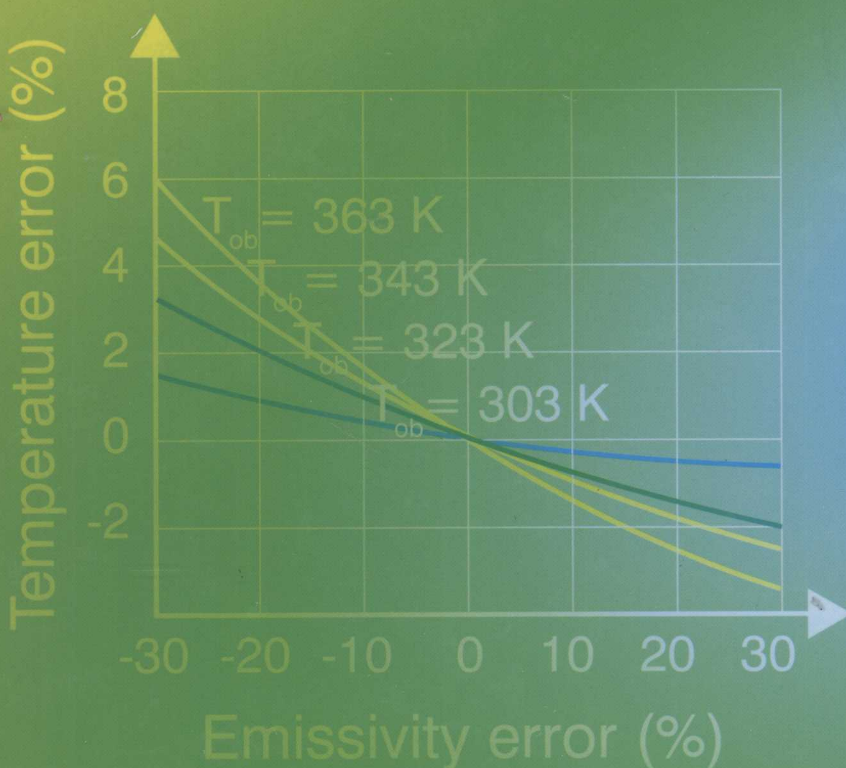
WALDEMAR MINKINA | SEBASTIAN DUDZIK

Infrared Thermography

Errors and Uncertainties



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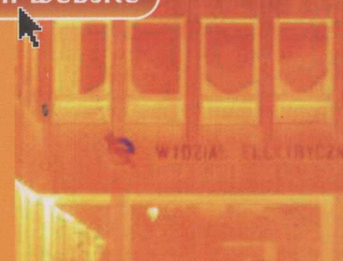

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Waldemar Minkina and Sebastian Dudzik

Częstochowa University of Technology, Poland

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Man, being the servant and interpreter of Nature, can do and understand so much and so much only as he has observed in fact or in thought of the course of nature. Beyond this he neither knows anything nor can do anything.

F. Bacon, *Novum Organum*, Aphor. I

To our wives

Elżbieta and Barbara

Preface

In our contact with users of infrared systems we were frequently asked, 'How do you estimate the accuracy of infrared thermography measurements, or how accurate are the data used from thermography measurements, for example, in the analysis of the temperature field of selected objects by the finite difference method (FDM), the finite element method (FEM) or the boundary element method (BEM) (Özisik, 1994, Minkina, 1994, Minkina, 1995, Minkina, 2004, Astarita *et al.*, 2000, Hutton, 2003)?'

The answer to such a question is not straightforward, so we decided to write this book, which is intended to deal with the problem in depth. It is worth underlining that the problem has not yet been fully solved in the literature. Authors, be they physicists, architects, mechanical engineers, power engineers or computer scientists, describe it in different ways, depending on the scientific field they represent. In this monograph we deal with the problem comprehensively, in accordance with international recommendations as published in the *Guide to the Expression of Uncertainty in Measurement* (Guide, 1995, Guide, 2004). This work is the first to deal with the issue in this manner. It is an extension and complement of the study presented in §10 of the monograph by Minkina (2004).

