Infrared thermography errors and uncertainties pdf

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Glossary. 1 Basic concepts in the theory of errors and uncertainties. 1.1 Systematic and accidental errors. 1.2 Uncertainty in indirect measurements. 1.3 Distribution Method. 2 Measurements in infrared thermal imaging. 2.1 Introduction. 2.2 Basic laws of radiation transmission of heat. 2.3 Emission. 2.4 Measuring infrared cameras. 3 Infrared camera measurement processing algorithm. 3.1 Processing information in measurements of the paths of infrared cameras. 3.2 Mathematical measurement model with infrared camera. 4 Measurement errors in infrared thermal imaging. 4.1 Introduction. 4.2 Systematic interaction in infrared thermal imaging measurements. 4.3 System Interaction Simulation. 5 Uncertainty of measurements in infrared thermal imaging. 5.1 Introduction. 5.2 Experiment modeling methodology. 5.3 Combined standard uncertainty for non-short input variables. 5.4 Simulation of combined standard uncertainty for correlated input variables. 5.5 Simulation of combined standard uncertainty for non-short input variables. 6 Summary. The Script and MATLAB app. Appendix B Normal emissions of various materials. Bibliography. Index. Infrared Thermography Errors and Uncertainty of Infrared Thermography Errors and Uncertainties by Waldemar Minkina and Sebastian Dudzik, Technical University, Poland This edition was first published in 2009 in 2009 by John Wylie and Sons, Ltd Registered Office of John Wylie and Sons Ltd, Atrium, South Gate, Chichester, West Sussex, PO19 8S, UK For details of our global newsrooms, for customer service and for information on how to apply for permission to reuse copyright materials in this book, please visit our website on www.wiley.com. The author's right to be identified as the author of this work was declared under the Copyright, Designs and Patents Act 1988. All rights are reserved. 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If you need professional advice or other expert help, you should seek the services of a competent specialist. MATLABS MATLAB and any related trademarks are used with permission. The MathWorks, Inc. 3 Apple Hill Drive Natick, MA 01760-2098, USA Tel: 508-647-7000 Fax: 508-647-7001 Email: protected email:www.mathworks.com Library of Congress Publishing Inamination of data in Minkin, Walmar. Infrared thermography : errors and uncertainties / Waldemar Minkina and Sebastian Dudzik. Includes bibliographic references and index. ISBN 978-0-470-74718-6 (issue) 1. Thermography. 2. Infrared visualization. Uncertainty. 4. Tolerance (engineering) I. Dudzik, Sebastian, 1975- II. Title. TA1570. M62 2009 621.36'2-dc22 2009031444 Catalogue entry for this book is available at the British Library. ISBN: 978-0-470-74718-6 (Hbk) Set at 10/12pt, Times by Thomson Digital, Noida, India. Printed in the UK by CPI by Anthony Rowe, Chippenham, Wiltshire. Man, being a servant and translator of Nature, can do and understand so much and so much only as he has observed actually or in thought of the course of nature. Besides, he knows nothing and can't do anything. F. Bacon, Novum Organum, Aphor. I our Wives El_zbieta and Barbara Content Foreword ix About authors xi Confessions of xiii Symbols XV Glossary XVII 1 Key Concepts in Error Theory and Uncertainties 1.1 Systematic and Accidental Errors 1.2 Uncertainty in Indirect Dimensions 1.3 Method distribution distribution 1. 1 1 4 8 2 Measurements in Infrared Thermography 2.1 Introduction 2.2 Basic Laws of Radiation Heat Transmission 2.3 Emission 2.4 Measuring Infrared Cameras 15 15 15 15 20 29 3 Infrared Camera Algorithm Measurement Processing Path 3.1 Processing information in measurements of infrared cameras 3.2 Mathematical measurement model with infrared camera 41 41 51 4 Measurement errors in infrared thermal imaging 4.1 Introduction 4.2 Systematic Interactions in Infrared Thermal Imaging Measurements 4.3 Simulation Systematic Interactions 61 61 62 66 5 Uncertainty Measurements Infrared Thermography 5.1 Introduction 5.2 Methodology Modeling Experiments 5.3 Components combined standard uncertainty for non-short input variables 81 81 82 95 viii 5. 4 Simulation of Combined Standard Uncertainty for Correlated Input Variables 5.5 Simulation of Combined Standard Uncertainty for Unrelated Input Variables Content 104 117 6 Summary 137 Application A MATLAB Scripts and Function A.1 Code Typing A.2 Component Calculation Procedure standard uncertainty in the infrared measurement of thermal imaging Presented A.3 software procedure for calculating coverage interval and combined standard uncertainty in the measurement of infrared thermal imaging using the presented A.4 software procedure to simulate cross-correlations between the input variables of the infrared camera model using the A.5 MATLAB Source Code (A.5 MATLAB Source Code (A.5 MATLAB Source Code (MATLAB Source Code (A.5 MATLAB Source Code (MATLAB Source Code)))Scripts) A.6 SOURCE code MATLAB (functions) A.7 Example MATLAB Sessions 141 141 141 142 143 143 163 172 Appendix B Normal Emissions of Various Materials (IR-Book 2000 , Minkina 2004) 177 Bibliography 185 Index 191 Foreword The question of how to assess the accuracy of infrared thermal imaging measurements, or how accurate the data used in thermal imaging measurements are, for example, in the temperature analysis of selected objects by the final difference method (FDM), the element method (FEM) or zosik, 1994, Minkin, 1994, Minkin, 1995, Minkin, the boundary element method (BEM) (O 2004) , Astarita et al., 2000, Hatton, 2003)? The answer to this question is not simple, so we decided to write this book, which is designed to solve the problem in depth. It is worth noting that this problem is not yet fully solved in the literature. The authors, whether physicists, architects, mechanical engineers, energy engineers or computer scientists, describe it differently, depending on the scientific field they represent. In this monograph, we have a comprehensive solution to this problem in accordance with international recommendations published in the Guide to the Expression of Uncertainty in Measurement (Guide, 1995, Guide, 2004). This work is the first to address the problem in this way. This is an extension and addition of the study presented in the x10 monograph minkina (2004). This book also aims to explain numerous misunderstandings in the interpretation of temperature measurements and possible metrological assessment of commercially available infrared systems. The first misunderstanding is the misinterpretation of the noise equivalent temperature difference (NETD), published in catalogs as heat sensitivity and sometimes interpreted as a parameter associated with the accuracy of the measurement of infrared thermal imaging. In fact, the NETD option is rather for marketing purposes and says little about the actual measurement error. This option only affects the quality of the thermogram, as it guarantees better homogeneity of signals received from specific detectors. In practice, it can provide information about the temperature difference error between the two points of this area of uniform emission, measured by the same pixel of the multipixel array (matrix) of detectors in idealized conditions of measuring the short distance from the camera to the object and without sources emitting alarming radiation. This occurs when a measurable model stored in the camera's microcontroller's memory is performed, and the model parameters (eob, Tatm, To, v, d) come in with zero error. Of course, it is actually difficult to make such a measurement. The second misunderstanding is the misinterpretation of another parameter published in the catalogues: namely, the accuracy of the measurement of infrared cameras. This accuracy is primarily related to the quality of the array detector calibration (Minkina, 2004). The better the x Precise calibration (i.e. the more accurate the static characteristics of individual detectors to the same general form), the lower the measurement error. Secondly, the accuracy of the measurements is influenced by the calibration carried out by the camera manufacturer. The parameters (R, B, F) of the static measurement trajectory determined during calibration are obviously error-laden. Therefore, if the catalog gives error as 2 C, 2%, then for this range of measurements you should take more of the two values. For example, for a measurement range of 0-100 C we have to take 2 C, while for a range of 100 -500 C we have to take 2%. As before, the error value refers to idealized measurement conditions: that is, an adequate measurement model stored in the memory of the microcontroller and zero errors in the model parameters (eob, Tatm, To, v, d). In real-world conditions (for example, at a long distance from the camera to the object or in the presence of external radiation interfering with the radiation of the object), the error can be many times greater. In extremely difficult atmospheric conditions, contactless temperature measurement is not possible at all. Analyzing the uncertainty of measuring the thermography using analytical methods is very difficult because it involves the complex shape of the model (Dudzik, 2005, Minkina, 2004). Therefore, to analyze the uncertainty of the processing algorithm in this work, we use the numerical method of distribution of distributions, recommended by Working Group 1 BIPM (International Bureau of Weights and Measures) (Guide, 2004). Uncertainty analysis was conducted for both correlated and unrelated model input variables. This book provides a quantitative assessment of the influence of individual factors on the increased uncertainty of the measurement of the temperature of the infrared camera. From a terminology point of view, this can be explained through different concepts. In literature, in addition to thermovision, the term thermography is often used. As measures are often computerized, the term computer-aid thermography is used as well. Thermography can be understood as an old technique (for example, recording thermal images on heat-sensitive papers with a thermograph). In this method, first, the image is obtained, and then, Taken. In addition, thermography suggests that we describe graphic systems, not vision systems. Computer thermography is often used in English literature. Modern thermal imaging systems are called infrared cameras. Sometimes they can be called thermographs. Thus, it seems that the terms thermography and thermal vision can be considered interchangeably; in this book, however, the first of these terms is preferable. The material presented is divided into six chapters. Chapter 1 gives the reader an introduction to the theory of error and uncertainty. Chapter 2 addresses the main measurements in infrared thermal imaging, such as the law of heat and radiation. In Chapter 3, we describe a typical measurement trajectory algorithm, as well as a generalized temperature measurement model using the FLIR ThermaCAM PM 595 LW infrared camera. It should be emphasized that for other types of infrared cameras and manufacturers the results and conclusions will be very similar. Chapter 4 examines the question of the error of measuring the infrared system using classical methods. In Chapter 5, we describe the results of simulations of measurement uncertainty studies in infrared imaging, derived from the numerical method of distribution. Waldemar Minkina and Sebastian Dudzik Częstochowa, Poland xi About the authors Waldemar Minkina was born in 1953 in stokhova, Poland. In 1977 he graduated from the Faculty of Electrical Engineering, university of technology, specializing in the automation of electric drives. In 1983, he received his Ph.D. from the Institute of Electrical Metrology at the Vrock University of Technology (Poland) and a degree in D.Sc. (habilitation) in 1995 from the Faculty of Automatic Management at the Lyvcrat Technical University, Ukraine, recommended by the Department of Measurement and Information Technology. On 22 June 2006, the President of Poland presented him with the nomination of a professor of engineering (full professor). Professor Minkina's scientific interests include thermometry, computerized thermography, heat measurements and theory, as well as thermal measurement methods. He is the author or co-author of four monographs in metrology: Measurements of thermal parameters of insulation materials - methods and tools (in Polish), Cze_Stokhov University of Technology Publishers, 2004 (ISBN 83-7193-216-2); Thermal vision measurements - methods and tools (in Polish), Cze_Stokhov University of Technology Publishers, 2004 (ISBN 83-7193-237-5); Compensation of dynamic characteristics of thermometric sensors - methods, systems, algorithms (in Polish), Cze_Stokhov University of Technology. 2004 (ISBN and measurements of thermal vision in practice (in Polish), PAK Agenda, Warsaw 2004 (ISBN 83-87982-26-1). He also published 110 journal papers (including 25 published), mostly as a sole author, in sensors and drives, measurement, Technisches Messen, Experimental Physics Techniques, Priborostroenie, MessenPruefen-Automatisierung, Messen-Steuern-Regeln, Meteorology and Measuring Systems and Mechanical Engineering Archives. He is the author of six patents, four patents and has been a member of many international scientific conferences. He worked as a visiting professor at the universities of Karlsruhe, West Berlin, St. Petersburg and Lviv, as well as at the Physics-Technish Bundesant (PTB) in Berlin and at the National Laboratory at Riso, Denmark. He was a visiting professor at the Institute of Solid State Electronics at the Technical University of Dresden. He works closely with the Department of Meteorology of the University of Rostock in the field of computerized thermal imaging. The result of this collaboration is the International Seminars Infrarot - Thermography. Professor Minkina is a member of the Instrumentation and Measuring Systems Section of the Committee of Measuring and Scientific Instruments of the Polish Academy of Sciences; Member of the Program Committee of the monthly magazine Pomiar Automation Control (measurement, automation and monitoring) and editor of the section Thermometry; member of the Polish Touch Technology Association, the Polish Association of Theoretical and Applied Electrical Engineers and the Association of Polish Electricians, where he is an expert in three fields. He has been a member of the Program, Scientific and Organization Committees of many international and national conferences and many times as a reviewer of the journal papers submitted for publication. He has also been a reviewer of many grants and projects conducted by the State Research Committee (KBN). Since 1996 he has occupied the Department of Microprocessor Systems, Automatic Heat Control and Measurement. In 1995-2005 he was director of the Institute of Electronics and Control Systems. Sebastian Dudzik was born in 1975 in czy, Poland. In 2000 he graduated from the Faculty of Electrical Engineering, specializing in measurement and control systems. Since 2000 he has been working in the Faculty of Electrical Engineering at the University of Technology Tse_Stokhov University of Technology, where in 2007 he received his Doctorate of Engineering. He is the author or co-author of 21 articles published in magazines and conferences both in Poland and abroad. His research interests include the use of active infrared thermography, artificial neural networks and neuro-fuzzy models heat-free and non-destructive testing. Confessions We would like to heartily thank the five reviewers of this book. The comments made in their reviews have greatly improved the content of this publication. We would also like to thank Dr. Janusz Baran for translating the text from Polish to English. Symbols A B Co 1/4 (5.670 32 0.000 71) 108 W m2 K4 c 1/4 299 792 458 1.2 m s1 c 1 1/4 2phc2 1/4 (3.741 832 0.000 020)1016 W m2 c2 1/4 hc/k 1/4 (1.438 786 0.000 045)102 m K D (L, T) d DTob DTob E(X) F F H I l4 (6.626 176 0.000 036)1034 W s2 lv k 1/4 (1.380 662 0.000 044)1023 W s K1 Lv l M n absorption ratio viewing angle, rad one of the three calibration constants of infrared camera (remaining F, R) technical constant of black body radiation (ISO 31) the speed of light in a vacuum (ISO 31) the first shining constant (ISO 31) the second shining constant (ISO 31) measured specific detectivity , see 1/2 W1 distance from the camera to the object (one of the input variables in the infrared camera model), m absolute error of the measurement of the infrared thermal imaging Absolute error of measurement in infrared thermal imaging ... Measurement error (of the measured value), ... relative error of the measured value ... relative error of the measurement in infrared thermal imaging (the relative error is the ratio of the absolute error to the actual value) X emission (one of the input variables in the infrared camera model), m2 (one of the three constant calibration of the infrared camera, the other B, R) thermal flow, W; Heat Power Density, W m2 Permanent Planck (ISO 31) Shining density, W m2 photon energy brightness, cd M2 wavelength, mm shining output, W m2 thermal flow density, W m2 xvi R r s(X) so 1/4 2 p5 k4 No15 h3 c2 (5.670 32 0.000 7 1)108 W m2 K4 T T Tob To Tatm u(x) uc (Tob) v Character Reflection Ratio (reflectivity) (one of three calibration constants infrared camera, remaining B, F); external radius, m correlation factor among input variables of the infrared camera measurement model, which describes the relative spectral sensitivity of the camera output signal from the detector, corresponding to the standard deviation of a random variable X Stefan-Boltzmann constant (ISO 31) of the object temperature transfer factor, the temperature of the ambient K or C atmospheric temperature, meaning that the standard uncertainty of the input variable x of the combined standard uncertainty, with the humidity of the uncertainty of the infrared camera output signal (one of the input variables in the infrared camera model), % Glossary Absolute error of measurement, Absolute error of measurement in infrared thermal imaging is the difference between the TC value calculated by the camera software algorithm for a single element (pixel) of the array detector, and the actual temperature of the TR surface area (represented by this element). Precision (measurement) is the maximum deviation expressed as a percentage of the scale or degrees Celsius that the readings of the device will deviate from the correct standard reference. The absolute error of measurement is equal to one. Bolometric detectors are resistors of very low heat capacity with a large, negative temperature resistance factor. Calibration is a procedure for checking and/or tweaking the tool. After calibration, the instrument readings will agree with the standard. Calibration eliminates systematic tool errors, but fails to remove accidental errors. The combined standard uncertainty of P uc(y) is a positive square root of the combined u2c variance defined as u2c y 1/4 Ni1/41 qf qxi qxi q2 u2 xi, where y 1/4 f (x1, . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . He said . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . A confidence level (1 (a) is a probability value associated with a confidence interval or statistical coverage interval. Uncertainty of the data processing algorithm is a measure of the spread of the output random variable, equal to the standard experimental deviation of this variable. The emission of the body for the full range of radiation, called total emission, is the ratio of the total radiant output of this body into the full radiant output of the black body at the same temperature. Extended U uncertainty is the uncertainty resulting by multiplying the combined standard uncertainty of uc(y) by expanding k:U 1/4 kuc.y. The expected E(X) P discrete random X variable, whose xi values appear with pi probabilities, is E.X 1/4 pi xi. Field of View (FOV) is an area that can be observed from a given distance using optics mounted on an infrared camera. The gray body is an object whose emission is a constant value less than unity over a certain spectral range. The 18th Glossary Instant Field of View (IFOV) is the field of view of a single detector (pixel) in the detector array. The error limitation is the smallest range around the measured value containing the actual value of y. Luminance or brightness is the surface density of glowing intensity in this direction. The glowing intensity of I v is the flow of light in this direction per unit angle. The intensity emitted in this direction. The intensity of each ... The common differential method (approximate method) is based on extending the function of the measurement model in the Taylor series around the point, defined by actual (true conventional) input values. Monochrome k is the ratio of monochrome radiant output of the Mbl (l,T) of the black body at the same wavelength, the same temperature and is observed at the same angle. Noise equivalent power (NEP) is the RMS (Root Medium Area) power of monochrome wavelength l radiation, which generates output voltage, the value of which is equal to the noise level normalized for a unit of bandwidth. The difference in noise equivalent temperature (NETD) is the difference between the temperature of the observed object and the temperature of the ambient, which generates a signal level equal to the noise level. A non-gray body is an object whose emission varies depending on the wavelength over the wavelength of interest. One-way coverage interval: If T is a function of observed values, so that for the calculated population parameter of value, the probability of Pr (T u) or Pr (T u) is at least equal to (1 a) (where (1 a) is a fixed number, positive and smaller than one), then the interval from the lowest possible value of you to T (or interval from T to the highest possible value of you) is a one-sided a). Pyroelectric detectors are built from semiconductors that have the so-called pyroelectric effect. The quantile of the order of b of probability distribution, described by the cumulative function of The Distribution of Goh, is such that for the value h random variable, the equality of Gyo 1/4 b is satisfied. This means that the probability of this value occurring is b. The shining output (emitted) is the ratio (temperature- and wavelength-dependent) of the radiant energy (shining flow) dF emitted arbitrarily by a small surface element containing the address point to the projected dF area of that element. The intensity of the radiation is a radiant flow per unit of solid angle. A random error is the difference between a result of an individual measurement and the average, calculated on an infinite number of measurements of the same measurement amount under the same conditions. The relative error of measurement is the ratio of the absolute error to the actual value. The relative error of measurement models in infrared thermal imaging is the ratio of the absolute error of DTob to the actual temperature of Tr. The response speed is a parameter determined by the constant time of the detector. The Slice Response Function (SRF) is a parameter that, like IFOV, describes the ability of an array detector camera to measure the temperature of small objects. The standard deviation of s(X) random variable is a positive square root of variance. The 19th Standard Measurement Uncertainty is the uncertainty of this measurement, expressed as a standard deviation. A systematic error (bias) is the difference between the average, designed for an infinite number of measurements performed under the same conditions, and its actual value. Cost. sensitivity is the parameter that describes the signal change per temperature change unit for the temperature of the Tob 1/4 To object. Thermopylene detectors are built as thermopill, that is, a system of thermocells connected in a row. The standard type A uncertainty is a standard uncertainty based on the observed frequency distribution. The uncertainty of the type B standard is a standard uncertainty based on the distribution of frequencies adopted by a priori. Measurement uncertainty is a parameter that characterizes the distribution of measured values that can be attributed to the measured amount in a justifiable manner. Voltage or current (spectral) sensitivity is the ratio of the RMS value of the first harmonic voltage of the detector output (current) to the value of RMS of the first harmonic radiation. 1 Basic concepts in error theory and uncertainties 1.1 Systematic and random errors Any measurement can be distorted by errors, and since it is not possible to perform measurements with sufficient accuracy, it is also necessary to estimate the uncertainty of measurement. ... Infrared Thermography Errors and Uncertainties Waldemar Minkina and Sebastian Dudzik 2009 by John Wylie and Sons, Ltd ... The absolute error of measurement is the difference between the measured value and the actual value of the U: Dy 1/4 y . Infrared Thermography: Mistakes and Uncertainties 2009 by John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik Ltd:1.1 Infrared Thermography 2 The relative measurement error is the ratio of the absolute measurement error to the true value of y: dy 1/4 Dy y y y 1/4 : y 1:2 In the unknown actual value of y in the formula (1.1) is replaced by the value of y. Because the exact value of the absolute error is unknown, it is important to estimate the range in which the actual value is located. Such reasoning leads to the definition of limiting error. The limiting error is the smallest range around the measured value, where the actual value of y (Guide 2004): y Dymin y y Dymax : 1:3 In the analysis of measurement errors occurring in repeated experiments, the division is made into systematic and random errors. Studying the results of repeated measurements of the same number leads to the observation that one component of the error does not change its mark or meaning or develops with changes in the terms of reference in accordance with a specific law (function). This component was called a systematic error or bias (Taylor 1997, Guide 1995). It is defined as follows: a systematic error (bias) is the difference between the average, designed for an infinite number of measurements of the amount made under the same conditions, and its actual value. The second component of the error is commonly referred to as a random error (Guide 2004). It can be reduced by repeating the measurement. In VIM (1993), an accidental error is defined as the difference between the result of the individual measurements and the average, calculated on an infinite number of measurements, made under the same conditions. When one component of the error is known, it can be corrected. The indirect measurement error is determined by the Law of Error Distribution (Taylor 1997). Under this law, one of two methods can be used to determine the error of output based on known input errors: extending the Taylor model features to the first-order terms (the general differential method) or the increments method. The increments method (the exact method) consists of determining the increments of the measurement model function for known increments of input quantities (i.e. absolute errors). Consider the measurement model as a function of several variables: y 1/4 f x1; x2 ; . . . ; xn th; No1:4, where x1, x2, . . . xn are inputs and y result measurement. Let's also refer to Dx1, Dx2, . . . Dxn as absolute input errors (increments of arguments f). Then we can write the increment of the function as: Dy 1/4 y y 1:5*The first two components on the right side (1.5) can be expressed as: x1 Dx1 and Dx2; . . . ; xn th Dxn: No 1:6 Basic Concepts in Error Theory and Uncertainty 3 Finally: Dy 1/4 f x1 x2 Dx2; . . . ; xn Dxn f x1; x2; . . . ; xn th: 1:7 Hence, from (1.7), relative error y is: dy 1/4 Dy ... In this work, the above method was used in the computer simulation of the error method in the infrared thermography presented in Chapter 4. Unfortunately for complex measurement models, the use of the increment method is very laborious. Therefore, the error is often evaluated using an approximate method, the general differential method (approximate method) is based on extending the function of the measurement model in the Taylor series around the point, defined by the actual (true ordinary) input values. Assuming that the feature (1.4) is continuous and, for simplicity, that only the input x1 is burdened with the Dx1 error, the extension in the Taylor series has the following form: f x1 x1 ; x2 ; . . . ; xn No 1/4 f x1; x2 ; . . . ; xn No Dx1 0 f x1 ; x2 ; . . . ; xn No 1! DDKS1 No2 00 DDKS1 3 000 f x1; x2 ; . . . ; xn e f x1; x2 ; . . . ; xn No . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3! Conditions of higher than the first order may be neglected with this expansion, suggesting that their impact on the result is negligible. Based on (1.6), we can write: Dy1 1/4 Dx1 f 0 x1 ; x2 ; . . . ; xn No 1/4 Dx1 @y ; @x1 where Dy1 is called the x1 output error component. Partial derivative of expected e-mail calculated at Nos1; x2 ; . . . ; xn, called the x1 entry sensitivity index. When you consider errors from all n1 inputs; x2 ; . . . xn, the total error of the indirect measurement can be written as the sum: Dy 1/4 n X i1/41 Dxi @y ; @xi 1:11, where partial derivatives (protected email) are calculated by x1; x2 ; . . . ; xn K. Since in (1.11) all increments of input variables x1; x2 ; . . . ; xn are taken with the same sign, the total error is overstated. In real-world experiments, the probability that all input measurements are burdened with positive (or negative) errors is small and decreases with the increase in input (Fuller 1987). Thus, a more realistic estimate of the indirect measurement of an absolute error is usually used in practice - the average square error: s @y 2 @y 2 @y 2 Dx2 dxn : 1:12 Dy 1/4 Dx1 @x1 @x2 @xn exp 1 with 4 In terms of temperature measurement uncertainty in infrared thermography This analysis can also be useful For strictly defined functions of systems, systems, system, system, error analysis are useful for thermography, for example, in simulation, to estimate how it is possible to determine the accuracy of temperature measurement when there is no information on these conditions. An additional purpose of the analysis is to compare the different measurement models used in modern infrared cameras. Finally, error analysis can be the starting point for sensitivity studies, where thermography is used to test numerical models (e.g., inverse problems). 