TESTING THERMAL IMAGERS

Practical guide

Krzysztof Chrzanowski

Military University of Technology
Warsaw, Poland

TESTING THERMAL IMAGERS

Practical guidebook

Krzysztof CHRZANOWSKI

Warsaw 2010

Publisher: Military University of Technology, 00-908 Warsaw, Poland

INSB 978-83-61486-81-7

Printed by: P.P.H Remigraf, 11 Ratuszowa Str., 03-430 Warsaw, Poland

Acknowledgement

Research needed to obtain results presented in book was partially financed by the grant from the Polish Ministry of Science and Higher Education no 6 ZR8 2008C/07035.

Notice:

Warsaw 2010

Author's Preface

Thermal imagers are electro-optical imaging systems sensitive to mid-wave and long-wave infrared radiation that generate images of the observed scenery using thermal radiation emitted by the scenery. They have found numerous applications in both defence&security sector (military, border guards, police, etc.) and civilian sector (industrial non-contact temperature measurement, non-destructive thermal testing, tests of electrical power lines, building industry, medical applications, fire rescue etc.)

A lot of myths about thermal imagers are known. There is a rich literature on subject of thermal imaging but there are also papers presenting conflicting conclusion about performance of these modern, fascinating imaging systems. Different rules how to choose an optimal thermal imager can be found in available literature, too. It is also known that quality of thermal imagers offered on the market vary significantly. The only way to be sure about quality of imagers of interest is to test them and to evaluate test results.

Testing thermal imagers is a very difficult task. Extended knowledge from different areas like physics, optics, electronics, thermal sciences, precision mechanics, metrology and practical experience with thermal imagers is needed to carry out effectively testing modern thermal imagers.

There is rich literature on the subject of testing and evaluation of thermal imagers and there are also several standards that regulate tests of these imaging systems. However in spite of available standards, valuable books and numerous literature less experienced test teams have a lot of problems to carry out their tasks due to lack of a practical guidebook in field testing thermal imagers.

This book presents knowledge of the author on testing thermal imagers that was accumulated during over two decades of scientific work in the field of electro-optical technology interconnected with a series of practical projects, and direct involvement in activities of one of manufacturers of equipment for testing thermal imagers (Inframet - www.inframet.com).

The author hopes that this book can become a practical guide for testing thermal imagers for wide community of people interested in this fascinating technology of thermal imaging.

PS. The Author hopes that reading this book will be much easier task than pronouncing his family name ☺. The Author also apologizes for imperfect language of this book because English is not his native language.

October 2010 Krzysztof Chrzanowski

Table of Contents

1 Introduction 1

1.1 Concept of electro-optical imaging system..1

1.2 Human sight..1

1.3 Division of electro-optical imaging systems..6

1.4 Concept of testing..8

1.5 Terminology..9

1.6 Basic metrological terms..11

1.7 Structure of the book..13

1.8 References..15

2 Review of thermal imagers..18

2.1 Thermal cameras versus thermal scanners..18

2.2 Applications of thermal cameras 19

2.3 Spectral band..20

2.4 Generations of thermal imagers..20

2.5 Technology trends..27

2.6 References..28

3 Parameters of thermal imagers 29

3.1 Subjective image quality parameters 31

3.1.1 MRTD..31
3.1.2 MDTD..35
3.1.3 Evaluation of ranges of effective surveillance 36

3.2 Response parameters 40

3.2.1 Responsivity function 40
3.2.2 Aperiodic Transfer Function..42
3.2.3 Slit Response Function..44

3.3 Noise parameters 44

3.3.1 3D noise model..45
3.3.2 Single parameter approach..47
3.3.3 Four parameters approach..48

