Evaluation of thermal cameras in quality systems according to ISO 9000 or EN45000 standards

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ABSTRACT

According to the international standards ISO 9001-9004 and EN 45001-45003 the industrial plants and the accreditation laboratories that implemented the quality systems according to these standards are required to evaluate an uncertainty of measurements. Manufacturers of thermal cameras do not offer any data that could enable estimation of measurement uncertainty of these imagers. Difficulties in determining the measurement uncertainty is an important limitation of thermal cameras for applications in the industrial plants and the co-operating accreditation laboratories that have implemented these quality systems. A set of parameters for characterization of commercial thermal cameras, a measuring set, some results of testing of these cameras, a mathematical model of uncertainty, and a software that enable quick calculation of uncertainty of temperature measurements with thermal cameras are presented in this paper.

Keywords: thermal imaging systems, ISO 9000, infrared, temperature, metrology, uncertainty

1. INTRODUCTION

There is nowadays a general trend in industry to accept the quality systems according to the international norms ISO 9001-9004 and in testing laboratories - according to norms the EN 45001-45003. According to these standards the centers that implemented the above mentioned quality systems are required to evaluate an uncertainty of measurements according to the rules presented in Ref.[1]

There are a few examples of calculation of uncertainty of different measurement results in Ref.[1]. More examples are presented in publications of the European Cooperation for Accreditation.[2,3] However, there has not published in available literature any method of determination of the uncertainty of measurement results with thermal cameras. Manufacturers of thermal cameras do not offer any data that could enable estimation of the uncertainty of measurements with these cameras. Therefore difficulties in determining the measurement uncertainty is an important limitation of thermal cameras as a verified technique of temperature measurement for the industrial plants and the co-operating accreditation laboratories that have implemented the quality systems according to the international standards ISO 9001-9004 and EN 45001-45003.

A set of parameters for characterization of commercial thermal cameras, a measuring set, some results of testing of these cameras, a mathematical model of uncertainty, and a software that enable quick calculation of uncertainty of temperature measurements with thermal cameras are presented in this paper.

A review of present day confused situation in area of testing and evaluation of measurement thermal cameras was done in Section 2. A set of parameters for characterization of commercial thermal cameras, a measuring set and results of testing of these cameras described in Section 3. Mathematical model and software that enable calculations of uncertainty of temperature measurement with thermal cameras are presented in Section 4. Finally, basic conclusions of this paper are presented in Section 5.

2. A REVIEW OF PRESENT-DAY SITUATION

2.1 Terminology and definitions

According to the *International Vocabulary of Basic and General Terms in Metrology* [4] (commonly referred as VIM) published jointly by seven leading international metrological organizations (the International Bureau of Weights and Measures BIPM, the International Electrotechnical Commission (IEC), the International Organization for Standardization ISO, the International Organization of Legal Metrology (OIML), the International Federation of Clinical Chemistry IFCC, the International Union of Pure and Applied Chemistry IUPAC, and the International Union of Pure and Applied Physics IUPAP) accuracy is defined as closeness of the agreement between the result of a measurement and the true value

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of the measured quantity. This means that the “accuracy” is only a qualitative concept that should not be associated with numbers. According to the VIM we are allowed to say only that accuracy is good, bad etc.

The VIM proposes as a measure of accuracy of measurement a parameter called uncertainty of measurement. It is defined as a parameter, associated with the result of a measurement that characterizes the dispersion of the values that could be reasonably attributed to the measured quantity. Rules of evaluation of measurement uncertainty are presented in the well known "Guide to the expression of uncertainty in measurement", commonly abbreviated as *GUM*, published in 1993 in the name of the seven mentioned above main international metrological organizations. [14,15] Uncertainty of measurement is an estimate of the likelihood of nearness to the best value that is consistent with presently available knowledge. It is not necessarily an indication of the likelihood that the measurement result is near the value of the measurand. The total uncertainty of the measurement result is determined as an estimated standard deviation of the dispersion of values that could reasonably be attributed to the measurand, which, in our case, is object temperature.

The uncertainty is usually evaluated using a mathematical model of a measurement procedure and the law of propagation of uncertainties assuming that the measurement procedure can be modeled mathematically to the degree imposed by the required accuracy of the measurement.

In order to fully evaluate thermal cameras we need to know two types of uncertainties: the intrinsic uncertainty of the thermal camera and the uncertainty of a measurement result.

The intrinsic uncertainty of the thermal camera is the uncertainty of temperature measurement with the thermal camera when all the external errors of the measurement process are negligible (a case of a measurement of temperature of a large blackbody from short distance). This parameter can be used to compare different thermal cameras.

The uncertainty of a measurement result is the uncertainty of a result of temperature measurement with a thermal camera at real measurement conditions when both the intrinsic and external sources of errors can influence the measurement result. This parameter is a measure of accuracy of the thermal camera at real measurement conditions and should be evaluated when the thermal camera is used in the ISO quality systems, metrological institutes or at any center that implemented recommendations of the above mentioned metrological organizations.

Any of the two types of uncertainties above mentioned cannot be determined on the basis of data provided by manufacturers of thermal cameras.

2.2 Information offered by manufacturers

Manufactures of measurement thermal cameras often state a parameter called “accuracy” that is measured as a range around the true object temperature T_{ob} in which the output temperature T_{out} is located when the external sources of errors are negligible. Typical values of this parameters are: ±1% of the output temperature T_{out} but not less than ±1 °C for scanning thermal cameras or ±2% of the output temperature T_{out} but not less than ±2 °C for matrix thermal cameras. As it was mentioned earlier according to the international metrological organizations “accuracy” is only a qualitative concept that should not be associated with numbers. Therefore the name of the “accuracy” is improper on the formal terminology ground. However, there are more serious limitations of usefulness of this parameter.

The “accuracy” parameter could potentially enable determination of the intrinsic uncertainty. Assuming uniform distribution dispersion of true temperature within limits determined by the “accuracy” parameter we could write [1]

$$\text{intrinsic uncertainty} = \frac{\text{"accuracy"}}{\sqrt{3}}\,. \tag{1}$$

However practically the “accuracy” parameter is not useful for estimation of the intrinsic uncertainty because the conditions in which the “accuracy” is measured are not clearly defined by manufactures. The question is whether the “accuracy” is measured at optimal calibration conditions when the measurement errors are the smallest or it is measured at real measurement conditions when the errors can be many times higher.

Manufacturers state very rarely at what environment temperature the “accuracy” was measured. After making review of many catalogs and internet pages the author has found only one case [5] when the manufacturer clearly stated that the “accuracy” equal to ±1% of the output temperature but not less than ±1 °C for a scanning thermal camera was referring to system temperature equal to 23°C.

During real measurements the temperature of the environment can vary significantly within wide limits determined by the manufacturer from about -10 °C to about 40 °C. Changes of the environment temperature can have significant effect on the measurement results due to several reasons. First, radiation emitted by the optical elements of the camera depends directly on temperature of these elements and indirectly on the temperature of the environment. Second, variation of the temperature of the environment can cause variation of the temperature of the detector and change detector sensitivity. Third, changes of the environment temperature cause direct changes of the temperature of the electronic blocks and indirect changes of the gain and the offset of these blocks.