1.2 Uncertainty in indirect measurements Because the exact value of the absolute error is unknown, the error of measurement cannot be determined. In practice, it is much more convenient to use the concept of measurement uncertainty, that can be attributed to the measured amount in a justifiable manner. Unfortunately, the aforementioned definition does not determine how this appointment can be made. Therefore, in order to accurately characterize the accuracy of the measurement, the following definition of standard uncertainty (Guide 1995) was introduced as a quantitative measure: the standard uncertainty of the measurement is the uncertainty of the measurement values expressed as a standard deviation. To estimate the quantitative accuracy of the measurement, the standard deviation is introduced. To describe the variables used in the model of the input measurements as random variables is introduced. These variables are characterized by specific functions for probability distributions. To measure accuracy, the most important statistics of random variables are the expected value and standard deviation. The expected E(X) of the discrete random X variable, the values of which appear with pi probabilities, is: E X 1/4 pi xi ; 1:13, where the amount is taken over by all possible values xi of the X variable. Thus, the expected value is replaced by its evaluator - arithmetic average from independent observations N (O'doerstr om and Stoica 1994): N 1 X 1/4 xi : 1:14 x N i1/41 Standard deviation s(X) random variable is a positive square root variance: 1:15 s'X 1/4 E1/2X E'X2 : Basic concepts in error theory and uncertainties 5 Practical problems are used by a standard deviation evaluator called an experimental standard deviation. It is calculated from the N independent observations xi: ... X N 1:16 Just like the combination of measuring errors, the methods of estimating uncertainties in the NC-1 Recommendation (1980) components of measurement uncertainty can be grouped into two categories (CIPM 1981, CIPM 1986): Type of standard uncertainty determined on the basis of observed frequency distribution. The standard type B uncertainty, determined by frequency distribution, assumed a priori. Example 1.1 Assessment of probability density parameters from a series of measurements - Type A Uncertainty In this example, we modeled an experiment consisting of multiple measurements of X quantity under repetitive conditions. The measured values of the X value are assumed to be subject to Gaussian distribution (this distribution was determined on the basis of the shape of the histogram). The results of numerical calculations are shown in figure 1.1a. A hard line denotes the probability density function obtained for calculated parameters. To assess standard uncertainty, we used the arithmetic average (1.14) and the experimental standard deviation of 1.16 as the best evaluators of the expected value and standard deviation X, respectively. In this way, we found the following values: x 1/4 0.91 s 1/4 0.06 As the typing uncertainty A took the value of the experimental standard deviation. This experiment illustrates how to evaluate the standard uncertainty of Type A. Figure 1.1 Assessment of standard uncertainty: a) Type A, Modeling in MATLAB; and b) Type B for even distribution (Guide 1995) Infrared thermography 6 Example 1.2 Assessment of Standard Type B Uncertainty by Single Distribution Density Feature Figure 1.1b shows the uncertainty of the type B standard can be determined by the equal distribution of the probability of variable X. The assumption of even distribution is made when there is information about allowable intervals of measured values. The standard deviation that characterizes the distribution of the X variable then: u 1/4 a/√3, where a is half the length of the interval. In the indirect measurement, uncertainty in the inputs of a complex analytical model affects accuracy indirect measurement. Uncertainty for indirect measurements (i.e. the assessment of measurement accuracy) often occur in practice. It is therefore necessary to assess the cumulative standard uncertainty. Depending on whether the inputs of the model are correlated or not, the covariance factor appears in the definition of combined uncertainty. Provided that input variables are not correlated, the cumulative standard of uncertainty is determined according to VIM (1993): the combined standard of uncertainty uc(y) is a positive square root of the combined u2c variance, defined as: N X @f 2 2 uxi; No1:18 u2c y 1/4 @xi i1/41 where f is the function of the measurement model (1.4) and u(xi) is the variance of the input. When input variables are correlated, an expression describing uncertainty is more complex because it includes estimates of input covariates. Measurement models in which inputs are treated as random variables with unknown values have standard uncertainties and are used as a measurement representation in the analysis of uncertainty (such as expected values, standard deviations) are also random variables. Therefore, we need to determine certain parameters using the concepts of probability. These concepts (VIM 1993) are described as follows: The one-way coverage interval is as follows: If T is a function of observed values, so that for the U population calculation, the probability of Pr (T u) or Pr (T u) is at least equal to (1 a) (where (1 a) is a fixed number, positive and smaller than one), then the interval from the lowest possible value of you to T (or interval from T to the largest possible value of you) is a one-way coverage interval with a level of confidence (1 a). A level of trust is a probability (1 (a) of probability associated with a confidence interval or statistical coverage interval. The extended U is an uncertainty obtained by multiplying the combined standard uncertainty of uc(y) by the expansion factor k: U 1/4 kuc'y: 1:20 Extended uncertainty determines the limits of the uncertainty interval for this level of confidence. The value of the expansion factor depends on the probability distribution of the variable output of the model. For example, if a random variable has a Gaussian field, the probability that the result of the measurement will fall in the interval from y uc(y) to y uc(y), that is for k 1/4 1, is about 68%; from y 2uc (y) to y 2uc (y), that is for k 1/4 2, about 95%; and from y 3uc(y) to y 3uc(y), that is for k 1/4 3, about 99%. Requiring an accurate knowledge of the type of output distribution variable is an inconvenience in determining the expansion factor. For models with a lot of input, we can assume that the theorem of the central limit is met. In this case, a priori assumes that the variable output has a Gaussian distribution. However, measurement practices reveal significant differences in the assessed extended uncertainty using the approximation of the Gaussian distribution, especially when the components that show strong non-linear differences and the true distribution of variable output is asymmetrical. When the probability of a variable output is not known, we need to determine the relationship between the expansion factor and the coverage interval (confidence level). This problem is usually solved by determining a large number of degrees of freedom using the Welch-Satterthwaite equation (Welch 1936, Satterthwaite 1941 : neff 1/4 u4c y : N X u4 yo 1:21 i 1/4 1 vi N1 and calculation of extended uncertainty as (Guide 1995): Up 1/4 kp uc y 1/4 tp neff uc y; 1:22, where the tp(neff) factor is taken from the tables of the student's t, calculated on the basis of the number of degrees of freedom given by formula (1.21). In summary, the following steps can be taken to assess the combined standard uncertainty (2004 Guide): 1. Assessment of expected values and standard deviations of ux' 1/4 xi' ... ux'n RT distribution probabilities of random X1 variables ... Xn, representing input x 1/4 x1 . . . . xn CT measuring models. If inputs correlate with each other, we should use a joint distribution of variable inputs. 2. Assessment of the covariance (mutual uncertainties) u'xi ; xj ... . i; xj and Xj K. 3. Calculating values for xi: inputs for the model output estimate ... 4. Calculating output estimates based on inputs ... 5. Evaluation of partial derivatives of model sensitivity indexes using partial derivatives at point x 1/4 x1 . . . xn K. 6. Assessment of standard uncertainty uc and model sensitivity indexes using formula 1.18 or 1.19. Infrared thermography 8 7. Estimating the number of degrees of freedom using, for example, formula (1.21). 8. Calculating extended uncertainty from formula (1.22). These steps lead to a proper assessment of extended uncertainty only when the following three conditions are met: 1. The model is negligible. Since it is difficult to specify an objective measure of non-linearity, we mean that the disregard for higher conditions in the Taylor series extending the function of the model does not greatly affect the results of the evaluation. 2. The assumptions of the central limit theorem are satisfied. Specifically, the distribution of the release model is Gaussian with good accuracy. 3. The approximation of the number of degrees of freedom from the Welch-Satterthwaite equation is quite accurate. In practical dimensions, it is often impossible to meet the above conditions. Therefore, Working Group 1 of the Joint Committee on Guides in Metrology has prepared a supplement No. 1 to the manual (1995) entitled The Number of Distribution Methods. This add-on provides the idea of numerically estimating the coverage interval. This approach does not require knowledge of the analytical form of the probability distribution function. In further parts of this book we present the main guidelines and goals of this method. 1.3 The distribution method In previous paragraphs, we have presented the basic concepts associated with assessing the accuracy of indirect measurements using classical methods. We have described the basics of error and uncertainty theory and pointed to problems in assessing extended uncertainty. These problems are the consequences of the fact that, in practice, the types of probability distribution of input random variables (i.e. measured quantities) are unknown. The General Committee on Major Problems in Meteorology took this into account when preparing the supplement mentioned above (Guide 2004). This supplement relates to assessing the accuracy of indirect measurements, with particular emphasis on highly non-linear models and all kinds of output distributions. In this approach, the measurement model is a highly non-linear function of input quantities; the uncertainties of individual input quantities are comparable; the probability distributions of input variables are not available; the distribution of variable output is not Gaussian. Indirect measurement models are often complex, the measurement model of an infrared camera can be highly non-linear. The idea of distributing distributions is illustrated in figure 1.2. The basic concepts in error theory and uncertainties Figure 1.2 Illustration of the distribution of distributions Symbols in figure 1.2 denote: gi yi ji, function of probability density of the valid values ji ith input amount Xi; and gyo, probability density function H output. Figure 1.2 shows the idea of a distribution method that is used to propagate the distributions of probability densities of input quantities through the measurement model to obtain a probability density of the output variable. The distribution of distributions using the Monte Carlo method. The main purpose of the procedure is to estimate the statistical coverage interval at a given level of trust. It is worth noting that the procedure gives the right results even for highly non-linear functions and asymmetric distributions of output. The assessment of expected value uncertainty using the method of distributions includes the following steps: 1. Determination of the output of measurement model received (indirectly measured number). 2. Definition of the number of inputs. 3. Developing a model of measurements based on the input. 4. Identify the probability density functions of input quantities based on an analysis of available knowledge. 5. Propagation of distributions of input probability density functions through the measurement model. 6. Obtain a probability distribution function of output and a defined distribution of input data. The calculations can be carried out using the Monte Carlo method. Assessing the expected value of output, as well as the coverage (confidence) interval, which includes measurements with a probability determined by the expected level of trust. The Monte Carlo method makes it possible to numerically approximate the cumulative distribution function output based on a selected number of random draws ... Therefore, a fairly large set of outputs derived from the model in this way can bring, to the required accuracy, the distribution of the probability of acceptable output values (measured quantity). The Monte Carlo simulation is carried out in the following steps (Guide 2004): 1. Generating a set of N values by independently sampling the probability density function of each input variable C; i 1/4 1; . . . ; N. In the case of statistically dependent variables, samples should be created using the function of joint density of variables. The sample is repeated M times where M is a large number. As a result, we get M independent sets of N input values. 2. models for each set of values. As a result, you get a set of M (implementation) variable output values of the Y model. No 3. Determining the approximation of Gooha's cumulative density of the Y function, based on a generated set of values. We use the fact that the distribution of the y(ks) ... 4. Assessing the statistical parameters of the output variable distribution based on Goh. In particular, this determines: the measured value of the well-known Goh value; standard uncertainty uc(y) as a standard deviation of Goh; and the endpoints of the lp/y coverage interval for the required coverage probability. The approximation of the cumulative distribution is the approximation of the cumulative density function of the amount of output. Steps for the approximation procedure are as follows: 5. Sorting the values of the year ( of output; yr; pr 1/4 1; . . . ; M, variable output (derived from Monte Carlo simulation) in order not diminished. The sorted values are additionally labeled as yorz; r 1/4 1; . . . ; M. 2. Appointment of equilibrium cumulative probabilities sorted values by formula (Cox et al. 2001): r 0.5; r 1/4 1; . . . ; M: No1:23 M No 3. Formation of the linear function of Goh by attaching the points of M coordinates of the year; pr: pr 1/4 - Goh 1/4 pr ... No1:24. As the linear function of Goh is in the pr ... (for the example). Once you have the approximation of G'Y probability distribution function, you can calculate its expected value, which is an estimate of the measured value of Y, and its standard deviation, which is an estimate of standard uncertainty. Estimates of expected value and variance can be calculated as: yo 1/4 M 1X yr M r1/41 ... No1:25 The last step in the distribution algorithm is to estimate the coverage interval for the variable output for a given probability (level of probability of coverage). As a rule, the level of trust at 95% or 99% is selected. The coverage interval is defined by the quantile of the order of b of a probability distribution, described by the cumulative function of The Distribution of Goh. This means that the probability of this value occurring is b. If we denote the value for the interval from 0 to 1 p., where p is the required probability of coverage, the end of the lp/y coverage interval can be defined as the quantiles of the order a and a p of the distribution for G'h. For example, if we take a 1/4 0.025, the end of the 95% coverage interval will be quantitatively about 0.025 and 0.0975. As a result, we get the coverage interval I0.95 (y). In general, if the probability distribution is symmetrical, the shortest coverage interval is associated with quantitative: a1/4 1p : 2 :1:27, as we see, for the coverage interval of 95% and provided that the distribution is symmetrical and satisfying (1.27), we get 1/4 0.025; that is, the value used in the example above. Monte Carlo simulations can show that the density of the output probability distribution is not symmetrical relative to the expected value (this is not the centered expected value). In this case, there are many intervals that satisfy equality: g'G 1 for th 1/4 gG 1 per pp; and we have to choose the one that gives the shortest coverage interval associated with the estimated probability of p. The value of the chosen one thus satisfies the condition: 1 for 1/4 minutes: 1 p. P. 1:29 Below we provide an example in which the distribution method was applied to determine the coverage interval. (The procedure described in this example is in principle consistent with a much more complex example: assessing the uncertainty of the infrared camera processing algorithm. Example 1.3 Using distribution distribution to determine the coverage interval of 95% of a simple nonlinear model, consider a simple measurement model with two inputs and one output with a given probability density distribution. Variable relationships. Relationship between input and output: Y 1/4 X12 No 2X2 : No1:30 Infrared Thermography 12 Table 1.1 Input numbers for modeling Monte Carlo model (1.30) Type input number X1 X2 x u2 x b 1.0 100 2 0 200 x2 1.0 7.550 92 25 124.3 107.7 Input variables X1 and X2 are subject to an even probability distribution (see a) to get the results for example: Dens. 1.1 / 2 q X; 50 a 1 ... b is a 1:32 where x 1/4 a1/4x b a : 0 for other x's: Options A and b of these distributions can be calculated based on this input statistics, namely expected values and deviations (square standard deviations): ... 1:32 Below are the variance and expected values of X1 and X2 inputs, as well as the assessment of the variance of output. The expected value of output is also an estimate of input , and uc was designated as an estimate of the standard deviation of output. They are input functions for the Monte Carlo simulation. The Monte Carlo simulation consisted of M 1/4 105 circuits and generated an approximate distribution of X1 and X2 input variables (for example from table 1.1. These distributions are presented in figures 1.3 and 1.4. In order to To determine the probability density function of the output of the Y, we also performed M simulations of the Monte Carlo model (1.30). Approaching cumulative figure 1.3 Distribution of probability density of input variable X1 Basic Concepts in Error Theory and Uncertainties 13 Figure 1.4 Distribution of probability density of the input variable X2 Approximation of the G(Y distribution function) distribution function Y was determined using formulas (1.23) to (1.24). This cumulative distribution approximation is shown in figure 1.5, and the corresponding approximation of the probability density function of the output of the Y, is presented in figure 1.6. The estimated amount calculated as arithmetic average variable Y is 1/4 302, standard uncertainty of uc'Y 1/4 30, and the coverage interval of 95%, marked by vertical lines in figure 1.6, is I0.95 Y 1/4 ... The example above shows the need to use distributions when there are nonlinearity in models and the distribution of output ... For a complex model, the use of the distribution method is justified rather than analytical. In addition, it gives 1 0.8 0.6 0.4 0.2 0 240 260 280 300 320 340 360 Values Y Figure 1.5 The numerical approximation of the cumulative distribution of the variable output model of infrared thermography 14 Figure 1.6 Density function with a marked 95% coverage interval is more accurate results than the classical method (Guide 2004). In this book, the distribution method is used to assess the uncertainty of the infrared thermal imaging algorithm (described in detail in Chapter 3). Carrying out the distribution method to assess the uncertainty of the thermal imaging measurement algorithm is described in Chapter 5. 2 Measurements in Infrared Thermography 2.1 Introduction 2.1.1 Brief history of thermography Knowledge of the human history of thermal radiation is very long. ... 2.1 The F. W. Herschel experiment, which revealed infrared radiation, was fundamental to the rise and development of research in the infrared spectrum. In his experiment, Herschel (1800a-d, 1830) observed thermal exposure associated with different spectral radiation ranges of the Sun. He placed blackened containers of sensitive mercury thermometers across the spectrum of solar radiation, obtained by splitting solar radiation into a glass prism. The energy of the random rays was absorbed by the containers, and the thermometers indicated the temperature above the ambient temperature. After studying the results of his experiment, Herschel found that the readings of thermometers located outside the red end of the spectrum, than thermometers located in the visible range. The experiment proved that the entire spectrum of radiation of the Sun is wider than the visible range, and the energy of the rays, which he called invisible rays or invisible thermometric spectrum. A little later they were commonly referred to as infrared rays. Further experiments conducted by other scientists have shown that infrared rays, like visible rays, are susceptible to reflection, refraction and absorption. Experiments on interference and polarization have proved that they are electromagnetic waves. It was Herschel who first identified the point of maximum thermal effect and stated that it is beyond the visible range of the spectrum. Although Herschel is considered a pioneer in infrared research, it is difficult to imagine modern infrared thermography without the basic laws of radiation transmission of heat. They are formulated and described below. 2.2 Basic laws of radiation transmission of heat At temperatures above 0 K, absolute zero temperature, each body emits electromagnetic radiation (thermal) radiation. The intensity of this radiation depends on the wavelength and body temperature (Gerashenko et al. 1989). Infrared thermography: Mistakes and Uncertainties 2009 by John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik Infrared Thermography 16 Figure 2.1 Pathways of heat radiation flow incident on a body surface The radiation exchanged between the bodies, and in a heat flow (F) of the radiant flux (the amount of energy of the radiation per unit time) (W) falls on the surface of the body of a certain thickness, and the FA (W) flow is absorbed, the FR (W) flow is reflected and the FT (W) flow is transmitted through the body, then the following factors are introduced: Absorption factor A, reflection ratio R and transmission ratio T T. They are defined as follows: A1/4 FA; R 1/4 FR F; T 1/4 FT F 1/4 FT F T : 2:1 Figure 2.1 The schematic paths of the heat flow of radiation are sketched in Figure 2.1. From (2.1), we get that A R T 1/4 1. 2.2 The concept of the ideal black body plays a very important role in the measurements of infrared thermography 2.2 (McGee 1998, Ricolfi and Barber 1990). The black body fully absorbs the radiation of the incident, so the coefficients determined (2.1) are equal to: A 1/4 1; R 1/4 0; T 1/4 0. Basic Laws of Radiant Heat Transmission 17 The ideal radiation absorption incident in the above models is the result of several internal reflections. This is followed by Kirchhoff's law. ... of radiation emitting body - Kirchhoff's law - is satisfied for each body: A T T T 1/4 ... No2:3 This law is performed not only for general radiation (emitted by the body in the full spectrum of the wavelength), but also for Radiation. For monochrome radiation, Al spectral absorbance is the monochrome radiation, Rl reflection and transmission of Tl. This relation takes as follows: q Al: FA; Fl Rl FR; FT ... Fl No2:4 Kirchhoff's law applies also to spectral coefficients: Al Rl Tl 1/4 1:2:5 Odds Values A, R and T depend on body material and its surface state, while spectral ratios also depend on the wavelength of l. It should be emphasized that in the general case the coefficients of the body are reasonably dependent on temperature. Some authors (e.g. Madura et al. 2001) have announced that for superthat thermal processes the ratios also depend on the time. The ratio (temperature-dependent and wavelength- depending on) of the radiant energy (shining flow) dF emitted by an arbitrarily small surface element containing the address point to the projected dF area of this element is called radiant output (emitted), and the radiant flow per solid corner unit is called shining intensity and denotes I (W sr1). Shining output expressed as (Kreith 2000, Hudson 1969): M'l; T NO 1/4 dF/ dF/; T.A.; W m2 : dF No2:6 Heat flow density q is expressed in the same units as the shining output: q'l; T NO 1/4 dF/ dA; T.A.; W/ m2 : dF No2:7 Monochrome radiant output is defined as: Ml Evil; T 1/4 dMul; T.A.; W m2 mm 1 : dl No2:8 q (Kisk 1973): Spectral shining output for black body (Black body's law (2.10) when it is true) for spectral black body (Planck's law (2.10) is: ... called the second shining constant (ISO 31); c1 1/4 2phc2 1/4 (3.741 832 0.000 020)1016 W m2 c2 1/4 hc/k (1.438 786 0.000 045)102 m K (called the second shining constant (second radiation constant) according to the International Temperature Scale, ITS-90, The formula (2.9) can be written in a more compact form: ... Charts in Figure 2.3 show the radiant output of Mb (l,T) of the black body calculated from the formula (2.10), compared to the wavelength l for different T temperatures (Minkina 2004). The black body radiant output of Mb (l,l2) of the black body is an integral part of the spectral intensity (2.10) over the band from the wavelength l1 to the wavelength l2: ... Law Planck The radiant output of Mb (l,T) of the black body for a given temperature and wavelength l. Sometimes it is necessary to determine the radiant output of Mb(l), measured for a specific l (Chrzanowski 2000). This can be done from the reverse law: ... In certain situations Planck's law can be simplified. These specific situations are described by Vienna law and the Reilly-Jeans Act. Vienna's law is the approximation of Planck's law for the values of the IT product. In such a case, the approximation of exp'c2 IT' 1 exp'c2 IT'... holds. The corresponding approximation of Planck's law: Relative error due to formula replacement (2.13) for (2.10) (Minkina 2004) ... Vienna's Law (2.14) ... The Reilly-Jeans Act is the approximation of Planck's law for IT. C. In such a situation, the denominator of formula (2.10) expands in a row: ... Relative error due to formula replacement (2.16) for (2.10) is ... The Wien's offset law is a derivative equating to zero derivative (2.10) in relation to wavelength ... determines the wavelength of lmax, for which the radiant output of the black body at the temperature T reaches the maximum: lmax T 1/4 2898 mm K: 2:19 Maximum exit radiant predicted the law of displacement of Vienna: ... Stefan-Boltzmann Law defines full output for black bodies at all wavelengths. The output can be calculated by integrating the formula (2.10) from zero to infinity ... Infrared thermography 20 The final formula of Stefan-Boltzmann has the following form: ... where so 1/4 2p5 k4 15 c2 h3 (5.670 32 0.000 71) 108 W m2 K4 is a constant Stefan-Boltzmann, a C0 1/4 so108 1/4 (5.670 32 0.000 71) W m2 K4 is a technical constant of black body radiation. Example 2.1 Calculate the approximate temperature of the Sun For calculations, it should be assumed that the maximum wavelength of the Sun's radiation, lmax, is (approximately) half of the visible range (i.e. lmax 0.50 mm) Using the Vienna Displacement Act: T 1/4 2898/lmax 1/4 2898/0.50 5800 K: It must be emphasized that the determined value of the temperature of the Sun's surface is approximate and refers to the black body temperature. The exact value of the Sun temperature will be different. Example 2.2 Calculate the temperature by measuring the spectral radiation output of Mb (l,T) of the Sun and the application of the law of Stefan-Boltzmann (2.22). Example 2.3 Calculate how much heat emitted from human skin above the surface of 1 m2 and 310 K (36.9 C) Based on the Stefan-Boltzmann Act: Mb 1/4 so T 4 1/4 5.67 10 8 310 4 500 W m2 : All laws and definitions refer to black bodies. Unfortunately, the black body can only be seen as an idealized model of real bodies. In fact, thermal imaging objects are not ideal black bodies and have limited absorbed radiation in a limited manner. Therefore, one of the very important concepts for explaining the work of modern infrared systems, as well as for the correct recognition of the sources of errors and uncertainty in thermal imaging measurements, is the concept of emission. It will be reviewed in the next section. 2.3 Emission 2.3.1 The main concepts The most important property of the surface, which affects the accuracy of thermal imaging measurements, is emission. If the surface emits the radiation, it is in stationary thermal condition (fixed temperature) is its emission. If the surface whose temperature was adopted to be measured, has the same properties as a black body, it would be appropriate to use Planck's law for determining the emissivity of the material concerned. If the surface does not absorb radiation at a fixed temperature, the emission of the radiation will have less than 1. ... The emission of the body over the entire range of radiation, called total emission, is the ratio of the full range of the radiant output of this body to the full range of the radiant exit of the black body at the same temperature (Kreith 2000, Minkina 2004): ... e(T) 1/4 M(T)/Mb(T) ... The monochrome emission is the ratio of monochrome radiant output of M (l,T) of the body at this wavelength l.T The same temperature and observed at the same angle: 1/4 Mf l.T M: Мбл 3л; С точки зрения свойств поверхности излучения физических тела можно разделить следующим образом (Kreith 2000, Minkina 2004): . . . b(a) 1/4 1, черные тела; e(a) 1/4 const, серые тела; e(l) 1/4 var, non-gray bodies (i.e. selectively emitting bodies). A dissipative body is a body whose emissivity is independent of angle of observation a. Its surface satisfies the conditions of Lambert's law (so it is called a Lambertian surface). Similarly, we can define a reflective body as a body whose reflectance R is independent of angle of observation a (Touloukian and DeWitt 1970, Touloukian and DeWitt 1972, Touloukian et al. 1972). To investigate how the observer angle affects the emission, we need to introduce some basic laws and definitions associated with the physical aspects of optics (ASTM E 1316). Lambert's law (cosine law of optics) determines the intensity of radiation emitted by a surface element of a black body versus the angle a (Michalski et al. 1991): Iba 1/4 Ib? cos a; W sr ... where Ib? is the radiant intensity emitted in a direction normal to the surface and Iba is the radiant intensity emitted at angle a to the normal to the surface. This equation states that the radiant intensity emitted from a Lambertian surface is directly proportional to the cosine of angle a between the observer's line of sight and the normal to the surface. Infrared Thermography 22 between the observer's line of sight and the normal to the surface. The radiant intensity of a black body surface in the surface normal direction Ib? 1/4 Ib ... Relationships (2.25) and (2.26) are true also for dissipative bodies. For non-black bodies, formula (2.25) is satisfied only approximately, especially in the case of polished metals and for a > 50 ... Светимость излучения поверхности Lv является постоянной ... Яркость или яркость Lv является поверхностной плотностью светящейся интенсивности в данном направлении. ... С учетом (2.27), формула (2.28) принимает форму: Lv 1/4 Div? потому что Div? : 1/4 dF DF cos a From (2.29) we see that the brightness of the surface of the black body does not depend on the angle of observation and is constant for all angles. This can be seen in Figure 2.4. ... In the case of non-black bodies, usually found in practice, the brightness is almost constant for angles between zero and p/4. In addition to the angle of observation, the emission also depends on the time of observation. This is due to emission fluctuations over time (see Madura et al. 2001). It turns out that superfast thermal phenomena are accompanied by significant changes in emissions. This effect can lead to a deterioration in the accuracy of thermal imaging measurements (e.g. active dynamic thermal imaging). Taking into account the emission, we can now say that the emission of a body surface in the direction of observation, the wavelength of the L, the body temperature T and the time of t: ... 2:30 Here in the case of translucent bodies, the emission ratio can be expressed as (Siegel 1992, Linhart and Linhart 2002, Orzechowski 2002): 1/4 1 RS1 TK 1 RT T 2:31 To make it possible to compare the properties of the material regardless of the state of its surface, sometimes used so-called specific emission. It is designated as 0, and specific emission is the total emission of a real metal surface as a wavelength function (Sala 1993): ... the emissivity of polished and rough surfaces ... Infrared thermography 23 emission of 0 l, and monochrome specific emission or 0 l1-l2 as a band of specific emission. All of these specific emissions are assessed in a normal direction for a flat, polished and opaque surface. They are also known and published as normal emissions, i.e. emissions are estimated on a normal surface (a 1/4 0) (see table of normal emission of various materials in Annex B). Many other factors, such as the condition of the surface of an object or its homogeneity, should be taken into account in order to accurately estimate the emission. They are very difficult to describe mathematically, so emission values for certain bodies are usually determined by an experimental method. Accurate knowledge of the emission of the surface of an object when measuring thermal images in the measurement trajectory of an infrared camera is very important for the correct estimation of its temperature. Thus, an assessment of the emission of the object is not only an important stage of each measurement process in infrared thermal imaging, and should also be considered a key stage. 2.3.2 Emission assessment methods of emission assessment. For example, Orlov (1982) proposes the following scheme: . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . Stick a piece of high and well-known emission (e.g., 1/4 0.95) and good thermal conductivity, or paint of it with special paint known and high. Heat the object to a temperature of at least 50 C above the ambient temperature. Set the known emission of stickers (or paints) on the camera and measure earlier atmospheric temperature, ambient temperature, distance from the camera to the object and humidity of the atmosphere. Read the point temperature of the area with known emission. Move the spot point beyond the known emission area. Change the emission parameter of the object in the chamber and read the spot temperature on the object until it is the same as for the clean area of the known emission area. The emission option in the chamber should then be the emission of the object. Another way is to measure the temperature of the object using a contact method. The emission value can then be adjusted before receiving the same temperature reading. The value of the last set of parameters reflects the emission of the object. In another way, a hole at least six times its diameter was drilled on the surface. Such a hole can be considered as the black body of the emission of ob 1. This method is quite accurate, as the hole distorts the temperature field of the object's surface. The emission factor of a high-temperature object (depending on the angle of observation a), for an arbitrary point on a curved cylinder or the emission of an arbitrary flat surface, can also be estimated in the method described below (Madura et al. 2001). This method was established in 1883 by C. Christiansen, heat flow is exchanged between surfaces 1 and 2, where surface 1 has an area of F1 much smaller than the F2 area of Surface 2. infrared thermography 24 is given as: F2 1/4 F1 Co T 100 4 T1 100 4 : C2 ... 2:32 Hence the formula for the temperature is ... Thermography 24 ... Heat flow emitted by the non-body point of view of chamber ... the absolute temperature of the black body detector in the chamber, it will show ... Comparing the right side (2.34) and (2.35), we get the following relationship for how to function the temperature of Td, Tbb and Ts: ... Tbb No2:36 When Ts (Tbb) is much higher than the temperature of the Td camera detector (with cooled Td detectors 70-200 K), formula (2.33) can be close to: ... the average emission in the direction of a normal to the surface, which is a function of e, n and ... coefficient and resistiveness W m ... Thus, it is possible to estimate the emission of various metal ... 25 Monochrome emission l non-conducting investigative materials compared to the results of nl (Michalski et al. 1991, Michalski et al. 1998): ... for inorganic compounds and 2.0-3.0 for metal oxides. Other methods for estimating emissions can be found in Marshall (1981), Modding (1999) and Modding (2000). 