3.4 Image resolution parameters 54

3.4.1 Parameters based on specifications of the IR FPA 54
3.4.2 MTF and derivative parameters..56

3.4.3 Parameters based on imager response to point/slit sources 61
3.4.4 Subjective parameters based on resolution targets 62
3.5 Accuracy parameters 63
3.6 Summary...68
3.7 References...70
4 Test equipment 73
4.1 Types of test systems...73
4.2 Blocks of test system..80
4.2.1 Collimator...81
4.2.2 Blackbody..92
4.2.3 Rotary wheel...99
4.2.4 Targets..101
4.2.5 Image acquisition/analysis module...106
4.2.6 Optional blocks...109
4.3 Manufacturing/R&D support equipment...110
4.3.1 Correction of spatial noise..110
4.3.2 Calibration of measurement thermal imagers...112
4.3.3 Boresighting to a reference optical/mechanical axis....................................113
4.4 References...114
5 Test procedures...116
5.1 MRTD...116
5.1.1 Test team...117
5.1.2 Detection criterion...117
5.1.3 Test environment...118
5.1.4 Targets...120
5.1.5 Offset...124
5.1.6 Imager settings..125
5.1.7 Static/dynamic images..126
5.1.8 Differential temperature steps...126
5.1.9 Measurement methods..127
5.1.10 Software support..140
5.1.11 Interpretation of MRTD measurement results...141
5.2 MTF...143
5.2.1 Measurement concept...143
5.2.2 Measurement procedure..145
5.2.3 Interpretation of measurement results..146

5.3 Responsivity function (SiTF)....147

5.4 Noise parameters....150

5.4.1 Measurement concept....150

5.4.2 Measurement procedure....152

5.4.3 Interpretation of measurement results....155

5.5 References....156

6 STANAG 4349 requirements....157

7 Guidelines for buyers of test equipment....162

1 Introduction

1.1 Concept of electro-optical imaging system

According to the International Lighting Vocabulary published by the International Lighting Commission CIE and the International Electrotechnical Commission CIE [15] considered nowadays as an international primary authority on terminology in radiometry, electromagnetic radiation between radio radiation and X radiation is termed the optical radiation. Thus, the optical radiation can be defined as radiation of wavelengths longer than about 1 nm and shorter than about 1 mm. The range of optical radiation is divided into three sub-ranges: infrared radiation, visible radiation, and ultraviolet radiation.

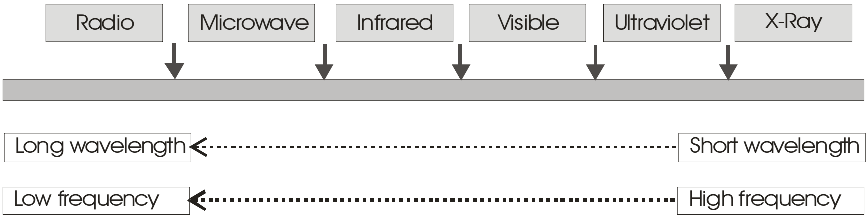


Fig. 1.1. Spectrum of electro-magnetic radiation.

Electro-optical imaging systems are the systems that:

1. create visible image of the targets being observed,
2. use optical radiation emitted or reflected by the targets to get information necessary to create the output image,
3. convert coming optical radiation into electrical signal, process signal, convert electrical signal into visible image or into electrical equivalent of visible image.

Human eye can be treated as a type of electro-optical imaging system because it uses visible radiation reflected by the targets, converts incoming optical radiation into electrical signals, processes signal in a brain, and finally converts electrical signals into electrical equivalent of a visible image understood by a human brain.

1.2 Human sight

Sensing of visible radiation (light) by a human eye provides about 90% information coming to the human brain which makes sight the most important of all senses. In spite of its importance, the phenomenon of human sight is complex and still not fully explained. However, to simplify it we can assume that in general the set: the biological eye, optic nerves, and brain enables humans the ability to sense visible radiation (light) and to see.

The eye converts optical signals into electrical signals that are later sent by the optic nerves to the brain, and finally after some kind of image processing we “see” the targets that are in our field of view. The biological eye consists of two systems: an optical system and a detection system. The optical system (cornea, crystalline lens, vitreous) refracts and focuses the incoming light into the detection system (retina). The latter system contains millions of rods and cones which convert light energy into electrical signals sent to the brain via the optic nerve. The retina contains about 100 millions of rods and about 6 millions of cones. The rods of relatively low sensitivity are to work in daytime conditions (the photopic vision) and can deliver high resolution color vision. The cones are high sensitivity detectors that work in night-time conditions (scotopic vision) but they can deliver only lower resolution monochromatic vision.