This book also aims to explain the many misunderstandings in the interpretation of temperature measurements and feasible metrological evaluation of commercially available infrared systems.

The first misunderstanding is the wrong interpretation of the Noise Equivalent Temperature Difference (NETD) parameter, published in catalogs as thermal sensitivity and interpreted sometimes as a parameter related to the precision of an infrared thermography measurement. In fact, the NETD parameter is rather for marketing purposes and says little about the actual error of a measurement. This parameter has an effect only on the quality of a thermogram, because it guarantees better uniformity of signals acquired from the particular detectors of the detector array. In practice, it can only give information on the error of temperature difference between two points of a given area of uniform emissivity, measured by the same pixel of a multipixel array (matrix) of detectors in idealized measurement conditions of short camera-to-object distance and no external sources emitting disturbing radiation. It takes place when the measurement model stored in the camera's microcontroller memory is fulfilled and the model parameters (ε_{ob}, T_{atm}, T_o, ω, d) are entered with zero error. Of course, it is difficult to conduct such a measurement in reality.

The second misunderstanding is the wrong interpretation of another parameter published in catalogs: namely, the accuracy of a thermography measurement. This accuracy is associated firstly with the quality of calibration of the array detector (Minkina, 2004). The better the calibration (i.e. the more accurate the bringing of the static characteristics of individual detectors to the same common shape), the smaller the measurement error. Secondly, the measurement accuracy is affected by calibration conducted by the camera manufacturer. Parameters (*R*, *B*, *F*) of the static characteristic of the measurement path determined during calibration are obviously burdened with errors. Therefore, if in a catalog this error is given as ±2 °C, ±2%, then for a given measurement range the larger of the two values should be taken. For example, for a measurement range of 0–100 °C we should take ±2 °C, while for a range of 100–500 °C we should take ±2%. As before, the error value refers to idealized measurement conditions: that is, an adequate measurement model stored in the microcontroller memory and zero errors in the entered model parameters. Under actual conditions (e.g. for a long camera-to-object distance or in the presence of external radiation interfering with the object radiation), the error can be many times greater. In extremely difficult atmospheric conditions, non-contact temperature measurement is not possible at all.

The uncertainty analysis of thermography measurement using analytic methods is very difficult because it involves a complex form of the model (Dudzik, 2005, Minkina, 2004). Therefore, for the uncertainty analysis of the processing algorithm in this work, we use the numerical method for the propagation of distributions recommended by Working Group No. 1 of the BIPM (International Bureau of Weights and Measures) (Guide, 2004). The uncertainty analysis was carried out for correlated as well as for uncorrelated model input variables. It allowed for quantitative evaluation of the influence of individual factors on the expanded uncertainty of infrared camera temperature measurement.

From a terminology perspective, this can be explained using various concepts. In the literature, besides 'thermovision' the term 'thermography' is often used. As the measurements are often computerized, the term 'computer-aided thermography' is used as well. 'Thermography' can be understood as the older technique (e.g. the recording of thermal images on heat-sensitive paper with a thermograph). In this method, firstly the image is obtained and next, observations are taken. Additionally, 'thermography' suggests that we describe graphic systems rather than vision systems. In the English literature, 'computer-aided thermography' is often used. Contemporary thermal imaging systems are called infrared cameras. Sometimes they can be called thermographs as well. Therefore, it seems that the terms 'thermography' and 'thermovision' can be treated interchangeably; in this book, however, the first of these terms is preferred.

The material presented is divided into six chapters. Chapter 1 gives the reader an introduction to the theory of error and uncertainty. Chapter 2 deals with the basic issues of measurements in infrared thermography, such as the law of heat exchange by radiation and emissivity. In Chapter 3 we describe a typical processing algorithm of the measurement path as well as a generalized model of the temperature measurement of the example of FLIR's ThermaCAM PM 595 LW infrared camera.