Influence of the temperature of the environment on measurement results can be corrected. Modern thermal cameras are equipped with software and hardware mechanisms that should automatically correct this influence. However, only a partial correction of this harmful influence is practically possible. Therefore accuracy of measurements carried out at real measurement conditions can differ significantly from accuracy at laboratory conditions.

There are also other parameters presented in catalogs of thermal cameras that give some indications about intrinsic errors of thermal cameras.

First, there is a parameter called “thermal sensitivity”, “thermal resolution”, “temperature resolution” or “ NETD” that provide information about the influence of noise in electrical channel on the measurement errors. The parameter have different names but is usually measured as noise equivalent temperature difference (NETD) defined as the blackbody temperature difference between a target and its background required to produce a peak-signal-to-rms-noise ratio of unity at a suitable point in the output electrical channel. It was shown in Ref.6 that NETD equals the standard deviation of the output temperature dispersion caused by noise of the system. Therefore, the NETD can be treated as a good estimation of uncertainties due to system noise.

We must however remember that the NETD depends on object temperature. It is typically measured only for one fixed value of this temperature usually close to 30°C and can be a few times higher for object temperatures at the lower limit of available temperature range close to -20°C. It can be calculated using this formula

$$NETD(T_{ob}) = NETD(T_{ob} = T_m)\frac{\int\limits_{\Delta\lambda} \frac{\partial L(\lambda, T_m)}{\partial T} sys(\lambda) d\lambda}{\int\limits_{\Delta\lambda} \frac{\partial L(\lambda, T_{ob})}{\partial T} sys(\lambda) d\lambda} \tag{2}$$

where T_m is object temperature for which the NETD was measured, $sys(\lambda)$ is the relative spectral sensitivity of the thermal camera and $L(\lambda, T)$ is Planck´s function.

On the basis of the known NETD we can determine “accuracy” due to system noise. If we assume normal distribution of true object temperature and apply typical 3σ safety interval then we get

$$"accuracy"_{noise}(T_{ob}) = 3 \cdot NETD(T_{ob})\ . \tag{3}$$

If we analyze catalogs of SW (short-wave) scanning thermal cameras we will find that the manufacturers typically claim that "accuracy" = 1% $_{Tout}$ or 1°C, the measurement range is from about –10°C to about 400 °C, the NETD = 0.1÷0.2°C for T=30°C. If we apply the formulas (2-3) for this situation we will get that *“accuracy$_{noise}$”*=1.2÷2.4°C for T_{ob}=-10°C. The obtained *“accuracy$_{noise}$”* is higher that the catalog *“accuracy”* that suggest impossible situation when the errors due to system noise are higher that the errors due to all sources within the system. This contradictory between the “accuracy” parameter and NETD confirms our earlier made prediction that the “accuracy” does not represent all sources of errors within the thermal camera and cannot be used to calculate the intrinsic uncertainty using the formula (1).

Manufactures of thermal cameras present in specifications of their products also other parameters related to the NETD. The MRTD is a function of a minimum temperature difference between bars of the standard 4-bar target and the background required to resolve the thermal image of the bars by an observer versus spatial frequency of the target. The MDTD is a function of a minimum temperature difference between a single circular target and the background required by an observer to detect the thermal image of the target versus inverse spatial dimension of the target. Although both MDTD and MRTD are functions they are often presented as single value parameters. MDTD is typically measured for targets of large size and then it equals 50 % to 70 % of NETD. For MRTD it is difficult to formulate a similar rule as it is measured for targets of different spatial frequency. Generally, the MRTD is the most important measure of ability of a thermal camera to detect and identify a target and is an excellent tool for evaluation of observation thermal cameras. However, its use for evaluation of measurement thermal cameras for absolute temperature measurement is problematic. The MRTD and MDTD give some indications about system temperature resolution and about system ability to measure small size objects. However, it is impossible to connect these parameters with the uncertainty of the thermal camera.

The instantaneous field of view IFOV is typically found among parameters of modern matrix thermal cameras. It defined as angular dimension of an element of a matrix of detectors. It is related to the minimum angular size of the tested object for which influence of the size of the tested object on measurement results is still negligible. However, this minimum size depends also on parameter of other blocks of the thermal camera like aberration of the optical block, diffraction effects, frequency bandwidth of the electrical channel and it is not possible to determine this minimum size on basis of the IFOV only.

The spatial resolution (or the geometrical resolution) is typically found among parameters of older scanning thermal cameras. It is usually measured as angular slit dimension for which the Slit Response Function (SRF) of the tested thermal camera is equal to 0.5. The SRF is defined as a function of signal generated by a slit versus width of the slit normalized to the signal generated by a very wide slit. The spatial resolution defined in a way presented above is a good measure of camera ability to create thermal image of the tested object and is sometimes called the observation spatial resolution. However this parameter does not give information whether the size of the tested object is high enough to assure negligible influence of this size on measurement results. This information is provided by the measurement spatial resolution defined as angular slit dimension for which the Slit Response Function of the tested thermal camera is equal to 0.99. When angular size of the tested object is higher than the measurement spatial resolution then we can assume that influence of the size of this object on temperature measurement results is negligible. However, the measurement spatial resolution is usually a few times higher than observation spatial resolution and manufacturers prefer to present only values of the first parameter.

Image resolution presented as a number of pixels or a number of lines per frame is a good measure of quality of thermal image of the tested object. It is related to the previously defined both observation and measurement spatial resolution. However, it is impossible to determine exact value of the measurement spatial resolution only on the basis of known image resolution.

2.3 Situation in literature

The publication "*Guide to the expression of uncertainty in measurement*" (commonly referred as *GUM*) presenting rules of expression and evaluation of uncertainty of measurements was originally published by the seven earlier mentioned international metrological organizations. Nowadays, these rules are fully accepted by other organizations like the National Institute of Standards and Technology in USA, the European Cooperation for Accreditation, the American National Standard Institute, the National Conference of Standards Laboratories, the American Association for Laboratory Accreditation, the International Laboratory Accreditation Cooperation and many national standards institutes all over the world. However, these recommendations are relatively new as they were published in 1993 in situation when the basis of the classical error theory are known for centuries and there some problems with their practical implementation. There are a few examples of calculation of uncertainty of basic physical quantities presented this publication, and more in publications of the European Cooperation for Accreditation.[2,3] Among them there is also a case of calibration of thermocouples used for contact temperature measurement.[7] However, no publication offered by any international metrological organization deals with the problem of evaluation of uncertainty of non-contact temperature measurements.

The problem of evaluation of uncertainty of non-contact temperature measurement has not received attention from the scientific centers working in this field. There are quite a few models of errors of temperature measurements with thermal cameras.[8] However, the author of this paper is not aware about any scientific papers offering methods of uncertainty evaluation for users of thermal cameras. Therefore the team of the author cooperating with Temperature Radiation Section of Physikalisch-Technische Bundesanstalt, Berlin, Germany has recently published two papers that try to help users of thermal cameras to determine both the intrinsic uncertainty and the uncertainty of a measurement result.[9,10]

3. INTRINSIC UNCERTAINTY OF THERMAL CAMERAS

3.1 Set of parameters for characterization of measurement thermal cameras

A set of seven parameters for characterization of measurement thermal cameras was recently proposed in Ref [9]: minimum error ME, noise generated error NGE, digital temperature resolution DTR, temperature stability TS, repeatability RE, measurement uniformity MU, and measurement spatial resolution MSR.