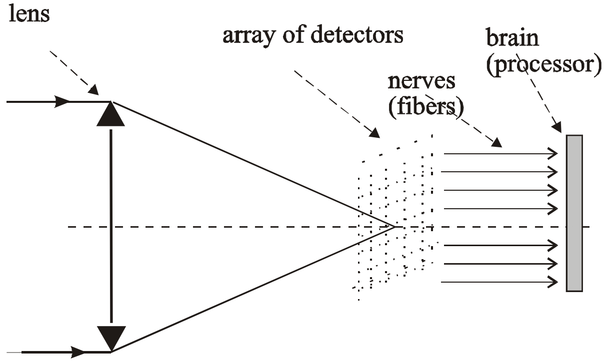


Fig. 1.2. Simplified optical diagram of human eye.

Human eye generates sharp image within rather narrow field of view (about 10°) because in the middle of the retina there is the highest concentration of rods and cones. The rest of the field of view is rather blurry. The experience of wide sharp human vision is achieved by turning the eyes towards the current point of interest in the field of view.

Each cone cell is built using three-color sensitive pigments: red-sensitive pigment, green-sensitive pigment, and blue-sensitive pigment. In the diagram above, the wavelengths of three types of cones (red, green, and blue) are shown. The peak absorption of blue-sensitive pigment is about 445 nm, for green-sensitive pigment - about 535 nm, and for red-sensitive pigment - about 570 nm. The pigments generate three electrical signals: α, β, and γ. A brain analyzes the signals and determines the color of the incoming light on the basis of the ratio between α, β, and γ signals. Next, the perceived brightness depends on the sum of the signals α, β, and γ. When the signals α, β, and γ are almost the same then the target will be perceived as white, gray or black (white - high sum of the signals; gray -medium sum of the signal; black – very low sum of the signals). The human eye can sense many gradation of color when red, green and blue signal are mixed. It is usually considered that human can sense about 380 000 color gradations.

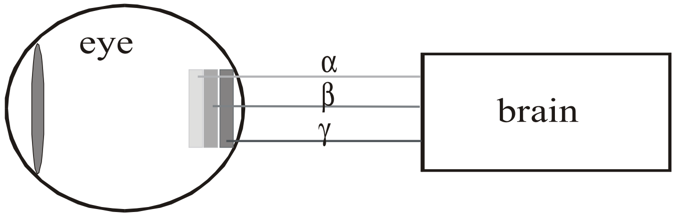


Fig. 1.3. Principle of color vision.

Power of the light coming to the light detectors, distributed on the retina surface, is automatically regulated by the iris. This component can change its diameter from about 2 mm to about 10 mm and this phenomenon enables us to work at different illumination conditions.

The distribution of the cones and rods on the retina is not uniform. The highest concentration of the cones is in the retina's center, much less concentration on the peripheral parts of the retina. In case of the rods we have an inverse situation. Therefore in daylight condition, a human eye has the highest acuity in the center of its field of view; in the night conditions – at periphery of the field of view.

The principle of seeing phenomenon is the following. The light emitted by the Sun or other light sources illuminates the observed scenery and it is reflected. The reflected light carries information about the targets that reflected the light. Different targets of the scenery differ in their ability to reflect the incoming light. The targets of high reflectance will be perceived as bright ones; the targets of low reflectance will be perceived as dark ones. Because reflectance depends also on a wavelength, then the reflected radiation carries also information about color of the observed target. To simplify, the target of high reflectance in the spectral band of 0.65-0.78 μm and low reflectance in the spectral band of 0.4-0.5 μm will be perceived as a red one. In case of inverse situation, the target will be perceived as a blue one.

The image generated by the eye lens must be created exactly on the retina. The distance between a human eye – an observed target can vary significantly. In order to compensate this distance variation, the focal length of the lens must vary. This adaptation is achieved by the change of a shape of the lens ball. This ability deteriorates together with aging process.

It is not possible to state what is exactly a spectral sensitivity range of a human eye, because the spectral limits differ among the humans and the spectral sensitivity band is also on the power of incoming light. However, the International Lighting Commission CIE and the International Electrotechnical Commission CIE [15] determined a relative spectral sensitivity function of a human eye in the spectral range from 0.38 μm to 0.78 μm and these values are often considered as limits of the visible range.

If we compare a spectral sensitivity curve of a human eye with a characteristic of spectral emission of light emitted by the Sun or reflected by the Moon then we will notice that a human eye is very well adapted for illumination conditions on the Earth where the light emitted by the Sun is the dominant source of light (Fig. 1.4).

