341] K.

Example 11

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.6. Calculate the combined standard uncertainty $u_c(T_{ob})$ and evaluate the 95% coverage interval $I_{95\%}$ assuming that the object temperature T_{ob} = 343 K (70 ^{o}C). The values of the input variables of the model (1) should be assumed according to the table 2. The standard uncertainties of the input variables of the model (1) should be assumed according to the table 3.

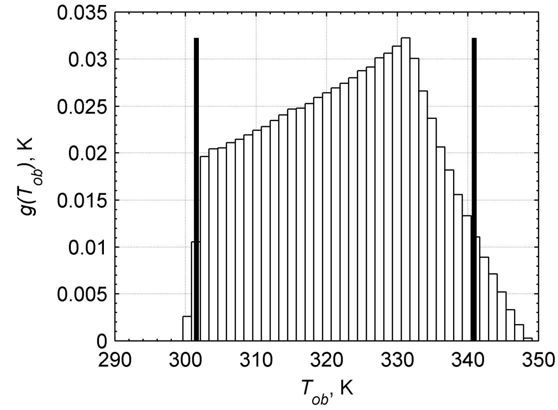

Figure 12: The normalized histogram of the probability density function $g(T_{ob})$ of output variable T_{ob} of model (1). Results of simulations for data collected in tab. 1 and 3 (example 7

To solve the task from this example, the simulations using data from tables 2 and 3 were carried out. The normalized histogram of the probability density function $g(T_{ob})$ of output variable T_{ob} of model (1) is presented in Fig. 13. The ends of the 95% coverage interval are marked by vertical lines. In simulations the uniform distributions of the input variables were assumed. The value of the combined standard uncertainty $u_c(T_{ob})$ of the object temperature for the input variable estimates collected in table 2 and the standard uncertainties collected in table 3, was equal to $u_c(T_{ob})$ = 6 K (1.7% of the expected value).

Calculations were carried out for ε_{ob} = 0.6 and T_{ob} = 343 K (70 ^{o}C). The width of the 95% coverage interval can be read from Fig. 14. The shortest width is equal to 22 K. The limits of the 95% coverage intervals read from Fig. 11 is $I_{95\%}$ = [333, 355] K.

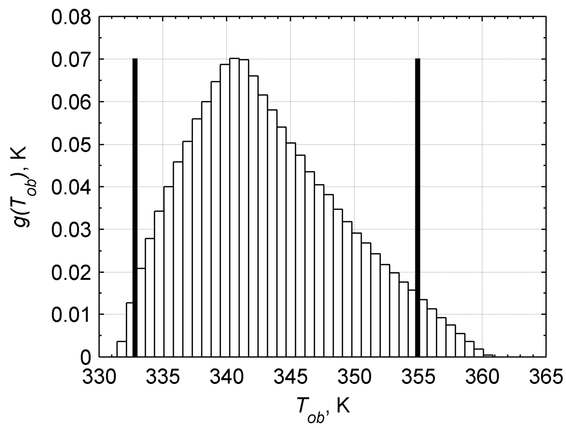

Figure 13: The normalized histogram of the probability density function $g(T_{ob})$ of output variable T_{ob} of model (1). Results of simulations for data collected in tab. 2 and 3 (example 8)

Example 12

The temperature measurement was conducted using the FLIR ThermaCAM PM595 infrared camera. The emissivity of the investigated object was equal to ε_{ob} = 0.9. Calculate the combined standard uncertainty $u_c(T_{ob})$ and evaluate the 95% coverage interval $I_{95\%}$ assuming that the object temperature T_{ob} = 323 K (50 ^{o}C). The values of the input variables of the model (1) should be assumed according to the table 2. The standard uncertainties of the input variables of the model (1) should be assumed according to the table 3.

To solve the task from example 11, the simulations using data from tables 2 and 3 were carried out. The calculations were made with the program for simulations of the combined standard uncertainty. The screenshot of the program is presented in Fig. 11 The normalized histogram of the probability density function $g(T_{ob})$ of output variable T_{ob} of model (1) is presented in Fig. 14. The ends of the 95% coverage interval are marked by vertical lines. The function $g(T_{ob})$ was evaluated with the method for the propagation of distributions and Monte Carlo simulations described in detail in [4]. In simulations the uniform distributions of the input variables were assumed. The value of the combined standard uncertainty $u_c(T_{ob})$ of the object temperature for the input variable estimates collected in table 2 and the standard uncertainties collected in table 3, was equal to $u_c(T_{ob})$ = 2.9 K (0.9% of the expected value) – see Fig. 11.

Calculations were carried out for ε_{ob} = 0.9 and T_{ob} = 323 K (50 ^{o}C). The width of the 95% coverage interval for data from this example can be read from Fig. 14. The shortest width is equal to 10 K. The limits of the 95% coverage intervals read from Fig. 11 is $I_{95\%}$ = [319, 329] K.

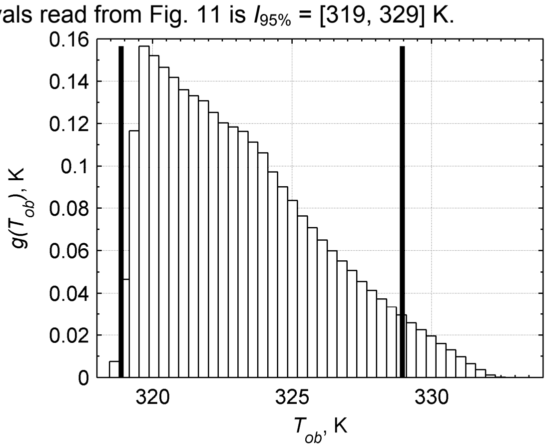

Figure 14: The normalized histogram of the probability density function $g(T_{ob})$ of output variable T_{ob} of model (1). Results of simulations for data collected in tab. 2 and 3 (example 8)

4. Conclusions

In this work, the twelve examples of numerical calculations were presented. The purpose of calculations was an estimation of the thermographic measurement accuracy in the presence of the random interactions. The model of the infrared temperature measurement was presented as well. Furthermore, the methodology of the 95% coverage in thermographic measurements interval was described. In addition, the methodology for calculation of uncertainty and the 95% coverage interval was discussed, and the latest recommendations of international metrology organizations were presented. Numerical calculations were carried out using author software. Summing up the results of the numerical calculations conducted in the examples, the following conclusions can be drawn:

- The greatest impact on the combined standard uncertainty in thermographic measurements has a component associated with the object emissivity ε_{ob}
- The component associated with the object emissivity ε_{ob} strongly depends on the temperature of investigated object T_{ob}
- The component of the relative combined standard uncertainty associated with the object emissivity ε_{ob} does not depend on the object emissivity value (cf. Figs 2–10)
- The value of combined standard uncertainty increases strongly as the object's emissivity decreases. Additionally, it can be seen that the increase in the uncertainty value is the faster the lower the object temperature.

By analyzing the results obtained in Examples 1 to 12, it is clear that due to the complexity of the model (1), the best method for estimating complex standard uncertainty and 95% coverage interval appears to be presented in this paper. In addition, according to the authors of this paper, it is appropriate to use specialized software to accurately estimate the uncertainty of temperature measurements based on model (1), allowing numerical prediction of this uncertainty for specific measurement situations.

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