2.3.3 Examples of emission assessment and its effect on temperature measurement Example 2.3 Experimental assessment of the surface emission of the central heating radiator (CH) in stationary heat-flowing conditions in the work of Dudz Dudzik (2007), Dudzik and Minkina (2008a) and Dudzik (2008), was used the following procedure for assessing the emission of the surface of the panel of the ch. Determining the coordinates of the measurement points on the thermogram. Measuring the temperature at certain points using the contact method (Minkin 1992, Minkin 1999, Minkin and Grys' 2002c) is accompanied by a simultaneous temperature recording in close proximity to the measurement point using the infrared imaging method; we use the smallest square method to estimate the release of the heater surface. The photo in figure 2.4 shows a simple panel-type heater which was used in the experiment. The heater was located in the chamber, and its emissivity was assumed to be constant (the surface of the heater was covered with a thin layer of paint). The measurement was produced by DeLonghi. Heat-like heater Figure 2.4 Photo of the heater with installed LM35A temperature sensors Infrared thermography 26 Figure 2.5 Heater Thermogram with marked temperature measurement points. See Color Plate 1 for the color version presented in Figure 2.5 was recorded on a cloudy day. The walls of the chamber were covered with high emission insulation (No. 1). Then 60 thermograms recorded during the test were averaged. The heater was supplied with water at a controlled flow temperature. All thermograms were recorded in stationary thermal conditions of the heating environment (water): . . . Inflow temperature: (58.67 0.01) C; Chamber temperature: (48.16 0.01) C; 3 pm: (47.9) I h1. The temperature values recorded in the area of the measuring points were read from the thermogram. LM35A temperature sensors have been installed at points The following coordinates: x1 1/4 165 pixels, y1 1/4 29 pixels, x2 1/4 165 pixels, y2 1/4 106 pixels, x3 1/4 165 pixels, y3 1/4 185 pixels, where the numbers indicate the coordinates of the camera array of 320,240 pixels. The measurement conditions are presented in Table 2.1. The following is a numerical example. ... Table 2.1 Measuring conditions emission assessment of the radiator surface ... 2.2 Atmospheric Temperature, C Relative Humidity, % Camera-Object Distance, m ... 0.5-0.2 0.252 0.001 Measurements in Infrared Thermography ... the inputs of Tatur, ... and To are permanent, the formula (3.17) of the temperature measured by the infrared camera of an object calculated from the model equation; sobbing - this is the value of the compensated object, sobbing (3.13) and obs (the object of emission). Denoting the temperature of the object by the contact method and the temperature of the object by the thermal imaging method. The values of measured and calculated temperatures using the least square method are shown in table 2.2. The results of the minimization problem. Emission value was determined in such a way that the measured and calculated temperatures using the least-square method were very similar (Minkina and Chudzik 2003): D1 1/4 TK ob i Tob2 D3 1/4 4 Requiring the sum: i-b No 1/4 3 X 1/2T i obi z--Toby 2 ; 2:43 i1/41 reaches low. The minimization (2.43) was carried out using the Nelles 2001 optimization algorithm. The limiting error of the contact measurement was supposed to be 0.5 C (Bernhard 2003). The negative limiting error of emission measurement caused by an increase in the temperature limit values of these points by 0.5 C (i.e. positive limiting error of contact measurement) and an estimate of the new (underestimated) emission value. As a result of this procedure, we received an emission of the heater surface of about 1/4 0.97 0.02. The limiting error (0.02) is about 2.1% of the estimated emission value. It should be noted that the worst possible measurement conditions were taken to assess the error, i.e. : . . LM35A sensors maximum margin limiting: according to the catalog, it is 0.5 C (Lienneweg 1976, Minkina and Grys' 2002c); Worst distribution of error-limiting sensors: Errors for all sensors were taken with the same sign (Taylor 1997, zuinn 1983). The emission was placed to obtain the same results as with other methods. Infrared thermography 28 Figure 2.7 Results of the emission assessment of the thermography of the aluminum cylinder (cross-section Li01) and plastic (cross-section Li02) in stationary heat flow conditions. Example 2.4 How the change in the observation angle affects the measurement temperature of the thermography of the aluminum cylinder ... (a) the thermogram; (b) Temperature profiles; and c) a top view of the experimental installation (Minkina2004). See Color Plate 2 for the color version. Reproduced at the resolution of Cze_stochowa University of Technology The dependence of temperature measurement results on emissions and the angle of observation are clearly visible in the image and graph in figure 2.8. The thermogram shows a cylinder made of aluminum sheet ('ob 1/4 0:09), cross-section of Li01 with stuck tapes of dielectric materials; rubber (1/4 0.95), cross-section Li02; paper (1/4 0.92), cross-section Li03; and plastic (1/4 0.87), cross-section Li04. The cylinder temperature was fixed and the same across the surface. It was filled with water temperature of about 80 C. In an experiment in a microcontroller infrared camera were recorded the following measurement parameters: ob 1/4 1; 1/4 Tatm 1/4 24 C (297.15 K); - 1/4 0.5; However, the camera sees a distinctly different temperature for each material. The highest temperature is shown for the rubber band, because the rubber has the largest emission of four materials. On the other hand, the aluminum surface is interpreted as the steepest because its emission is the lowest. Because emission measurements are often burdened with significant errors, calibration of infrared cameras is important. this issue is discussed further in Chapter 4. Next, we present basic information about infrared cameras with a special reference to measuring cameras. 2.4 Measuring infrared cameras The main component of the system is an infrared camera. Since the atmosphere has two bands of good transmission in the infrared range (i.e. a short-wave band of 2 to 5 mm and a long-wave band from 8 to 14 mm), most detectors and infrared (IR) cameras are naturally divided into short-wave (SW) and long-wave (LW) devices. However, there are 30 infrared thermal imaging detectors that work in near IR (0.78-1.5 mm), such as quantum and photo-intensive detectors, and detectors that work in the far IR (20-1000 mm), such as thermal detectors (Maldague 2001). Another classification derives from the type of detector: there are cameras with cooled detectors containing a refrigerator block (cooling) and uncooled detectors working at ambient temperature. Prior to 1997, all IR cameras produced were equipped with detectors cooled to temperatures from 70 (seldom) to 200 C (most often). Manufacturers offer many types of infrared cameras. Visualization cameras are cheaper, so they are used more often, for example, by border guards or police for night surveillance. Detectors in such cameras are divided into: point (single) detectors, linear and array detectors (FPA, Focal Plane Array). In addition, matrix of 640 480 individual detectors (pixels). Cameras with a single detector or line of detectors are sometimes called point (single) detector scanners or linear scanners, respectively. In such chambers, the temperature field image is created by an optomechanical scanning system built from rotating or oscillating mirrors or scanning prisms. The scanning frequency is usually 25 Hz (50 Hz) for the PAL system in Europe, or 30 Hz (60 Hz) for the NTSC system in the United States. In one camera of the detector, an image of the observed area is built point by point at consecutive points in time. The radiation coming to the detector is converted into electrical signals proportional to the radiant output of individual points of the image. The signals are amplified and transmitted in synchronization with the scanning module to the display (thermify area) where the temperature field image (thermogram) is created. This principle of work was used for 20 years after the first camera came out. The systems had one detector, and the characteristic of which determined the type of scanner and its thermal and spatial resolution, that is, its ability to distinguish the temperature in two adjacent points and the number of pixels in the thermogram respectively. Cameras One detector have a unique shape Properties. All detectors in the array have the same parameters because the temperature at each point is measured by the same detector. This is especially important when detecting temperature differences at two points of a homogeneous object. Such a camera can perform self-calibration before each measurement, compensating, for example, changes in the sensitivity of the detector or changes in the amplification of electronic circuits (Machin and Chu 2000, Machin et al. 2008). It is also easier to design and make lenses that do not introduce optical or energy distortions (de Mey 1989, De Mey and Wiecek 1998). The next step in the development of thermal imaging systems was the construction of a line of detectors and linear scanning cameras (Figure 2.9c). Such systems have one scanning unit, vertical or horizontal, depending on the orientation of the detector line. Since 1993, cameras have been more and more equipped with FPA detectors. A typical array of 640,480 detectors (pixels). Each pixel reads 25 (50) (pal system - Europe) or 30 (60) (NTSC - USA) once a second in visual imaging. The frequency of array reading is published in directions as image frequency. Arrays containing a larger number of detectors are available. There are no mechanical scanning parts in the chambers with array detectors. The matrix looks at the object through the lenses of the camera (Figure 2.10). The development of fast array detectors has allowed the creation of cameras capable of high-speed measurements of irmographic measurements called superfast thermography. Measurements in Infrared Thermography 31 Figure 2.9 Creating a thermogram in (a) point (single detector) and (b) linear scanner: 1, horizontal mirror deviation; 2, optics; 3, vertical deviation mirror; 4, point (single) detector (e), linear detector (c) Currently there are infrared systems supported only by cooling and uncooled radiation measurement (FPA) detectors. The next step in the development of IR cameras was the introduction in 1997 of the first camera with a microbolometric array of non-cooled detectors. A few later, neo-cooled arrays built from pyroelectric detectors were built. Eliminating mechanical scanning and cooling has improved the operational parameters of IR cameras, which have become lighter, more reliable and able to operate much faster. Cooling the detector to cryogenic temperature took more than 10 minutes, while stabilizing the operating temperature in a cell without a cooler does not exceed 2 minutes. Measurement and imaging of cameras are characterized by many parameters. Detailed information describing their image and measurement properties (ASTM E 1213, ASTM E 1311). From the point of view of metrology, the most important are... Figure 2.10 Detectors Record the temperature in the focal plane of the array (FPA) camera: 1, camera optics; 2, array Thermography of 32 books deals with errors and uncertainties of measurements in IR-thermographs, we focus on the metrological properties of thermography cameras. The properties of IR cameras are described in detail, for example, in Minkin (2004), Khrzanovskey (2000) and Novakovsky (2001). Below we will list and describe the most important parameters of modern measuring IR cameras. 2.4.1 Noise equivalent temperature difference (NETD) is the difference between the temperature of the observed object and the temperature of the ambient, which generates a signal equal to the noise level. It's also called temperature resolution. NETD is defined as the ratio of RMS Un noise voltage to dUs voltage increments generated by the temperature difference dTob between the object (or technical black body) and the background temperature of To, divided by this difference: NETD 1/4 Un Tob To 1/4 ; K: DUs DUs Tob To Un No2:44' The temperature of the technical measurement area of the black body is usually 30 C, with a background temperature of 22 C, and the difference of tobe should be within 5-10 K (Figure 2.11). There is also another, slightly different definition of the NETD parameter: it is defined as the temperature difference to Tobe and To in response of the detector, which results in a change in the output signal equal to the sound of the detector. NETD is determined by the observation of the area of technical black body (test body) of the Do (Figure 2.11a). An example of a signal coming from a detector along line 1 shown in Figure 2.11b. NETD is determined by when the Us signal is equal to un sound level. In both cases, NETD is defined as a minimum increase in temperature difference, or as a minimum temperature difference for Tob and To, which can be discerned by a point (single) detector or even amplifier bandwidth. According to the theory presented in Belecki and Rogalski (2001), narrowing the bandwidth of the amplifier leads to a reduction in noise voltage (i.e. lower NETD), but, on the other hand, worsens spatial resolution (for example, for constant scanning speed). Circular or rectangular test fields of the stable temperature of the Tob can be used in measurements instead of the technical black body measurement field. The presented NETD definitions do not take into account the size of the figure 2.11 Interpretation of the definition of the NETD parameter (Nowakowski2001) Measurements in infrared thermography 33 objects, the physiology of human perception or the dynamics of the image. To better assess how netD is evaluated, we present below an example based on Minkina's work (2004). Example 2.5 Comparison of noise properties of two infrared systems Let's determine which of the systems have less noise voltage Un. We assume identical increments of the DUs signal detector for both cameras. Background temperature up to 22 C. Let's also assume that the values of the NETD parameter of the camera are given in the technical specification: . NETD1 1/4 0.1 K for Tobe 1/4 30 C, NETD2 1/4 0.2 K for Tob2 1/4 50 C. By formula (2.44) we get: Un 1/4 NETD1 DUs 1/4 Uni 1/4 Un2 NETD1 0.1 DUs DUs 1/4 0.0125 DUs; Tob1 To 30 22 Tob 1/4 To 8 NETD2 0.2 Un2 1/4 DUs 1/4 0.007 DUs : DUs 1/4 Tob2 To 28 No2:46' We come to the conclusion that Camera 2 has less noise voltage, even though its NETD2 ratio is longer than NETD1. NETD2 A simplified NETMOD of measuring NETD can be found in www.vigo.com.pl. Measurements are made for the first range of the camera measurement, and the temperature tob of the observed object is set so that it is in the middle of that range. It is assumed that the temperature of the object is known, constant and homogeneous. In the recorded thermogram, we select a temperature distribution profile line that crosses the geometric center of the object, as in figure 2.11a, and find on this line an interval in which the average temperature is constant. If you specify the highest and lowest temperature specified in this Tmax and Tmin interval, respectively, NETD can be defined as: NETD 1/4 Tmax Tmin; K: 2:47 Measurement should be repeated within a few lines. You can also choose from the thermal lines, so that after specifying NETD for each of them, the average temperature distribution of which is constant. NETD is the average of these measurements. NETD depends on the toba temperature, it must be installed once near the bottom and then near the upper limit of the camera measurement range. Examples of NETD's relationship with Tob for the FLIR SC 3000 camera with the qWIP detector are shown in figure 2.12. Similar graphs for the SW and LW cameras are compared in figure 2.13a and b. In 34 Infrared Thermography Figure 2.12 NETD Temperature Resolution compared to Tob for THE FLIR SC 3000 camera with a qWIP detector derived from the Series of Dimensions (WIP Seminar2000) Figure 2.13 Typical NETD temperature resolution graphs compared to Tob for: a) LW Camera (1) and SW Camera (2) (IR-Book2000); (b) 760 BB Inframetric Camera with filters in the LW 8-12 mm (12 mm ( 1) range and SW 3-5 mm) (2) (Chrzanowski2000) Measurements in infrared thermography 35 Figure 2.13a, assumed for both types of cameras that NETD 1/4 100 mK for Tob 1/4 30 C. Notice the significant sensitivity of NETD to Tob temperature, especially for SW cameras. A higher NETD indicates a lower sensitivity of the camera. Therefore, in the technical data of IR cameras, the NETD option is called thermal sensitivity or temperature resolution. The value of the temperature resolution NETD is defined as for the following typical values: . . . 10-30 mK - for cameras with HIA detectors designed for research and development applications; 50-100 mK - for measuring cameras; 200 mK for cameras. Temperature and observation cameras. As the VALUES of NETD depend on the measurement conditions, it should always be accompanied by tobe, where NETD was rated. Temperature resolution of thermal imaging cameras, as the NETD is one of the most popular parameters for assessing the metrological properties of an IR camera. As a result, a number of attempts have been made to standardize the measurement NETD, but no methods have not yet been standardized. Thus, the VALUES of NETD obtained for the same camera may differ, depending on the measurement method and the conditions in which it was tested. Therefore, the measurement option is freely used by camera manufacturers to describe the measurement properties of their cameras. It should be noted that if the spectral characteristics of normalized detector detectability are known, then the NETD option can be evaluated theoretically. This is a broad issue just beyond the topics discussed beyond this monograph (Madura et al. 2004). 2.4.2 Field of View (FOV) This parameter determines the spatial (geometric) resolution of the camera's optical system. FOV is defined in meters and determines resolution in both horizontal (n) and vertical (V) directions. Typical FOV values are given for 24 18 optics are given in Table 2.2. FOV for other optics is calculated as: Field of View (FOV) 1/4 H sin24 ; m' 1/4 sin18 ; m2:48 2.4.3 Instant Field of View (IFOV) This defines FOV of one detector (pixel) in the array. For a circuit of the eye of view, it should be called a minimum field of view. This is the second parameter that determines the spatial resolution of an IR camera. In technical data it is called Table 2.2 Field of View (FOV) vs. distance for 24 18 optics (Minkina2001) d, m 0.50 1.0 2.0 5.0 10 20 100 H, m 0.20 0.15 0.41 0.31 0.83 0.62 2.1 1.6 4.1 3.1 8.3 6.2 41 31 Measurements in Infrared thermography 36 spatial resolution. Example, FOV H 1/4 m at a distance of 1 m for a camera with optics 24 18 is 0.41 0.31 m (see table 2.2). In the case of a matrix of 320,240 detections, FOV of one Hmin Vmin detector: 0.41 0.31 1/4 1.3 mm 1/4 1.3 mm: 320 240 This means that at a distance of 1 m from such a camera, a surface measuring 1.3 mm 1.3 mm is visible (pixel). Therefore, each ireadation has the right to the cross-section of its internal structure, so that in such local overheating 1.3 mm by 1.3 mm is seen by the detector, so for d 1/4 10 m to 13 mm to 13 mm. Another IFOV assessment method is based on determining the optical angle of the flash radians) aradi for one detector: aradi 1/4 Hmin 1/4 d Vmin; d 2:49 IFOV which for an IR camera with a resolution of 320 240 mm is: aradi 1/4 1.3 mm 1/4 0.0013 rad, 180 320 rad 180 240 2:50, which gives IFOV 1/4 1.3 mrad. In other words, IFOV is the area that the detector sees and determines the possible minimum size of the spot. The IFOV parameter determines the spatial resolution of an IR camera and determines the absolute size of the cooler seen at a distance of one unit of the object. The camera's spatial resolution depends on the applied optics and the number of detectors (pixels) in the array. The smaller the optical angle of the flash and the larger the number of pixels, the better the spatial resolution of the camera (i.e. the fewer objects it can observe). However, there are obvious limitations on the size of array detectors in pixels and the production of lenses with smaller angles (i.e. smaller FOV). The spatial resolution of the camera is usually expressed in milliradians (mrade). For example, if technical data indicates a spatial resolution of 1.3 mrad for 24 18 optics, this parameter is IFOV (Hmin and Vmin) of a single detector (pixel) calculated by formulas (2.49) and (2.50). A more detailed analysis of this situation is illustrated in figures 2.14a and b. Figure 2.14b, the object completely irradiates at least one detector, while in figure 2.14 pa, the object does not completely irradiate any detector. In the case shown in Figure 2.14a, is lower than shown in figure 2.14b. Measurements in infrared thermography 37 Figure 2.14 (a) we see that the maximum anchor clamp temperature, measured from point to a short distance (Figure 2.14d), is lower than the actual temperature of the object located close to the camera completely irradiates one or more detectors in the array. When an object is warmer than the background, its temperature will be underestimated if the detector is not completely irradiated. Otherwise, for example, when the background is warmer, the temperature of the object will be overestimated. The term instant means that fulfilling the requirements of the IFOV parameter is sufficient for proper irradiation of the detector theoretically only at some point and for the ideal electronics and optics. In the spatial domain, instant refers to the detector's reaction to the objects radiant output. Symbols in drawings 2.14c and d have the following meaning: Measurements in infrared imaging 37 Figure 2.14 Images of a small object (anchor clip for the bridge connection of the high voltage anchor support line) on the array detector, allowing to correctly measure the temperature: a) no detector is completely exposed; (b) At least one detector is fully irradiated (1, object; 2, array detectors); (c) The clip thermogram, registered at a long distance - about 40 meters (optical and digital zoom); (d) A short-distance clip thermogram (Minkina2001). View Colored Plate 3 for Color . . IRmax is the maximum temperature of the entire thermogram area, i.e. the maximum indication selected from the readings of all detectors in the array; ARmax is the maximum temperature of the selected thermogram area (marked with a rectangle), i.e. the maximum indication chosen from the detector readings in the selected area. 38 Infrared Thermography From Figures 2.14c and d IRmax 1/4 ARmax show that the location of maximum temperature thermograms is correct. From figure 2.14b, it can be concluded that to correctly measure the temperature of a small object, the point object must be exposed to at least 2 2 pixels (then at least one detector is completely irradiated). In practice, this may not be enough if the shape of the object is not square or rectangular. In addition, real optical systems introduce distortions of the image. These distortions are the result, for example, of chromatic and/or spherical aberration and many other optics imperfections - figure 2.15. This can be described in a simple way by the uniform distribution function (PSF). One of the popular models is given as: x2 and y2 ; 2:51 PSF'x; y' 1/4 exp 2s2 38 Infrared thermography Figure 2.15 Determining the size of the measurement area: (a) ideal optics - irradiation area 2 detectors needed for correct measurement; (b) Real optics, blur of images - irradiation of area 3 3 or 4 4 (sometimes 5 5) detectors needed for correct measurement (Dajoux2001, Minkina2001). See Color Plate 4 for the color version. Where s is the deviation of PSF functions. Typical values - s 1/4 0.5 mrad for better spatial resolution measuring chambers; s 1/4 1.0 mrad for lower spatial resolution measuring chambers; s 1/4 2.0 mrad for cameras for observation. Measurement in infrared thermography 39 2.4.4 Slit Response Function (SRF) is a parameter that, like IFOV, describes the ability of an array detector camera to measure the temperature of small objects. Figure 2.16 This shows three situations that can occur when measuring the temperature of a small object (the slit) by observing a black body. The Toba temperature observed through a vertical slit. The surface area of the black body seen by one detector (pixel) through a slit with the width of the slits; the higher the temperature of the black body, the higher the temperature of the pixel, when the size of the slit is larger compared to pixel size. Tob temperature is measured correctly. The measurement field is gradually covered by the temperature diaphragm to open-slit going to the signal so from the detector. The sobbing value changes (decreases) as the slit width decreases. Left parts of the characteristics from figure 2.16 are shown in Figure 2.17 (Danjoux 2001) (as an optical angle function of the arad flash) for one detector (pixel) (2.49) and (2.50). The arrows indicate the ideal case, and graph 2 describes a real case, given that both optics and electronic systems are not perfect. Description of real characteristics of detector modulation as the response compared to the optical flash angle of a smaller detector) for measuring cameras (curve 1), 2) and visualization cameras (curve 3) is shown in Figure 2.18. We can see that the value of the angular aperture corresponding to 50% modulation is much smaller for measuring chambers, due to the function of the slit reaction is steeper. Taking into account the observations we made when we discussed the IFOV parameter, it can be concluded that the greater the value of the modulation function, the more accurate the temperature reading. For example, a value of 99% means that the temperature measurement error is 1%. Figure 2.16 Response Function of the gap (SRF) Slit 40 Infrared thermal imaging 39 Figure 2.16 The response detector is sobbing compared to observing a slit width. The size of object (IR-Book2000). Reproduced with the permission of ITC FLIR Systems detector, the signal is 10% less small: that is, the specified temperature is underestimated by 10%. This is too great an unacceptable. The acceptable value of the modulation function should be no less than 98%. In figure 2.17b it corresponds to the angle of the arad flash 1/4 5-8 mrad for measuring cameras (characteristics 1, 2) and arad flash 1/4 15-20 mrad for imaging cameras (characteristic 3). The above observations on the characteristics of the modulation of the slit reaction function confirm an earlier conclusion that to ensure the correct temperature measurement Figure 2.17 The characteristics of the modulation of the detector depending on the optical angle of the flash of one detector: (a) generalization: 1, ideal camera; 2, real camera; (b) Typical characteristics: 1, 2, measuring cameras; 3, imaging camera (Minkina2004). Reproduced at the permission of Cz e stochowa University of Technology 40 infrared thermography with the camera of this spatial resolution, defined by the IFOV parameter, the size of the object should not be less than 3 3 to 5 5 IFOV. These parameters are important for accurate temperature measurement with an IR camera. Another important component of the measurement pathway is the microcontroller that processes measured signals. It implements a programmed algorithm, which in turn is developed on the basis of a mathematical model of the measurement process. In the next chapter, we will discuss in detail both the measurement trajectory and the generalized mathematical model of in-thermal measurements. 3 Infrared Camera Measuring Processing Path 3.1 Processing information in Infrared cameras Measuring processing Path of FPA infrared cameras Infrared Camera Processing Algorithm is important for assessing the uncertainty of measurement in the infrared thermography method. This algorithm determines how measurement data is derived from detector signals. Signal processing in the trajectory of the infrared camera can be divided into the following stages (Minkina et al. 2000, Minkina and Dudzik 2005): . . . Detection of infrared radiation in the array detector; calibration or mapping (i.e. linearity and temperature compensation of signals from individual array detectors); processing compensated signals by the camera measurement algorithm according to the appropriate measurement model. The first component in the thermograph measurement trajectory, whether it is a scanner or an infrared camera, is an infrared detector. 3.1.1 Infrared detectors In the work of Rogalsky and his colleagues (Beletsky and Rogal 2001, Rogal 2000, Rogal 2003), infrared detectors are divided into thermal and photon detectors. It is also often proposed to divide them into chilled and non-cooled (working at ambient temperature). Until 1997, all manufactured infrared cameras were equipped with detectors cooled to temperatures from 70 (seldom) to 200 C (most often). Another unit, based on the design of the detector, is divided into simple, linear, or massive (FPA, Focal Plane Array) detectors. Array detectors are matrixes, for example, 640 480 single detectors and are standard today. Infrared thermography: Mistakes and uncertainties 2009 By John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik 42 Infrared Thermography Figure 3.1a Spectral transmission of infrared radiation through the earth's atmosphere layer T Tatm thickness d 1/4 1.5 km with absorption bands of the most common gases (Minkina 2004). Reproduced by the permission of Cz e stochowa University of Technology It is known that atmospheric transmission depends on the wavelength of radiation (Figure 3.1) (DeWitt 1983, Schael and Rothe 2002). Therefore, infrared devices work in the ranges of the maximum possible transmission (minimum absorption). The operating group is another criterion for separation. There are two infrared bands of the best transmission, so, traditionally, two types of detectors differ most often: . . Short-wave (SW) detectors operating in the 2-5 mm range; Longwave (LW) detectors operating in the 8-14 mm range. Figure 3.1b Changes in the atmospheric transmission T Tatm for different distance values from camera to object (Minkina 2004). Reproduced by permission of Cz e stochowa technology algorithm infrared cameras processing Pathway 43 Production of infrared detectors is now a fast-paced technology developing industry. Hundreds of original publications, surveys and patents are produced each year on this topic. The main types of heat detectors are listed below. Bolometric detectors are resistors with very little heat intensity and a large negative temperature resistance factor. As with the thermistors, this ratio is defined as: aT 1/4 1 dRT B 1/4 2: RT dT T No3:1' Measured infrared radiation changes bolometer resistance. Bolometer heads of the most common bolometric detectors are: Bolometric Metal bolometers, made of fine foil or evaporated layers of nickel, bismuth or antimonia, are still in use today. They can work at room temperature. Semiconductor, superconductor and ferroelectric bolometers are also manufactured. The structure of one pixel of an uncooled array detector (microbolometer) is really ingested in figure 3.2. The detector absorbs infrared wavelength 1/4 8-14 mm. Microbridge is supported by two metal pins fixed in a silicone base. The pins work also as thermometer connectors with the ROIC system. The microbridge contains a thin (0.1 mm) layer of refined synthetic amorphous silicon with hydrogen. Their works figure 3.2 The structure of one pixel: 1, insulation section; 2, metal pin; 3, metal washer of the ROIC chain (integrated reading scheme); 4, roIC chains; 5, reflecting layer. (b) Block signal processing chain; (c) Image of a scanning electron microscope (Tissot et al. 1999) Infrared thermography 44 as a 2.5% K1 sensitivity thermometer, which does not significantly absorb radiation. The radiation is absorbed by a very thin (8 nm) reactively deposited film thin titanium nitride. The thin film structure with an absorbent layer (1.2107 K W1) insulates the thermometer from the reading circuit. The role of the reflector (aluminium layer) placed on the surface of roIC is to reflect the infrared radiation passed through the absorbent layer. The size of one pixel shown in Figure 3.2 is 50 mm. The array detector is a matrix of 256 64 pixels. The signal is read by multiplexing each pixel into the ROIC system. The entire reading cycle takes 40ms. The reading frequency is 25 or 50 Hz for the PAL system (European standard) and 30 or 60 Hz for the NTSC signal (US standard). Microbolometric detectors work at room temperature (i.e. 300 K) stabilized with Peltier cooler. Therefore, unlike detectors cooled to cryogenic temperatures, such detectors are used for the first time since the mid-1990s and are now very common. Thermopyl detectors are built as a thermistor, that is, a system of thermal elements connected in a row. The measuring node is connected to a photon-sensitive element (illuminated by radiation), and the reference node is stored at ambient temperature. The difference in temperature of the connection generates thermoelectric power: E 1/4 kT1 to th: No3:2 Infrared Thermography 45 where T and T0 - temperature of the measuring and reference connection, respectively (T0 1/4 To - ambient temperature); k - the thermocouple coefficient (mV K1). Pyroelectric detectors are built from semiconductors that have the so-called pyroelectric effect. Their operation is based on the fact that the spontaneous polarization of these materials changes with temperature. The surface active temperature is called the so-called Curie TC (Figure 3.3) any change of charge causes a charge that produces an electric current that can be measured by the ROIC scheme. The pyroelectric effect is characterized by the pyroelectric