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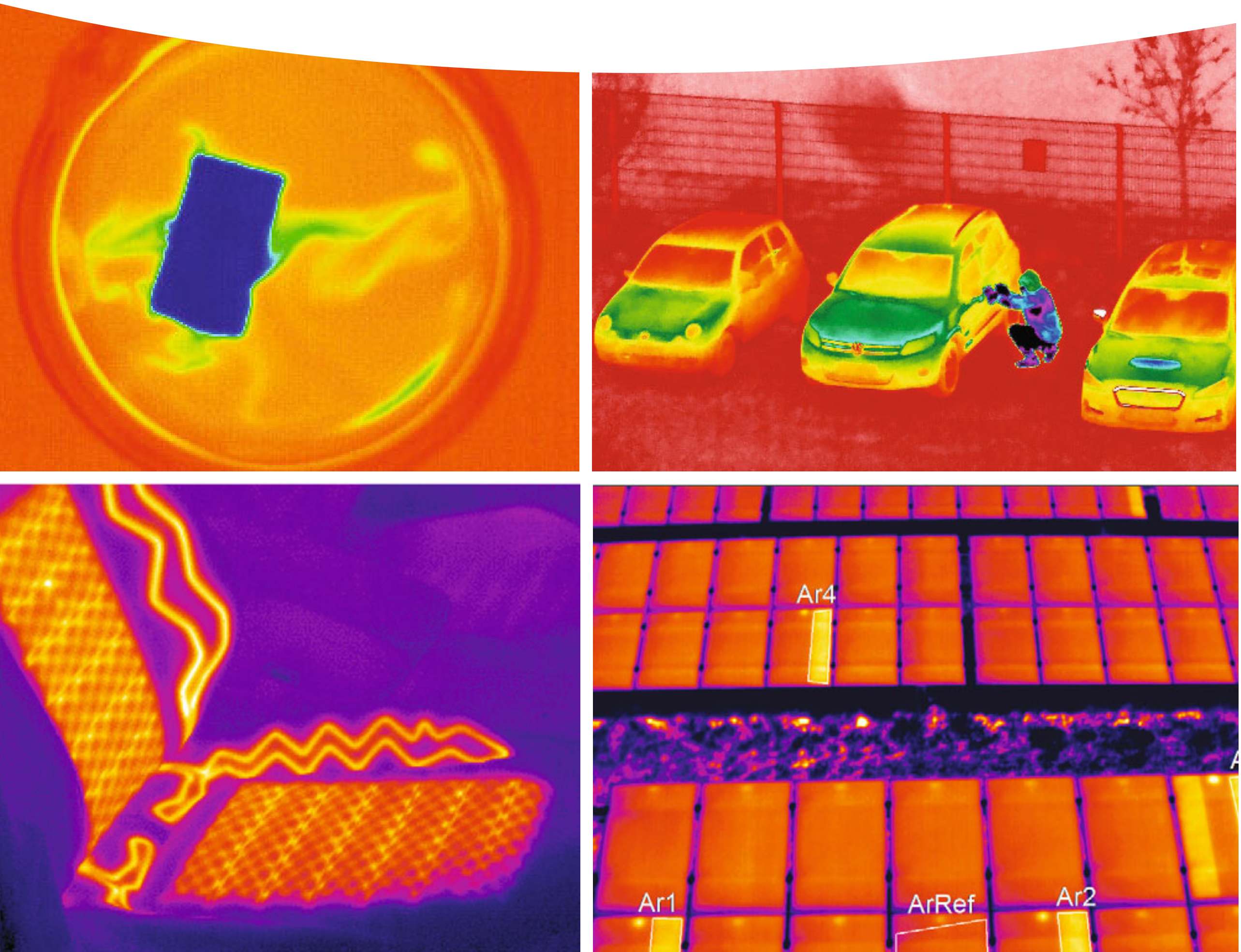
Michael Vollmer and Klaus-Peter Möllmann

Infrared Thermal Imaging

Fundamentals, Research and Applications

Second Edition



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Preface to Second Edition

In Infrared Thermal Imaging, seven years is a long time. On the one hand, the development cycles are short which means that many new devices have meanwhile become commercially available and others are in the pipeline. On the other hand, many new application fields have been opened up and partially breathtaking new IR imagery has been published.