The minimum error ME was defined as a range around the output temperature T_{out} in which the true temperature T_{ob} is located when the measurements are carried out in conditions identical with the conditions during calibration of the thermal camera. The calibration conditions are exist when the tested object is a sufficiently large blackbody, the distance between the tested object and the thermal camera is short in order to have influence of limited transmittance of the atmosphere negligible, temperature of the environment is in typical laboratory range 20°C-30°C, the object is located in the center of the system field of view, measurements are carried out for the shortest temperature span of the thermal camera,averaging effect of a dozen or more of measurement results is used.

The Noise Generated Error NGE was defined as the standard deviation of the output temperature dispersion caused by noise of the system.

The digital temperature resolution *DTR* was defined as the smallest difference between two temperature levels that can be distinguished because of the limited resolution of the digital channel of the thermal camera.

The temperature stability *TS* was defined as a range in which the results of the measurements carried out in different environment temperatures, within limits determined by the camera manufacturer, are located.

The repeatability *RE* is defined as a range in which the results of the measurements are located when measurements are repeated in identical measurement conditions. Measurements of the repeatability should be carried out in conditions identical with the conditions during measurement of the *ME*.

The measurement uniformity *MU* is defined as a range in which the results of the measurements are located when the tested object is located at different places within the field of view of the camera.

The measurement spatial resolution *MSR* is defined as the minimum angular dimension of the tested object when there is still no the influence of limited size of this object on temperature measurement results. We can say in other words that if the angular size of the tested varies but is always higher than MSR than the output temperature will be the same.

The first six parameters give information about the ranges around the output temperature T_{out} in which the true temperature T_{ob} due to different sources of errors like: noise in the analog channel of the thermal camera, limited resolution of the digital channel of the thermal camera, changes of temperature of environment, changes of camera parameters with time, changes of camera parameters within its field of view, and due to all other sources that exist in calibration conditions. The last parameter from this group gives information about the minimal size of the object which temperature can be measured with the thermal camera without fear that results will be effected due to limited size of the tested object.

It was later shown that if these parameters are known then it is possible to determine the intrinsic uncertainty of a thermal camera using the formula

$$u_{\mathrm{int}} = \sqrt{u_{ME}^2 + u_{NGE}^2 + u_{DTR}^2 + u_{TS}^2 + u_{RE}^2 + u_{MU}^2} \qquad (4).$$

where $u_{ME} = \dfrac{ME}{\sqrt{12}}$ $u_{NTR} = NGE$ $u_{DTR} = \dfrac{DTR}{\sqrt{12}}$ $u_{TS} = \dfrac{TS}{\sqrt{12}}$, $u_{RE} = \dfrac{RE}{\sqrt{12}}$, $u_{MU} = \dfrac{MU}{\sqrt{12}}$.

There have been also developed formulas that enable calculation of *NGE, TS, RE, MU* for any object temperature T_{ob} when the parameters were measured for only one temperature.

3.2 Results of testing of commercial thermal cameras

There has been carried out in Physikalisch-Technische Bundesanstalt, Berlin, Germany testing of several modern matrix thermal cameras from different manufacturers in order to determine the above mentioned parameters. The names of the manufacturers or other data that could precise types of the tested thermal cameras cannot be presented according to the conditions of the agreement with the suppliers of these cameras. Here there will be presented and discussed measurement results of three thermal cameras that can be treated as a representative of a whole group. The “accuracy” parameter of all the tested cameras was always the same: ±2% of the output temperature or ±2 °C. Details of the laboratory set-up used for testing are presented in Ref.11.

The tests of the minimal error *ME* were carried out by measurement of temperature of a blackbody at laboratory conditions of stable environment temperature about 20°C. The measurements were carried out for blackbody temperatures varying from -20°C to 500°C. This span covered fully the measurement ranges of all tested thermal cameras.

The results of the measurements are presented in Figure 1. The sharp changes in values of error ΔT of the camera nr 1 are not caused by a physical phenomenon but by a change of the neutral filter in the camera optical channel in order to extend the measurement range.

As we can see the measurement errors of the thermal cameras nr 1 and 2 are significantly outside the limits determined by the “accuracy” parameter. Therefore, we can conclude that real accuracy of some thermal cameras can be worse that the catalog “accuracy” even when the measurement are carried out in laboratory conditions.

The minimum error ME can be determined as a range in which the measurement errors are located. Different analytical functions can be used to determine this range. However, let us use the typical function: x% of the output temperature T_{out} but not less than x°C. Then that we could roughly estimate: ME=±5% T_{bb} or =±5 °C – the camera nr 1, ME=±4% T_{bb} or =±4 °C – the camera nr 2, and ME=±2% T_{bb} or =±2 °C – the camera nr 3.

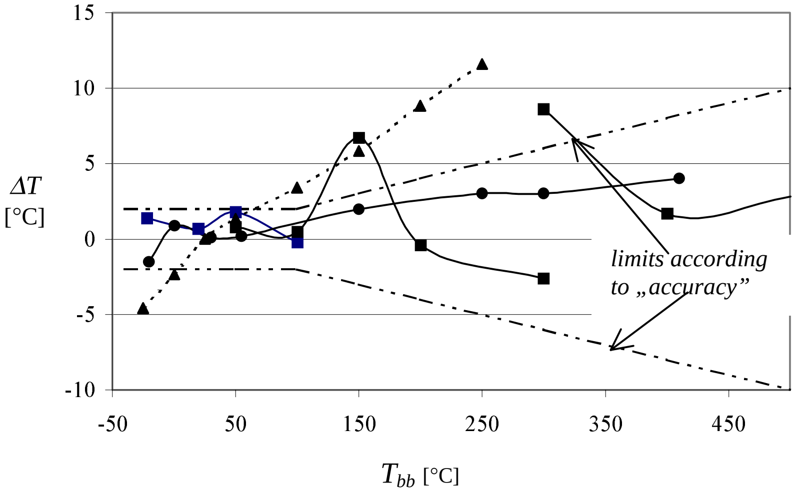


Figure 1. Measurement errors ΔT of blackbody temperature T_{bb} in laboratory conditions (squares – camera nr 1, triangles – camera nr 2, circles– camera nr 3)

The noise generated error *NGE* of the tested thermal cameras was measured as the standard deviation of the output temperature dispersion caused by noise of the system. Two different measurement methods were used in case of the thermal camera nr 1: temporal and spatial. Using the first method the NGE was determined as the standard deviation of variation in time of indication of a single pixel. Using the second method the NGE was determined as the standard deviation of the camera indications of a hundred or more pixels within a single frame corresponding to a blackbody of uniform temperature.

It could be suspected that the values of the *NGE* determined using the second method will be higher as the dispersion of the measurement results is caused both by the noise and detector non-uniformity. However, the latter effect is almost fully corrected in modern matrix cameras and both the measurement methods generated almost the same results.

In case of the cameras nr 2 and nr 3 only the second method could be used as these cameras do not enable recording and analysis of variation in time of measurement result of a single pixel.

The results of measurements of the *NGE* of the tested thermal cameras are shown in Figure 2. It is a common conception that the influence of noise on camera indications decreases quickly with temperature. However, as can we see in this figure this influence can be as important for cold object as for hot objects. The reason is that although the power of the radiation emitted by hot object is higher because of use of neutral filters or shortening of the integration time the signal to noise ratio can actually decrease during measurements of hot objects. Anyway the errors due to system noise, with the exception of a few particular points in camera measurement range, are small.