factor pT, the rate of the polarization of P and the temperature of T (Tissot et al. 199). Reproduced with the permission of Cz e stochowa technological algorithm of infrared cameras processing Path 45 pyroelectric effect (from a pyroelectric field can be increased to a value proportional (depending on temperature) to the electric figure 3.3 Spontaneous polarization P of the pyroelectric detector compared to temperature T (Tissot et al. 1999). This is called field amplification of pyroelectric effect or bolometric ferroelectric effect. Pyroelectric p ratio is described as: qE p 1/4 p0 or dP; qT No3:3, where: po is a pyroelectric coefficient without polarization; m is an absolute electrical permittivity (F m1); and E is the intensity of the electric field (V m1). Pyroelectric detectors are sensitive to the rate of temperature change, not to the temperature change itself. This is the property that distinguishes them from other thermal detectors. Therefore, special apertures vibrating at a frequency of 25 (30) or 50 (60) Hz should be used in infrared cameras with pyroelectric detectors to compare the level of radiation incident on individual detectors (pixels). When the radiation intensity difference, a signal representing the difference is generated. Otherwise, the signal from such a detector is zero. This is why pyroelectric detectors are sometimes used as motion sensors. They are also manufactured as non-cooled detectors. Photon detectors are the second type of infrared detectors. They can be divided into the following types: Photoconductive detectors (photo-resister or photoconductor) are the so-called detectors with an internal photovoltaic emission. The infrared radiation that falls on the photo-resistant layer causes its conductivity to change. Changes in conductivity are measured on contacts connected to the detector plate. Typically, the cross geometry of photoresistors is used, where the radiation of the incident is perpendicular to the direction of the polarizing current. Changing the drop in the voltage of the resistor, connected in a series with a detector, is a measured signal. In the case of high-resistance detectors, a permanent voltage pattern is preferable. The measured signal is then current in the detector chain. Photovoltaic detectors are also detectors with so-called internal photovoltaic emission. They are constructed from structures containing built-in potential barriers. The photovoltaic effect occurs when excess media are inserted near barriers. Barriers can be photodiodes with intersections p-n or Schottky. Photo-media detectors are also with so-called external photovoltaic radiation. In this case, the electrons are thrown away photo-angled material from photons of incidents and emitted outwards. Photons are absorbed by photocatodic material, deposited on a special basis, which is often transparent to the radiation of the incident. Detectors based on quantum wells were developed by ATT in the early 1990s. Their structure is built of thin but AlGaAs and GaAs. To ensure proper operating conditions, cooling to a temperature of 203 C (70 K) is required, which is more than conventional cooled detectors that require 196 C (77 K). Strong cooling by cooling such as Dewar flasks is used in the array of 256 256 detectors. The system achieves a temperature resolution of 20-40 mK. For this reason, they are used mainly in complex scientific studies. They have the best spectral detectability in the narrow subband (1 mm wide) of the LW range, from 8 to 9 mm. An important advantage of these detectors is the relatively high homogeneity of individual elements (pixels) in the array. Images can be recorded with a 14-bit resolution (example. (i.e. 214 1/4 16,384 quantitative level) of an analog digital converter. Information about the main features of photo detectors is presented in table 3.1 (Rogalski 2003). Infrared Thermography 46 Table 3.1 Highlights of photonodetector detector type Carrier arousal Electrical Signal Examples of Detectors Internal Interband Doped Free Carrier WIP Doping Level - Intraband Band Between Discrete quantum Levels of Photoconductivity, Photovoltaic Conductivity, Power Photoconductivity Photovoltaic Conductivity Photovoltaic Photoconductivity, HgCdTe Si, InGaAs, InSb, HgCdTe Si: In, Si:Ga, Ge:Cu GaAs/CdS PtSi GaAs/AlGaAs InAs/InGaSb Since infrared photons are not able to create electron-hole pairs in a perfectly clean semiconductor based on the metric theory (Tissot 2002). The metrological parameters of infrared detectors are described, for example, in monographs (Rogalski 2000, Rogalski 2003) and work Breiter et al. (2000), Breiter et al. (2002), Tissot et al. (1999) and Minkina et al. (2000). The parameters that are most important for the accuracy of the infrared camera measurement trajectory are discussed below. Voltage or current (spectral) sensitivity is defined as the ratio of the RMS value of the first harmonic voltage of the output detector (current) to the value of RMS of the first harmonic radiation. The spectral sensitivity is given as sensitivity to black body radiation at a certain temperature, usually 500 K. Sensitivity temperature coefficient is a parameter, determines the change of signal per unit of temperature change for the temperature of the object (object 1/4 To. Response speed is a parameter that characterizes the constant time of the detector. Typically, the constant time of detectors extends from milliseconds to a few seconds (pyroelectric, pneumatic detectors); that is, they are relatively slow. The maximum frequencies of the fastest thermal detectors do not exceed several hundred hertz. Photon detectors are much faster. Their limit frequency reaches several hundred megahertz. The constant time of the detector should be as short as possible so that the thermograms of fast or even superfast thermal processes can be recorded (ultrafast thermography). Infrared cameras for quick recording are equipped with superfast photodetectors. Noise equivalent power (NEP) is an RMS power incident monochrome radiation wavelength l, which generates output voltage. The ratio of the RMS which is equal to the noise level normalized for a unit of bandwidth. In other words, it is the radiation force needed to obtain a signal factor to the noise of one unit at the exit of the detector. NEPI is also expressed in the W Hz1/2 for the specified bandwidth, usually 1 Hz. NEP per unit of bandwidth: defined in this way, it is expressed as the reverse NEP, ratio (W Hz1/2). Normalized spectral detectability D (defined as reverse NEPI; ratio as: D/L f 1/4 D1 (Nowakowski 2001)) No3:4, where the Fd is an active detector surface (cm2) and Df frequency bandwidth (Hz). The D detection index is linked to the detector surface area and the bandwidth of the device. Expressed in cm Hz1/2 W1 (cm Hz1/2 W1 called Jones in honor of R.K. Jones). Normalized detectability signifies the signal-to-noise ratio normalized relative to the frequency bandwidth and the active surface of the detector for random thermal radiation of the unit energy. The more detectability and the wider the bandwidth of the frequency used, the better the detector. Photos of the approximate array detectors used in THERIR infrared cameras (www.flir.com, www.flir.com.pl, www.infraredtraining.com) and Raytheon (www.raytheon.com) are shown in Figure 3.4. The next stage in processing information in the measurement pathway of an infrared camera with an array detector is the linearity and compensation of temperature signals from individual detectors (calibration of the array or mapping (Minkina 2004, IR-Book 2000). 3.1.3 Processing The array detector is composed of several hundred thousand detectors (pixels). These are individual detectors, so they have, in different measurement characteristics: s) 1/4 f M), No3:5 where s is the output signal of a single detector, M - radiation power affecting the detector. The characteristics of each detector are slightly different from each other (Figure 3.5). Consequently, infrared images are burdened with noise, the so-called constant noise of the array. When the camera is turned on, the detectors are not calibrated. This condition is illustrated by the example of Figure 3.4 Array Detectors (FPA) used in cameras from FLIR: (a) an uncooled microbolometer detector (Peltier element), a working temperature of about 30 C (www.flir.com, www.flir.com.pl), www.infraredtraining.com); and Raytheon (www.raytheon.com). (b) 512 512 ALADDIN III quadrant; (c) 1024 1024 ALADDIN III. See Color Plate 5 for Color 48 Infrared Thermography Figure 3.5 Termogram from uncalibrated camera and calibration of static characteristics of pixel detectors si 1/4 f(M) (ND, radiation output on the detector; sj, jth detector signal output) (WIP Seminar 2000). Reproduced with the permission of ITC Flir Systems, shown in Figure 3.5a. The recorded thermogram is compared to a set of static pixel detector processing characteristics shown in Figure 3.5b. To measure the detectors correctly, they must be calibrated according to the same 10 (Figure 3.5c). The calibration is automatic every time you turn on the power. It takes 2 steps (IR-Book 2000, Minkina 2004): . . . Step I is the adjustment of the vertical ranges of all static characteristics to the T value (Figure 3.5b) range-long A/D converter used in the detector circuit. Typically, its resolution is 12 or 16 bits. Step III is equivalent to the slope ratios of the aja characteristics (Figure 3.5b). Step III is the correction of all static processing characteristics to the same (Figure 3.5c), so that the average point of the measurement range of the DS A/D. The camera microcontroller recalculates the signal values from the calibrated detector array to the T temperature according to the measurement model described in section 3.2. To do this, you need to evaluate the calibration constants R, B, F. Assessment of these calibration constants is carried out individually for each part of the camera. This procedure is described in section 4.2. To estimate the temperature distribution (in the detector), a measure (i.e. a mean effect) of the processing characteristics described above (Figure 3.5b). Compensation is made using the infrared camera measurement algorithm Processing Path 49 by Formula (TOOLKIT IC2): absPixel 1/4 globalGain 1/4 FuncImgPixel 3:6, where absPixel is the signal of the detector compensated, signal of the detector processing linearity function for the imgPixel argument, which is the pixel value before the compensation (raw pixel); GlobalGain and globalOffset are constants that correspond to the parameters of the instrument amplifiers of the measurement path. The linear LFunc function is based on two factors: Obas, the basic offset used in nonlinear conversion; and L, calibrating the constant linearity of untreated pixel values. LFunc 1/4 p Obas ; 1 L P. Obas 3:7, where p is a raw pixel value. Another important task of the processing algorithm is to display the thermogram for each pixel, to display the recorded thermogram as a color image. To get an image of the temperature field, the camera performs a visualization procedure that assigns temperature reading values to a specific color map (color palette). The description of the coloring algorithm used in the original TermoLab software, which works with FLIR cameras. TermoLab is a thermal analysis system (Minkina et al. 2002, Minkina et al. 2003), which accepts camera radiometric data stored in a thermogram format (img) created by a special format of camera manufactured by AGEMA/FLIR. The AFF file includes a table of 16 values describing the colorization of the thermogram. Two coloring methods are shown in drawings 3.6 and 3.7. The first - isothermal algorithm - is used internally in the camera, the second - the histogram algorithm - is used by the software TermoLab (TOOLKIT IC2, Dudzik 2000). The isotherm algorithm is based on a table stored in the .img file. This table determines the purpose of values over 16 consecutive intervals determined by the algorithm. The number of colors per interval is calculated after the coloring stage of the thermogram to the table (Figure 3.6). Each pixel is mapped to a color from a 3-6 table. 50 Infrared Thermography Figure 3.6 Isothermal coloring algorithm used in THE FLIR (TOOLKIT IC2) programming (Dudzik 2000) Figure 3.7 Histogram Coloring Algorithm used in TermoLab (Dudzik 2000) Next, each pixel is filtered using the destination algorithm (which allows you to calculate the corresponding index in the color map (table coloring). The final step is the 3.6 Isothermal Coloring Algorithm used in THE FLIR (TOOLKIT IC2) programming, reading a value consistent with the calculus index from a color map. As a result, each pixel is represented by the color defined in the color map used. Pixels create a thermogram image of the temperature distribution. The scale is the Pixel scale give the impression of a continuous image. A suitable selection of color maps allows you to get a better representation of the temperature distribution. In the color palette, for example, you can create images that represent invisible bands of radiation (e.g. ultraviolet, infrared, X-rays, etc.), but we need to keep in mind that colors are nothing. This visualization method is called pseudocolorization because the selected sets of colors are not naturally related to measured values or perceived by humans. The method of pseudo-coloration can be explained by the example of the color map RGB (red, green, blue). Intermediate colors are produced as a mixture of these three basic colors (RGB) is an enhanced digital image for different color maps: (a) gray scale; (b) Iron (Ironbow) color map; c) Hot; HSI (Intensity of Shade Saturation) Spring; (f) Summer; Autumn; (h) Winter. See Color Plate 6 for the color version of the Infrared Camera Measurement Processing Algorithm Way 51 where r, g, b, are the weights of the main colors (r, g, b, represent the weights of the red, green, blue). For example, in the color K 1/4 r 1/4 g 1/4 b. The cross-section is equivalent to K 1/4 r R g G b B. Where are, g, b are the weights taking values from 0 to 1. Computer systems make it easier to store integrative values, so 1 byte (i.e. 8 bits) are represented by weights. This way, there are 256 possible values for each of the primary colors. To present the image using RGB components requires three matrices with stored weights r, g, b, respectively. Each weight is represented by 256 levels, so you get a total of 28 1/4 256 shades of each primary color. Overall, the 3 bytes or 24 bits of RGB allow to represent 2(8)3 1/4 256 256 16 777 216 colors. There are also advanced RGB formats that use 32 bits for color coding. In an 8-bit gray scale, the scales of color components are equal, r 1/4 g 1/4 b, so you can imagine 256 shades of gray. Most thermogram programs, like the TermoLab program, allow you to identify users' color maps (Dudzik 2007). Thermograms containing the same measurement data, presented using different color maps, are shown in Figure 3.8. Usually, when choosing colors, you should consider that some colors have an additional meaning: for example, red is used for warning. We must remember to emphasize the distinction between the measurement of the temperature of the thermogram - the data matrix from the array detector - and its image, which is created using color maps. When all the data is transferred to the computer, you can easily change the color map. For infrared cameras, the following precisely defined color maps: rainbow, rainbow 10, iron and iron 10. Number 10 means that the thermogram display range for a given color card using only 10 colors. Other color cards, such as glowbow, gray, medical, midgreen, midgrey and yellow, are used less frequently. In the Figure 3.8 Different color maps: (a) gray scale; (b) iron; (c) hot; (d) rainbow; (e) spring; (f) summer; (g) autumn; (h) winter. 52 Infrared Thermography alternative form of thermogram presentation is a 3D diagram. The height of the bar in the third dimension is proportional to the temperature of the corresponding pixel. The equivalent of a pixel on a 3D thermogram is called a hoksel (volume pixel). A 3D presentation can be more useful for quality heat evaluation. Additional measurement also to present time. Useful when changes quickly and it is difficult to investigate changes on numerous sets of thermograms recorded in the measurement sequence. The size of the thermogram (in pixels) can be larger than the original size of the detector array due to either interpolation, which generates a larger image of the thermogram and to a maximum point (Nowakowski 2001) or subpixel processing taking into account the neighbors of near-temperature wash-up of zik 1998, B ja bka and Minkina 2001, Minkina et al. (Astarta et al. 2000, Bayazitto glu and O 2001, B ja bka and Minkina 2003a). A detailed discussion of digital thermogram processing goes beyond this book. More information on this issue can be found in Nowakowski (2001) and Nowakowski (2004). For example, the final work of the infrared system algorithm measurement is the way the compensated signal is processed according to the measurement algorithm. The basis of this processing is a mathematical model of the measurement, which is discussed below (Minkina 2004, Minkina and Dudzik 2005, Minkina and Dudzik 2006). The accuracy of temperature assessment using the infrared system depends heavily on the error of the method caused by the measurement model used. The following section focuses on this issue. 3.2 Mathematical model of measurement with infrared camera Base temperature measurement with infrared camera theory of thermal radiation of bodies (Schuster and Kolobrodov 2000, Stahl and Miosga 1986, Walter and infrared thermography 52 Gerber 1983). In the mathematical model of temperature measurement, the following thermal flows entering the infrared detector (Minkina 2004, Dudzik B 2002) should be taken into account: . . . The web stream emitted by the subject The shelf emitted by the environment and reflected from the object; The web stream emitted by the atmosphere; The flow emitted by optical components and camera filters is considered insignificant. These three flows incident on the detector, its impact on measurement is considered insignificant. Their interaction is shown in figure 3.9. This model is expressed as: wob 1/4 ob T ob T Tatm Mob Tob ; No3:8a'wrefl 1/4 1/21 Obr KOr T 1 Tatm Atm Mo No3:8b watm 1/4 1/21 Patm Atm Atm No3:8c, where: ob is the emission of the subject ; o is the emission of the surface of the object; o is the emission of the environment, the temperature of the atmosphere, Matm, Mob, Mo are radiant outputs of the object, the environment and the atmosphere, respectively (W m2). TTatm is a band of air transmission; Tatm, Tobe, To be the temperature of the atmosphere, object and environment, respectively (K). A diagram illustrating the interaction of heat flows is shown in figure 3.9. The total radiation flow detected by the camera, is: s C'wob and swatm; Figure 3.9 Interaction of radiation streams in measurement with an infrared camera (Minkina 2004) Reproduced with permission of Cz e stochowa the technological algorithm of infrared camera Measuring the Processing Path 53, where C is a parameter depending on atmospheric damping, optical camera components and detector properties. Based on (3.8) and (3.9), the detector signal can be expressed as (Minkina and Dudzik 2005): s 1/4 'ob T ob T atm 1'ob s out ; 3:11, where s is the detector signal corresponding to the thermal radiation coming out of the object, so that so signals of the detector, corresponding to the radiation of the environment, and satm is the radiation of the atmosphere. The influence of ambient temperature and thermal radiation of the reflected in the intensity of the thermal radiation of the black body, is at the relation to the calibration characteristic described below in section 4.2. Taking into account (3.11) and (3.12), we can get a general model of the temperature of the object (Tob R B exp'B/To F 1 Tatm F Tatm 1 ob 1 ob ob T 1 exp ob T 3:13 T Tatm ratio also received as an input parameter of the measurement model. The atmospheric transmission coefficient is used in the atmospheric radiation of the layer of the atmosphere, plays an important role in this model. Absorption, in turn, is caused by vapor molecules (H2O), carbon dioxide (CO2) and ozone (O3). The concentration of these compounds in the atmosphere varies depending on the height above sea level, time of the year, temperature, climate, season or geographical location. As mentioned in section 3.1, there are bands of less infrared absorption, called atmospheric windows, including a short-wave window SW (2-5 mm, atmospheric window I) and LW window (8-14 mm, atmospheric window III). Consequently, infrared cameras are made to work in these windows. Water vapor is noticeable here. It is evident that at a distance of 10 m from the object, the absorption of radiation for the wavelength of 1 1/4 4.3 mm is played by carbon dioxide, present in the exhaled air. Rudovsky (1978) stated, for example, that after 3 hours in an enclosed room of about 30 cubic meters, the concentration of CO2 exhaled by two people was such that at a distance of 1 d of 0.8 m, 70% of the wavelength radiation l 1/4 4.3 mm was absorbed by air. Depending on the infrared camera model, there are several different models of atmospheric transmission, such as FASCODE, MITRAN, MODTRAN, PcModWin, SENTRAN, WATRA and others (Pr g owski and S'widerski 1996, Pr g owski 2001). For example, in THEMA 40 Pro Series and AGEMA 880 LW Systems, the manufacturer uses the following formula for transmission: T Tatm 1/4 expmLd1/2 ; 3:13, where d is the distance from camera to object, m; L for LW; Lens: 1/4 0.008 m1/2, L 1/4 0 m1, L 1/4 0.011 m1/2 for SW. For example, in THEMA 40 Pro Series and AGEMA 880 LW Systems, the atmospheric transmission conditions of 1/4 15 C and relative humidity v% 1/4 50%. Other sets, such as model from the LOWTRAN transmission model: 1 pffffffffffffffff3:14 T Tatm 1/4 Tatm De 1/4 d 1/4 dual b'dcal;3:14 Infrared Thermography 54 Infrared thermography 55 where 1/4 ... FOR SW camera: 1/4 0.0063 91 m1/2, b 1/4 0.000 40 m1; for LW camera: 1/4 0.008 m1/2, b 1/4 0 m1/2, b 1/4 0 m1. The T atm coefficient versus the D distance shown in figure 3.10a for LW (1) and SW (2). These two values were the camera value (default) at 1/4 15 C and v% 1/4 50%, where v% - relative humidity of air at the time. Table 3.1a You can see that the atmosphere has the best transmission in the LW infrared band. Very similar results are presented in Pr_gowski (2001). Figure 3.10a Atmospheric Simulation Characteristics compared to camera-to-object D for various transmission models: a) Tatm 1/4 15 C, v% 1/4 50%, LOWTRAN (3.14) for LW and SW cameral; and for comparison: b) Tatm 1/4 20 C, v 1/4 50% model (3.15) for ThermaCAM PM 595 LW camera; (c) Tatm 1/4 20 C, v% 50%, model (3.15) for ThermaCAM PM 595 LW camera (c) Tatm 1/4 20 C, v% 1/4 50% model (3.15) for ThermaCAM PM 595 Infrared Camera Algorithm Measuring The Way of Processing 55 Transmission Model developed by FLIR for ThermaCAM PM 595 is a function of three variables: atmospheric relative humidity v%, distance from camera to object d and ambient temperature Tatm (Minkin and Dudzik 2005, Dudzik 2007: T Tatm 1/4 f v% ; d; Tatm No:3:15 which will be applied to the analysis of errors and uncertainties performed later in this monograph. The model (3.15) is implemented into the camera. It is not explained, because the coefficients were adjusted empirically; show in 3.10b-d drawings, where we showed the simulated values using numerical modelling using full form (3.15). It should be noted that Formula (3.15) applies to most infrared cameras produced by AGEMA (e.g. series 900) and FLIR (e.g. ThermaCAM series). Tatm transmission characteristics against distance d for the LW and SW camera is presented in figure 3.11. Measurements were taken on two values of relative humidity v% and three values of the temperature of the Tob object. The purpose of the experiment was to test how the temperature of the object affects its visibility in the infrared range under given conditions. Given (3.12)– (3.15) the temperature of the object can be expressed Tob 1/4 B; K: R'F In sob No3:16' Finally, the model of measuring an infrared camera is defined as the function of five variables: Tob 1/4 fob; Tob; For; v; D E ; K: We emphasize that the model above is a simplified model. In fact, the camera detector receives radiation not only from the object, but also from other sources. The simplification can be explained by looking at figure 3.12. The signal appearing in the detector, proportional to the intensity of the thermal radiation of the black body, is and depending on the temperature of the object, depends on the thermal figure for and on the atmospheric temperature of Tatm. All these temperatures are slightly different from each other (Orlove 1982, DeWitt 1983, Saunders 1999). The aforementioned model (3.16) does not take into account all possible measurement situations. For example, an object under study may be in an oven, in a vacuum chamber, or in a wind tunnel. In such cases, the camera looks at the window of inspection. The model of the infrared camera with window in thermal imaging 56 Infrared Thermography Figure 3.11 Examples of object visibility characteristics taking into account the atmospheric transmission of TTatm, camera to object distance d, atmospheric relative humidity v% and object (camera) type: 1, LW camera; 2, SW Camera (IR-Book 2000). It is reproduced with the permission of ITC Flir Systems bandwidth. Other requirements may relate to mechanical strength (in the case of pressure difference inside and outside the window) or resistance to chemicals or to rapid temperature changes. The spectral characteristics of the transmission factor of the aperture should correspond to the operational capacity of the camera (SW: 2-5 mm; LW: 8-14 mm). To make visual measurement control possible, the window must also be transparent in the visible 56 Infrared Thermography Figure 3.12 Model of measurement situations with a camera and its control of atmospheric windows in thermal imaging Processing Path 57 Figure 3.14 The characteristic mode of reflection of the environment Tatm and temperature of the object, the thickness of the window should be clarified, as well as restrictions on the mechanical strength and maximum working temperature of the window. When measured through inspection windows, additional radiation flows, shown in figure 3.13. Explanation of symbols used in figure 3.13. Ambient temperature (e.g. Tc) clouds, the atmosphere of Tatm, the earth Tgr and the buildings OT (Minkin 2004). Воспроизводится по разрешению Cz e stochowa Технологический институт 1 : Tatm1 '' T Tw нв Tw Tatm2 1 «оb » Tatm1 »Tatm1 » T Tw T Tatm2 »Tatm2 » so1 »To1 » / 21 T Tatm1 »Tatm1 » T Tw T Tatm2 хтм2 с сатм1 хтм1 в Tw ТТМ2 Атм2 Tw Тв й 2 Ттм2 2 'To2 No 1/21 T Tatm2 'Tatm2: 3:18' Рисунок 3.13 Коэффициент передачи нескольких материалов, используемый для проверки окон: 1, Al2O3; 2, CaF2; 3, BaF2; 4, YongS; 5, NoNSe (IR-Book 2000). Reproduced with the permission of ITC Flir Systems Using formula (3.18) we can derive sob (Minkina 2004): sob 1/4 s1 »ob T ob s1 T Tatm1 Tw T Tatm2 :ob T Tatm1 T Tw T Tatm2 «w s» Rw so2 s1 T Tatm2 s 1/4 sob T 'ob 1/21 Tatm1 T Tw T Tatm2 ss1 T Tatm2 s1 Tw T Tatm2 s1 T Tatm1 Tw T Tatm2 ... 'ob ' T Tw T Tatm2 ... 83:19 The transmission of the window should be of a material that does not absorb or a certain extent. The calculated values of the special range of the infrared camera T Tw (. ). It should also be used with the model. consider the following conditions: T-use of a range filter in which the atmosphere between the camera and the object have been passed (best vacuum); or T location of the camera, perhaps close to the window of inspection (i.e. TTatm2 1). In this case, the Tatm1 is manually included in the camera software. The transmission of the window TTw should be corrected. In the measurement uncertainty analysis, in accordance with (3.19), it was considered that the measured method used to create the figure 3.14 can also be used to create an accurate, general model of the infrared camera measurements, taking into account the radiation of the inspection window. Infrared camera measuring processing path 59 and radiation of the camera's components (Minkina 2004). 3.3 Infrared Thermography Software Measuring Processing 59 and radiation of the camera's components in various conditions. Thermograms recorded by infrared camera measurements are stored for further analysis. The most popular imaging systems allow the user to perform the basic analysis of the recorded thermogram in the camera. The infrared camera measurement chamber is used in the processing of the basis of the mathematical model described above. However, this does not mean that the algorithm should be performed by an online camera microcontroller. It is very often implemented in off-line. Infrared Camera Measuring Processing 59 and Independent and processing on the PC. In one case, raw radiometric data (i.e. uncompensated pixel values, calibration parameters, etc.) are transferred from the camera in special format data. Digital infrared data processing is conducted using special software. Various algorithms for processing recorded data using different mechanisms. Below we present a brief description of the TermoLab system developed by one of the authors for their own needs (Dudzik 2007). TermoLab is a versatile approach and allows for analysis of temperature fields recorded with a camera of any type. The only requirement imposed on the recording device is the matrix output format (temperature matrix). TermoLab uses the MATLAB format for its input. This approach expands the scope of the possible application of the system. The manufacturer's specialized software usually allows for standard engineering analysis (temperature calculation, presentation), basic statistical analysis (medium, maximum, etc.) and reporting for measurement documentation. TermoLab is designed for research purposes and makes possible an advanced statistical analysis of thermogram data. A novelty compared to typical manufacturers' software is the use of advanced digital imaging (filtering, noise-canceling, etc.) and comparative analysis of thermograms with the detection of inconsistencies (for diagnostic applications). You can expand the system depending on the individual needs of the user. There are five main features of TermoLab: 1. Compensation for exposure . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