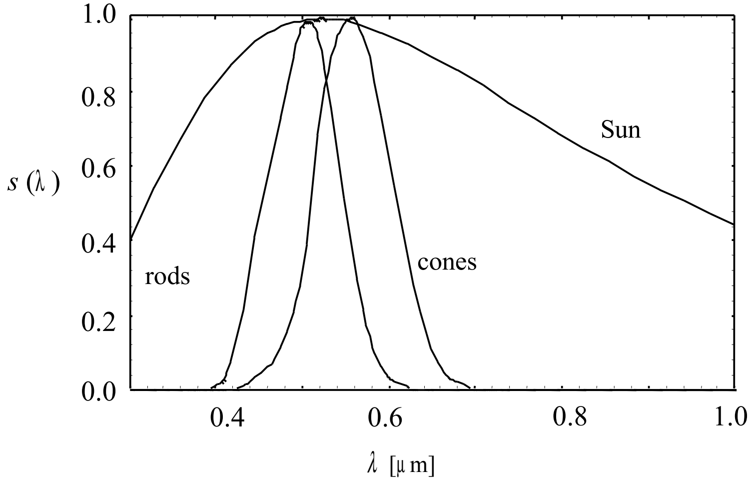


Fig. 1.4. Relative spectral sensitivity of human eye.

Horizontal field of view of a human eye is about 40° and vertical field of view is about 30°. Due to its ability to rotate, a human eye can effectively see (detection of movement) almost in full hemisphere. However, good sharpness of an image is achieved only in the central 10°-field of view; the best sharpness in 2° field of view.

Due to aberrations of the lens of the human eye and diffraction phenomenon, some limitations of spatial resolution of the human eye exist, it means that there are some limits how small can be the targets that the eye can still perceive. This limit depends on the target contrast and illumination conditions. Generally, it is considered that at bright moon night (illumination 3×10^{-2} cd/m^2) the resolution is about 1.5 mrad but in bright day conditions (illumination 3×10^{3} cd/m^2) the resolution is 0.35 mrad [21]. This means that when the distance to the targets is 25 cm, then human cannot recognize as separate two slits of a width smaller than 0.37 mm for weak illumination and 0.09 mm for strong illumination.

There are generally two types of vision. The first type, photopic vision (daylight vision) when the cones are active as light sensors. The second type, scotopic vision (nightlight vision) when the rods are active as light sensors. The cones are active at illumination levels over 0.03 cd/m^2. The upper limit for proper work of the cones is about 300 000 cd/m^2. The rods are activated by illumination conditions below ~0.03 cd/m^2. After sufficient dark adaptation time (even 30 minutes is sometimes needed) the rods can enable us seeing even at 0.03 cd/m^2. However, quality of an image generated by the rods in night conditions is much lower than quality of an image generated by the cones in daylight conditions. Next, the rods are not sensitive to a wavelength of the incoming light and therefore cannot perceive color of the incoming light.

A human eye is characterized by a certain temporal inertia of about 0.1-0.2 s. It means that if a sequence of still images is shown in rapid succession, the brain will reassemble the still images into a single, moving scene. Therefore this phenomenon enabled development of television and computer animation but at the same time temporal inertia of a human eye is a significant handicap of human sight when fast phenomena are to be observed.

The eye can perceive images of maximal contrast not higher than about 100:1. However, the eye can adapt to different illumination conditions by readjusting its exposure both chemically and by adjusting the iris. Several seconds are needed for initial dark adaptation. Full adaptation through adjustments in retinal chemistry can take as much as about thirty minutes. However, if we consider the possibility of a human eye to perceive images at both very bright day and dark night then we can say that after full adaptation, a human eye can achieve dynamic contrast ratio of about 1000000:1. The process is nonlinear and multifaceted. An interruption by light, nearly starts the adaptation process over again.