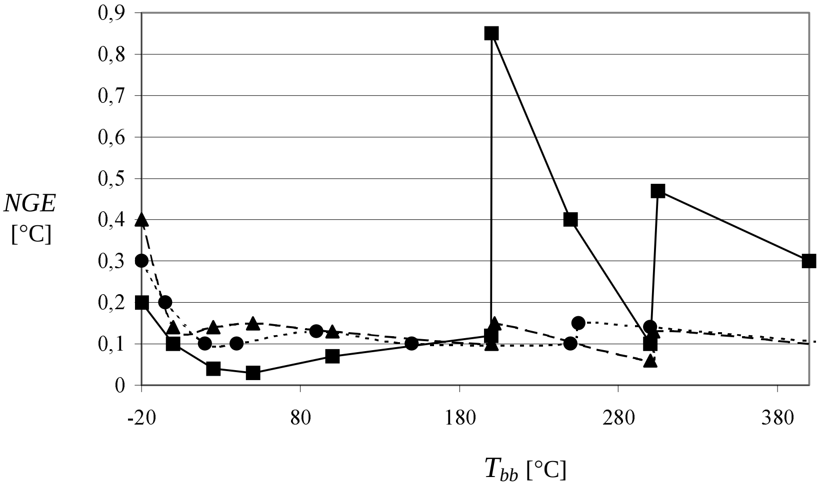


Figure 2. The *NGE* of the tested thermal cameras at different temperatures of the blackbody

The tested thermal camera during measurements of the temperature stability *TS* was inside an environmental chamber enabling regulation of ambient temperature. An opaque window was opened during measurements enabling the camera to see a blackbody of constant temperature T_{bb}=90°C. Errors of temperature measurement ΔT equal to difference of camera indications T_{out} and true blackbody temperature T_{bb} for different temperature of the environment T_{en} within the operating temperature range specified by the manufacturers were measured. The latter temperature range of the tested thermal cameras was from about -10°C to about 40°C with little variation depending on the camera model.

As the temperature of the environment varied within the operating temperature range specified by the manufacturers we could expect that the errors ΔT should be small and within determined the catalog limits ±2 °C. However, as can we see in Figure 3 the influence of the environment temperature on the measurement errors of the thermal cameras nr 1 and nr 2 exceed many times the acceptable range.

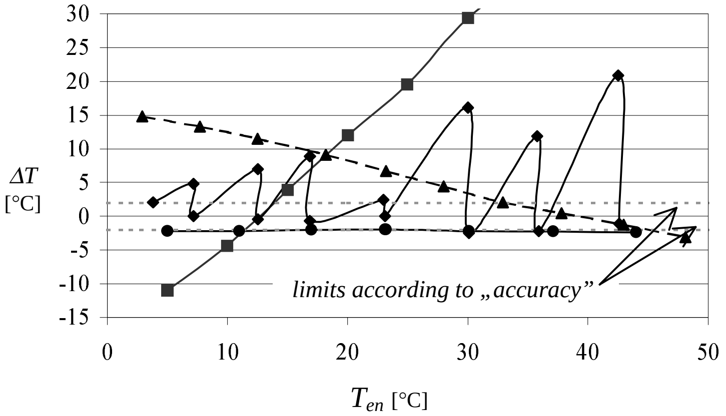


Figure 3. Errors of temperature measurement ΔT of a blackbody of temperature Tbb=90°C with a few thermal cameras at different temperature of the environment Ten (squares – camera nr 1 for measurements without switching off, rotated squares– camera nr 1 for measurements with switching off, triangles – camera nr 2, circles – camera nr 3)

The camera nr 1 (the squares) is a particularly interesting case. The tests of this thermal camera were carried out in two different versions: the measurements without switching off and the measurements with switching off.
The thermal camera during measurements in the first version was switched on at the environment temperature T_{en} = 15 °C. The measurement errors were then small and within limits determined by "accuracy" parameter. However, when the temperature of the environment was changed then the errors increased sharply. Generally the errors ΔT are proportional to difference of the current temperature T_{en} and the temperature the camera was switched on T_{en} = 15 °C and are very significant when this temperature difference is high.

The thermal camera during measurements in the second version (rotated squares) was frequently switched off. It was turned on at temperature T_{en} = 3.8 °C and the measurement errors were then almost within the range ±2°C as ΔT was equal 2,11°C. Next, the temperature T_{en} was increased to 7.2 °C and the error ΔT increased to 4,8 °C. However, when the camera was temporally switched off and again switched on then the measurement error ΔT for the same environment temperature decreased to 0.06°C. The same situation occurred also at other temperatures of the environment. Therefore we can conclude that the measurement errors of the camera nr 1 are small and within the range ±2°C immediately after the camera is switched on, but the errors increase rapidly when the environment temperature changes. This means that this camera can produce accurate measurement results only at environments of stable temperature.

The situation is different for the thermal cameras nr 2 and nr 3. In both cases switching temporally off the tested thermal camera did not influenced the measurement results. However, there is a significant difference between these cameras. The influence of temperature of the environment T_{en} on camera indication is almost negligible in case of the camera nr 3 but is quite significant in case of the camera nr 2.

The temperature stability *TS* was earlier defined a range in which the results of the measurements carried out in different environment temperatures, within limits determined by the camera manufacturer, are located. Let us simplify that the range of environment temperatures allowed by manufacturers is from 5 °C to 40 °C although the real range was a little wider. Then we can determine the temperature stability *TS* of the camera nr 3 as equal to 0.2 °C, and the temperature stability *TS* of the cameras nr 2 as equal to 17 °C. In case of the camera nr 1 there exists question which version of measurements should we use: without switching off or with switching off and we will not determine any value.

The digital temperature resolution *DTR* was included into the set of parameter for characterization of thermal cameras to represent the influence of the limited resolution of the camera digital channel on camera indications. The *DTR* can be measured as the smallest difference between two temperature levels of a blackbody that can be distinguished when the influence of analog noise on camera indications is negligible. However, when the *DTR* is comparable or lower than *NGE* when the latter condition cannot be fulfilled and the *DTR* cannot me measured accurately. Experiments with slowly increasing temperature of a blackbody showed that such a situation occurred in case off all the tested thermal cameras.

These experimental results are in agreement with theoretical prediction from Ref.[9] that proposes to estimate *DTR* using this formula

$$DTR = \frac{\Delta T_{span}}{2^k}\ , \tag{5}$$

where ΔT_{span} is the temperature span of the camera used during measurements, and k is the bit number of the A/D converter of the thermal camera.

As the widest measurement span of the tested cameras did not exceed 200 °C and the modern thermal cameras typically use 12-bit A/D converter then the *DTR* can be estimated to have values below 0.1°C. This means that the influence of the limited resolution of the digital channel can be treated as negligible. Additionally, the effect influence of the limited resolution of the digital channel has already contributed to measurement results of the *NGE.* Therefore, it seems that the *DTR* can be excluded from the set of parameters for characterization of thermal cameras.

The repeatability *RE* was included into the set of parameter for characterization of thermal cameras presented in Ref.[9] to represent the influence limited time stability of the thermal camera on the measurement results. However, the logical flaw in this reasoning is that the measurements of all the mentioned earlier parameters are time consuming and the influence of the limited time stability is already represented in such parameters like *ME, NGE, TS.* Therefore, no testing of the repeatability *RE* was carried out.