. . . . . . . . . . . Compensation for exposure due to the emission of the object, surrounding and atmospheric radiation. This function is performed by reading additional data (emission, humidity, etc.) from AFF files. Compensation for self-radiation of camera components. The software calibrates the detector readings using coefficients, compensating for the radiation of the camera components. The filtering thermogram is an image of temperature fields using different color maps and achieving the optimal matching of the color map to the temperature range. Identify nonthermal areas. Evaluation of histograms - the system allows you to calculate the frequency of temperature for any subarea thermogram. Assess minimum, maximum and average temperatures for any area of the thermogram. It is also possible to estimate the temperature distribution profile in any direction - it is possible to generate and analyze horizontal and vertical profiles. Superposition of thermograms - correlation analysis with definition inconsistencies. Create pseudo3D thermograms. The presentation of the series of images is the simultaneous display and analysis of several thermograms thanks to the applied multi-document interface. Interface: decision-making process. Special communication interfaces are used to ensure the interaction of the camera microcontroller software and specialized PC software. These interfaces and data formats are closely related to certain types of cameras. Because the cameras available on the market are very different, data analysis is often possible with software from only one manufacturer. 60 TermoLab's infraredrmography has a built-in UMI (Universal Matrix interface) that reads data either as a matrix of temperature values stored in MATLAB files (from any type of camera) or as a digital signal from AFF files (only from FLIR cameras). The first option allows data analysis from any camera that stores images as matrix. The system offer simple opportunities for statistical analysis of infrared data, as well as data reporting. It generates text reports. Results, including measurements and calculations obtained during the program, can also be stored in MATLAB files and processed in the MATLAB environment if necessary. The AFF input format is the original FLIR (TOOLKIT IC2) product and directly supports FLIR cameras (formerly AGEMA). So far, we have focused on describing the measurements of infrared thermal imaging in terms of the measurement method, the physical phenomena that occur during measurements, and the processing of infrared camera trajectory signal. In the following chapters, we will focus on error, error analysis and uncertainty analysis of the output which can be used... In the next chapter, taking into account the complexity of the problem, we have to explain the relationship of data... these chapters of the monograph thermography, they complement each other and allow the reader to form a general opinion on the accuracy of measurement methods in infrared thermography. 4 Errors in measuring infrared thermography 4.1 Introduction The concept of measurement error has a basic value for assessing the accuracy of the measurement process in infrared thermography. In this book, errors and uncertainties are associated with the subject of measurement methods in infrared imaging, and are discussed for example, as described for the FLIR ThermaCAM PM 595 LW model infrared camera. For other types of cameras and manufacturers, the results and conclusions can be the same or very similar. Measurement in infrared imaging is a complex processing algorithm (based on a mathematical model of measurement) of the trajectory of the infrared camera (Minkina 2004). To properly assess accuracy, you need to evaluate errors in the method introduced by the application model. In this monograph we use the definition of errors measuring the infrared system below. Absolute measurement error in infrared thermography, the difference between the TC value calculated by the camera and the actual temperature of a single element (pixel) of the array detector and the actual temperature of the surface (displayed) (represented) by this element (Minkina 2004): DTob 1/4 TC TR; K:4.1, where TC is a temperature value calculated for one peak of the thermogram and TR actual temperature. It is assumed that the surface temperature displayed by one pixel is constant. The relative error of the measurement in infrared thermal imaging is the ratio of the absolute error of DTob to TR: dTob 1/4 TR : TR No4:2 In this definition, the actual value of the TR detector is unknown. Therefore, in practice, we will replace the true value (sign) with the value of the reference or (in standard) calibration (after 2 In Chapter 1 we divided errors into systematic and random errors. In the practice of measurement in infrared thermography, systematic errors strongly affect the accuracy of infrared thermography. Mistakes and uncertainties 2009 John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik 62 Infrared temperature assessment thermography. Therefore, in the next section we discuss the sources of systematic interactions in the thermographic measurement system. 4.2 Systematic interaction in measurements of infrared imaging In the work of Khrzanovsky (2000), Minkin et al. (2000) and Minkin and Wild (2004), temperature measurement errors using infrared cameras are classified as follows: . . . Method errors Calibration errors e-path errors. In real-world conditions, errors in the method are dominant. They result from the causes below or the interactions occurring during the measurement: . . . incorrect assessment of the emission of objects direct and/or incorrect assessment of Tatm, To, v, d; exposure to ambient radiation - direct and/or reflected from the object - arrival on the camera detector; incorrect assessment of atmospheric and atmospheric aurora transmission; incorrect the error of measurement in thermogram, the main causes of the inaccuracy of the spectral and directional emissivity of the object depends on the temperature, material, surface condition, distance (or observation, polarization, and - in superfast thermal processes - in real time, etc. It is possible - by evenly heating it, and then make an emission card. The application of these solutions is easy in the laboratory, but usually not possible in industrial conditions. Therefore, it is very important to correctly assess the measurement error of the temperature due to incorrect value. This follows from (3.11). The effect is more significant for To. Additional errors due to solar radiation appear in infrared measurements performed in the open air. The sun can be seen as a black body at high temperature. The radiation incident of the Sun at the object is reflected by the atmosphere and depends on the day, time and atmospheric conditions. The study of the effect of solar radiation on accuracy in infrared thermal imaging becomes almost impossible, except for qualitative studies of high temperature objects, whose about 1. The situation is even more complex when the observed object reflects the radiation of the sky, the radiation of buildings and the radiation of the earth (as in Figure 3.12). Limiting the effects of atmospheric radiation can be achieved by inserting measurement in the microcontroller chamber. Unfortunately, the problem is determining the temperature in a reliable way. This is difficult because the proximity of the observed object can cover many components of different emission values located close to it or further away. The method of reducing the impact of ambient radiation is described in Dudzik (2007) and Dudzik and Minkina (2002). The object under study is placed in an open measuring chamber, the walls of which are covered with material, the emission of the environment should be around 1. The influence of external radiation. In addition, the walls of the camera were covered with an emulsion of a high (close to unity) emission factor. Unfortunately, this method only allows only a small class of objects to be studied in the laboratory. Since the environment is environment, the practical measurements assume that it is equal to the temperature of the atmosphere. The effect of self-radiation of the atmosphere can be ignored when the distance from the camera to the object does not exceed a few meters. When evaluating errors of thermographic measurements, it is important to note that in the work of... In addition, the temperature of the environment (Dudzik 2004) and if, in addition, the observed object has low emission capacity, then, the second source of errors calibrating infrared cameras 2002). The temperature measurement error due to the calibration process usually arises from: . . . Differences in the self-radiation of optical components and camera filters during calibration and measurement and variation of self-radiation of the photodetector reflected from the black body, and limited resolution of the temperature... reference standard; limited accuracy of the reference standard, as well as errors in the transfer of calibration points and interpolation errors. Since the calibration process is a significant source of systematic error, we summarize its steps and the theoretical basis the manufacturer to the calibration laboratory, where it undergoes a calibration of the infrared camera. Calibration certificate is attached to each part that goes through this process. This certificate includes (among other things): . . . The name of the laboratory Serial camera number Camera components (e.g. optics, filters) used during calibration; The standard that determines the calibration process - the ITS-90 standard is currently in force; Certificate validity the date and signature of the persons concerned (performance and approval of the person). Technical data for each camera manufacturer indicates the accuracy of measurements, such as 2 C or 2% of the range. This parameter should be interpreted as accuracy under strictly defined calibration conditions (e.g. during calibration). In practical measurements, accuracy can be much worse (e.g. outdoors), accuracy can be assessed. The calibration of the infrared camera is carried out using a technical black body, whose ob 1 is above the operating range of the calibrated device. For more information on calibration, see the chapter 4 (Minkin 2004). Calibration of an infrared camera. Suppose that the temperature of To that on ob 1 and To is known, and objects (Tatm 1 and ob 1, infrared calibration camera) 1. The calibration curves are determined for the specified value (Figure 4.1). Then, from (3.13) we get: sob 1/4 s 1/4 Laboratory calibration is done by measuring s signals corresponding to the temperature of a black body. As a result, we get Figure 4.1 and Figure 4.3 by adding a calibration parameter. The calibration curve described by (4.3) is the approximation of points (si, Ti) by function: si 1/4 R; exp'B/Ti F 4:3 Ti 1/4 B; K; R F In si No4:4, where R, B, F are constants, are estimated to get the best fit function (4.3) to calibration points. From a theoretical point of view, the constants of the calibration curve (4.3) have the following physical interpretation. R is the approximation of the integration of the product of the black body of the radiant output M(l.T) on the detector (according to Planck's law) and the function (l) describing the relative spectral sensitivity of the detector (Mathematical); B, is a constant resulting from the emission law (l, l2). From a theoretical point of view, the constants of the black body: R 1/2 s/T1 dl 1/4 exp 1 1/4 Exp 1/4 S4:5 Characteristic Sr(l) of the B - Camera Approximation of the equation F depends on the physical properties of the optical system; F 1 is used to calculate the characteristics for a SW detector type ... T Spektralna characteristic; characterizes the relative spectral sensitivity of the camera (Walin 1994, Kaplan 2000). This product is equal to that of the detector type (constant for (4.1). An example of the characteristic of the relative spectral sensitivity of the SW (shortwave) and LW (longwave) cameras are presented in Table 4.1. Reproduced with the permission of ITC Flir Systems Measurement Errors in Infrared Thermography 65 Table 4.1 Options R, B, F gauge function of the camera ThermaCAM PM 595 (LW) (TOOLKIT IC2) Measuring Ranges, C 40-120 80-500 350-2000 R, B, K F 101 920 17 250 1 870 1463.4 1466.6 1491.8 1 1 1 Typical Static Characteristics s 1/1 The shortwave (SW: 3-5 mm) and longwave (LW: 8-14 mm) cameras are shown in figure 4.2. Constants R, B, F are stored in the memory of the camera microcontroller, which calculates each time the measured temperature of s based on the digitized detector signal S, the model of measurement (3.17) and the set values: ob, Tatm atmosphere temperature, ambient temperature To, distance from camera to object d and relative atmospheric humidity v%. The calibration procedure is described in DeWitt (1983), Machin and Chu (2000) and Machin et al. (2008). To estimate the calibration parameters of infrared cameras and a set of technical black bodies are shown in the photos in figure 4.3. The third source of systematic errors is the error of the trajectory of the camera measurement path. . . . Detector noise related to the detector's temperature. Fluctuations in presentation and/or detector cooling temperature (in cooled chambers); Fluctuation in uneven system; linearity of A/D converters. They are the main source of errors in measuring infrared imaging. The relative errors of the trajectory measurement camera is not accurate. Measuring the temperature in infrared imaging is not accurate. It demonstrates inaccuracies Figure 4.2 Examples of static characteristics representing of the measurement signal of the shortwave (SW: 3-5 mm) and longwave (LW: 8-14 mm) camera 66 Infrared Thermography Figure 4.3 (a) Laboratory room for calibration of infrared cameras; (b) A set of technical black bodies (IR-Book 2000). See Color of the Plate 7 for the color version. It is reproduced with the permission of ITC Flir Systems, similar to well-known and widely used optical pyrometers. Contact methods sometimes cannot be applied. The inaccuracy of the infrared thermal imaging method may be obvious, especially when measuring temperature of a heterogeneous object but have different emissions. Therefore, this method is recommended for remote determining the temperature distribution of objects at a temperature of about 0.05-0.1 K, the temperature should be carefully analyzed and the measuring staff should have a great deal of experience in interpreting measurements in infrared thermography. Therefore, another part of this monograph we will actively investigate such errors in different measurement conditions. 4.3 Simulation of system interaction As mentioned earlier, knowledge of the measurement model is necessary to assess errors in the infrared camera measurement method. In this book, we analyze an error in a model-based method (3.16), (3.17) with atmospheric transmission determined (3.15). Similar models are used by other manufacturers of infrared cameras. Such models and their parameters must be determined in the camera software: the object of the emission ob, the temperature of the atmosphere Tatm, the temperature of the environment To, the atmosphere Tatm, the relative humidity v and the distance from the camera to the object d. Further in the analysis of these variables on the accuracy of the measurements is given. In the variable analysis, Figure 4.4 for the value assumed in Tob is (formula (1.8)) to assess measurement error in infrared thermal imaging 67 Table 4.4 Reference values of input parameters projected in model (Minkina 2004) Measurement model (3.17) Object Emission (Ob) Ambient Temperature (To), K Atmosphere Temperature (Tatm), K 0.98; 0.80; 0.6; 0.40 293 293 Relative humidity (v) 0.5 Distance from camera to object (d), m 1, 100 offset components depending on the errors of the infrared camera measurement method in the MATLAB R2006b environment. The model was modeled for different measurement conditions (multiple objects) and different inputs. The measurement conditions (input data) are included in Table 4.2, and the relative error ranges of input parameters are given in table 4.3. The work of Orlove (1982), DeWitt (1982) and Hamrelius (1991) is devoted to metrological analysis. It is limited to narrow intervals because the generalization of the results condenses the graphs and makes them unclear, making it impossible to detect changes in the function of the error. In our view, the use of absolute values is less legible. For example, is the absolute DTob error 1/4 50 K big or small? If the tob object temperature is 2000 K, it seems small (relative margin of error dTob 1/4 2.5%) for a typical contactless temperature measurement. Taking these inconveniences into account, we decided to analyze the sensitivity of the infrared camera measurement model using relative errors in the affecting amounts. We believe that the modeling results presented further graphs of relative error are legible and make possible conclusions about the impact of errors. In Figures 4.4 and 4.5. The error of the object should be considered as relative. Section 2.3 discussed the issue of emission errors in the measurement of temperature, so that the installation of the object surface emission in the chamber is incorrect. The error of dTob temperature measurement in infrared thermal imaging we analyze the following relationships: DTob relative dT is a reference relationship. Here we present the modeling results obtained for the temperature Tob of the object and the error in figure 4.4 and 4.5. Figure 4.4 relates to the temperature range from the case of Tob and Tob. Tob and Tob are given in Table 4.3. Tatm simulated for the following values: equal to: 303 K (30 C), 323 K (50 C), 343 K (70 C), 363 K (90 C). In Table 4.3 Ranges Relative errors of the parameters of the model (3.17) Input parameter Emission Object (Ob) Temperature Ambient Temperature (To), K Atmospheric Temperature (Tatm), K Relative Humidity (v) Distance to camera (d), m 30 3% 30 3% Temperature range of the object (Tob) at 303 K 0.5% to 0.98 (or 0.8) ... ob 1/4 0.90, 363 K 1 0 , % 5 4 3 Tob 323 K Tob 343 K Tob 363 K 0 2 1 0 -30 Tob 363 K Tob 343 K Tob 323 K Tob 303 K Tob 0.80 Tob 363 K 8 -25 -20 -2 -15 -10 -5 -5 -4 -30 -20 10 5ob, % (c) from 8 d (9 -30% 0 0.60 (d) Tob 363 K Tob 343 K Tob 323 K 8 4 4 Tob 393 K, -4 -30 ... 2 0 0.40 -2 -2 -10 0 10 0 Tob 363 K Tob 343 K Tob 323 K Tob 303 K Tob 393 K, % 2 -30 -20 -10 0 6 6 Tobe, % 10 20 0ob, % 2 10 g80 20 30 % 4 1/4 3 2 ... 20 30 point, % ... Figure 4.4 Effect of emission object setting error: d'Tob 1/4 3% Tob 1/4 % (Minkina and Ba jka 2002) and Tob 293 K (Minkina 2004). Reproduced by permission of Cz e stochowa University of Technology by the following: (a) ob 1/4 0.98, 4 % (b) ob 1/4 0.8, 76 C, 0. (a) 2 8 (b) 2 ... In Figure 4.4 we see that the re-evaluating about leads to a lesser error than an underestimation. For example, for d' 1/4 30%, dTob 1--4 error, while for d'1/4 30%, its to 4% (Tob 303 K) dTob error is 2---7% provided that: Tatm 1/4 To 1/4 Tatm 1/4 293 K, 1/4 50%, Tob 1/4 50 K, Tob 1/4 (300-400) K and ob 1/4 0.4-0.98. In Figure 4.4 we see that the error dTob 1/4 4% 1 dob error does not depend on 'ob' and increases greatly when tob decreases. This is the situation when the measurement of infrared thermal imaging are unreliable. When Tob approaches To, the dTob error is not as great... In figure 4.5 we see that a change in the sign of the dTob error for Tob's to, Tob and To. Tob is very sensitive to changes in the object temperature caused by ob 1/4 To, and the error becomes less and less when Tob increases. Figure 4.5 illustrates a situation where the object's temperature is close to the ambient temperature. ... and the error dTob is not dependent on ob. When Tob approaches To, the error is more significant. The situation is almost measurable at relative to the ambient temperature when the object is approaching the ambient temperature. When Tob 1/4 To, tob error can be approached, the error becomes 0.5-1 4 5 2.5 20 10 0 30 K when the Tob 1/4 10 K 10 0 -10 -20 -30 for emissivity in the figure... for Tob 1/4 To 1/4 293 K (Minkina 2004). Reproduced with the permission of Cz e stochowa University of Technology ... for To, Tatm, or v. We call this a special point model. Described features of the model will follow from the mathematical form of formula (3.17). On the other hand, when Tob 1/4 To, the results of measurement of thermography, carried out at volume of Tob are unreliable. In Minkina's work (2004), measuring sensitivity to the changes, for Tob 1/4 To 1/4 Tatm, is presented. Contributions of individual components of radiation coming to the detector are presented graphically in figure 4.6. Figure 4.6 Components of radiation coming to the detector: the radiation flows from the object, from the atmosphere and from the environment. Each of these streams in proportion to the intensity of radiation (which increases with the issue of ob, atm and 0 and 1 - ob, respectively. The expected value of so 1/4 ob can be seen within the 30% of the radiation received by the detector is so and atmosphere. The remaining 70% coming from the environment and atmosphere is a noise. The situation shown in figure 4.6b is unfavorable; the object has low emissivity and is cooler than the surrounding and the environment. It is possible for the object with 1... Emission... thermal measurements are closed to the environment. This is a typical... 4.4 measured component... Figure 4.6 Graphical illustration of the object, the atmosphere and the environment for a critical case (Tob, Tatm) and also because of the emission of an object and ob... In this case, the contribution of the object radiation component is significantly smaller the radiation of the environment; in contrast to figure 4.6. Кроме того, мы можем исследовать влияние ошибок собственного объекта в модели измерения (3.17), предполагая постоянный (свой) сигнал радиации (Ba jka и Minkina 2002), где: 1 1 ob R 1 Tatm F 4 6 рыдать 1/4 c ob exp'B/To F ob T Tatm exp To F ob T Tatm 1 Графики температурных объектов, рассчитанных из модели , по сравнению с предполагаемой объектом эмиссии об, для постоянного рыдания и атмосферной передачи T Tatm, представлены на рисунке 4.7. Figure 4.7 The effect of the object's emission on the temperature measurement for the object constant sobbing (constant shining output) (Ba jka and Minkina 2003b) Measurement errors in infrared thermal imaging 71 Figure 4.7 The temperature of the To effect of the model, the influence of the To and Tatm, depending on the temperature of the Toba object for constant sobbing (constant shining output) (Ba jka and Minkina 2003b) Measurement errors in infrared thermal imaging 71 The obvious idea of Toba sensitivity on the object emission. In these curves, we see that the higher the temperature of the To... numbered 1 is represented by a curve in figure 4.7. Other curves in Figure 4.7 point to Toba's dependence on ob for 6 1/4 To. The ob curve, since the emission is 0.1, 0.9 object it is not the only unfavorable situation that occurs during the temperature measurement of low-emission objects, such as mirrored surfaces or polished aluminum. The reflection of the radiation of the object itself may be present... the object which affect it. In other words, the effect of reflected radiation can change at least by a few times... The thermal image of the object of polished metal... Let's look at the following example. Example The thermograms of a low-emission object in Figure 4.8 are the thermograms of a polished aluminum sheet, the temperature of which is equal to the ambient temperature. The issue of polished aluminium is 0.1. Figure 4.8a shows a human reflection as measuring the temperature of the sheet, while the 4.8b pattern shows a glass figure of 4.8 Thermograms of polished aluminum sheet, the temperature of which is close to the ambient temperature: (a) mirror image of a person, measuring the temperature of the sheet; (b) The image of a glass of hot water in the background of the sheet and its reflection (the right edge of the paper sheet stuck on the aluminum is marked with a dotted line), (c) view (Minkina 2004). See Color Plate 8 for the color version. Reproduced with the permission of the Cz e stochowa University of Technology reflected in an aluminum sheet. A sheet of white paper, emission 0.8, stuck on the left side of aluminum for comparison. The right edge of the paper sheet is marked by a white dotted line. As you can see, the reflection of the glass is carved along the edge of the paper. The visible temperature of the reflected objects (man, glass) is lower than the temperature because the aluminum sheet is not an ideal white body (its emission ob 0.1). If the emission were close to zero (ob 0), the recorded temperatures would be close to the actual one. This example confirms earlier observations: infrared thermal measurements of low-emission objects whose temperature is close to the ambient temperature (atmosphere) are unreliable. Figure 4.8c shows the view with water at the temperature... 4.3.2 The effect of the ambient temperature setting error and atmosphere temperature (To) on measurement error... The next analysis, we investigate the effect of incorrect setting of the To ambient temperature for measuring chambers... We analyzed the effect of the incorrect ambient temperature adjustment on the error in measuring the temperature of the object in the figures 4.9 and 4.10. Results are shown in 4.9 is 0.5 1 2 3 4 for 303 K for the temperature setting values of 293 K... Reproduced by resolution of Cz e stochowa University ... Figure 4.9 Effect of Ambient Temperature Error: dTob 1/4 f dTo (Minkina and Ba jka 2002, Minkina 2004). Measurement errors in infrared thermal imaging 73 Figure 4.10 Effect of Ambient Temperature Setting on the setting of an error in the error of the object temperature... Reproduced by permission of the Cz e stochowa University of Technology. Figure 4.9 shows that the higher the error (dTo) of To... The temperature of the toba is the temperature of the environment... The rest of the error of the dTob error of the temperature (To)... Fig. 4.10 confirms the dTob error increases greatly when the Tob and To... approaches Tob... 4.3.3 Effect of the atmospheric temperature setting error - In the error of measurement of Tatm... The error in... In the error measurements errors of object temperature Tatm... Figure 4.11 The effect of the atmosphere temperature setting error... Figure 4.11 The effect of the atmospheric temperature of Tatm setting on the error of measuring tob temperature (Tob and Tob get; for Tatm 1/4 To 1/4 293 K (Minkina 2004). by resolution of the Cz e stochowa University of Technology Measurement Errors in Infrared Thermography 75 Figure 4.12 The influence of atmospheric temperature Tatm setting error on the error of measuring temperature of Tob (Tob and Tob get); for Tob 1/4 To 1/4 293 K... The error in the Tob measurement is proportional to the error in setting up the Tatm. For example, if you make a dTatm error of 5% up to 1/4 Tatm 1/4 293 K, Tob 1/4 (300-400) K and ob 1/4 0.4-0.98. The error increases with Tob and Tob gets, and it does not depend on the ob emission. In the figures, 4.11 and 4.12, in terms of the effect of incorrect Tatm settings on the dTob error, we can see that it is very small, if Tob 1/4 Tatm 1/4 To, up to 1/4 Tatm 1/4 To, error is not large, measurement results should not be carried out under such conditions, it follows from the general principles of infrared thermography. 4.3.4 Simulation of the measurement error of thermography. 4.4 Effect of incorrect atmosphere humidity v and the distance... Figure 4.13 effect of adjustment in the industrial plant 76 Infrared thermography 4.13 Effect of incorrect Tatm and K installation of the atmospheric temperature of the industrial plant (Minkina 2003). See Color Plate 9 for the color version. Reproduced with the permission of Cz e stochowa University of Technology The camera allows you to adjust the stiffness of the chamber and the sides of the object. To illustrate the error after the wrong Tatm and To settings in the camera, we first entered the correct Values Tatm 1/4 To 1/4 0 C and the recorded thermogram is shown in figure 4.13a. The camera calculated the temperature of the object (the lining temperature) at the marked point as Tob 1/4 6.7 C. Then the settings are wrong: Tatm 1/4 To 1/4 20 C, and the recorded thermogram is shown in figure 4.13b. The object in the same place as the Tob 1/4 1.2 C. In both cases, the camera software is calculated tobe for the same emission, 1/4 0.8. The difference in readings is due to the. In these conditions, the temperature of Tob is... Tob 1/4 To 0 C, to show the less intensity of radiation components are more, in error the camera, even though more radiation from the object and less from the environment and atmosphere (figure 4.13b). We can analyze the contribution of specific radiation components coming to the detector (Figure 4.6). In this case, emission 1/4 0.8, which is about as much of the radiation of the environment of the atmosphere (Figure 4.13c and d) as done earlier (Figure 4.6) in the case Tob 1/4 20 C (Tob 1/4 6.7 C). When the settings are wrong, Tatm 1/4 To 1/4 20 C, the camera takes the contribution of the object's radiation components and the share (contribution) of the environment and atmosphere (Figure 4.13d). Consequently, camera temperature readings are too low (figure 4.13b). Measurement errors in infrared thermography 77 4.3.4 Effect of the distance error from camera to object and the relative humidity of the atmosphere on the measurement error... The effect of the atmosphere Tatm, humidity v and the distance d on the infrared measurement error are 1/4 0.8 4.14 As described in section 3.1, the relative humidity of the atmosphere, depending on the infrared radiation of the object absorption of the L, the temperature of the Atmosphere Tatm, humidity v and the distance d are shown in figure 4.14, in particular, the model of atmospheric transmission model (3.15) (T Tatm) (3.15) show the effect of the object to the (Figures3.1aand b). Intheselection wedealwiththe dependence of error of temperature due to the incorrect setting of the distance from the camera to the object. The effect of adjusting relative humidity is discussed in the next section. The results of the simulations in the 4.14 and 4.15 models for the measurement model (3.17) with the atmospheric transmission model (3.15). The charts in 4.14 to Tob and the graphics on Figure 4.15 for Tob and To 1/4 Tatm. Analysis of the presented results shows that the error associated with the distance from the camera to the object can be calculated as follows: . . . The dTob error depends on the distance from the camera to the Tob range; ... dTob zlt; 0 for Tob... The error is very small for dTob 30% if up to 10% for ... Tob 1/4 To (400-400) K... Figure 4.14 Effect of camera-to-object D error on dTob temperature measurement... 78 Infrared Thermography... Figure 4.15 Effect of the camera-to-object distance d installation on the error of measurement of object temperature (Minkina and Dudzik ...) 80 Infrared thermography... The effect of relative humidity setting error v on... Figures 4.16 and 4.17 ... 4.3.5 Effect of relative humidity ... the graphs figure 4.17 are similar to the graphs in figure 4.15. ... 4.3.6 Summary Summing up the chapter on modelling the causal effect of the errors due to the systematic interaction, we can say that the main component of the temperature measurement... error is the emission of the object... the higher the temperature of the object... the lower the emissivity, the greater the measurement error. ... In the case of low emission, objects, the accuracy of temperature measurement is... The radiation of the background should be high... temperature can be... it is difficult to achieve... 80 Infrared Thermography Figure 4.17 Atmospheric relative humidity v setting on error (Tob To and Tatm 1/4 293 K (Minkina 2004). Reproduced at the permission of Cz e stochowa University of Technology All of the above observations lead to the conclusion that the assessment of the uncertainty of an infrared measurement should be carried out on a case-by-case basis. Theoretical analysis of such errors of uncertainty from systems... The result, dTob, obtained in this chapter, concerns the ThermaCAM PM 595 LW, FLIR camera. However, the model (3.17) is valid for other cameras. Thus, dTob and conclusions will be similar for cameras produced by other manufacturers. As mentioned earlier, the model (3.17) is typical, we can present the methodology and results of the uncertainty of the infrared thermal imaging model are presented in Chapter 5. 5 Uncertainty of measurements in infrared thermography 5.1 Introduction In Chapter 1 we presented the basics of the theory of measurement uncertainty and special attention is paid to indirect measurements. In Chapter 4, we used an infrared thermal imaging measurement model defined by the function of five variables (3.17) and by increments (described in Chapter 1) to assess the impact of errors in individual input variables on the output error. The precision model, defined in this way, is fully determined. The approach presented in Chapter 4 allows an analysis of the systematic errors (with defined variations of input quantities). However, some of the sources of inaccuracy should be found only in the features of the model itself, but also in the structure of measurement equipment. In the figures of 4.14 ... it is described as random interactions. Interactions of this type ... uncertainty (the actual systematic) can be described by random variables... Another approach to the problem of accuracy assessment is based on the modern theory of uncertainty (Guide 1995). The main definitions of this theory, as well as the method of assessing uncertainty are presented in Chapter 1. As this chapter shows, uncertainty is a statistical indicator. A model of precision based on uncertainty can be called a random model. The main feature that distinguishes the statistical model from the deterministic model is its ability to simultaneously account the structure of input data represented by probability density function or cumulative distribution function, and the properties of the measurement model. When we use the theory of uncertainty, the accuracy assessment is based on a single input, not on the accounting of information included in large sets of representative outputs. Therefore, you need to define these sets as random variables. Unfortunately, the statistical properties that determine infrared thermography: Mistakes and uncertainties 2009 by John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik 82 Infrared temperature assessment thermography based on the theory of uncertainty are defined in the random processing algorithm of infrared camera Dudzik 2005), which is a measure of the spread of the output random variable, is the standard experimental deviation of the ... 5.2 Experiment Modeling Methodology To correctly assess the uncertainty of measurements we made the following assumptions (Minkina and Dudzik 2005, Minkina and Dudzik 2006b): . . . Model inputs (3.17) are random variables of this frequency distribution; they will also be called input variables. Using a model of infrared thermography. The distribution of random variable is represented by the density function... of the probability distribution... For a fairly large number of input variables, the output random variable can be considered normal (Gaussian) distribution... The intervals of the expected value of uncertainty of the output... In our case... For the model of measurement (3.17), including the characteristics of the combined standard uncertainty of measurement ... 1. Assessing the distribution parameters of input variables; 2. Generation of variable input implementations of parameters assessed in step 1 for a certain level of variable correlation. 3. Modelling a measurement result of the model (3.17) for a series of data 2. 4. Analysis of the results of the simulation. In addition to identifying the uncertainty, we also conducted a simulation designed to assess the combined standard uncertainty and coverage interval of 95% in accordance with the procedure described in chapter 1, to ensure that the statistics of the numerical algorithm generated by random variables. To ensure that the model is properly modeled (3.17), two types of input random variable distribution... Logarithmic Gaussian distribution Uniform distribution Such as Uncertainty of Measurements in Infrared Thermography 83 5.2.1.1 Assessment of Input Variable Distribution Parameters 5.2.1.1 Logarithmic Gaussian Distribution Given as: x 2 2 pffffffffffffff Exp 5:1 zs 2s 2p, where z and s, ожидаемое значение переменной и заметное от логарифмического гауссовского распределения: s2 - exp m No 2 Дисперсия случайной переменной определяется как: В3 1/4 Е1/2Е2 1/4 5:4 Из формул (5,1) в (5,4), ожидаемое значение переменной x определяется как: В3 1/4 exp'2 m 2 c2 exp'2 m s2 Решение системы уравнений (5,3) и (5,5) для параметров m и с руках из-за >>>> (Руководство 1995 г.): г: 1/4 z 1/2 ... (5,6) 1/4 z 1/4 ... >>> (5.6) > >>> (электронная почта защищена) Ifbbfbfbbfbffbbfbbfbbfbfbbfbbfbfbb >>> >> >> >> > >>> ...
>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> ... : E2 No5:5'6 С помощью уравнений (5,6) мы ...