Therefore a second edition of this up-to date textbook was nearly overdue. Again it is designed as a desk reference for practitioners as well as a textbook for beginners. We have taken this opportunity not only to add a completely new chapter and many new subsections of preexisting chapters but also to very carefully revise the whole text including necessary corrections of usually unavoidable small misprint errors. Overall this second edition has been largely extended including more than 100 new IR images and graphs.

In the first three more theoretical and technology based fundamental chapters, we added a detailed discussion of the history of IR science and technology (Section 1.7), elaborated on recent detector developments and the problem of the proper waveband selection (Sections 2.2.5.5 and 2.3.3), and discussed potentials of polarization sensitive IR imaging and the theoretical deblurring algorithms for images (Sections 3.4.2 and 3.5.2.6).

Chapter 4 on physics of heat transfer and some respective applications was only very slightly modified. In Chapter 5 on the use of IR imaging for teaching and education purposes we added quite a few new examples including for example, imagery from a formula one racing car, the thermal properties of stretching rubber bands , or visualization of heat transfer through paper and more. We then also added a completely new chapter on Short Wave IR imaging which has become more important within the last decade (new Chapter 6). All subsequent old Chapters 6 to 10 were accordingly shifted in the second edition. In the building thermography chapter we added an extended section on proper choice of palette, level, and span, optically induced thermal effects and other new developments (Sections 7.1.2.3, 7.5.2 and 7.8). Quite a few new developments in the field of optical gas imaging have been achieved within the last few years which we accounted for by a new subsection (Section 8.6). The chapter on microsystem was just revised, but not extended. In contrast the two final chapters on other application fields have been thoroughly revised, restructured and extended. Besides new examples on for instance storage rack fires and investigation of furnace tubes, and newly reported space shuttle investigations we also focus on remote sensing with IR cameras, in particular with drones (new Section 10.11). Finally we also included a number of new applications of IR imaging in nature such as imaging of clouds, sun, moon, mirages and some new geothermal phenomena (Sections 11.5.1, 11.5.3 to 11.5.5).

Books on evolving fields in science and technology can never reach perfection, they can always only present snapshots of the state of the art. Still we hope that the content provides a comprehensive coverage of the field and that all readers will enjoy this second edition.

Preparing this edition meant a lot of work and we need to thank again many colleagues who send us comments to the first edition, who contributed by providing new fantastic IR images and who had helpful discussions at conferences with us. We did of course get very professional support by the publisher and we want to thank in particular Mrs. Gudrun Wüst for her ongoing support and always fast response to queries and help in problem solving of any technical issues. In addition we appreciated the professional help of Mrs. Petra Moews and Mrs. Annegret Krap from le-tex publishing services during production as well as corrections due to an anonymous professional language check. Last not least, we need of course again thank our families for their permanent support, in particular in the final stages within the editing stage and proofreading.

We also thought about adding new author photos, but refrained from doing so. The old IR images are still perfect since they do not change as rapidly with time as do, for example, visible photos concerning the color of our hair.

Brandenburg, June 2017 *Michael Vollmer* and *Klaus-Peter Möllmann*

Preface to First Edition

The really large steps in the history of thermal imaging took place in intervals of hundred years. First, infrared radiation was discovered in 1800 by Sir William Herschel while studying radiation from the sun. Second, Max Planck was able to quantitatively describe the laws of thermal radiation in 1900. It took more than 50 years thereafter before the first infrared-detecting cameras were developed; initially, these were mostly quite bulky apparatus for military purposes. From about the 1970s, smaller portable systems started to become available; these consisted of liquid nitrogen cooled single photon detector scanning systems. These systems also enabled the use of infrared imaging for commercial and industrial applications. The enormous progress due to microsystem technologies toward the end of the twentieth century – the first uncooled micro bolometer cameras appeared in the 1990s – resulted in reliable quantitatively measuring infrared camera systems. This means, that the third large step was taken by about the year 2000. Infrared thermal imaging has now become affordable to a wider public of specialized physicists, technicians and engineers for an ever growing range of applications. Nowadays, mass production of infrared detector arrays leads to comparatively low price cameras which – according to some advertisements – may even become high-end consumer products for everyone.