The measurement uniformity *MU* can be measured as a range in which the results of the measurements are located when a blackbody is located at different places within the field of view of the camera. The experiments showed that the dispersion of such measurement results was similar to the dispersion during measurement of the *NGE.* Therefore we can conclude that the influence of location of the tested object within the field of view on camera indications was negligible in case of all tested thermal cameras.

The last parameter from the mentioned earlier set of parameter for characterization – the measurement spatial resolution *MSR* - was defined as the minimum angular dimension of the tested object when there is still no the influence of limited size of this object on temperature measurement results. However, the Ref. [9] does not offer any precise measurement method of this parameter. Therefore let us precise this general definition and find suitable measurement method.

First, let us define slit temperature response function *STRF* as a function of the output difference between the temperature of a slit and the temperature of its background versus angular width of the slit normalized to the temperature difference generated by a very wide slit. Second, let us define the *MSR* as the angular slit dimension when the slit temperature response function *STRF* equals 0.99.
The *STRF* is a modified version of the well known slit response function *SRF.* The *STRF* is based on the normalized output temperature, when the concept of the *SRF* is based on the normalized output signal. The concept of the *STRF* was introduced because for a significant group of modern matrix cameras there is no possibility to measure the output electrical signal or the output luminance.

There have been carried out measurements of the newly defined *STRF* of the tested thermal cameras by determination of a normalized difference between maximal temperature of the image of the slit and the temperature of the uniform background. It was found that in spite of the sampling effect of the matrix detector the *STRF* does not depend on location of the slit in both horizontal and vertical direction or that this dependence is within measurement errors of the apparatus and can be treated as negligible. As we can see in Figure 4 the *MSR* of the first camera equals 3.5 mrad; the *MSR* of the second camera equals 10 mrad. However, better *MSR* does not mean that the first camera camera is better than the second camera as the compared cameras have different field of view. More interesting conclusions can be found if we compare the determined *MSR* with values of the IFOV provided by manufacturers: camera nr 1: IFOV=0.75 mrad; camera nr 2 : IFOV=2 mrad. As we see the real measurement spatial resolution is a few times worse than the resolution suggested by the values of the IFOV presented typically in catalogs.

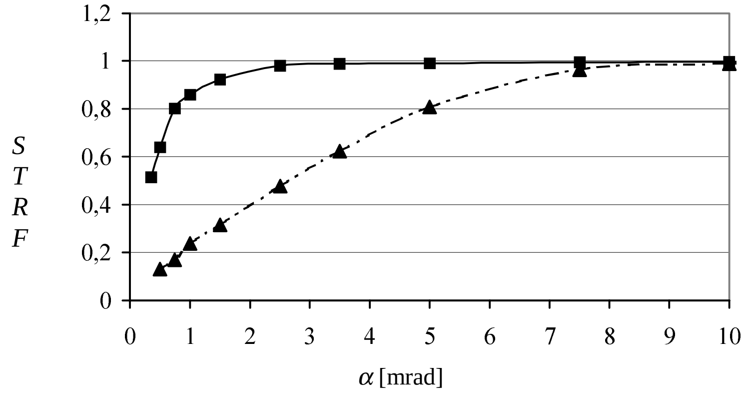


Figure 4. Slit Temperature Response Functions of two example thermal cameras

3.3 Modified set of parameters for characterization of thermal cameras

On the basis of the measurement results there can be made the following conclusions.

First, accuracy of commercial cameras offered on the market varies significantly. Accuracy of some cameras is very close to their catalog “accuracy” : ±2% of T_{out} or ±2 °C. However, there are also thermal cameras of real accuracy many times worse than suggested by the “accuracy” parameter presented in catalogs. This means that the parameters presented by manufactures in catalogs cannot be fully trusted. If thermal cameras are to be used in as verified measuring instruments they should be tested in an independent laboratory.

Second, the temperature stability *TS* is the most important, critical parameter from the proposed set of parameters for characterization of thermal cameras. Therefore, the tests of the temperature stability *TS* should have priority before measurement of other parameters.

Third, the set of seven parameters proposed in Ref.[9] for characterization of measurement thermal cameras can be for typical thermal cameras reduced to a set of four parameters: the minimal error *ME*, the noise generated error *NGE*, the temperature stability *TS*, and the measurement spatial resolution *MSR*. The parameters like the digital temperature resolution *DTR*, the repeatability *RE*, and the measurement uniformity *MU* were dropped because of the reasons presented their contribution the camera intrinsic uncertainty is negligible. The intrinsic uncertainty of a thermal camera can be calculated on the basis of measured *ME, NGE, TS* and *MSR* using the formula (4) modified by dropping the parameters *DTR, RE, MU*.

Fourth, the intrinsic uncertainty u_{int} can be measured directly as a standard deviation of a dispersion of temperature measurement results of a large blackbody using a dozen or more thermal cameras of the same type when all parameters and measurement options on which the result of measurement depends are varied within limits determined by the manufacturer. Temperature and humidity of the environment, number of integrated images or pixels, use of neutral filters etc. are to be included to the group of parameters and measurement options on which the result of measurement depends. It is the most reliable way to measure intrinsic uncertainty of thermal cameras. However, this option of direct measurement is rather limited to the manufacturers as only they have a dozen or more thermal cameras of the same type. Therefore, the users of thermal cameras should determine the intrinsic uncertainty of the basis of the above mentioned set of parameters.

3.4 Measuring set for testing of commercial thermal cameras

Blackbodies and an environmental chamber of very high accuracy were used during the earlier mentioned measurements carried out in Physikalisch-Technische Bundesanstalt. [11] However, the blackbodies and the environmental chamber are characterized by large size, large mass, and high inertia what makes testing of thermal cameras very time consuming and limit possibility of testing only to PTB facilities.

A mobile measuring set MMS 2000, of general diagram shown in Figure 5, for testing of measurement thermal cameras has been developed in Military University of Technology, Warsaw, Poland. It consists of the following blocks: the IRC 1500 collimator, the thermoelectrically cooled blackbody TCB, the cavity blackbody HB1000, the environmental chamber EC 30, the rotary wheel RW with a set of slit targets, and a PC computer. Parameters of the measuring set MMS2000 are presented in Table 1, and the photos in Figure 6.