распределение that the expected value and variance of the random variable are equal to E(j) and V(j) respectively. 5.2.1.2 The uniform distribution of the probability density function of uniform distribution is given as: f(x) 1/4 1 для a ≤ x ≤ b ... для других x; No5:7 Инфракрасная термография 84 Таблица 5.1 Уравнения, определяющие параметры дистрибутивных единиц, используемых в анализе моделирования модели (3.17) распределение чувствительности Ожидаемое значение E(j) Вариант V(j) Логарифмический Гауссовский ... b 1/4 a 12 ... The variance distribution determine... >> >> >>; where: ... ES 3 WH, where distribution a and b parameters are ... the expected value... Equation solution (5.8) and (5.9) for a and b, we can determine As for the logarithmic Gauss distribution, the relationship between parameters, a and b, as well as, the expected value and variance are given by statistics in Table 5.1 (Minkina and Dudzik 2006a). 5.2.2 Generation of a series of variable input components As mentioned above, random values of input variables were created for the assessment process. The measurement model with the function of pseudo-random generators. In the analysis, we generated the implementation of the distributions of input parameters using the method in the MATLAB environment. The parameters of input variables were set on the ... Infrared Thermography 85 Table 5.2 Model - Input Estimates (3.17) are intended to model the components of the combined standard uncertainty Input amount Value Object Emission (ob) 0.9, 0.8, 0.6, 0.4 Ambient temperature (To), K 293 Air Temperature (Tatm), K 293 Relative Humidity (v) 0.5 Distance from camera to object (d), m 1, 100 functions Generated probability density functions calculated earlier from (5.6) - (5.10) - for even distribution. Input, right data for (5.6) and (5.10) were given in the pre-study of this variable input. The ratings of the five input variables for the (3.17) model (3.15) (Table 5.2) ... The ambient and atmospheric temperatures ... are the same and equal to the absolute temperature ... uncertainty (according to the theory of model... (3.17) with the ... 1 - 30% ... as described in section 1.3 ... the use of the ... In the analysis, the ... function (3.15) ... the variable probability ... Sections 5-1 ... for each variable ... 10 000 ... 5.2.3 ... Figure 5.5 ... (from the generated distribution ... Histograms of 20-bin normalized histograms for 10 000 variables ... 5-5 ... (Logarithmic) Gaussian distribution ... The variables of the combined standard uncertainty of the ... created for the same statistics (expected value and standard deviation) as before, and we were used to simulate the components of shared uncertainty. Table 5.3 Ranges of Relative Standard Uncertainty Model Uncertainty (3.17), expected to model components of the combined standard entry-number uncertainty range (%) Object Emission (Ob) 0-30 Environment Temperature (To), K 0-3 Atmospheric Temperature (Tatm), K 0-3 Relative camera-object humidity distance (v) (d), m 0-30 0-30 86 Figure 5.1 Infrared thermography Probability variable density function, variable density function, Presenting Emission (Uniform Distribution) Figure 5.2 The probability density function of the variable representing the ambient temperature (uniform distribution) Figure 5.3 The function of probability of a variable representing the atmospheric temperature of Tatm (even distribution) Uncertainty of measurements in infrared thermal imaging 87 Figure 5.4 Probability probability function of the variable, relative humidity v (even distribution) Figure 5.5 The probability density function of a variable representing the distance from the camera to object of (even distribution) Figure 5.6 Function of probability of the variable representing the emission (logarithmic Gaussian) Distribution) 88 Infrared Thermography Figure 5.7 Function of probability probability of a variable representing the temperature of the environment (logarithmic Gaussian distribution) Figure 5.8 Function of probability probability of a variable, Atmospheric Temperature Tatm (Logarithmic Gauss distribution) Figure 5.9 Variable Probability of Relative Humidity v (Logarithmic Gaussian Distribution) Uncertainty of measurements in infrared thermal imaging 89 Figure 5.10 Variable Probability Density Function, representing the distance from camera to object d (logarithmic Gauss distribution) 5.2.4 Correlated input variables of combination standard uncertainty component modeling were conducted using MATLAB and its Statistical Instrument (MATLAB 2005). Therefore, the description of the input variable generation below refers to the MATLAB environment. The wound function allows a simple generation of multidimensional random variables of Gaussian marginal distributions. It is also possible to determine the correlated variables. As a result, variables are subject to Gaussian distribution and are compared with certain correlation rates. Unfortunately, the STATISTICAL set of MATLAB tools does not include the equivalent of mvnrnd () to generate multidimensional random variables of any marginal distribution (implemented in the Statistical Tool Set). This method is used in this monograph to generate interconnected input variables of the model (3.17) and atmospheric transmission models (3.15). The algorithm of this method can be divided into the following steps (Dudzik 2005): 1. A generation of the required number of pairs of two Gaussian random variables. These variables are correlated at levels defined by the corresponding records of the coririan matrix. 2. The application of the Gaussian cumulative distribution function (CDF), referred to here f, to a normalized Gaussian random variable. As a result, we get a random U variable, subject to normalized even distribution at intervals of 0, 1. CDF variable U 1/4 f () expressed as (MATLAB 2005b): PrfU u0 g 1/4 PrFf u0 g 1/4 Prf f 1 u0 g 1/4 u0 : This is a CDF uniform random variable U at intervals 0, 1. No5:11 90 Infrared Term 3. According to the theory of pseudo-random generators of one-dimensional random variables, the application of the reverse CDF of any distribution of probability F to (normalized uniform) random U variable gives a random variable subject to a F distribution. The proof of this statement is reverse (5.11). Thus, the correlation algorithm can generate the implementation of the random variable X subject to the distribution F. After the generation we obtain a set of variables correlated with the desired coefficients. However, the correlation coefficients between the values of the generated variables differ from the correlation rates of the original variables. Unfortunately, the use of non-linear reverse CDF changes the initial cross-correlations of variables: linear ratios the resulting variables differ from the correlation rates of the original variables. For this reason, it is recommended to use rank correlations (i.e. coefficients that determine levels of non-linear relationships between variables). In MATLAB (2005b) the correlation of Spearman's rank and the correlation of The Kendall T rank are used to assess nonlinear correlations between random variables. In this monograph, we use simple correlation between variables according to the scenario of calculations as this resulting distribution of correlated variables. In this case, the linear correlation ratio remains, so it is then used as a numerical index of relationships between variables. The model input variable generation algorithm (3.17) with the atmospheric transmission model (3.15) was implemented in the MATLAB environment. The main window of the program is shown in figure 5.11. The main program window allows you to study the effect of cross-correlations between input variables on the combined standard uncertainty (Dudzik 2007). See Color Plate 10 for the color version of Uncertainty Measurements in Infrared Thermography 91 Figure 5.11 The main program window of the program. The program performs the following functions: ... Reading the measurement conditions from the thermogram file Generating a number of variable input implementations with a specified correlation ratio Figure 5.12 Simulation of a correlated algorithm for ob and to variables, correlation r 1/4 0.99 (even distribution). graphic representation of results, including: T cross-correlation, T sensitivity of the combined standard uncertainty of the model to changes in input variable correlation rates, T cumulative distribution function and T histogram input variables. The simulation results of the program are presented below for illustrative purposes. Figures 5.12-5.16 show cross-correlations of the two input variables: the ob emission and the temperature of the environment To, provided that they are subject to an even distribution of possibilities. Expected E (ob) 1/4 0.7 and standard s deviation (ob) 1/4 0.07 (10%) were assigned to random number 5.13 Simulation of the correlated algorithm of variables ob and to, correlation r 1/4 0.5 (uniform distribution) 92 Infrared thermography Figure 5.14 Simulation of the ob and To variable correlation algorithm, correlation r 1/4 0 (linked variables, ie expected E(To) 1/4 296 K and standard s(To) deviation 1/4 29.6 K (10%) were assigned to the temperature of the environment To. The simulation was conducted for five correlation ratio values: 0.99, 0.50, 0.0, 0.50 and 0.99. As mentioned earlier, output values of the measurements examined were also generated using the Logarythmic Gauss distribution, as well as. The algorithm has been tested for this purpose. It was assumed that in the 17-5.21 figures were obtained for the same values of the expected E, standard deviation and correlation of r as for even distribution (shown in figures 5.12-5.16). Figure 5.15 Simulation of the correlated algorithm of variables ob and To, correlation r 1/4 0.5 (uniform distribution) Uncertainty measurements in infrared thermal imaging 93 Figure 5.16 Simulation of the correlated algorithm of variables ob and To, correlation r 1/4 0.99 (uniform distribution) Figure 5.17 Simulation of correlated algorithm of variables ob and to, correlation r 1/4 0.99 (logarithmic Gaussian distribution) Figure 5.17 Simulation of correlated algorithm of variables ob and To, correlation r 1/4 0.99 (uniform distribution) Figure 5.17 Simulation of the correlated algorithm of variables ob and to, correlation r 1/4 0.99 (logarithmic Gaussian distribution) Figure 5.18 Simulation of a correlated algorithm of variables ob and To, correlation r 1/4 0.5 (logarithmic Gauss distribution) 94 Infrared thermography Figure 5.19 Simulation of correlated algorithm of variables ob and to, correlation r 1/4 0.5 (Logarithmic Gauss distribution) Figure 5.21 Simulation of the correlated algorithm of variables ob and To, correlation r 1/4 0.99 (Logarithmic Gauss distribution) Uncertainty of measurements in infrared thermal imaging 95 Effect of correlations between input variables entering the model on the combined standard uncertainty of ambient temperature measured using infrared thermal imaging as discussed in Section 5.3 In section 5.3, we evaluate and discuss the components of the combined standard uncertainty, assuming that the model input variables are not interconnected. 5.3 Components of the combined standard uncertainty for unrelated input variables The modelling of infrared thermal imaging uncertainty components was conducted using the authors' software developed at the Cze Electrical Faculty, Stokhov University of Technology. The software was written using MATLAB 7.1 (R13 SP1). THE built-in MATLAB features allow you to generate random variables representing model input variables. The simulations presented in this section relate to uncorrelated input variables. The most important functions of the computer program are: . . . A generation of series of implementations with user-defined distribution frequency and parameters -Section 5.2. Read the reference values and calibration parameters from the AFF (AGEMA File Format) (TOOLKIT IC2) and atmospheric transmission models (3.15). Model-based processing algorithm simulation (3.17). Graphic representation of modeling results, including: Histograms of t input quantities; T frequency histograms of components Standard uncertainty; T linear graphics graphics combined standard uncertainty. The main window of the model simulation of the infrared camera measurement is shown in figure 5.22. The distribution of the input variables and their frequencies is determined by a series of implementations generated for user settings (Gajda and Szyper 1998). Two procedures described in section 5.2 were used to model the uncertainty components: the uniform and the logarithmic Gauss distribution. In this monograph, we examine the effect of the probability distribution of the five input variables of model (3.17) and the atmospheric transmission model (3.15) on the probability function of the variable output model. The purpose of the simulation was to assess the uncertainties of the processing algorithm associated with the impact of a particular contribution on the joint uncertainty. As for the simulation of errors in Chapter 4, the uncertainty analysis was conducted on four object temperature values: 30 C (303 K), 50 C (323 K), 70 C (343 K) and 90 C (363 K). Set up benchmarks, as in table 5.2. The ranges of input variable uncertainty expected for modeling are represented in table 5.3. To examine the dependence of individual components of the combined standard uncertainty on the emission and the distance from the camera to the object d, the processing algorithm was modeled for four different ob values and two values d. 96 Infrared thermography Figure 5.22 The main window of the ThermaCAM PMA 595 camera measurement program window for modeling the sensitivity of the Therma PMCAM 595 camera measurement model. See Color Plate 11 for color version 5.3.1 The combined standard uncertainty component associated with Emissivity Figures 5.23 and 5.24 show the results of modeling the uncertainty component associated with the uncertainty of the object's emission, assuming an even distribution of probability. The simulation was conducted for four ob emission values and two distance values from camera to object, as in Table 5.2. The results of the simulation of the uncertainty component associated with the uncertainty of the u (ob) of the object's emission (ob) 1/4 100 m are shown in figure 5.24. Analysis of graphs in 5.23 and 5.24 allows the following conclusions: . . . The u(Tob) component of the combined standard uncertainty is highly dependent on the temperature of the Tob object. For example, in figure 5.23a, we see that an object temperature increase of 60 K (from 303 to 363 K) results in a five-time increase in the combined standard uncertainty (from about 1% to more than 5%) for the maximum standard uncertainty considered for the issue of u (ob) 1/4 30%. The estimated value of an object's emission does not affect standard uncertainty. For example, figure 5.232a-d figures show that for a Tob 1/4 343 K object temperature, the value of the component is the same as you (Tob) 1/4 3% for standard u(ob) 1/4 30%. In fact, by comparing the numbers 5.23 and 5.24, we can see that the temperature graphs of the Tob object relative to the uncertainty associated with the emission are identical in both digits, regardless of the temperature of the Tob object. Uncertainty of measurements in infrared thermal imaging 97 Figure 5.23 Component of the relative standard uncertainty associated with the uncertainty of emission for a temperature object of ob, assuming an even distribution. Graphs of the relative standard uncertainty associated with the emission of the object, with the results obtained for other components (shown below in this section) we can say that the uncertainty associated with the emission of an object has the strongest impact on the total uncertainty of the measurement model. 5.3.2 The combined standard uncertainty component associated with ambient temperature Figures 5.25 and 5.26 present the results of modelling the combined standard uncertainty component associated with the uncertainty of u(To) ambient temperature, with an even distribution being assumed. Results for the distance from camera to the object d 1/4 1 m are shown in figure 5.25 and results for d 1/4 100 m in figure 5.26. Based on the calculations presented in the figures 5.25 and 5.26, we can say that: . . . The u(Tob) component of the object temperature contains the standard uncertainty associated with To's ambient temperature, which is highly dependent on emissions. Comparison 98 Infrared Thermography Figure 5.24 Component of the relative standard uncertainty associated with the emission of an object ob, assuming an even distribution. Results for the distance from the camera to the object d 1/4 100 m . . . graphs corresponding to the component u(To) 1/4 3% in the 5.26a figure a shows that for you (To) 1/4 3%, this component changes from about 0.2% to 1/4 0.9 to 2.6% for ob 1/4 0.4. The uncertainty component associated with To, is approximately 2% for u(To) uncertainty 1/4 3% and Tob 1/4 363 K. In addition, we see from figure 5.25a, the lower the temperature of the Tob object, the weaker the effect of environmental temperature u (To) on the total uncertainty of the 5.25 and 5.26 Of observations can be concluded that Environmental temperature uncertainties regarding the accuracy of temperature measurement can be neglected at very high measured temperatures, especially if the object's emission is high. This conclusion is very important for the practice of measurements in infrared thermal imaging. Comparing the numbers 5.25 and 5.26, we can say that the component considered on the combined standard uncertainty depends very little on the distance from the camera to object d. Uncertainty of measurements in infrared thermal imaging 99 Figure 5.25 Component of the relative standard uncertainty associated with To's ambient temperature uncertainty, assuming an even distribution. The results for the distance from the camera to the object d 1/4 1 m 5.3.3 Component of the combined standard uncertainty associated with atmospheric temperature Figures 5.27 and 5.28 show the results of modeling the uncertainty component associated with the uncertainty of u(Tatm) atmospheric temperature, with an even distribution. The modeling took place under the same conditions as in previous sections. Analysis of the graphs shown in the 5.27 and 5.28 figures allows us to draw the following conclusions: . . . Object emission above does not affect the component of the relative standard uncertainty associated with the temperature of the atmosphere Tatm in the figures 5.27 and 5.28. The uncertainty of components associated with atmospheric temperature depends on the temperature of the Tob object. From figure 5.28c we can see, for example, that for you (Tatm) 1/4 3%, it is slightly higher than 0.05% when Tob 1/4 303 K and about 0.3% when Tob 1/4 363 K, which is almost six times more. A comparison of the results presented in the figures 5.27 and 5.28 indicates that the uncertainty component considered depends on the distance from the camera to the object d. For example, the value of you (Tob) read from figure 5.27b, for you (Tatm) 1/4 3% and Tob 1/4 323 K, multiple 100 Infrared thermography Figure 5.26 Component of the relative combined standard uncertainty associated with the uncertainty of To ambient temperature assuming an even distribution. Results for the distance of d 1/4 100 m from the camera to the object. Results for the distance of d 1/4 100 m, is about 0.15%, that is 15 times more. Analyzing the simulation of the uncertainty component of u(Tob) associated with u(Tatm), it can be concluded that its contribution to the combined standard uncertainty is very small for a very long distance from the camera to the object d. 5.3.4 The combined standard uncertainty component associated with relative humidity The results of modeling for the combined standard uncertainty associated with the uncertainty of u(v) relative humidity, are shown in figures 5.29 and 5.30. Modeling, as before, for four different ob emission values and two chamber-object values D. Based on the calculations presented in the 5.29 and 5.30 figures, we can say that: Uncertainty of measurements in infrared thermal imaging 101 Figure 5.27 Component of relative standard uncertainty associated with atmospheric temperature Tatm, assuming even distribution. The results for the distance from camera to the object d 1/4 1 m . . . The u(Tob) component of the combined standard uncertainty associated with u(v) uncertainty) is independent of the issue of the ob object - figures 5.29 and 5.30. In figure 5.30, we can see that the graphs of the component in question are identical in all four a-d cases. In fact, comparing the results in figure 5.30 for you (v) 1/4 30% and Tob 1/4 343 K, for example, shows that in all four cases the value of the component is about 0.15%. The combined standard uncertainty component considered depends on the temperature of the Tob object, passing and its contribution to the overall uncertainty of the model increases as the temperature decreases. For Tob and d 1/4 100 m (Figure 5.30), the component increases with Tob for any fixed uncertainty u(v). A comparison of the results presented in 5.29 and 5.30 indicates that the u (Tob) associated with you (v) depends on the distance from the camera to the d object. For example, the value of you (Tob) read from a figure of 5.29b for you (V) 1/4 30% and Tob 1/4 323 K is about 0.006%, while the value of you (Tob) read from a figure of 5.30b, for the same conditions, d 1/4 100 m, is about 0.08%. Analysis of the simulation of the combined standard uncertainty component associated with the relative uncertainty of u(v) humidity shows that it is insignificant. The effect of this component on the cumulative uncertainty of the measurement system is even weaker than the impact associated with (Tatm) discussed earlier. 102 Infrared thermography Figure 5.28 Component of the relative standard uncertainty associated with the uncertainty of the Tatm atmosphere, assuming an even distribution. The results for the distance from the camera to object d 1/4 100 m 5.3.5 Component of the combined standard uncertainty associated with camera-to-object distance Figures 5.31 and 5.32 show the results of the simulation of the uncertainty u(d) distance from camera to object d, assuming even distribution. Simulation was conducted under the same conditions as in previous sections. Analysis of the graphs shown in the figures 5.31 and 5.32, allows us to draw the following conclusions: The combined standard uncertainty component associated with the distance from camera to object does not depend on the emission of the object expected for the emission of the ob object (as is the case of the ob, Tatm and To components previously mentioned). For example, looking at a 5.31 figure for you (d) 1/4 30% and Tob 1/4 363 K, it is 0.014% for all four a-d cases. The component considered depends on the Tob temperature and its contribution to the standard uncertainty increases with the temperature of the object. In fact, taking into account the uncertainty of measurements in infrared thermal imaging 103 Figure 5.29 Component of the relative standard uncertainty associated with relative v humidity, assuming an even distribution. Results for camera distance to object d 1/4 1 m It's easy to see that for you (d) 1/4 30% and Tob 1/4 303 K, the uncertainty of the combined standard uncertainty and distance d is approximately 0.03%, while for Tob 1/4 363 K, it exceeds 0.15%. Comparing the graphs shown in 5.31 and 5.32 shows that the component depends on the distance from the camera to object d. For example, u(Tob) associated with d read from figure 5.31b for you (d) 1/4 30% and Tob 1/4 323 K and the 1/4 The corresponding u(Tob) the same values (for (Tatm) and Tob) read from a figure of 5.32b is about 0.08%, that is 10 times more. Analysis of the results presented in 5.31 and 5.32 shows that the impact of the distance uncertainty component on the entire uncertainty budget can be ignored in practice, even with a lot of uncertainty u(d). Comparing the previous analysis conducted in Chapter 4 with the uncertainty analysis presented above suggests that in both cases, the components (common error or combined uncertainty) associated with the same amount of input have a similar character. 104 Infrared thermography Figure 5.30 Component of the relative standard uncertainty associated with relative V humidity, assuming an even distribution. Results for camera distance to object d 1/4 100 m 5.4 Correlated Uncertainty Analysis in Introduction In Section 5.3 we investigated the impact of specific variable input models (3.17) and (3.15) (figures 3.10b-d) on the relative combined standard uncertainty of the model. Modelling the results allowed us to evaluate the components of the combined uncertainty, provided that the input variables are not related. In fact, measurements of two or more input quantities can be statistically correlated. The cross-correlation between the two random variables is qualitatively expressed for 1 r 1, as defined (Taylor 1997), as: Pyy and Oxy x 5:12 r1/4 11 In this section we are concerned about the impact of correlations between pairs of input variables of the model (3.17) and (3.15) (figures 3.10b-d) on the combined standard uncertainty of variable. Model uncertainty was performed on the methodology described by Measurement Uncertainty in Infrared Thermal Imaging 105 Figure 5.31 Component of the relative standard uncertainty associated with the distance from the camera to object d, assuming an even distribution. Results for the distance from the camera to the object d 1/4 1 m distribution. Results for d 1/4 100 m. 5.5.1 Example Example Random variables representing the individual input amounts of the model reviewed, generated by the correlation algorithm, are shown in figures 5.12-5.21. Below are the results of the simulation performed for each pair of input variables. Inputs for modeling, namely estimated estimates and relative standard volume uncertainty, are given in tables 5.4 and 5.5, respectively. The model's analysis of the temperature dependence of the combined uncertainty by cross-correlation between input variables was conducted for the three selected object temperature values: Tob 1/4 323 K (50 C), Tob 1/4 343 K (70 C) and Tob 1/4 363 K (90 C). Since the exact temperature of the ambient do unknown is assumed to be equal to the temperature of the Tatm atmosphere (as warranted earlier). Therefore, as we can see from table 5.5, the dependence of the combined uncertainty on cross-correlations between input variables is being studied in the light of the standard uncertainty allowed by the measurement conditions. 106 Infrared thermography Figure 5.32 Component of the relative standard uncertainty associated with the distance from the camera to the object d, assuming an even distribution. Results for the distance from the camera to object d 1/4 100 m. Situations discussed in this monograph do not exhaust the question of the dependence of combined uncertainty on correlations between variables entering the model. This is also due to the fact that this dependence is strongly influenced by measurement conditions (i.e. estimates of influencing quantities, standard uncertainty of specific input variables, etc.). Another infrared thermography 106 Figure 5.32 Component is a relative standard uncertainty associated with the distance of D from camera to object, assuming an even distribution. Results for distance from camera to object d 1/4 100 m Table 5.4 Estimates of input variables, estimated in the analysis of the impact of correlations between model inputs (3.17) and (3.15) (figure 3.10b-d) on the combined standard uncertainty (Tob), Object emission ('ob) Ambient temperature (To), K 0.9, 0.8, 0.6, 0.4 293 Air Temperature (Tatm), K 293 Relative Humidity (v) 0.5 Distance from camera to Object (D) , m 50, 100 Table 5.5 Relative standard uncertainty of input variables estimated when analyzing the impact of correlations between model inputs (3.17) and (3.7 15) (figures 3.10b-d) on relative combined standard uncertainty uc (Tob), % object emission (ob) 10% Environment temperature (To) 10% Atmospheric temperature (Tatm) 10% Relative Humidity (v) 10% Distance from camera to object (d) 10% Measurement uncertainty in infrared thermal imaging 107 interesting cases of correlations discussed in Minkin and Dudzik (2005) and Dudzik and Minkina (2007). 5.4.2 Correlations between individual input variables of the infrared camera model and the atmospheric transmission model The combined standard uncertainty uc (Tob) of object temperature, as a function of cross-correlations between pairs of random variables representing selected input variables of models (3.17) and (3.15) (pictured) 5.3.5-52 as uc (Tob) on r. Figures 5.33 and 5.34 show the results for two distances from camera to object: d 1/4 50 and 100 m. Values of are supposed to be performed in simulations from practical circumstances: on the one hand, for a short distance from the camera to the object (for example d 1/4 50 m) the effect of atmospheric transmission may be neglected; On the other hand, d of 100 m appears to be the upper limit for most typical checks in infrared thermal imaging. Figure 5.33 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the object of emission ob and ambient temperature To, for d 1/4 50 m 108 Infrared thermal imaging Figure 5.34 Modeling relative to the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the object of emission ob and the temperature of the atmosphere Tatm, for d 1/4 50 and 1/4 100 m, m, r as shown in figures 5.35 and 5.36 respectively. Simulation of the combined standard uncertainty uc (Tob) compared to the correlation ratio r of random variables representing the emission ob and atmospheric relative humidity v, for two distances from the camera to the object d 1/4 50 and 1/4 100 m, is shown in figures 5.37 and 5.38. Figures 5.39 and 5.40 show a simulation of the combined standard uncertainty uc (Tob) compared to the correlation ratio, suggesting a correlation between random variables representing the emission of the ob object and the distance from camera to object d. Figures 5.41 and 5.42 show the results for the To ambient and Tatm the temperature of the atmosphere, for d distances 1/4 50 and 100 m, respectively. Figures 5.43 and 5.44 show a simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of R, suggesting a correlation between random variables representing To ambient temperature and relative humidity v, for two distances from the camera to the object d 1/4 50 and 1/4 100 m. Uncertainty of measurements in infrared thermal imaging 109 Figure 5.35 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the object of emission ob and atmospheric temperature Tatm for d 1/4 50 m random variables representing To ambient temperature and distance from camera to object d, for d 1/4 50 and 100 m Figures 5.45 and 5.46 show a simulation of the combined standard uncertainty of uc (Tob) compared to the correlation factor r, suggesting a correlation between random variables representing the distance from the camera to the object d, for d 1/4 50 and 100 m is displayed in 5.45 and 5.46 figures. Figures 5.47 and 5.48 show a simulation of the combined standard uncertainty of uc (Tob) and the r correlation ratio, suggesting a correlation between random variables representing the temperature of the Tatm atmosphere and atmospheric relative humidity v, for d 1/4 50 and 1/4 100 m. Simulations of the combined standard uncertainty of uc (Tob) compared to the r correlation ratio of random variables representing the relative humidity of the atmosphere v and the distance from the camera to object d, for d 1/4 50 and 1/4 100 m, are shown in Figures 5.49 and 5.50. Figures 5.51 and 5.52 show a simulation of combined standard uncertainty uc (Tob) correlation ratio of random variables representing the temperature of the Tatm atmosphere and the distance from camera to object d, for d 1/4 50 and 100 m. 110 Infrared thermography Figure 5.36 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the object of emission ob and atmospheric temperature Tatm for d 1/4 100 m 5.4.3 Conclusions Analysis provided by the simulation of the combined standard uncertainty of uc (Tob), taking into account the possible cross-correlations between the input quantities of the infrared camera model, allowed us to draw the following conclusions: . . . The relative combined standard uncertainty of the uc (Tob) model (3.17) with the model (3.15) (figure 3.10b-d) mainly depends on correlation between input variables representing object emission ob and ambient temperature To (Tob) and the correlation between ob and To depends on the distance from camera to object. Comparing, for example, drawings of 5.33a and 5.34a, we see that the graphs of uc (Tob), for d 1/4 50 and 1/4 100 m, are different. The effect of the correlation between ob and To on the uncertainty of uc (Tob) depends on the distance from the camera to the object d. The correlation between ob and To on uc (Tob) depends on the distance from the camera to the object d, Figures 5.33 and 5.34. The relationship between uc combined standard uncertainty (Tob) and the correlation between ob and To depends on ob - compare, for example, the numbers 5.33a-d. Uncertainty in measuring the temperature of a Tob object (as mentioned before) in the range Uncertainty of measurements in infrared thermal imaging 111 Figure 5.37 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the emission of ob object and atmospheric relative humidity v for d 1/4 50 m . . . The graphs presented in the figures 5.35 and 5.36 show that the correlation between input variables representing the object emission ob and the atmosphere temperature Tatm. In addition, we can see from figures 5.35 5.36 that the impact of this correlation decreases with the decrease in ob. Figures 5.35 and 5.36 show that the effect of correlation on the uncertainty can be seen by comparing, for example, the figures 5.36a and d. Charts in these figures are at odds with the decrease in the emission of the ob object. This effect can also be observed for all pairs of correlated input variables. Thus, we can conclude that the lower the emission of an object ob, the greater the function of uc (Tob) 1/4 f(r) depends on the correlation of the relative combined standard uncertainty on the temperature of the Tob object. Figures of 5.41 and 5.42 suggest that the combined standard uncertainty of uc (Tob) also depends on the correlation between the temperature of the environment To and the temperature of the atmosphere Tatm. A comparison, for example, of 5.41a-d shows that the effect of the correlation between To and Tatm on uc uncertainty (Tob) decreases with a decrease in ob. From the drawings 5.41 and 5.42 we also see that the emission of the object o, in principle, does not affect the 112 Infrared thermography Figure 5.38 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing object emission ob and atmospheric relative humidity v for d 1/4 100 m . schedules of combined uncertainty. The C values taken in the simulations are followed by practical circumstances: for a short distance from the camera to the object, the influence of atmospheric transmission can be neglected. On the other hand, the distance of 100 m appears to be the upper limit for most infrared thermal imaging inspections. Analysis of the submitted modeling results leads to the observation that the combined uncertainty of uc (Tob) depends mainly on correlations between the input variables representing the emission of the object ob and the temperature of the environment To. The dependence of uc (Tob) on the correlation between To and Tatm is worth noting. All other cases of cross-correlation between the two input variables have little or no effect on the cumulative uncertainty of the model - see Figures 5.37-5.40. Summing up the above considerations on the effect of correlations between input variables of models (3.17) and (3.15) (figures 3.10b-d) on the relative combined standard uncertainty uc (Tob) of the temperature measurement system using infrared thermal imaging, we can say that this effect is strongly dependent on emissions ob. Looking at the uc (Tob) graphs, we can conclude that the values received do not contribute much to the overall uncertainty budget. However, the results relate to the so-called uncertainty of 1 sigma, which is determined as a relatively low level of confidence. To determine extended uncertainty, standard uncertainty of measurements in infrared thermal imaging 113 Figure 5.39 Simulation of the combined standard uncertainty uc (Tob) by r-correlation ratio of random variables representing the emission of ob object and distance from camera to object d, for d 1/4 50 m should be multiplied by the expansion factor k - see (1.20) in section 1.2. This increases the impact of correlations on uncertainty. In addition, our analysis is associated with relative uncertainty. The actual impact of correlations can be obtained by recalculating the values shown in the graphs on absolute uncertainties (expressed in Kelvin, K). For example, the relative uncertainty in figure 5.33d for Tob 1/4 343 K is about 12%, i.e. about 41 K in absolute units when input variables are not related (1/4 0). From the same graph (Tob 1/4 343 K), we can see that for 1/4 0.99 (high positive correlation), relative uncertainty is about 11.5%, so absolute uncertainty is about 39 K. For r 1/4 0.99 (high negative correlation), relative uncertainty is about 13.5%, so absolute uncertainty is about 46 K. This example shows how large the discrepancies between the absolute values of the combined standard uncertainty can be. The reason for focusing on the dependence of uc (Tob) combined uncertainty on the correlation between the ob and To emission and the choice of this pair for the closer analysis is not purely theoretical. As described in section 2.3, the emission of an object depends on its temperature. Since practical considerations relate to gray bodies 114 Infrared thermography Figure 5.40 Simulation of the combined standard uncertainty uc (Tob) compared to the correlation ratio of r random variables representing the emission of the ob object and the distance from camera to object d, for d 1/4 100 m (whose emission is about qlt; 1), the emission estimate is highly dependent on the surrounding radiation, which in turn depends on the radiation. Example 2.3 in section 2.3 describes the measurement of emissions in open measuring chambers. Placing an object in a chamber is designed to make measurements as independent as possible from ambient radiation. Unfortunately, the complete separation of the object from the surrounding area is impossible, so the surrounding radiation (and therefore the ambient temperature To) affects the measurement of infrared thermography to some extent. Taking into account the cross-relationship between ob and To is not a theoretical issue and may be necessary in practical measurements of infrared thermal imaging, because as we have shown, the impact of this correlation on combined uncertainty is significant. Similar reasoning can be performed for other pairs of input variables if correlations between them are likely. For example, the ambient temperature To is generally thought to be equal to the Tatma or strictly dependent on the Tatma, because the temperature of some or all of the emitting objects located in the infrared scene is the ambient temperature. It is generally thought to be equal to Tatma - figure 3.12. 