This rapid technological development leads to the paradoxical situation that there are probably more cameras sold worldwide than there are people who understand the physics behind and who know how to interpret the nice and colorful images of the false color displays: IR cameras easily produce images, but unfortunately, it is sometimes very difficult even for the specialist to quantitatively describe several of the most simple experiments and/or observations.

The present book wants to mitigate this problem by providing an extensive background knowledge on many different aspects of infrared thermal imaging for many different users of IR cameras. We aim at least for three different groups of potential users.

First, this book addresses all technicians and engineers who use IR cameras for their daily work. On the one hand, it will provide extensive and detailed background information not only on detectors and optics but also on practical use of camera systems. On the other hand, a huge variety of different application fields is presented with many typical examples with hints of how to notice and deal with respective measurement problems.

Second, all physics and science teachers at school or university level can benefit since infrared thermal imaging is an excellent tool for visualization of all phenomena in physics and chemistry related to energy transfer. These readers can particularly benefit from the huge variety of different examples presented from many fields, a lot of them given with qualitative and/or quantitative explanations of the underlying physics.

Third, this text also provides a detailed introduction to the whole field of infrared thermal imaging from basics via applications to up to date research. Thus it can serve as a textbook for newcomers or as a reference handbook for specialists who want to dig deeper. The large number of references to original work can easily help to study certain aspects in more depth and thus get ideas for future research projects.

Obviously, this threefold approach concerning the addressed readers does have some consequences for the structure of the book. We tried to write the ten chapters such that each may be read separately from the others. In order to improve the respective readability, there will be some repetitions and also cross references in each chapter (that more information can be found in other chapters or sections).

For example, teachers or practitioners may initially well skip the introductory more theoretical chapters about detectors or detectors systems and jump right away into the section of their desired applications. Obviously, this sometimes means that not every detail of explanation referring to theory will be understood, but the basic ideas should become clear – and maybe later on, those readers will also get interested in checking topics in the basic introductory sections.

The organization of this book is as follows: the first three chapters will provide extensive background information on radiation physics, single detectors as well as detector arrays, camera systems with optics, and IR image analysis. This is followed by a partly theoretical chapter on the three different heat transfer modes, which will help enable a better understanding of the temperature distribution that can be detected at the surfaces of various objects as for example, buildings. Chapter 5 then gives a collection of many different experiments concerning phenomena in physics. This chapter was particularly written with teaching applications in mind. The subsequent three chapters discuss three selected application as well as research topics in more detail: building thermography as a very prominent everyday application, the detection of gases as a rather new emerging industrial application with very good future prospects and the analysis of microsystems for research purposes. Finally, the last two chapters give a large number of other examples and discussions of important applications ranging for example from the car industry, sports, electrical, and medical applications via surveillance issues to volcanology.

Our own background is twofold. One of us had originally worked in IR detector design before switching to microsystem technologies whereas the other worked on optics and spectroscopy. Soon after joining our present affiliation, a fruitful collaboration in a common new field, IR imaging, developed, starting with the purchase of our first MW camera in 1996. Meanwhile, our infrared group has access to three different IR camera systems from the extended MW to the LW range including a high speed research camera and a lot of additional equipment such as microscope lenses and so on. Besides applied research, our group focuses also on teaching the basics of IR imaging to students of Microsystem and Optical Technologies at our university.

Obviously, such a book cannot be written without the help of many people, be it by discussions, by providing images, or just by supporting and encouraging us in phases of extreme work load towards the end of this endeavor. We are therefore happy to thank in particular our colleagues Frank Pinno, Detlef Karstädt, and Simone Wolf for help with various tasks that had often to be done at very short notice.

Furthermore, we want to especially thank Bernd Schönbach, Kamayni Agarwal, Gary Orlove, and Robert Madding for fruitful discussions on selected topics and also for permission to use quite a large number of IR images.