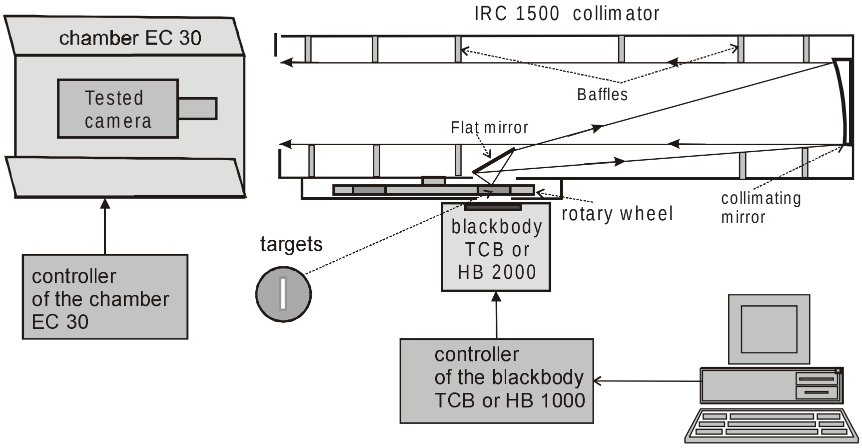


Figure 5. General diagram of the measuring set MMS 2000 for testing of commercial thermal cameras (the laboratory version)

Table 1. Basic parameters of the measuring set MMS 2000

Parameter	Value
collimator IRC 1500	
free aperture	140 mm (option 70 mm)
spectral range	3-15 µm (option: 0.6-15µm)
spatial resolution	<0.1 mrad
type of optics	reflective, off axis
coating	gold (option: silver or aluminium)
dimensions/ mass	360 × 385 × 1660 mm / 30 kg
Blackbody TCB	
Active area	45×45 mm
Emissivity	0.97±0.01
Temperature range	-10°C-100°C
temperature resolution	0.01°C (option – 0.001°C)
temperature uniformity	< 0.01°C (at ΔT<5C)
blackbody HB 1000	
diameter of the active area	10 mm
emissivity	0.995±0.001
temperature range	50°C-1000°C
temperature resolution	0.1°C
temperature uniformity	< 0.1°C (center of the cavity)
Environmental chamber EC 30	
temperature range	-10°C ÷ 60°C
humidity range	20% ÷ 95%
temperature resolution	0.4°C
rotary wheel RW and the set of slit target	
target emissivity	0.97±0.01
slit width	0,1; 0,20; 0,4; 0,56; 0,8; 1,3; 2; 3; 4; 6; 10;15, 20, 30 mm
rotation method	motorized (option: manual)

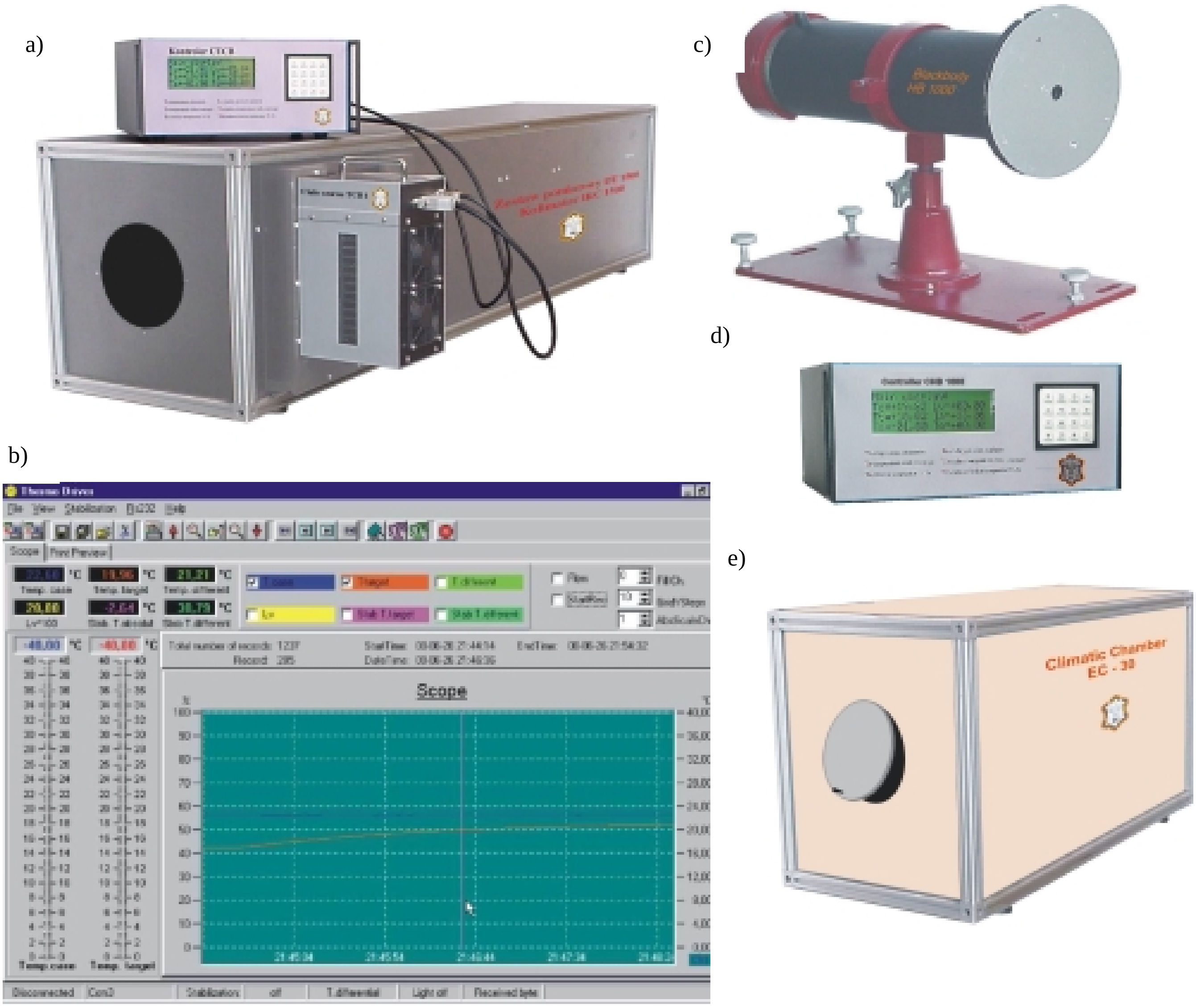


Figure 6. Photos of the measuring set MMS 2000

a) the collimator DT 1500, the blackbody TCB (connected to the side of the collimator), the rotary wheel RW with targets (inside the collimator), and the controller CTCB (on the collimator),

b) basic form of the ThermoDriver software

c) the blackbody HB 1000 (can be exchanged with the TCB blackbody when higher temperatures are needed)

d) the controller CHB 1000

e) the environmental chamber EC30

The measuring set MMS 2000 can be configured into two versions: the laboratory version with the IRC 1500 and a PC computer, and the mobile version without the latter blocks.

The tested thermal camera is mounted inside the environmental chamber EC 30 enabling regulation of the temperature and humidity of the air around the camera. When the shutter on the front wall of the environmental chamber EC 30 is rotated then the camera can receive radiation from the exchangeable blackbodies TCB or HB 1000.

In case of the laboratory version the blackbodies are fixed just behind the focal plane of the IRC 1500 collimator. The rotary wheel RW with the slit targets is located exactly at the focal plane just before the blackbodies. An empty hole in the rotary wheel RW is placed before the blackbody during the measurements of the minimal error *ME*, the noise generated error *NGE*, and the temperature stability *TS*; while the slit targets are placed before the blackbody during the measurements of the measurement spatial resolution *MSR*.

Rotation of the wheel and temperature of the radiator of the blackbodies TCB and HB 1000 can be controlled directly from the stand-alone controllers CTCB and CHB 1000 or from a PC using the developed ThermoDriver software.

In case of the mobile version the blackbodies TCB or HB 1000 are placed about 1 m in front of the outlet of the chamber EC 30. The rotary wheel RW with slit targets is additionally placed before the blackbody during measurement of the *MSR.*

A significant advantage of mobile option is that the measuring set MMS 2000 becomes much smaller and lighter and it is easier to transport the set to user facilities. However, there are also advantages of the laboratory version. When the collimator is used then the influence of the radiation reflected by the radiator of the blackbody TCB or by the slit targets is fully negligible and better stability of the temperature of the radiator of the TCB blackbody can also be achieved.