It is necessary to emphasize that, for other types of infrared cameras and manufacturers, the results and conclusions will be very similar.

Chapter 4 deals with the issue of the measurement error analysis of an infrared system, performed using classic methods. In Chapter 5 we describe the results of simulation research on the uncertainty in measurement in the infrared thermography obtained, using numerical methods for the propagation of distributions.

Waldemar Minkina and Sebastian Dudzik
Częstochowa, 2009

About the Authors

Waldemar Andrzej Minkina was born in 1953 in Częstochowa, Poland. In 1977 he graduated from the Faculty of Electrical Engineering of Częstochowa University of Technology, specializing in the automatization of electric drives. He received a first class honors Ph.D. degree in 1983 from the Institute of Electrical Metrology at Wrocław University of Technology, Poland, and a D.Sc. (habilitation) degree in 1995 from the Faculty of Automatic Control at Lwów Technical University, Ukraine, recommended by the Chair of Measurement and Information Techniques. On 22 June 2006, the President of Poland presented him with a professorial nomination in technical sciences (full professor).

Professor Minkina's research interests include thermometry, computerized thermography, heat measurements and theory, and the techniques of heat exchange. He is the author or co-author of four monographs in metrology: *Measurements of thermal parameters of heat-insulating materials – methods and instruments* (in Polish), Częstochowa University of Technology Publishers, 2004 (ISBN 83-7193-216-2); *Thermovision measurements – methods and instruments* (in Polish), Częstochowa University of Technology Publishers, 2004 (ISBN 83-7193-237-5); *Compensation of dynamic characteristics of thermometric sensors – methods, systems, algorithms* (in Polish), Częstochowa University of Technology Publishers, 2004 (ISBN 83-7193-243-X); and *Thermovision measurements in practice* (in Polish), PAK Agenda Publishers, Warsaw 2004 (ISBN 83-87982-26-1). He has also published 110 journal papers (including 25 published, mainly as the single author, in *Sensors and Actuators, Measurement, Technisches Messen, Experimental Technique of Physics, IVUZ Priborostroenije, Messen-Pruefen-Automatisieren, Messen-Steuern-Regeln, Metrology and Measurement Systems* and *The Archive of Mechanical Engineering*). He is an author of six patents, four patent announcements and supervisor of three Ph.D. theses defended with honors.

Professor Minkina has been a visiting professor to institutes of metrology at the Universities of Karlsruhe, West Berlin, Sankt Petersburg and Lviv, as well as in the Physikalisch-Technische Bundesanstalt (PTB) in Berlin and in Risø National Laboratory, Denmark. He was a guest lecturer for Ph.D. studies conducted in the Institute of Solid-State Electronics at Dresden Technical University. He closely collaborates with the Chair of Metrology at Rostock University in the field of computerized thermography. The results of this collaboration are the International Workshops 'Infrarot – Thermografie'.

Professor Minkina is a Member of the Instrumentation and Measurement Systems Section of the Committee of Measurement and Scientific Instrumentation of the Polish Academy of Sciences; a Member of the Program Committee of the monthly journal *Pomiary Automatyka Kontrola* (*Measurement, Automation and Monitoring*) and editor of the Thermometry section; a Member of the Polish Association of Sensor Technology, the Polish Association of Theoretical and Applied Electrotechnics and the Association of Polish Electricians, where he is an expert in three fields. He has served as a Member of the Program, Scientific and Organization Committees of many international and national conferences and many times as a reviewer of journal papers submitted for publication. He was also a reviewer of many grants and projects conducted by the State Committee for Scientific Research (KBN). Since 1996 he has held the Chair of Microprocessor Systems, Automatic Control and Heat Measurements. In 1995–2005 he became the Director of the Institute of Electronics and Control Systems.