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Finally we need to especially thank our families for their tolerance and patience, in particular during the final months. Last not least we also need to express special thanks for the effective working together with Mrs. Ulrike Werner from Wiley/VCH.

Brandenburg, June 2010 *Michael Vollmer* and *Klaus-Peter Möllmann*

List of Acronyms

AGC	Automatic Gain Control
APE	Advanced Plateau Equalization
BLIP	Background Limited Infrared Photodetection
BP	Band Pass (filter)
CCS	Carbon Capture and Storage
CM	Condition Monitoring
DDE	Digital Detail Enhancement
DoLP	Degree of Linear Polarization
DSLR	Digital Single-Lens Reflex (camera)
EM	ElectroMagnetic (waves, spectrum, …)
FLIR	Forward Looking InfraRed (camera)
FOV	Field Of View
FPA	Focal Plane Array
FTIR	Fourier Transform InfraRed (spectroscopy)
FWHM	Full Width at Half Maximum
GPS	Global Positioning System
HITRAN	HIgh resolution atmospheric TRANsmission
HOT	High Operating Temperature
HSM	High Sensitivity Mode (FLIR cameras)
IFOV	Instantaneous Field Of View
IR	InfraRed spectral range
ITC	Infrared Training Center
LDAR	Leak Detection And Repair
LOWTRAN	LOW resolution atmospheric TRANsmission
LW	Long Wave (IR)
MEMS	Micro Electro Mechanical Systems
MCT	Mercury Cadmium Telluride
MDTD	Minimum Detectable Temperature Difference
MODIS	MODerate-resolution Imaging Spectroradiometer
MODTRAN	MODerate resolution atmospheric TRANsmission
MQW	Multiple Quantum Wells
MRTD	Minimum Resolvable Temperature Difference

MST	Micro System Technologies
MSX	MultiSpectral dynamic imaging (FLIR patented image software tool)
MTF	Modulation Transfer Function
MW	Mid Wave (IR)
NBP	Narrow Band Pass (Filter)
NDT	Non Destructive Testing
NEP	Noise Equivalent Power
NESR	Noise Equivalent Spectral Radiance
NETD	Noise Equivalent Temperature Difference
NIR	Near InfraRed (Spectral Range)
NUC	Non Uniformity Correction
OGI	Optical Gas Imaging
PdM	Predictive Maintenance
PE	Plateau Equalization (FLIR software)
PET	PolyEthylene Terephthalate
PSF	Point Spread Function
PVC	PolyVinyl Chloride
QWIP	Quantum Well Infrared Photodetetor
R&D	Research and Development
ROI	Region Of Interest
ROIC	Read Out Integrated Circuit
SNR	Signal to Noise Ratio
SRF	Slit Response Function
STS	Space Transportation System (numbers for space shuttle missions)
SW	Short Wave (IR)
T2SLS	Type II Strained Layer Superlattice
TSR	Total Solar Reflection
UAV	Unmanned Aerial Vehicle
UV	UltraViolet spectral range
VGA	Video Graphics Array (standard for images with 640 · 480 pixels)
VIS	VISible spectral range
VOC	Volatile Organic Compounds
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional

Chapter 1
Fundamentals of Infrared Thermal Imaging

1.1
Introduction

Infrared (IR) thermal imaging, also often called *thermography* for short, is a very rapidly evolving field in science as well as industry owing to the enormous progress made in the last three decades in microsystem technologies of IR detector design, electronics, and computer science. Thermography nowadays is applied in research and development as well as in a variety of different fields in industry, such as nondestructive testing, condition monitoring, and predictive maintenance, reducing energy costs of processes and buildings, detection of gaseous species, and many more areas. In addition, competition in the profitable industry segment of camera manufacturers has recently led to the introduction of low-cost models at a price level of just several thousand dollars or euros, and smartphone accessories even below five hundred dollars, which has opened up new application fields for the cameras. Besides education (obviously schools' problems with financing expensive equipment for science classes are well known), IR cameras will probably soon be advertised in hardware stores as "must-have" do-it-yourself products for analyzing building insulation, heating pipes, or electrical components in homes. This development has both advantages and drawbacks.