4. UNCERTAINTY OF TEMPERATURE MEASUREMENT WITH THERMAL CAMERAS

4.1 Mathematical model of uncertainty of temperature measurement

A mathematical model of uncertainty of temperature measurement with thermal cameras was recently developed and presented in Ref.[10]. The model proposes that the combined standard uncertainty u_c of the output temperature T_{out} can be determined as a square root of a sum of the partial uncertainty u_ε caused by the unknown error of determination of the real object effective emissivity ε_r , the partial uncertainty u_T due to unknown error of determination the real effective temperature of the background $T_{ba(r)}$, the partial uncertainty u_τ due to unknown error of determination the real effective transmittance of the atmosphere $\tau_{a(r)}$, and the intrinsic uncertainty u_{in} of the thermal camera

$$u_c(T_{out}) = \sqrt{u_\varepsilon^2 + u_T^2 + u_\tau^2 + u_{in}^2} = \sqrt{\left(c_\varepsilon u(\varepsilon_r)\right)^2 + \left(c_T u(T_{ba(r)})\right)^2 + \left(c_\tau u(\tau_{a(r)})\right)^2 + u_{in}^2} \ . \tag{6}$$

where $u(\varepsilon_r)$ is the standard uncertainty of determination of the object effective emissivity ε_r, $u(T_{ba(r)})$ is the standard uncertainty of determination of the effective background temperature T_{ba}, $u(\tau_{a(r)})$ is the standard uncertainty of determination of the effective atmospheric transmittance $\tau_{a(r)}$, and c_ε, c_T, c_τ, are the sensitivity coefficients that can be calculated as

$$c_\varepsilon = -\frac{\int_0^\infty \frac{sys(\lambda)}{\lambda^5\left[\exp(c_2/\lambda T_{out}) - 1\right]} d\lambda - \int_0^\infty \frac{sys(\lambda)}{\lambda^5\left[\exp(c_2/\lambda T_{ba(a)}) - 1\right]} d\lambda)}{\int_0^\infty \frac{\varepsilon_a sys(\lambda) c_2 \exp\left(c_2/\lambda T_{out}\right)}{\lambda^6 T_{out}^2\left[\exp\left(c_2/\lambda T_{out}\right) - 1\right]^2} d\lambda} , \tag{7}$$

$$c_T = -\frac{\int_0^\infty \frac{\exp(c_2/\lambda T_{ba(a)})\left(1-\varepsilon_a\right) sys(\lambda)}{\lambda^6 T_{ba(a)}^2\left[\exp(c_2/\lambda T_{ba(a)}) - 1\right]} d\lambda)}{\int_0^\infty \frac{\varepsilon_a sys(\lambda) \exp\left(c_2/\lambda T_{out}\right)}{\lambda^6 T_{out}^2\left[\exp\left(c_2/\lambda T_{out}\right) - 1\right]^2} d\lambda} , \tag{8}$$

$$c_\tau = -\frac{\int_0^\infty \frac{\varepsilon_a sys(\lambda)}{\lambda^5\left[\exp(c_2/\lambda T_{out}) - 1\right]} d\lambda - \int_0^\infty \frac{\left(1-\varepsilon_a\right) sys(\lambda)}{\lambda^5\left[\exp(c_2/\lambda T_{ba(a)}) - 1\right]} d\lambda)}{\int_0^\infty \frac{\varepsilon_a \tau_{a(a)} sys(\lambda) c_2 \exp\left(c_2/\lambda T_{out}\right)}{\lambda^6 T_{out}^2\left[\exp\left(c_2/\lambda T_{out}\right) - 1\right]^2} d\lambda} . \tag{9}$$

In order to calculate the combined standard uncertainty $u_c(T_{out})$ it is necessary to know not only the coefficients c_ε, c_T, c_τ, c_{in} but also the standard uncertainties $u(\varepsilon_r)$, $u(T_{ba(r)})$, $u(\tau_{a(r)})$.

Users of thermal cameras usually do not know the uncertainties $u(\varepsilon_r)$, $u(T_{ba(r)})$, $u(\tau_{a(r)})$. However, the uncertainties usually can be estimated as the users almost always can estimate the bounds of the random variables ε_r, $T_{ba(r)}$, $\tau_{a(r)}$. This means that it is known that the real effective emissivity ε_r is located within the range $[\varepsilon_a$-$\Delta\varepsilon$,ε_a+$\Delta\varepsilon]$, the real effective background temperature $T_{ba(r)}$, is located within the range $[T_{ba(a)}$ -ΔT_{ba} , $T_{ba(a)}$ +$\Delta T_{ba}]$, the real effective transmittance $\tau_{a(r)}$ is located within the range $[\tau_{a(a)}$ -$\Delta\tau$,$\tau_{a(a)}$ -$\Delta\tau]$.

Although the users can usually estimate bounds of the random variables ε_r, $T_{ba(r)}$, $\tau_{a(r)}$ they rarely can estimate type of probability distribution of these quantities. Therefore, let us assume a uniform distribution of these quantities within the earlier specified ranges as such an assumption is commonly made when there is no specific knowledge about possible values of quantity x within a certain range. [1] Then the uncertainties $u(\varepsilon_r)$, $u(T_{ba(r)})$, $u(\tau_{a(r)})$ can be calculated as

$$u(\varepsilon_r)=\frac{\Delta\varepsilon}{\sqrt{3}} \qquad u\left(T_{ba(r)}\right)=\frac{\Delta T_{ba}}{\sqrt{3}} \qquad u\left(\tau_{a(r)}\right)=\frac{\Delta\tau}{\sqrt{3}}. \tag{10}$$

Next, it was shown in the previous sections that the intrinsic uncertainty u_{in} can be determined on the basis of the measured *ME, NGE, TS* using the formula (4).

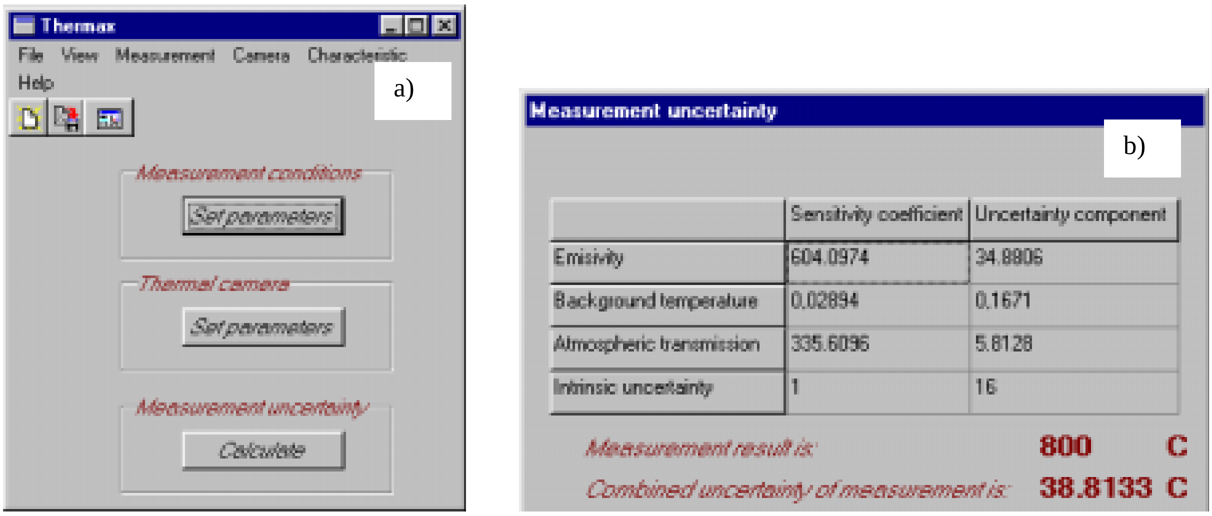
Now, using the formulas (4-10) we can calculate the combined standard uncertainty $u_c(T_{out})$.