3.12. You can suspect that the correlation between To and Tatm Uncertainty Measurements in Infrared Thermal Imaging 115 Figure 5.41 Simulation of the relative combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the temperature of the environment and atmospheric temperature Tatm for d 1/4 50 m can strongly affect the function of the combined standard uncertainty - see figures 5.41 and 5.42. Taking into account all possible kinds of measurement conditions in infrared thermal imaging, this chapter can be considered more as an introduction than as a comprehensive study of the subject. In our opinion, in addition to simulation studies, a broad experimental test of the presented results of measurements of infrared thermography, atmospheric transmission, etc. The final stage of the model will take into account the combined standard uncertainty - the estimated coverage interval. Below we uc (Tob) uncertainty estimates with calculations of coverage intervals. A practical numerical example will illustrate considerations about the dependence of the relative combined standard uncertainty of uc (Tob) on the correlation between input variables of models (3.17) and (3.15). Infrared thermography 116 Figure 5.42 Simulation of the relative combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing environmental temperature and atmosphere Tatm for d 1/4 100 m Example 5.1. Assessment of the relative combined standard uncertainty taking into account correlations between the selected input variables of the model (3.17) and the model (3.15) (Figure 3.10b-d) Uncertainty uc (Tob) will be calculated for input volumes (i.e. measurement conditions), as in table 5.6. The relative standard uncertainty of Tob temperature occurs only between the object of the emission about and the temperature of the atmosphere Tatm. Let's also assume that in order to set the estimates qb Table 5.6 Emission (Ob) 0.9 Estimates of Input Quantities, taken in Example 5.1 Ambient Temperature (To), K 293 Atmosphere Temperature (Tatm), K 293 Relative Humidity (v) 0.5 Distance from Camera to Object (d), m 50 Uncertainty in Infrared Thermal Imaging 117 Figure 5.43 Simulation of the relative combined standard uncertainty uc(Tob) compared to the correlation ratio of r random variables representing environmental temperature and relative humidity atmosphere v for d 1/4 50m and Tatm, which will be set in camera and r correlation ratio of two variables, a series of 20 pairs measurements (ob, Tatm) was performed. The results are shown in Table 5.7. Based on these results, a correlation ratio of r 1/4 0.296 K. Correlation ratio is determined by formula (5.12): it gives r 1/4 0.5. Finally, let's assume that the temperature of the object read from the camera is Tob 1/4 343 K. Now, with a figure of 5.35a, we can see that when the correlation is 1.6%. 5.5 The introduction of a measurement model accuracy study in terms of measurement uncertainty leads to an assessment of the combined standard uncer- 118 Infrared thermography Figure 5.44 Simulation of the relative combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing environmental temperature and atmospheric relative humidity v for d 1/4 100 m in tainty uncorrelated variables, with a certain amount. Uncertainty in the measurement of the measurement value is generally determined as a statistical sense. The uncertainty the combined uncertainty from its components associated with individual quantities. Unfortunately, it is usually assessed at a relatively low level of confidence, which means that the probability of finding a result within the interval defined by the combined uncertainty is relatively low. As mentioned in section 1.2, in order to increase the likelihood of finding a measurement result in a certain interval, extended uncertainty is used. U, which is determined by the multiplication of the combined standard uncertainty by a factor of coverage k. In section 1.2, we indicated that the value of the expansion factor depends on the function of the density of the probability of the variable of the measurement value. In general, this probability distribution is unknown, so different methods are used to approximate the number of degrees of freedom. This monograph assesses the combined uncertainty of measuring infrared thermal imaging using the distribution method presented in section 1.3. The components of the combined standard uncertainty associated with the uncertainty of individual inputs were discussed in section 5.3. Uncertainty Measurements in Infrared Thermography 119 Figure 5.45 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the temperature of the environment to and the distance from camera to object d, for d 1/4 50 m Section 5.4 we reviewed combined uncertainty when correlations between input variables. In this section, we present a simulation of the combined standard uncertainty of uc (Tob) of the output variable of the model (3.17) and (3.15), for a different probability distribution described in section 5.2, namely logarithmic Gaussian or even distribution. The simulation was carried out, for example, with data from standard volume uncertainty. The final step in our simulation is determining the value of the so-called expansion factor, which we used to determine the coverage interval of 95% in accordance with the Recommendations of the Guide (2004). It was determined on the basis of the probability distribution of the variable of the output variable models (3.17) and (3.15) (figure 3.10b-d) obtained from modelling. The results of the simulation are presented in table 5.8. 5.5.2 Simulation of the Combined Standard Uncertainty Simulation was carried out in 12 cases of different estimates of the emission and temperature tobe (a combination of four emission estimates and three object temperature estimates). As in the combined uncertainty investigation, the simulation was performed for the temperature of the Tob object equal to: 323 K (50 C), 343 K (70 C) 120 Infrared thermography Figure 5.46 Simulation of relative combined standard uncertainty uc (Tob) vs. correlation ratio of r random variables, representing the temperature of the environment and the distance from the camera to the object d, for d 1/4 100 m and 363 K (90 C). All other input estimates were as in Table 5.8. If the range of a typical camera, so the simulation results were applied only for this range - other measurement temperature ranges have different calibration constants. For each simulation, an interval of 95%-size was assessed. Certain coverage intervals are compared with intervals calculated for the Gaussian distribution. In this case, the combined uncertainty should be, in two dimensions, a variable distribution of the output variable is a k-2 expansion ratio in a k-2 expansion ratio k 1/4 2 with a coverage probability of 95%. It is clear, however, that the probability distribution of variable probability of output variable is not known. As mentioned in section 1.3, we modeled the width of the 95% coverage interval calculated for the distribution of variable probability of output relative to expected cost. For example, a factor that appears in (1.27) directly determines the quantitative probability of covering 95% p. For a symmetrical distribution of 1/4 0.025. To determine the wide coverage interval in the distribution asymmetry, we present for each case a 95% coverage interval as a quantitative order function (Dudzik and Minkina 2008b). This allows us to compare the minimum width of I95% with the width for the estimated symmetrical distribution of the variable output (a 1/4 0.025). Uncertainty of measurements in infrared thermal imaging 121 Figure 5.47 Simulation of the combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the temperature of Tatm and the relative humidity v for d 1/4 50 m environment. The input for modeling (i.e. estimates and uncertainties of input variables) is given in tables 5.7 and 5.8. For each case, we present a normalized histogram of the G(Tob) probability density function of the variable output model, conducted in accordance with the 95% coverage interval are marked by vertical lines. These limits were determined based on the distribution of the values from the cumulative distributions, with the dashed lines is the comparison of the interval of 95%, determined from modelling and intervals determined by the Gaussian distribution of the variable output. Table 5.7 Estimates of input volumes expected to analyze combined standard model (3.17) and (3.15) (figure 3.10b-d) Object emission (about) 0.9, 0.6, 0.4 Environment temperature (To) 293 K Atmospheric Temperature (Tatm) 293 K Relative Humidity (v) 0.5 Camera Distance to Object (d) m 10 Infrared Thermography 122 Table 5.8 Standard uncertainty of input quantities accepted for analysis of combined standard uncertainty model (3.17) and (3.15) (figure 3.10b-d) Object emission (about) 10% (10%) 9 K (3%) Air temperature (Tatm) 9 K (3%) Relative Humidity (v) 0.05 (10%) Distance from camera to the object (d) 1 m (10%) Left side graphs in the figures 5.56-5.72 figures show the probability density of the output variable (Tob) and the equivalent estimate of the extended coverage intervals of 95%. These limits were determined by the cumulative distribution, assuming that the distribution of output variable models (3.17) and (3.15) were subject to the Gaussian distribution. The right side shows the distribution of output variables (3.17) and (3.15) of the simulated variables, we assumed an even distribution of input variables. This follows from the fact that the distribution is that the worst case in terms of combined uncertainty of uncertainty. Similar to our study, we also looked at logarithmic Gaussian distributions of input variables. However, as figure 5.48 Simulation of the relative combined standard uncertainty of uc (Tob) compared to the correlation ratio of r random variables representing the atmospheric temperature of Tatm and camera d, for d 1/4 50 m intervals were determined on the basis of cumulative distributions, assuming the Gaussian distribution of the output variable. Uncertainty of the measurements in infrared thermal imaging 123 Figure 5.49 Simulation of the relative combined standard uncertainty of uc (Tob) Compared to the ratio of the correlation r of random variables representing the relative humidity v and distance from the camera to the object d, for d 1/4 100 m Uncertainty of measurement in infrared thermal imaging 123 Figure 5.49 ... Dependence on Coverage intervals of 95% - the lower quantum order are represented in the charts. The right side of the graphs interval is shown in the figures, shown as a quantitative order graph 5.56-5.72. The I95%-norm refers to a 95% coverage interval calculated as a result of an output variable that is distributed to Gaussian. Values in I95%-sim brackets are identified as the width of the 95% coverage interval identified in brackets in the same row of the table. Infrared thermography 124 Table 5.9 Simulations of 95% coverage intervals for output variables of model (3.17) and (3.15) (figure 3.10b-d) results in infrared thermography ... 1/4 323 K 1/4 343 K 1/4 363 K .... 95% uc (Tob) K ... (fig. 5.56) ... 95%-norm ... (with other table entries)... Figure 5.50 Simulation of the relative combined standard uncertainty of uc (Tob) vs. correlation ratio r of random variables representing atmospheric temperature Tatm and relative humidity v and distance from camera to object d, for d 1/4 100 m 5.5.3 Conclusions Analysis of simulation of the combined standard uncertainty and coverage intervals made it possible to draw the following conclusions: . . . From the results presented in table 5.9, the standard uncertainty uc (Tob) of the measured Tob decreases with increasing ob. Combined standard uncertainty increases significantly with the reduced emission of the object. For example, the absolute uncertainty of uc (Tob) increases as the rise in temperature of the Tob object. At the same time, as the Tob 1/4 363 K increases, this is the back-link. Additional simulations have confirmed that for low object emission this trend inversion is common: for ob below 0.5, combined uncertainty decreases with the increase in Tob. The results of the combined uncertainty ... not included in the monograph ... Figure 5.54 ... 127 Values of 20 measurements of temperature Tatm Coverage interval I95% is greatly extended with a decrease in the emission of the object ob. For example, table 5.9 shows that for ob 1/4 0.9 and Tob 1/4 323 K, the width of the interval, defined for cumulative distribution derived from modeling, is 10 K, while for ob 1/4 0.4 and Tob 1/4 323 K it increases to 39 K. This trend is also seen when comparing the charts ... by the approximation of the output of the cumulative distribution function ... coverage intervals determined for Gaussian distributions, we may notice that the differences are insignificant. In general, assuming that the Gaussian distribution of the output variable is appropriate to determine the limits of the coverage interval, it is safe to assume that the probability of coverage of 95% is more than 95% for lower and upper intervals ... The infrared thermography of 95% coverage intervals ... It is, therefore, can be concluded that in order to assess the extended uncertainty of measurements using models (3.17) and (3.15) with a confidence level of 95%, it is safe to assume that the expansion ratio is k 1/4 2 as for the Gaussian distribution. ... The simulation performed for selected reference quantities and for a certain standard uncertainty of input variables ... in infrared thermal imaging. The results of the model of measurements in infrared thermal imaging, ... Figure 5.57 Probability Function ... Figure 5.58 129 95% coverage intervals compared to the quantum order A for Tob 1/4 343 K and ob 1/4 0.9 ... Figure 5.59 Probability Function of the Output Variable Tobe Models (3.17) and (3.15) ... Figure 5.60 ... Figure 5.61 Probability Function ... Figure 5.62 ... Figure 5.63 ... Figure 5.64 ... Figure 5.65 ... Figure 5.66 ... Figure 5.67 ... Figure 5.68 ... Figure 5.69 Probability Function of the Output Variable Tobe Models (3.17) and (3.15) (figure 3.10b-d) ... Figure 5.70 Coverage intervals compared to quantum order A for Tob 1/4 343 K and ob 1/4 0.4 ... Figure 5.71 Probability Function of the Output Variable Tobe ... Figure 5.72 thermography 95% coverage intervals compared to the quantitative order A for Tob 1/4 363 K and ob 1/4 0.4 ... The analysis of the results leads to the conclusion that: the width of the combined standard uncertainty ... In this case, it is shown that when measuring the temperature of high-emission objects, it should be taken into account that the combined standard uncertainty (both absolute and relative) increases with the temperature of the object. A similar situation occurs when errors (Figure 4.4a). Another interesting result of the simulation of the combined standard uncertainty is that the relative combined standard uncertainty component associated with object emission is not dependent on, not (generally) the combined standard uncertainty (absolute as well as relative) depends on ob - see table 5.9. To make this dependence clearer, we have increased the relative standard uncertainty associated with object emission to 30%. Then, for ob 1/4 0.9 and Tob 1/4 323 K, the cumulative standard uncertainty is 9.8 K, which is about 3% of the measured value. The calculations were then repeated for ob 1/4 0.4 and after other simulations intact. The new combined standard uncertainty is 16 K, which is about 5% of the measured value. We must emphasize that in these two cases, the relative combined standard uncertainty associated with emissions was 30 per cent. We could not have reached this conclusion if we had only considered the components of the combined standard uncertainty separately. The results of an uncertainty analysis also confirmed the conclusions reached in chapter 4, regarding the components of the common error in section 4.3). Thus, the analysis of uncertainty components alone is not enough to assess the impact of reference input variables on the uncertainty of the temperature measured in infrared thermal imaging. Additional modelling of the combined standard uncertainty is required. Another important finding from the above results is the 95 per cent estimates of coverage intervals. The Monte Carlo distribution and modelling method allowed the limits of these intervals to be determined. Uncertainty of measurements in infrared thermal imaging 135 assumptions about the Gaussian probability distribution of the output variable that the cumulative distribution is the best for estimation purposes. ... Summing up this we can say that the concept of uncertainty of infrared thermography thermography ... the combined standard uncertainty and 95% coverage interval of the measured temperature of the ... Example 5.2 Assessment of the Combined Standard Uncertainty and Coverage Interval in Infrared Thermal Imaging Consider a set of several thermograms recorded for an object whose surface has a constant emission. The temperature estimate of the Tob object is 1/4 363 K. The emission measured by the contact method is ob 1/4 0.9 and the estimated relative standard uncertainty of u (ob) is 10 per cent. The relative standard uncertainty of other input variables (3.17) is assumed as in Table 5.8, and the estimates of these variables, as in table 5.7. A uniform probability distribution of all input variables of the model (3.17) is expected to be used to assess the combined standard uncertainty. The results presented in Table 5.9 are valid for a measurement defined in this way. For Tob 1/4 363 K and ob 1/4 0.9 relative combined standard uncertainty uc (Tob) 1/4 1.5%. In Figure 5.60 and table 5.9, we see that the minimum coverage interval width I95% is 18 K and that the coverage interval limits are (355, 373). 6 Summary The purpose of this monograph was to present questions related to the assessment of errors and uncertainties in infrared thermal imaging measurements. Each contactless temperature measurement (e.g. pyrometry, infrared thermal imaging) is carried out under conditions that include uncertainties of the reference quantities. In addition, our measurements are restricted to the specific limits, first of all, only by the large number of influencing quantities, therefore the task of estimating the uncertainty is difficult and requires effective analytical methods of assessing accuracy. In this paper, we proposed using the (accurate) increments method to assess temperature measurement errors using an infrared camera. First, we introduced the basic laws and definitions related to the measurements of infrared thermal imaging, namely radiation transmission of heat (section 2.2), the concept of emission (section 2.3), as well as the basic metrological parameters of modern infrared cameras (section 2.4). Next, we discussed the camera trajectory processing algorithm and the mathematical measurement model in infrared thermal imaging, according to the model provided by the ThermaCAM PM 595 camera manufacturer (section 3.2). The algorithm is described in the example of the 595 FLIR ThermaCAM PM series, which is universal and typical of most thermal imaging cameras of the infrared camera model (model. Knowledge of the mathematical model of temperature measurement allowed us to analyse the components of the error in the method. Analysis of the results of the calculation showed that the error of temperature measurement mainly depends on the components associated with the uncertainty of the object whose temperature is measured (section 4.3.1). The second important number, in terms of its impact on the measurement error, was the temperature of To the environment. Our results also proved that the error components associated with relative humidity v, camera-to-object d distance and Tatm's atmospheric temperature do not contribute significantly to the overall error of the method (sections 4.3.3-4.3.5 and 5.3.3-5.3.5). Analysis of the method error also allowed us to investigate the sensitivity of the model to changes in input variables. We would like to emphasize that the classic error analysis only takes into account the impact of systematic interactions. This interaction is related to strictly defined measurement conditions that are difficult to implement in practice. Therefore, in this monograph we also investigated random interactions. This study is based on the presumed interpretation of the processing algorithm (Chapter 5). Then we presented a methodology for modeling studies of combined standard uncertainty in infrared thermal imaging. Infrared Thermography: Errors and Uncertainties No. 2009 John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik 138 Infrared Measurement Thermography components of the combined standard uncertainty were evaluated provided that measurements of the input number of each model could be represented by a random variable (section 5.3). The parameters (i.e. standard deviations and expected values) of random input distributions were predetermined. We have taken on one of two typical (in measurement theory) distributions: a uniform distribution that describes a critical case; or the logarithmic Gaussian distribution, the random variable of which has only positive meanings. The results of the simulation are presented as graphs of the components of the combined standard uncertainty for individual input variables of the processing algorithm. The combined standard uncertainty was also determined for a different probability distribution of the input variable for temperature and emission values in infrared thermal imaging for several different estimates of input quantities (such as object emission and object temperature). First, studies were conducted on uncorrelated variables of the measurement model in infrared thermal imaging. However, it turns out that assessing the effect of cross-correlations between input variables is an important issue. In our view, in general, some variables correlate with each other (section 5.4). This does not necessarily mean that interdependence arises between physical quantities. Here we assume, as in the case of all input random variables represent the results of measurements of a certain number of models. Analysis of the effects of correlations has shown that this effect depends on the measurement conditions and they can vary greatly. The modelling results showed that the combined standard uncertainty depends mainly on correlations between input variables representing the emission of the object ob and the temperature of the To ambient (section 5.4.2). The simulation showed that the correlation between variables representing the To environment and the temperature of the Tatm environment affects the uncertainty of temperature measurement to some extent as well. Overall, we have stated that neglecting the correlations between these input variables can lead to an underestimation of the combined standard uncertainty uc (Tob) object. This effect should be considered when assessing the uncertainty of a particular measurement. At the same time, this is only the case under certain conditions. The results obtained in section 5.4 can be used to assess the combined standard uncertainty of the infrared camera measurement models. Additionally, there are other specific measurement conditions in order to determine its dependence on individual input variables; and, secondly, we estimate of coverage intervals of 95%, taking into account the actual distribution of the probability of a variable output model. The simulation of the combined standard uncertainty of a variable output model (measured object temperature) was assessed using the distribution method proposed by Working Group 1, formed by the General Committee on Fundamental Problems in the Metrology of the International Bureau of Weights and Measures. The distribution of distributions based on Monte Carlo simulation and design allowed us to estimate 95% of the measurement interval in infrared thermal imaging. One of the main findings drawn from the analysis of the combined standard uncertainty is that, despite the actual asymmetry of the distribution of output variables, it is safe It turned out that the distribution of the output variables is close to Gaussian. This is an ideal tool for assessing the combined standard uncertainty in infrared thermal imaging, for example, coverage intervals associated with it. The subject of our findings may be very relevant for those studying in this field. It is worth noting that the modelling approach presented in this monograph is extensive and covers numerous branches of technology. Summary 139 does not exhaust all possible cases, so the study should include an analysis of different models and conditions of measurement, models of phenomena affecting accuracy (such as atmospheric Etc. On the other hand, such in-depth analysis would not be practical. An extensive set of tables, characteristics and other detailed data would not necessarily allow the reader to find the necessary data. We therefore focused on the broader conclusions that allow for the practical application of results presented. We hope that the methods described in assessing errors and uncertainties will help improve the accuracy of measurement of infrared thermal imaging in real-world conditions. However, the final test of any theory is an experiment . . . A MATLAB Scripts and Functions A.1 Typesetting of the Code This work explored the accuracy of infrared thermal imaging measurements using sophisticated software created in the MATLAB computing environment. In order to help interested readers to pursue their own studies, we have included the source code of the MATLAB programs used in this book. It can be prepared by incorporating into the MATLAB environment editor or by digitizing with OCR (optical character recognition) software. M-files must be located in the same folder as the MATLAB environment (for example, in Matlab-Work). M-files were created as functions and scripts. Table A.1 lists the collected scripts, and in table A.2 - functions. Below are procedures for calculating the accuracy of measurements of infrared thermal imaging. When calculating, you must provide measurement parameters from the img file. For this reason, the first stage of the program is to enter the name of this file (recorded with an infrared camera). A.2 The procedure for calculating the components of errors in infrared thermal imaging measurements The procedure for calculating error components in infrared thermal imaging It should be emphasized that the stories created with the software are difficult from those described in this book. This is the result of different compilation of the measurement procedure. The script name of the infrared calculation program is the scripts of the measurement model which you can use the parameters to include table 2. 1. The components are in the MATLAB command window. 2. Enter numerical data (measurement conditions, standard uncertainties, and so on) according to the messages on the screen. 3. When the script is finished, enter the plot components in order to stitch up the results of the calculations. As a result, five graphs of suitable components will be built. Infrared thermography: Errors and Uncertainties No. 2009 John Wylie and Sons, Ltd Waldemar Minkina and Sebastian Dudzik Appendix A 142 Table A.1 M-file Scripts used in calculations of accuracy measurements Infrared thermal imaging The name of the component of the file Description m The uncertainty of the object for infrared cameras FLIR ThermaCAM Uncertainty of the relative combined standard uncertainty of the thermographic measurement using infrared cameras FLIR ThermaCAM coefficients to the input random variables with components m Areas of correlation between the transverse variables entering FLIR ThermaCAM measurement models A.3 Procedure for calculating uncertainty components compensation.m plotcomponents.m To calculate the uncertainty components of the model of infrared camera measurement using the software presented. 1. Enter the script in the MATLAB command window. 2. Enter numerical data (measurement conditions, standard uncertainties, and so on) according to the messages on the screen. 3. When the script is finished, enter the plot components to build the uncertainty components. As a result, five graphs of the relevant components will be built. Table A.2 M-file Features used in the calculations of the accuracy of infrared thermal imaging measurements Title m-file Description cameramodel.m distribute.m Then measurement model with the ThermaCAM infrared camera on the combined standard uncertainty calculates the approximation of the distribution for the input random variable Of the logging parameters based on the expected value and variance of the Score of even distribution based on the expected value and deviation, cross-correlated journal-corrected Cross-correlation Input Generation Even Distribution Downloads the .img file header Creates a plot of cross-correlated input variables for a given value of correlation Plots the distribution of the input random variable for uncertainty components and combined standard uncertainty meastrunifdid.m estunifpars.m genoorrlog.m genoorrunif.m loadimgheader.m plotdistrib.m plotcomponents.m plotscoverage.m plotcoverage.m Reads one typed value from the file calculates the pixel value at the Toolbox to Computer Help. It will be shown the input distribution readtable.m plotdist.m tempsignal.m App A3 A.4 Procedure for calculating the combined standard uncertainty. 1. The script in the MATLAB command window. 2. Enter numerical data (measuring uncertainty and so on) according to the messages on the screen. 3. When the script is finished, use the plotcomponents to build cross-entry correlation diagrams. As a result, five graphs of the combined standard uncertainty output model will be built. Five graphs show histograms of the input variables with the random variable. The graphs show the probability of a random variable, and the cumulative graph shows the approach of the cumulative function of the output variable distribution. A.4 The procedure for modeling cross-correlations between input variables To calculate the combined standard uncertainty of the infrared camera model using the software 1 presented. Type of correlations in the MATLAB command window. 2. Enter numerical data (measuring uncertainty and so on) according to the messages on the screen. 3. When the script is finished, announce storylines to build cross-entry random variables. As a result of the script, a graph of the right pair of cross input variables will be built. 4. Type plotcorrns to build a combined standard uncertainty against the correlation ratio between input variables selected in the correlation scenario. A.5 MATLAB Source code (scenario)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% M % % Calculates the components of the combined % % standard object uncertainty % Temperature for FLIR ThermaCAM infrared % % camera with the method to distribution % % with the assumption % different types of distribution of input % % variables. % % copyright February % 2008 Sebastian Dudzik % % (mail protected) % %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% disp (yap.) ; disp (' - Calculation of components to'); disp (' combined standard uncertainty'); 144 disp ('object temperature'); disp ('' for infrared cameras FLIR ThermaCAM'); disp ('yap.') ; disp (' - - - - - - - - - - - - - - - - - - - - - - - - - - - fileName-input (file name' ...'; ) (should be in the same cut',' ); % Reading radiometric data from the g img file % structure % SEE ALSO: loadimgheader m function fileName), % Entry for the temperature of the specified pixel % in the tObject-input thermogram ('Value of measured temperature (K):' ; disp ('); disp (' REFERENCE CONDITIONS BLOCK); disp (); % Entry for emission value (installed in the chamber) emisUn input (emission value:'); % Entry for the value of the ambient temperature % (set in the chamber) tAmb'input (AmbiOinput:'); % Entry for the value of the atmosphere temperature % (set in the chamber) tAtm'input ('Value relative humidity: '); % Entry for the camera Distance from object (m) : '); % Calculation of the signal value from the detector % based on (Object temperature) % SEE ALSO: tempsignal m function signal - tempstosignal (tObject, emisUn, tAtm, humRel, dist,... h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, h.obas, h.L, h.globalGain, h.globalOffset); % SEE ALSO: Appendix A App A disp ('); disp (yap.'); disp ('RANGE STANDARD OF UNCERTAINTY ' ... 