The advantages may be illustrated by an anecdote based on personal experiences concerning physics teaching in school. Physics was, and still is, considered to be a very difficult subject in school. One of the reasons may be that simple phenomena of physics, for example, friction or the principle of energy conservation in mechanics, are often taught in such an abstract way that rather than being attracted to the subject, students are scared away. One of us clearly remembers a frustrating physics lesson at school dealing first with free-falling objects and then with the action of walking on a floor. First, the teacher argued that a falling stone would transfer energy to the floor such that the total energy was conserved. He only used mathematical equations but stopped his argument at the conversion of initial potential energy of the stone to kinetic energy just prior to impact with the floor. The rest was a hand-waving argument that, of course, the energy would be transformed into heat. The last argument was not logically developed; it was just one of the typical teacher arguments to be believed (or not). Of course, at

Infrared Thermal Imaging, Second Edition. M. Vollmer and K.-P. Möllmann.

those times, it was very difficult in schools to actually measure the conversion of kinetic energy into heat. Maybe the students would have been more satisfied if the teacher had at least attempted to visualize the process in more detail. The second example – explaining the simple action of walking – was similarly frustrating. The teacher argued that movement was possible owing to the frictional forces between shoe and floor. He then wrote down some equations describing the underlying physics, and that was all. Again, there were missing arguments: if someone walking has to do work against frictional forces, there must be some conversion of kinetic energy into heat, and shoes as well as the floor must heat up. Again, of course, at those times, it was very difficult in school to actually measure the resulting tiny temperature rises of shoes and floors. Nevertheless not discussing them at all was a good example of bad teaching. And again, maybe some kind of visualization would have helped. But visualizations were not a strength of this old teacher, who rather preferred to have Newton's laws recited in Latin.

Visualization refers to any technique for creating images, diagrams, or animations to communicate an abstract or a concrete argument. It can help bring structure to a complex context, it can make verbal statements clear, or it can give clear and appropriate visual representations of situations or processes. The underlying idea is to provide visual concepts that help to better understand and better recollect a context. Today, in the computer age, visualization is finding ever-expanding applications in science, engineering, medicine, and other fields. In the natural sciences, visualization techniques are often used to represent data from simulations or experiments in plots or images in order to make analysis of the data as easy as possible. Powerful software techniques often enable the user to modify the visualization in real time, thereby allowing easy perception of patterns and relations in the abstract data in question.

Thermography is an excellent example of a visualization technique that can be used in many different fields of physics and science. Moreover, it has opened up a totally new realm of physics in terms of visualization. Nowadays, it is possible to visualize easily the (to the human eye) invisible effects of temperature rise of the floor upon impact of a falling object or upon interaction with the shoe of a walking person. This will allow totally new ways of teaching physics and the natural sciences starting in school and ending in the training of professionals in all kinds of industries. Visualization of "invisible" processes of physics or chemistry with thermography can be a major factor creating fascination for and interest in these subjects, not only in students at school and university but also for the layperson. Nearly every example described later in this book can be studied in this context.

The drawbacks of promoting IR cameras as mass products for a wide range of consumers are less obvious. Anyone owning an IR camera will be able to produce nice and colorful images, but most will never be able to fully exploit the potentials of such a camera – and most will never be able to correctly use it.

Typically, the first images recorded with any camera will be the faces of people nearby. Figure 1.1 gives an example of IR images of the two authors. Anyone confronted with such images for the first time would normally find them fascinating since they provide a totally new way of looking at people. The faces can still be

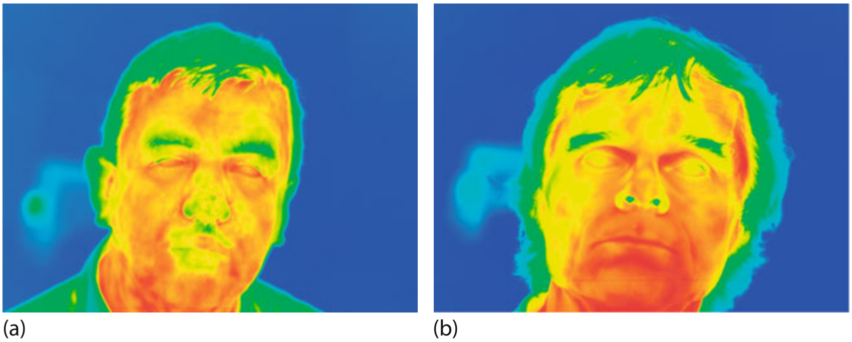

Figure 1.1 IR thermal images of (a) K-P. Möllmann and (b) M. Vollmer.