It is a practical consequence of the Central Limit Theorem that if there are at least 3 uncertainty components and the combined standard uncertainty is not dominated by one of them then probability distribution of the measurement result y is approximately normal (Gaussian). This condition is generally fulfilled in our case and then the $u_c(T_{ob})$ defines an interval $T_{out} - u_c(T_{ob}) \leq T_{ob} \leq T_{out} + u_c(T_{ob})$ within which the value of the true object temperature T_{ob} is believed to lie with a level of confidence p of approximately 68%.

4.2 Software for calculation of uncertainty of temperature measurement with thermal cameras

A software package Thermax that enables quick and convenient for its user calculations of uncertainty of temperature measurements with thermal cameras has been recently developed. [12] It requires from its user to make 2 following steps to calculate the combined standard uncertainty $u_c(T_{out})$ of the output temperature T_{out}.

1. Insert parameters characterizing the measurement conditions:
   - output temperature T_{out},
   - the temperature span of the thermal camera used during measurements,
   - angular size of the tested object,
   - assumed by the user value of the object emissivity ε_a
   - assumed by the user value of the background temperature $T_{ba(a)}$,
   - assumed by the user value of the effective transmittance of the atmosphere $\tau_{a(a)}$,
   - some indications of possible dispersions of the parameters ε_a, $T_{ba(a)}$, $\tau_{a(a)}$ (the user can insert bounds within which these parameters are expected to lie and type of distribution, or to insert the standard deviation).
2. Insert parameters characterizing the thermal camera
   - the spectral sensitivity function sys(λ),
   - the intrinsic uncertainty.



	Sensitivity coefficient	Uncertainty component
Emisivity	604.0974	34.8806
Background temperature	0.02894	0.1671
Atmospheric transmission	335.6096	5.8128
Intrinsic uncertainty	1	16

Measurement result is: 800 C

Combined uncertainty of measurement is: 38.8133 C

Figure 7. View of two forms used in software Thermax : a) the introductory form, b) the final output form.

The user of this software can choose between typical spectral sensitivity function sys(λ) for 3-5μm thermal cameras or 8-12 μm thermal cameras or define its own spectral sensitivity function sys(λ).

In case of the intrinsic uncertainty the user has two options. First, to insert directly value of the intrinsic uncertainty u_{in}. The form x% of the T_{out} but not less that y°C is the default function for presentation of the intrinsic uncertainty u_{in}. Second, the user can insert the presented earlier parameters: the minimum error *ME*, the noise generated error *NGE*, the digital temperature resolution *DTR*, the temperature stability *TS*, and the measurement uniformity *MU*, the measurement spatial resolution MSR and then the intrinsic uncertainty u_{in} will be calculated by the software.

On the basis of the inserted data Thermax calculates standard uncertainty or the extended uncertainty of determination of the output temperature.

Let us carry out calculations for the case of the measurement conditions and the camera parameters presented in Table 2. It seems that similar situations like presented in Table 1 can be met in many applications of thermal cameras.

The results of the calculations of the combined standard uncertainty of the output temperature using the Thermax software are shown in Table 3.

Table 2. The assumed measurement conditions and the camera parameters

Parameter	Value
output temperature T_{out}	400 °C
camera temperature span during measurements	100 °C
angular size of the tested object	150 mrad
assumed value of the object effective emissivity and its possible dispersion	0.7±0.1 (uniform distribution)
assumed value of the background temperature $T_{ba(a)}$ and its possible dispersion	40°C ±10°C
assumed value of the effective transmittance of the atmosphere $\tau_{a(a)}$ and its possible dispersion	0.95±0.3
spectral sensitivity *sys*(λ)	typical for 8-12μm thermal cameras
intrinsic uncertainty of the camera	2% of T_{out} but not less than 2°C

Table 3. Results of the calculations

Source of uncertainty	*Partial standard uncertainty*
errors of determination of the object effective emissivity	35.3°C
errors of determination of the background effective temperature	0.68°C
errors of determination of the effective transmittance of the atmosphere	8.1°C
intrinsic uncertainty of the thermal camera	8°C
Output temperature	*Combined standard uncertainty* u_c
400°C	37.1 °C

The calculations of combined standard uncertainty of the output temperature using the Thermax software for the situation presented in Table 2 or any other can be carried out within a second. Therefore, the software Thermax can save user of thermal cameras many hours of time spent on estimation of uncertainty of measurements with these cameras. It is difficult to determine accuracy of the calculations carried out using the Thermax software. We can say that the software is based on a mathematical model that was developed in according to the recommendations of the main international metrological organisations presented in Ref.[9]. However, accuracy of the Thermax software depends not only on the mathematical model but also on the input data inserted by the user of this software who is expected to estimate the possible dispersion of the assumed values of the object effective emissivity, the effective background temperature, the effective atmospheric transmittance, and to determine intrinsic uncertainty of the thermal camera. The accuracy of determination of these parameters by the user can vary significantly depending on the user and applications. However, it seems that for a case of an experienced user of thermal cameras and in typical application it is always possible to determine the combined standard uncertainty of the output temperature with errors smaller than 20-50%. Such a level of possible error of determination of the uncertainty is typically acceptable in many of the industrial plants and laboratories that implemented the quality systems according the international standards ISO 9000 and EN 45000.

The software Thermax works in the following systems: Windows NT, Windows 98, Windows 95. It enables calculations of the combined standard uncertainty and the expanded uncertainty. Two version of reports produced by Thermax : the simplified version (the estimate of the output quantity and its standard uncertainty of its extended uncertainty) or the full version (the table recommended by EA). The report may be printed, transferred via clipboard or to data files. Two different formats are supported (Text only format or HTML). The latter format is particularly important as it enables possibility to create sophisticated reports in a well known format and to run such applications like Internet Explorer, Netscape Navigator to interpret it and to print from this applications.

5. CONCLUSIONS

International metrological organizations recommend nowadays characterization of measuring systems and measurement results by their uncertainties. The set of parameters, the measuring set and the testing methods, the mathematical model of uncertainty of a measurement results, and the software Thermax presented in this paper combined together enable determination of the intrinsic uncertainty of commercial thermal cameras and the uncertainty of measurement results with these cameras. Therefore this paper enables users of thermal cameras to fulfil the above mentioned recommendations what is particularly important for the users in the industrial plants and testing laboratories implemented the quality standards according to the international standards ISO 9001-9004 and EN 45001-45003. However further research this area is needed in order to improve the testing methods, the mathematical model, and the software presented in this paper and to develop international standards regulating testing and evaluation of commercial thermal cameras.

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