Sebastian Dudzik was born in 1975 in Łódź, Poland. In 2000 he graduated from the Faculty of Electrical Engineering at Częstochowa University of Technology, specializing in measurement and control systems. Since 2000 he has been in the Faculty of Electrical Engineering at Częstochowa University of Technology, where he received his Ph.D. degree in technical sciences in 2007. He is the author or co-author of 21 papers published in journals and conference proceedings in both Poland and abroad. His research interests include the applications of active infrared thermography, artificial neural networks and neuro-fuzzy models of heat exchange and non-destructive testing.

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We would like to cordially thank the five reviewers of this book. The remarks in their reviews have considerably improved the contents of this publication.

We would also like to thank Dr Janusz Baran for translating the text from Polish to English.

Symbols

A	absorbance coefficient
α	angle of observation, rad
B	one of three calibration constants of the infrared camera (the others being F, R)
$C_o = (5.670\,32 \pm 0.000\,71) \cdot 10^8\ \mathrm{W\,m^{-2}\,K^{-4}}$	technical constant of black body radiation (ISO 31)
$c = 299\,792\,458 \pm 1.2\ \mathrm{m\,s^{-1}}$	speed of light in vacuum (ISO 31)
$c_1 = 2 \cdot \pi \cdot h \cdot c^2 = (3.741\,832 \pm 0.000\,020) \cdot 10^{-16}\ \mathrm{W\,m^2}$	first radiant constant (ISO 31)
$c_2 = h \cdot c/k = (1.438\,786 \pm 0.000\,045) \cdot 10^{-2}\ \mathrm{m\,K}$	second radiant constant (ISO 31)
$D^*(\lambda, T)$	normalized spectral detectivity, $\mathrm{cm\,Hz^{1/2}\,W^{-1}}$
d	camera-to-object distance (one of the input variables in the infrared camera model), m
$\Delta_{T_{ob}}$	absolute error of a measurement model in infrared thermography, K or °C
Δf	frequency bandwidth, Hz
$\delta_{T_{ob}}$	relative error of a measurement model in infrared thermography
$E(X)$	expected value of a discrete random variable X
ε	emissivity (one of the input variables in the infrared camera model)
F	area, $\mathrm{m^2}$ (one of three calibration constants of the infrared camera, the others being B, R)
Φ	heat flux, W; power density of thermal radiation, $\mathrm{W\,m^{-2}}$
$h = (6.626\,176 \pm 0.000\,036) \cdot 10^{-34}\ \mathrm{W\,s^2}$	the Planck constant (ISO 31)
I_v	luminous intensity, cd
$k = (1.380\,662 \pm 0.000\,044) \cdot 10^{-23}\ \mathrm{W\,s\,K^{-1}}$	the Boltzmann constant (ISO 31); expansion factor
L_v	luminance, $\mathrm{cd\,m^{-2}}$
λ	wavelength, μm
M	radiant exitance, $\mathrm{W\,m^{-2}}$
q	thermal flux density, $\mathrm{W\,m^{-2}}$

R	reflectance (reflectivity) coefficient (one of three calibration constants of the infrared camera, the others being B, F); outer radius, m
ρ	correlation coefficient among input variables of infrared camera measurement model
$S_k(\lambda)$	function describing relative spectral sensitivity of the camera
s_{ob}	output signal from a detector, corresponding to the object temperature
$\sigma(X)$	standard deviation of a random variable X
$\sigma_o = 2 \cdot \pi^5 \cdot k^4/(15 \cdot h^3 \cdot c^2) = (5.670\,32 \pm 0.000\,71) \cdot 10^{-8}$ W m^{-2} K^{-4}	the Stefan–Boltzmann constant (ISO 31)
TT	transmission coefficient
T_{ob}	temperature of object, K or °C
T_o	ambient temperature, K or °C
T_{atm}	atmospheric temperature, K or °C
$u(x_i)$	standard uncertainty of ith input variable in the infrared camera model
$u_c(T_{ob})$	combined standard uncertainty of object temperature
ω	humidity (one of the input variables in the infrared camera model), %

Glossary

Absolute error of a measurement is the difference between measured value $\hat{y}$ and actual value y.