'FROM THE INPUT VARIABLES BLOCK NO); disp (' '); % Entry for the camera environmental uncertainty range % of the emission maxEmissUn'input (Maximum emission uncertainty (%): '); 'maxEmissUn'input ('Maximum emission uncertainty (%)): '); % Environmental temperature range of... (%): '%K'; Environmental temperature measurement of the minimum minTAmbUn input ('Minimum temperature uncertainty' ... 'atmosphere (%): '%K'; maxTAmbUn input ('Maximum temperature uncertainty' ... 'Atmospheric temperature (%): '); % Entry for the range of standard uncertainty of the humidity measurement minHumRelUn input ('Minimum uncertainty'... 'relative humidity (%): '%K'; maxHumRelUn input ('Maximum uncertainty' ... 'relative humidity (%): '%K'); % Entry for the range of standard uncertainty % of the distance measurement from the camera to the minDistUn input ('Minimum uncertainty'... 'distance from camera to object (%): '); maxDistUn input (maximum uncertainty ... 'distance from camera to object (%): '%K'; % Entering the number of nPoints and linspace (minnPoints input (number of modeling points (Number of modeling points)'; % Calculation of uncertainty vectors % emissionUn and linspace (minEmissUn'emiss)/100,... (maxEmissUn'emiss)/100,nPoints); % Environment temperature ... (Tamb input ... (minTAmbUn*tAmb)/100,... (maxTAmbUn*tAmb)/100,nPoints); Infrared Thermography 145 Appendix A 146 humRelUn/100,... (maxHumRelUn*humRel)/100,nPoints); distUn and linspace ((minDistUn*dist)/100,... (maxDistUn*dist)/100,nPoints); disp (''); disp ('- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ' ... 'RANDOM VARIABLES BLOCK); disp (''); disp ('1 - Lognormal Distribution); disp ('2 - Even Distribution); disp (''); typeOfDist - input ('Enter type of distribution (1/2)'); disp (''); - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - для i'1:nPoints если typeOfDist 1 a,b'estlogpars (emiss, emissUn(i),2); hlpVar-lognrnd (a,b,1,10000); emissDistribution-emissDistrib-hlpVar; конец ясно hlpVar; если typeOfDist-2 a,b'estunifpars (эмисс, emissUn(i),2); hlpVar-unifrnd (a,b,1,10000); emissDistribution-emissDistrib-hlpVar; конец ясно hlpVar; % Распределение для ввода случайной переменной, представляющей % температуру окружающей среды для i'2:nPoints если typeOfDist-1 a,b'estlogpars (tAmb, tAmbUn(i),2); hlpVar-lognrnd (a,b,1,10000); tAmbDistribution-tAmbDistrib-hlpVar; конец ясно hlpVar; если typeOfDist-2 a,b'estunifpars (tAmb, tAmbUn (i),2); hlpVar-unifrnd (a,b,1,10000); tAmbDistribution-tAmbDistrib-hlpVar; конец ясно hlpVar; еее а,бетеунифпары (tAmb, tAmbUn (i),2); hlpVar-unifrnd (a,b,1,10000); tAmbDistribution-tAmbDistrib-hlpVar; конец; ясно hlpVar; конец; % Распределение для ввода случайной переменной, представляющей % температуру атмосферы tAtmDistribution-zeros (1,10000); для i'2:nPoints a,b'estlogpars (tAtm, tAtmUn(i),2); hlpVar-lognrnd (a,b,1,10000); tAtmDistribution-tAtmDistrib-hlpVar; конец ясно hlpVar; tAmbDistribution-tAmbDistribution-hlpVar; для i'2:nPoints a,b'estlogpars (tAtm, tAtmUn (i),2); hlpVar-lognrnd(a,b,1,10000); tAtmDistribution-tAtmDistrib-hlpVar; конец; % Распределение для входной случайной переменной, представляющей % humRelDistribution-zeros (1,10000); если typeOfDist-1 a,b'estlogpars (humRel, humRelUn (i),2); hlpVar-lognrnd (a,b,1,10000); humRelDistribution-humRelDistrib-hlpVar; конец ясно hlpVar; для i'2:nPoints a,b'estunifpars (humRel, humRelUn (i),2); hlpVar-unifrnd (a,b,1,10000); humRelDistribution-humRelDistrib-hlpVar; 147 148 конец; ясно hlpVar; еее а,беетунифпары (хумРел, хумРелУн(i),2); hlpVar-unifrnd (a,b,1,10000); humRelDistribution-humRelDistrib-hlpVar; конец; ясно hlpVar; % Распределение для ввода случайной переменной, представляющей расстояние от камеры к объекту distDistribution-zeros (1,10000); если typeOfDist-1 a,b'estlogpars (dist, distUn(i),2); hlpVar-lognrnd (a,b,1,10000); distDistribution-distDistrib-hlpVar; конец ясно hlpVar; еее a,b'estunifpars (dist, distUn (i),2); hlpVar-unifrnd (a,b,1,10000); distDistribution-distDistrib-hlpVar; конец; ясно hlpVar; для i'2:nPoints a,b'estlogpars (dist, distUn(i),2); hlpVar-unifrnd (a,b,1,10000); distDistribution-distDistrib-hlpVar; конец; ясно hlpVar; конец; - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - для i'1:nPoints emissComponent (:,i) - камероджель (сигнал, ..., emissDistribution (i,:), tAmb, tAtm, humRel, dist, h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, ..., h.L, h.globalGain, h.globalOffset); emissStd(Component) - std (emissComponent); % Сигнал ... emissStd (:, i) std (emissComponent); еее 1000000-more-meta-a-year-high - the number of people in the World Cup - has been in the process of ensuring the use of the world's binge. eeeeee i'n 1:nMM PointsComponent (:,i) - ceeeeeea (ceeeaa, eccceee, ..., tAmbDistribution (i,:), tAtm, humRel, dist, h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, h.obas, h.L, h.globalGain, h.globalOffset); eeeee emiStd (AtmComponent); tAmbStdToObject (tAmbComponent); tAmbStd(TObject) ... 1000,000 - 10000,000 - ceeeeeea (ceeeeea, eccccniiiiiiii, ..., tAmb, tAtmDistribution (i,:), h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, ... h.obas, h.L, h.globalGain, h.globalOffset); tAtmStd(TObject) 100; tAtmStdRel (tAtmStd(TObject) 'eeeeeeeeiiiiiiiii comedian HumRelComponent No(1000,000); eeeeee i'n HumRelComponent (:,i) - ceeeeeea (ceeeea, eccciiiiiii, ..., tAmb, tAtm, humRel, distDistribution (i,:), h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, ..., h.obas, h.L, h.globalGain, h.globalOffset); distStd = std (distComponent); distStdRel (distStd(Object) 100; eeeeeeeea i'n 1:nPoints emissComponent (:,i) - ceeeeeea (ceeeea, cиcccиии, ..., tAmb, tAtm, humRel, distDistribution (i,:), h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, ..., h.obas, h.L, h.globalGain, h.globalOffset); distStd = std (distComponent); distStdRel (distStd(Object) 100;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% M % %Сраaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa ииииииииииииииииииии срeда сpeдaaaaaaaa сpeaaaaaaaaaaaaaaaa иииааааааааааааaaaaaaaaaaaaaaaaaaaaaaaaa срeдиииииииии ... M % %149 150 % СИИИИИИИЕЕЕЕ: Cаррсррррррррррррррррррррррррррррррррррррррррррррррррррррррррррррррррррррррр M % %eeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeeee 2008 Срeeeeeeeeeeeeeeeeeeeeeeeee (eeeeeeeeaa) ... % %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% % Plot of histogram of emission variable h1'gca (ob, 'baby'); set (h1,'FaceColor', 'none',' ... 'EdgeColor','blue') title ('Histogram input random variable'; ... 'representing the emission); xlabel ('Emissivity) epsilon_'); ylabel ('Size (samples)); abstract ('textbox', 0.5,0.5,0.3,0.1 , 'BackgroundColor', ... 'white', 'String', 'Expected value: ... num2str (average (x1),3) '; 'Standard deviation: ... num2str (std(x1),3)); % Plot of histogram of ambient temperature figure; Hist (x2,45); h2'gca (Ambient, 'baby'); set (h2,'FaceColor', 'none', 'EdgeColor','blue'); title ('Histogram input random variable'... ambient temperature'); xlabel ('Ambient temperature T_o (K)'); ylabel ('Size (samples)'); abstract ('textbox', 0.5,0.5,0.3,0.1 , 'BackgroundColor', ... 'white', 'String', 'Expected value: ... num2str (average (x2),3) 'K'; 'Standard deviation: ... num2str (std(x2),3) 'K'); % Plot of histogram variable of the atmospheric temperature figure; Hist (x3,45); h3'get (gca, 'baby'); set (h3,'FaceColor','none','EdgeColor','blue') title ('Histogram input random variable'; ... 'representing the temperature of the atmosphere) xlabel ('Atmospheric temperature T_{0 rm (K)'); ylabel ('Size (samples)); abstract ('textbox', 0.5,0.5,0.3,0.1 , 'BackgroundColor', ... 'white', 'String', 'Expected value: ... num2str (average (x3),3) 'K'; 'Standard deviation: ... num2str (std(x3),3) 'K'); % Plot of histogram input variable relative humidity figure; Hist (x4,45); h4'get (gca, 'baby'); set (h4,'FaceColor', 'none', ... 'EdgeColor','blue') App A Appendix A 151 set (h4,'FaceColor','none','EdgeColor','blue') title ('Histogram input random variable'... relative humidity'); xlabel ('Relative humidity (omega)'); ylabel ('Size (samples)'); abstract ('textbox', 0.5,0.5,0.3,0.1 , 'BackgroundColor', ... 'white', 'String', 'Expected value: ... num2str (average (x4),3); 'Standard deviation: ... num2str (std(x4),3)); % Plot of histogram of the camera's distance to the object variable figure; Hist (x5,45); h5'get (gca, 'baby'); set (h5,'FaceColor', 'none', 'EdgeColor','blue'); title ('Histogram input random variable'... 'representation of distance from camera to object') xlabel ('Distance from camera to object (d) (m)'); ylabel ('Size (samples)'); abstract ('textbox', 0.5,0.5,0.3,0.1 , 'BackgroundColor', ... 'white', 'String', 'Expected value: ... num2str (medium (x5),3) 'm'; 'Standard deviation: ... num2str (std (x5),3) 'm'); % Plot of histogram of the camera's histogram the output variable figure n,k'hist (tObject, 40); nn'(40'n)./ (maximum (temperature)-min (temperature)) 1e6); hbar - bar (k,nn,1); Mesh on; xlabel ('Output temperature T_{ob} (K)'); title ('Probability function of a random variable' ... 'representing the output variable') ylabel ('Size (samples)'); set (gca, 'XMinorTick','on'); set (gca,'YMinorTick','on'); hold on; set (hbar,'FaceColor','white') Hold it. h1 - plot (TLow, tLow, 0 max (nn)); set (h1,'LineWidth',2); set (h1,'Color', 'black'); h2 - plot (tHigh, tHigh), 0 max (nn)); set (h2,'LineWidth',2); set (h2,'Color', 'black'); % (The probability density function of a random variable is a random variable); ... Abstract representing the output variable of the object) textbox, 0.5,0.5,0.3,0.1, BackgroundColor, ... 'white', 'String', 'Expected value: ... num2str (medium (temperature), 3); 'Standard deviation: ... num2str (std(temperature), 3)) % A site close to the temperature distribution figure; hplot - plot (tDist(:,1), tDist (:,2),'b-'); set (gca,'XMinorTick','on'); set (gca,'YMinorTick', 'on'); (Approaching cumulative distribution of the output variable T_{ob}' ...'); xlabel ('Temperature T_{ob} (K)'); ylabel ('F_T(T_{ob})'); hold it; h1 - line (tLow, tLow, 0 1, Color, red, LineWidth,2); h2 - line (tHigh, tHigh, 0 1, Color, red, LineWidth,2); legend ('Approaching cumulative distribution...', '95% coverage interval', 'Location', 'best'); % % End plotRESULTS

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% M % % simulates the effect of % cross-correlation between infrared camera model input variables. % % copyright February, 2008 Sebastian Dudzik % % (mail protected) % %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% disp (yap.) ; disp (japanese) disp (''simulates the influence of K); disp (' cross-correlations between input); disp (variable FLIR ThermaCAM, h); disp ('-infrared camera model on K); disp (' combined standard uncertainties); disp (yap.) ; disp (yap.) disp (' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ' ... FILE NAME AND MEASURED TEMPERATURE BLOCK'); disp (''); % Entry for the name of a file recorded with an infrared disp camera (' FILE NAME AND MEASURED TEMPERATURE BLOCK' ...); disp (''); fileName-input (file name' ...'; ) (should be in the same cut',' ); % Reading radiometric data from the g img file % structure % SEE ALSO: loadimgheader m function h - loadimgheader (fileName), % Entry for the temperature of the specified pixel % in the tObject-input thermogram ('Value of measured temperature (K):' ; disp ('); disp (' REFERENCE CONDITIONS BLOCK); disp (); % Entry for emission value (installed in the chamber) emisUn input (emission value:'); % Entry for the value of the ambient temperature % (set in the chamber) tAmbUn'input (Ambient temperature value (K): '); % Entry for the value of the atmosphere temperature % (set in the chamber) tAtm'input (Atmospheric temperature value (K): '); % Entry for the relative humidity (installed in the chamber) humRel'input ('Value relative humidity: '); % Entry for distance from camera to object dist'input (Distance from camera to object (m): '); disp (' '); disp (STANDARD UNCERTAINTY OF THE BLOCK VARIABLES); disp (' '); % Entry for standard uncertainty emissUn'input (Standard emission uncertainty:'); % Entry for standard uncertainty of the ambient temperature tAmbUn'input (Standard environmental uncertainty' ... 'Temperature (K):'); % Entry for standard uncertainty of atmospheric temperature tAtmUn'input (Standard atmospheric temperature uncertainty' ... 'atmosphere (K):'); % Entry for standard uncertainty relative humidity humRelUn'input (Standard uncertainty relative humidity:'); % Entry for standard uncertainty distance from camera to object distUn input (Standard uncertainty' ... 'distance (m): '); % NOSAMPLES - 10 000 EURO; % Number of random variables % Vector of standard uncertainty parsNorm(1)' emissUn; parsNorm(2) parsNorm(3) - tAmbUn; parsNorm(3) - tAtmUn; parsNorm(4) - humRelUn; parsNorm(5) - distUn; % Number of random variable samples noSamples-10,000; % Vector of standard uncertainty parsNorm(1)' emissUn; % Vector of estimates of input variables vEmis - emiss; vAmb - tAmb; vAtm - tAtm; ... ; Appendix A 154 disp (VECTOR BLOCK CROSS-CORRELATION OPTION); disp (' '); % Input data to the correlation vector jBegin and input ('starting value of cross-correlation vector:'); jStep and input ('Step value in cross-correlation vectors:'); jEnd - entry (End of cross-correlation vector value:'); jCorrCoef - jBegin:jStep:jEnd; jLen - length (jCorrCoef); disp (' '); disp (' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ' ... 'RANDOM VARIABLES BLOCK); disp (''); disp ('1 - Logonormal Distribution); disp ('2 - Even Distribution); disp (''); typeOfDist - input ('Enter type of typeOfDist - 1/5 % Distribution type choice if typeOfDist-1 15% Journal-normal distribution - Rate of normal log allocation parameters for i - 1:5 (parsUn) (1,1) parsLog(i) (1,2)... estloggars (parsNorm(i), 1,2), NOSAMPLES, ES); end; disp (' '); disp (' CROSS-CORRELATED TIME RANDOM ...'VARIABLES BLOCK); disp (''); disp ('1 - Emission'); disp ('2 - Temperature'); disp ('3 - Temperature'); disp ('4 - Relative humidity'); disp ('5 Distance from camera to object); disp (' '); disp ('Index Input variable'); disp (' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - '); iPopup and input ('Enter the index first'... 'cross-correlated input variable:'); jPopup and input ('Enter the index second'... 'cross-correlated input variable:'); % Auxiliary array of parameters for selected log distributions of pNorm parsNorm(1) parsNorm (1,1) parsNorm(1,2); pNorm(2) parsNorm(1); pNorm(1) - parsLog (ipParsVar), 1); pLog(1) - parsLog (iPopup (1,1) parsLog kPopup (1,1) parsLog kPopup (1,1) parsLog jPopup (1,1); pLog(2) - parsLog (jPopup (1,2); pLog(2) - parsLog jPopup (1,2); end; % Generation of correlated input random variables if typeOfDist-1 genocorrlog (pNorm, pLog, jCorrCoef, NOSAMPLES); ell % Now Generation Uniform Distribution - Number of samples for i - 1:5 (parsUn) (1,1) parsUn (1,2) ... estunifpars (parsNorm(i)), 1, NOSAMPLES); end; disp (' '); disp (' CROSS-CORRELATED TIME RANDOM ...'VARIABLES BLOCK); disp (''); disp ('1 Emission'); disp ('2 Ambient temperature'); disp ('3 Atmosphere temperature'); disp ('4 Relative humidity'); disp ('5 Distance from camera to object'); disp (' '); disp ('Index Input variable'); disp (' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - '); iPopup and input ('Enter the index first' ... 'cross-correlated input variable:'); jPopup and input ('Enter the index Second'... 'cross-correlated input variable:'); % Auxiliary array of parameters for selected uniform distributions of pNorm parsUn(iPopup, 1) parsUn (1,1) parsUn (1,2); pUn(1) parsUn (jPopup (1,1) parsUn (kPopup (1,1) ...); 155 Appendix A 156 pUn(2) ... end; % Generation of correlated input variables bCorrVariable variables - genunicorr (pNorm, pUn, jCorrCoef, NOSAMPLES); end; % Conversion of cell array variables into matrix for i'1:jLen bCorrVar(i) - bCorrVar(i) ... % iPopup iPopup % Place cross-correlated variables in array of cells of the input random variables of (iPopup) and kPopupVariable (iPopup) - iPopupVariable; jPopupVariable; % Simulation of output random variable (temperature signal) display (tObject, emiss, tAmb, tAtm, humRel, dist, h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, h.obas, h.L, h.globalGain, h.globalOffset); for i'1:jLen tOut (:,i) - camera model (signal, inputs{1} (:,i), entrances{2} (:,i), entrances{3} (:,i), entrances{4} (:,i), entrances{5} (:,i), h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, h.obas, h.L, h.globalGain, h.globalOffset); disp ('Results'); end; % End of CORRELATIONS. M %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% % % % - COVERINT. M % % % Calculates the coverage interval for FLIR % % ThermaCAM infrared cameras with method to distribution % % assuming an even distribution of input % % % % % of Copyright Of February, 2008 Sebastian Dudzik % % (mail protected) %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% disp (yap.) ; disp (yap.) disp (' - Coverage interval calculation'); disp ('' for infrared cameras FLIR ThermaCAM'); disp ('yap.') ; disp (' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - ' ... FILE NAME AND MEASURED TEMPERATURE BLOCK'); disp (' '); % Entry for the name of a file recorded with an infrared disp camera (' FILE NAME AND MEASURED TEMPERATURE BLOCK' ...); disp (''); fileName-input (file name' ...'; ) (should be in the same cut',' ); % Reading radiometric data from the g img file % structure % SEE ALSO: loadimgheader m function h - loadimgheader (fileName), % Entry for the temperature of the specified pixel % in the tObject-input thermogram ('Value of measured temperature (K):' ; disp ('); disp (' REFERENCE CONDITIONS BLOCK); disp (); % Entry for emission value (installed in the chamber) emisUn input (emission value:'); % Entry for the value of the ambient temperature % (set in the chamber) tAmb'input (Ambient temperature value (K): '); % Entry for the value of the atmosphere temperature % (set in the chamber) tAtm'input (Atmospheric temperature value (K): '); % Entry for the relative humidity (set in the chamber) humRel'input ('Value relative humidity: '); % Entry for distance from camera to object dist'input (Distance from camera to object (m): '); disp (' '); disp (STANDARD UNCERTAINTY OF THE BLOCK VARIABLES); disp (' '); % Entry for standard uncertainty of emissUn'input (Standard emission uncertainty:'); % Entry for standard uncertainty of the ambient temperature tAmbUn'input (Standard environmental uncertainty' ... 'Temperature (K):'); ISF 158% Entry for standard uncertainty of atmospheric temperature tAtmUn'input (Standard atmospheric temperature uncertainty' ... 'atmosphere (K):'); % Entry for standard uncertainty relative humidity humRelUn'input (Standard uncertainty relative humidity:'); % Entry for standard uncertainty distance from camera to object distUn'input (Standard uncertainty distance (m): '); % Assessment of the parameters of uniform distribution % for object emission input variable % SEE ALSO: function estunifpars.m a1 b1 estunifpars (emiss, emisUn-2); % Assessment of the parameters of uniform distribution % for ambient temperature input variable % SEE ALSO: estunifpars.m function a2 b2 estunifpars (tAmb, tAmbUn-2); % Assessment of the parameters of uniform distribution % for atmosphere temperature input variable % SEE ALSO: estunifpars.m function a3 b3 estunifpars (tAtm, tAtmUn-2); % Assessment of the parameters of uniform distribution % for relative humidity of the input variable % SEE ALSO: estunifpars.m function a4 b4 estunifpars (humRel, humRelUn-2); % Assessment of the parameters of uniform distribution % for the distance from camera to object % SEE ALSO: estunifpars.m function a5 b5 estunifpars (dist, distUn-2); % Generation random variables according to parameters calculated above (1e6 samples) x1-unifrnd (a1,b1,1e6,1); % Generation of uniform distribution of the ambient temperature (1e6 samples) x2-unifrnd (a2,b2,1e6,1); % Generation variable input ambient temperature according to the parameters calculated above (1e6 samples) x3-unifrnd (a3,b3,1e6,1); % Generation of relative humidity ... % above (1e6 samples) x4-unifrnd (a4,b4,1e6,1); % Generation variable of distance from camera to object according to parameters calculated above (1e6 samples) x5-unifrnd (a5,b5,1e6,1); % Use of the method to distribute % of distribution to obtain temperature signal (temperature) SEE ALSO: cameramodel.m - camera model (signal, x1, x2, x3, x4, x5,... h.alpha1, h.alpha2, h.beta1, h.beta2, h.X, h.R, h.B, h.F, h.obas, h.L, h.globalGain, h.globalOffset); disp (''); disp ('RESULTS BLOCK') disp (''); disp (Combined standard uncertainty object temperature) ; disp (...); disp (Combined standard uncertainty of object temperature... % Calculation of the combined standard uncertainty, as well as its coverage interval using Monte Carlo ... SEE ALSO: distribution.m tDist function and tLow, tHigh - coverint (tObject, ...); tFind (tDist(:,2)) ... find; ...; % End of coverint. A.5 An example of MATLAB session 1 ... Example of data for MATLAB: ..., Name of the recorded file (should be in the same cut): D1017-10.img Value of measured temperature (K): 363 REFERENCE CONDITIONS BLOCK - Emission value: 0.9 Environmental temperature value (K): 293 Atmospheric temperature value (K): 293 Relative humidity: 0.5 Value distance from camera to object (m): 1 - RANGE S OF THE STANDARD UNCERTAINTIES OF INPUT VARIABLES BLOCK - Any value 1 A.7.3 Minimum Emission Uncertainty (%): 0 Maximum Emission Uncertainty (%): 30 Minimum Ambient Temperature Uncertainty (%): 0 Maximum Environmental Temperature Uncertainty (%): 3 Minimum atmospheric temperature uncertainty (%): 0 Maximum atmospheric temperature uncertainty (%): 3 Minimum uncertainty of relative humidity (%): 0 Maximum uncertainty of relative humidity (%): 30 Minimum distance uncertainty from camera to object (%): 0 Maximum distance uncertainty from camera to object (%): 30 Number of simulation points: 10 Dental distribution: 2 - Even Distribution Type Type (1/2): 2 Appendix A 160 Reading the current results - The resulting plot can be computed to compute uncertainty components for the data shown in example A.9 Session of MATLAB the data shown in example 1/4 363 K where 1/4 363 K for standard uncertainty measuring reference value according to table. Value when you were creating the resulting plots of the measurement 363 K example 5.23a, 5.24a, 5.27a, 5.28a, 5.29a, 5.30a, 5.31a (section 5.3.1-5.3.5). A.7.2 Calculation of the combined standard uncertainty and coverage interval The cumulative standard uncertainty and the 95% coverage interval of the measured temperature problem. Calculate the cumulative standard uncertainty and coverage interval of 95% for the measured temperature of an object, assuming an even distribution of all input variables (table A.4). Measurement conditions: Emission (ob) 0.9 Environmental Temperature (To), K 293 Atmospheric Temperature (Tatm), K 293 Relative Humidity (v) 0.5 Distance from Camera to Object (m), m Estimated Value 0.9 293 293 0.5 10 Uncertainty range 0.09 9 0.05 1 Table 5.9 Temperature value, the following measurement, measured by the camera, 363 K. The thermal image, recorded with an infrared camera, was stored in the file: D1017-10.img. Solution. Below is an example of a MATLAB session in order to calculate combined standard uncertainty and coverage interval of 95% by using m-files coverint.m and plotresults.m from sections A.5 and A.6. Appendix A 174 script, coverint - FILE NAME AND MEASURED TEMPERATURE BLOCK - The name of the recorded file (should be in the same cut): D1017-10.img Value of measured temperature (K):363 Emission: 0.9 Environmental temperature value (K): 293 Atmospheric temperature value (K): 293 Relative humidity: 0.5 Value distance from camera to object (m): 10 VARIABLES BLOCK STANDARD OF UNCERTAINTY - Standard emission uncertainty: 0.09 Standard environmental temperature uncertainty (K): 9 Standard uncertainty of atmospheric temperature (K): 9 Standard uncertainty of relative humidity: 0.05 Standard uncertainty of distance (m): 1 - RESULTS BLOCK (Combined Standard Uncertainty of Object Temperature Lica) - 5.6505 95% coverage interval (K) (tLow tHigh) : 355,063, 374,2662 plotresults Results can be compared with those in table 5.9 and figure 5.59 (section 5.5.2). A.7.3 Simulation of cross-correlations between input variables The measurement problem. Calculate the combined standard uncertainty of the object temperature is 363 K. Correlation factor values have changed in the range from 0.99 to 0.99 in 0.01. The thermal image, recorded with an infrared camera, was stored in file: D1017-10.img. Annex A 175 Table A.5 Measurement Conditions for Sample Sessions calculating combined standard uncertainty with correlation input variables, taking into account the correlations of selected problem of random input variables (table A.5) (see section 5.4.2 and table 5.4 and 5.5): The conditions of measurement: Emission (Ob), K Ambient Temperature (To), K Atmospheric Temperature (Tatm), K Relative Humidity (v) Camera Distance to Object (d), m Estimated value: Uncertainty range 0.9 293 293 0.5 10 0.09 29.3 29.3 0.05 50 5 Solution. To simulate the effect of cross correlations between two input variables (ob and Tatm) ... calculated results for an example of a MATLAB session to address this issue using m-files correlations.m and plotcorrns.m from sections A.5 and A.6. Appendix A 176 script cross-correlations - FILE NAME AND MEASURED TEMPERATURE BLOCK - The name of the recorded file (should be in the same cut): D1017-10.img Value of measured temperature (K): REFERENCE CONDITIONS BLOCK - Emission value: 0.9 Ambient temperature value (K): 293 Atmospheric temperature value (K): 293 Relative Humidity: 0.5 Value distance from camera to object (m): 50 - STANDARD UNCERTAINTY OF THE INPUT VARIABLES BLOCK - Standard emission uncertainty: 0.09 Standard Environmental Temperature Uncertainty (K): 29.3 Standard Uncertainty Of Standard Atmospheric Temperature (K): 29 Relative humidity: 0.05 Standard distance uncertainty from camera to object (m): 5 PARAMETERS CROSS-CORRELATION VECTOR BLOCK - Original value of cross-correlation vector: -0.99 Step value in cross-correlation vectors: 0.01 End of the value of cross-correlation vector: 0.99 176 APPENDIX A DISTRIBUTION OF THE RANDOM RANDOMS BLOCK No 1 - Lognormal Distribution 2 - Even Distribution Type VARIABLES BLOCK - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - 363 K in 5.35a (section 5.4.2). Appendix B Normal Emissivities of Various Materials (IR-Book 2000, Minkina 2004) Temperature specification material. C Spectrum Emittance 10 mm 3 mm T T T LW 0.04 0.09 0.04 0.04-0.06 0.05 0.05 95 METALS and METAL OXIDES Aluminium, Aluminium Aluminium Oxide Oxide Vacuum Deferred Lys Polish Plate Anodized, AOXIDES Black Aluminium Aluminium Oxide Aluminium Oxide Oxide Vacuum Deferred Lys Polished Plate Anodized, AnOXIDEzed Black, Real Boring anodized sheet 27 27 20 50-100 100 70 100 27 T T 0.55 0.6 0.28 T T 0.4-0.6 0.16 100 200 100 27 T T 0.03 0.06 50-150 T 0.1 0.5 500-1000 50 T 0.28-0.38 0.10 Powder Anodized, Powder, Clean, Powder, Alumina (aluminium) Brass polished, highly polished sheet, rolled Bronze polished porous, coarse chrome polished polished (continued) Infrared thermography : Mistakes and Uncertainty 2009 John Wylie and Sons, Ltd. Waldemar Minkina and Sebastian Dudzik Appendix B 178 METALS and METAL OXIDES (continued) Material Copper Oxide Copper Precision, polished electrolytic, carefully polished pure, carefully prepared surfaces polished, mechanical polished oxidized, black oxidized. Температура порошка, С 34 Спектрум Излучение 250 T 0.006 80 T 0.018 22 T 0.008 22 T 0.015 50-100 T 0.02 27 T 0.03 T T 0.018 0.02-0.03 0.02 железо и сталь ... 0.3 0.21 0.87-0.95 0.95 ... 0.88 0.76 0.78 ... 0.82 0.88 ... 0.7 ... 0.6-0.7 ... 0.27 ... 0.13-0.16 ... 0.05 0.05 ... 0.02 ... 200 ... 0.30 ... 600 1000 200-600 ... 24 92 30 20 ... 0.14-0.38 0.80-0.064 0.07 0.23-0.28 0.64 0.85 ... T уголь консервированный ... 0.89 ... уголь оцинкованный ... свинец неокисленный, polished shiny oxidized on 200 C lead red польский порошок магния 100 T 0.05 250 100 T T 0.08, 0.63 93 22 T T T 0.07 0.86 Приложение B 179 METALS и METAL OXIDES (продолжение ) Материальная спецификация температуры молибдена, C

Спектра Излучение Filament 600-1000 700-2500 1500-2200 T T T 0.08-0.13 0.1'0.3 0.19-0.26 Нихром свернутый пескоструйной проволоки, чистый провод, чистая проволока, окислено 700 700 500-1000 50-500 T T T T T 0,25 0,70 0,71-0,79 x 0,65 0,95-0,98 Никель Электролитический электролитический 22 38 500-650 1000-1250 T T T T 0,04 0,0,6 0,52-0,59 0,75-0,86 Лента 17 22 100 260 538 900-1100 T T T T T T 0.016 0.03 0.05 0.06 0.10 0.12-0.17 Серебряный польский Чистый, полированный 100 200-600 T T 0.03 0.02-0.03 Нержавеющая сталь Типа 18-8, отполированный тип 18-8, окисляется при 800 C листе, полированном листе, полированный лист, необработанный, несколько поцарапан лист, необработанные, несколько поцарапан Rolled Sandblasted 20 60 T T 0,16 0,85 70 70 70 SW LW SW 0,18 0,14 0,30 70 ЛВт 0,28 700 700 T T T 0,45 0,70 20-50 100 T T 0,04-0,06 0,07 200 500 200 200 T T T T 0.15 0.20 0.40 0.05 600-1000 1500-2200 3 300 T T T 0.1-0.16 0.24-0.31 0.39 Никель оксид Платина Олово Burnished олово покрытием листового железа Титан полированной полированной Окисленный при температуре 540 C Вольфрамовая нить (продолжение) Приложение B 180 METALS и METAL OXIDES (продолжение) Материальная спецификация цинка полированная окисляется при температуре 400 C листа окисленного поверхности , C 200-300 400 50 1000-1200 Spectruma Emittance T T T T 0.04-0.05 0.11 0.20 0.50-0.60 T T SW T T 0.40-400.60 0.78 0.94 0.96 0.96 0.93-0.95 ДРУГИЕ МАТЕРИАЛЫ Асбест Порошок Ткань Напольная плитка Доска Шиферная бумага Асфальтовый кирпич 35 20 20 40-400 4 Силлиманит, 33% SiO2, 64% Огнеупорные Al2O3, Магнезит огнеупорный, корунд огнеупорный , weakly radiating Waterproof Red, rough Red, common Masonry Masonry, plastered LLW 0.967 1500 T 0.29 1000–1300 T 0.38 1000 T 0.46 500–1000 T 0.65–0.75 SW T T SW T 0.87 0.88–0.93 0.93 0.94 0.94 T T 0.95 0.95–0.97 17 20 35 20 Carbon Candle soot Lampblack Chipboard Clay Cloth Untreated Fired Black 20 70 20 SW T T 0.90 0.91 0.98 Dry Rough Walkway 20 36 17 5 T SW SW LLW 0.92 0.95 0.97 0.974 Грубый 80 T T 0.89 0.85 Лаккер 20 20 T T 0.9 0.85-0.95 Хард, необработанные Пористые, необработанные masonite 20 20 70 SW SW LW Бетонный Эбонит Эмери Enamel Fiberboard 20 20-400 0,85 0,85 0,88 Приложение B 181 ДРУГИЕ МАТЕРИАЛЫ (продолжение ) Материал Гранит Спецификация Температура , C Полированный Грубый Грубый, четыре различных образцов Gypsum Ice: см. Вода Лаккер Кожа Алюминий на грубой поверхности Bakelite Черный , матовый черный, тупой белый LLW LLW SW 20 T 0,8-0,9 20 T 0,4 80 100 40-100 40-100 T T T T 0. 83 0,97 0,96-0,98 0,8-0,95 T 0,75-0,80 T 0,3-0,4 Лайм Сухое масло, смазка краска бумаги фильм на базе Ni: Ni базы только : 0,025 мм пленки : 0,050 мм пленка : 0,125 мм пленка : толстое покрытие Алюминий , различные возрасты Кадмий желтый Хром зеленый Кобальт голубое Grey Glitter Plastic, Black Yellow-Red Blue, Dark Green Black Coated With lacquer White White bond Black, dull Black, dull Emittance 20 21 70 Tanned Mortar Spectruma 0.849 0.879 0.95–0.97 17 36 SW SW 0.87 0.94 20 T 0.05 20 20 20 20 T T T T 0.27 0.46 0.72 0.82 50–100 T 0.27–0.67 T T T SW SW 0.28–0.33 0.65–0.70 0.7–0.8 0.87 0.96 0.95 17 20 20 T T T T T T 20 20 70 70 T T SW LW T 0.72 0.76 0.84 0.85 0.90 0.93 0.7-0.9 0.93 0.86 0.89 0.94 (continued) Appendix B 182 OTHER MATERIALS (continued) Material specification Plaster Porcelain Rubber Spectrum Emitted 17 20 20 SW SW 0.86 0.91 0.90 SW 0.94 70 LW 0.93 White, Shiny Glazed 20 T T 0.70-0.75 0.92 Hard Soft, Grey, rough 20 20 T T 0.95 0.95 20 T 0.60 0.90 Rough Wool Plaster untreated plastic temperatures, C PVC, plastic floor, dull, structured PVC, plastic floor, blunt, structured sandstone Polished Rough 19 19 LLW LLW 10.th 909 0.935 Human Skin 32 T 0.98 Slag Cauldron 0-100 200-500 T T 0.97-0.93 0.89-0.78 Soil Dry Water Saturated 20 20 T T 0.92 0.95 Stucco Rough, Lime 10-90 T 0.91 Styrofoam Insulation 37 SW 0.60 Paper 20 T Tile Glazed 17 SW 0.94 Wallpaper A small template , светло-серый небольшой узор, красный 20 SW 0.85 20 SW 0.90 Varnish Flat На дубовом паркетном полу На дубовом паркетном полу 20 70 70 SW SW LW 0.93 0.90 0.90-0.93 Снежный слой воды > 0,1 мм толщиной Лед, гладкий лед, лед, гладкий лед, покрытый тяжелыми кристаллами мороза T T T T T T T T 0.8 0.85 0.95-0.98 0.96 0.96 0.98 T 0.98 Tap 10 0-100 20 0 0 0 0.79 0,84 0,91-0,93 Приложение B 183 OTHER MATERIALS (продолжение ) Температура Material specifications, C Wood Ground Planned Oak White, Wet Planned Oak Planned Oak 20 20 20 70 70 Spectra T T T SW LW T, total spectrum (0-th) mm; SV, 2-5 mm; LW, 8-14 mm; LLW, 6.5-20 mm. Emissions 0.5-0.7 0.8-0.9 0.90 0.7-0.8 0.77 0.88 Bibliography Links

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 Heatgram heater with a marked temperature point. (See page 26) Plate 2 Measuring the temperature of the infrared thermography of the aluminum cylinder (cross-section Li01) with stuck tapes of dielectric materials: rubber (cross-section Li02), paper (cross section Li03) and plastic (cross-section Li04) in stationary conditions. The infrared camera shows a distinctly different temperature for each material: (a) the thermogram; (b) Temperature profiles; and c) a top view of the experimental installation (Minkina 2004). Reproduced by Czȩ Technical University of H.S. (see page 29) Plate 3 Image of a small object (anchor clip for the bridge connection of the high-voltage anchorage line) on the array detector, allowing to correctly measure the temperature: a) no detector is completely exposed; (b) At least one detector is completely irradiated (1, object image; 2, array detectors); (c) The clip thermogram, registered at a long distance - about 40 meters (optical and digital zoom); (d) A short-distance clip thermogram (Minkina 2001). (See page 37) Plate 4 Determining the size of the measurement area: (a) the ideal optics is the irradiation of area 2 2 detectors needed for correct measurement; (b) Real optics, blur of images - irradiation area 3 3 or 4 4 (sometimes 5 5) detectors needed for correct measurement (Danjoux 2001, Minkina 2004). (See page 38) Plate Detector 5 Array (FPA) used in FLIR cameras: (a) uncooled microbolometers with (Peltier element), air temperature is about 30 C (www.flir.com, www. flir.com.pl, flir.com.pl, and Raytheon (www.raytheon.com): b) 512 512 ALADDIN III quadrant; (c) 1024 1024 ALADDIN III. (see page 47) Plate 6 Enhanced digital image for various color maps: (a) grey scale; (b) Cool; (c) Hot; HSI (Intensity of Shade Saturation); Spring; (f) Summer; Autumn; (h) Winter. (See page 50) Plate 7 (a) Laboratory room for calibration of infrared cameras; (b) A set of technical black bodies (IR-Book2 2000). It is reproduced with the permission of ITC Flir Systems. (See page 66) Plate 8 Termograms of polished aluminum sheet, the temperature of which is close to the ambient temperature: (a) mirror image of a person, measuring the temperature of the sheet; (b) The image of a glass of hot water in the background of the sheet and its background reflection (the right edge of the paper sheet stuck on the aluminum is marked with a dotted line), c) view (Minkina 2004). Reproduced at the permission of Czȩ Technical University named H.S. (see page 71) Plate 9 Effect of incorrect Settings Tatm and To on the measurement of the temperature of the industrial plant (Minkina 2003). Reproduced by resolution of Czȩ The technical university named H.S. (see page 76) Plate 10 The main program window to study the effect of cross correlations between the input quantities of the ThermaCAM PM 595 camera measurement model on the combined standard uncertainty (Dudzik 2007). (See page 90) Plate 11 The main window of the program to simulate the sensitivity of the camera measurement model ThermaCAM PM 595. (See page 96) 96) infrared thermography errors and uncertainties pdf. minkina and dudzik's infrared thermography errors and uncertainties