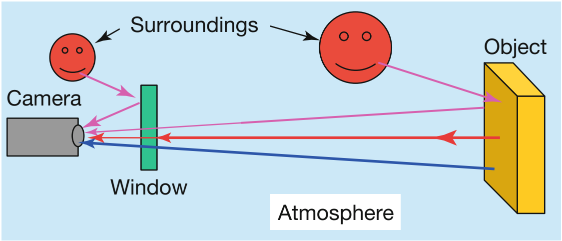

Figure 1.2 Various signal contributions entering an IR camera due to external influences.

recognized, but some parts look strange, for example, the eyes. Also, the nostrils (Figure 1.1b) seem to be distinctive and the hair to be surrounded by an "aura."

For artists who want to create new effects, such images are fine, but thermography – if it is to be used for the analysis of real problems like building insulation, for example – is much more than this. Modern IR cameras may give qualitative images, colorful images that look nice but mean nothing, or they can be used as quantitative measuring instruments. The latter use is the original reason for developing these systems. Thermography is a measurement technique that, in most cases, is able to quantitatively measure surface temperatures of objects. To use this technique correctly, professionals must know exactly what the camera does and what the user must do to extract useful information from images. This knowledge can only be obtained through professional training. Therefore, the drawback in IR cameras is that they require professional training before they can be used properly. A multitude of factors can influence IR images and, hence, any interpretation of such images (Figure 1.2 and Chapters 2 and 7).

First, radiation from an object (red) is attenuated via absorption or scattering while traveling through the atmosphere (Section 1.5.2), IR windows, or the camera optics (Section 1.5.4). Second, the atmosphere itself can emit radiation owing to its temperature (blue) (this also holds for windows or the camera optics and housing itself), and third, warm or hot objects in the surroundings (even the thermographer is a source) may lead to reflections of additional IR radiation from the

Table 1.1 Several parameters and factors affecting images recorded with modern IR cameras systems.

Parameters affecting IR images generated from raw detector data within camera that can usually be adjusted using camera software; quantitative results can strongly depend on some of these parameters! They can often be changed while analyzing images (after recording) if proper software is used (this may not be possible for the cheapest models!)	• Emissivity of object • Distance of camera to object (usually in meters, feet in the USA) • Size of object • Relative humidity • Ambient temperature (usually in degrees Celsius or Kelvin, degrees Fahrenheit in the USA) • Atmospheric temperature • External optics temperature • External optics transmission
Parameters affecting how data are plotted as an image; if chosen unfavorably, important details may be disguised	• Temperature span ΔT • Temperature range and level • Color palette
Some parameters that can significantly affect quantitative analysis and interpretation of IR images	• Wavelength dependence of emissivity (wavelength range of camera) • Angular dependence of emissivity (angle of observation) • Temperature dependence of emissivity • Optical properties of matter between camera and object • Use of filters (e.g., high temperature, narrowband) • Thermal reflections • Wind speed • Solar load • Shadow effects of nearby objects • Moisture • Thermal properties of objects (e.g., time constants)

object or windows, and so on (pink arrows). The contributions from the object or windows may, furthermore, depend on the material, the surface structure, and so on, which are described by the parameter emissivity. These and other parameters are listed in Table 1.1; they are all discussed in subsequent sections.

Even if all of these parameters are dealt with, some remaining open questions will need to be answered. Consider, for example, someone who uses IR imaging in predictive maintenance doing electrical component inspections. Suppose the recording of an IR image shows a component with an elevated temperature. The fundamental problem is the assessment criterion for the analysis of IR images. How hot can a component become and still be okay? What is the criterion for an immediate replacement, or how long can one wait before replacement? These questions involve a lot of money if the component is involved in the power supply