Absolute error of a measurement model in infrared thermography is the difference between value T_C calculated by the camera measurement path algorithm for a single element (pixel) of the array detector and actual temperature T_R of the surface area mapped (represented) by this element.

Accuracy (of measurement) is a maximum deviation, expressed as % of scale or in degrees Celsius, that the reading of an instrument will deviate from a correct standard reference.

Black body, black body radiator is a body that absorbs all incident radiation. From Kirchhoff's law it follows that a black body is also a perfect radiator. The emissivity of a black body is equal to one.

Bolometric detectors are resistors of very small heat capacity with a large, negative temperature coefficient of resistivity.

Calibration is a procedure for checking and/or adjusting an instrument. After calibration, the readings of the instrument will agree with a standard. Calibration removes instrument systematic error but is not able to remove random errors.

Combined standard uncertainty $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$, defined as $u_c^2(y) = \sum_{i=1}^{N} (\partial f/\partial x_i)^2 u^2(x_i)$, where $y = f(x_1, x_2, \ldots, x_n)$ is the measurement model function and $u^2(x_i)$ is the variance of the ith input of the model.

Confidence level$(1-\alpha)$ is a value of probability associated with a confidence interval or statistical coverage interval.

Data processing algorithm uncertainty is a measure of the spread of an output random variable, equal to the standard experimental deviation of this variable.

Emissivity ε of a body for the full radiation range, called the total emissivity, is the ratio of full-range radiant exitance of that body to full-range radiant exitance of a black body at the same temperature.

Expanded uncertainty U is the uncertainty obtained by multiplying combined standard uncertainty $u_c(y)$ by expansion factor k: $U = ku_c(y)$.

Expected value $E(X)$ of a discrete random variable X, whose values x_i appear with probabilities p_i, is $E(X) = \sum p_i x_i$.

Field of view (FOV) is an area that can be observed from a given distance d using the optics installed on an infrared camera.

Gray body is an object whose emissivity is a constant value less than unity over a specific spectral range.

Instantaneous field of view (IFOV) is the field of view of a single detector (pixel) in a detector array.

Limiting error is the smallest range around the measured value $\hat{y}$ containing actual value y.

Luminance or ***brightness*** L_v is the surface density of luminous intensity in a given direction.

Luminous intensity I_v is the light flux in a given direction per unit solid angle.

Method of increments (exact method) consists of determining the increment of a measurement model function for the known increments of input quantities (i.e. absolute errors).

Method of total differential (approximated method) is based on the expansion of a measurement model function in a Taylor series around the point defined by the actual (true conventional) values of the inputs.

Monochromatic emissivity ε_λ is the ratio of monochromatic radiant exitance $M_\lambda(\lambda,T)$ of a body at a given wavelength λ to monochromatic radiant exitance $M_{b\lambda}(\lambda,T)$ of a black body at the same wavelength, the same temperature and observed at the same angle.

Noise equivalent power(NEP) is the RMS (Root Mean Square) power of incident monochromatic radiation of wavelength λ that generates an output voltage whose RMS value is equal to the level of noise normalized to unit bandwidth.

Noise equivalent temperature difference (NETD) is the difference between the temperature of an observed object and the ambient temperature that generates a signal level equal to the noise level.

Non-gray body is an object whose emissivity varies with wavelength over the wavelength interval of interest.

One-sided coverage interval: if T is a function of observed values, such that for estimated parameter of population θ, probability $Pr(T \geq \theta)$ or $Pr(T \leq \theta)$ is at least equal to $(1-\alpha)$ (where $(1-\alpha)$ is a fixed number, positive and smaller than one), then the interval from the smallest possible value of θ to T (or the interval from T to the biggest possible value of θ) is the one-sided coverage interval θ with confidence level $(1-\alpha)$.

Pyroelectric detectors are built from semiconductors that exhibit the so-called pyroelectric effect.

Quantile of order $\boldsymbol{\beta}$ of a probability distribution described by cumulative distribution function $G(\eta)$ is such that, for a value η of the random variable, equality $G(\eta) = \beta$ is satisfied. This means that the probability of occurrence of this value is equal to β.

Radiant exitance (emittance) is the ratio of (temperature- and wavelength-dependent) radiant power (radiant flux) $d\Phi$ emitted by an arbitrarily small element of surface containing the considered point to a projected area dF of that element.

Radiant intensity is the radiant flux per unit solid angle.

Random error is the difference between the result of an individual measurement and the mean value calculated for an infinite number of measurements of a quantity, carried out under the same conditions.

Relative error of a measurement is the ratio of the absolute error to the actual value.

Relative error of a measurement model in infrared thermography is the ratio of absolute error $\Delta_{T_{ob}}$ to actual temperature T_R.

Response rate is a parameter determined by the detector's time constant.

Slit response function (SRF) is a parameter that, similar to IFOV, describes the capability of a camera with an array detector to measure the temperature of small objects.

Standard deviation $\sigma(X)$ of a random variable is the positive square root of the variance.

Standard uncertainty of a measurement is the uncertainty of that measurement expressed in the form of the standard deviation.

Systematic error (bias) is the difference between the mean value calculated for an infinite number of measurements of a quantity – carried out under the same conditions – and its actual value.

Temperature sensitivity is a parameter that determines change of signal per unit change of temperature for object temperature $T_{ob} = T_o$.

Thermopile detectors are built as a thermopile, that is a system of thermoelements connected in series.

Type A standard uncertainty is the standard uncertainty determined on the basis of the observed frequency distribution.

Type B standard uncertainty is the standard uncertainty determined on the basis of a frequency distribution assumed a priori.

Uncertainty of a measurement is a parameter characterizing the spread of measurement values that can be assigned to the measured quantity in a justified way.

Voltage or current (spectral) sensitivity is a ratio of the RMS value of the first harmonic of a detector output voltage (current) to the RMS value of the first harmonic of incident radiation power.

Contents

1

Basic Concepts in the Theory of Errors and Uncertainties

1.1 Systematic and Random Errors

In modern measurement systems we can observe, along with growth of complexity, the evolution of measurement methods to estimate accuracy. On one hand, this is a consequence of the increasing complexity of measurement models: the number of input quantities increases and dependencies between inputs and outputs become more and more complicated. It makes it difficult to estimate accuracy with the use of classical methods that employ analytical descriptions. On the other hand, technical progress enables better insight into physical reality, which, among other things, involves changes to definitions of units of measure, which are the basis of each metric system. For example, consider how the definition of the meter has evolved over the last two centuries (www.gum.gov.pl):

1793: The meter is 1/10 000 000 of the distance from the equator to the Earth's North Pole (i.e. the Earth's circumference is equal to 40 million meters).
1899: The meter is the distance, measured at 0 °C, between two engraved lines on the top surface of the international prototype meter standard, made of a platinum–iridium bar (102 cm in length) with an H-shaped cross-section.
1960: The meter is equal to 1 650 763.73 wavelengths of the orange–red radiation of the krypton-86 isotope.
1983: The meter is the distance traveled by light in vacuum in 1/299 792 458 seconds.

For the evaluation of measurement accuracy, it is necessary to define basic theoretical concepts of error and uncertainty. Below we present definitions of the measurement error for a single value of a measured quantity.

The **absolute error** of a measurement is the difference between measured value $\hat{y}$ and actual value y:

$$\Delta y = \hat{y} - y. \tag{1.1}$$

Infrared Thermography: Errors and Uncertainties Waldemar Minkina and Sebastian Dudzik