To summarize, a human imaging system can be considered as a small-size, universal, electro-optical imaging device of very high capabilities that enables human perceiving high quality images of the neighbor scenery at a variable level of illumination. The human eye has much better dynamic response than any artificial light sensing device and high power to adapt to different illumination conditions. It is characterized by high accuracy of alignment and it can distinguish between hundred of thousands of colors or tones. It can operate the best in daylight condition but also works relatively well in weak illumination conditions. However, a human eye is not perfect and there are a few serious disadvantages of human eye from the point of its effectiveness as a surveillance tool:

1. Limited spatial resolution that limits perceiving small details of the targets, particularly long distance targets.
2. Limited sensitivity that decreases effectiveness of observation in night conditions.
3. Short surveillance ranges in bad visibility conditions in a visible range (fog, rain, snow, dust).
4. No capabilities to record images, to process them and to transfer to other humans in easy, accurate way.
5. Relatively easy camouflage in a visible range.
6. Human eye is sensitive only in a narrow spectral band of optical radiation, i.e., in the visible range.

Electro-optical imaging systems improve capabilities of a human eye and remove, at least partially, the mentioned above limitations.

1.3 Division of electro-optical imaging systems

From a point of view of a support to human eye there are basically three types of electro-optical imaging systems: night vision devices (night vision devices), TV cameras, and thermal imagers.

Night vision devices NVD (called also night vision devices I2S) improve human eye sensitivity and offer observation in most night conditions. TV cameras generate high quality color or monochromatic images of the observed scenery in day conditions and ensure later recording, processing and later transfer of these images using modern telecommunication equipment. Some types of TV cameras (often called LLTV cameras) offer improved sensitivity and can be used in night conditions for similar applications like NVDs. Finally, thermal cameras due to different spectral ranges can work even at total darkness, in bad visibility conditions, and make camouflage much more difficult. All types of the mentioned earlier imaging systems, when working at narrow field of view, provide visualization of small details of the scenery being observed and in this way improve spatial resolution of a human eye.

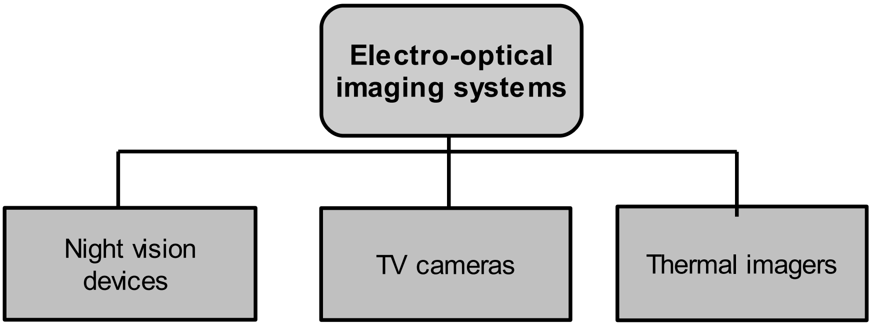


Fig. 1.5. Basic types of electro-optical imaging systems.

Night vision devices (NVD) are the imaging systems built using an image intensifier tube consisting of a photocathode, an anode in form of a phosphor screen, and other optional components. The tube intensifies a low-luminance image of the observed objects created on the photocathode into a brighter image created on the anode. NVDs are direct viewing devices that generate the output image by optical amplification of the input image. They can be treated as optical intensifiers of a scenery at low illumination conditions to the levels when human eye can carry out effective surveillance.

TV cameras are electronic devices that convert the input image into an electrical signal that after electrical amplification generate the output image in analog or digital formats used by television or video technology. The TV camera technology offers inherent capabilities to record, process and transmit image of the observed scenery. There are many types of TV cameras: color/mono CCD cameras, color/mono CMOS cameras, intensified charge couple device (ICCD) cameras, cooled CCD cameras and electron-bombarded charge couple device (EB CCD) cameras, silicon intensified target (SIT) tube cameras, intensified silicon intensified target (ISIT) tube cameras, etc.

Thermal imagers are the imaging systems sensitive to mid-wave and long-wave infrared radiation that generate images of the observed scenery using thermal radiation emitted by the scenery.

The origin of all three groups of electro-optical systems is connected with military applications. However, at present, these imaging systems are used in high numbers of military and civilian sectors.

According to a type of radiation used to create an image of the observed scenery, electro-optical imaging systems can be divided into two distinct groups: the systems that create image using the radiation emitted by the observed targets and the systems that create an image using the radiation reflected by the observed targets. Imaging systems of spectral bands located in wavelengths of over 3 μm belong to the first group; imaging systems of spectral bands located in visible or NIR spectral range up to 1 μm belong to the second group.

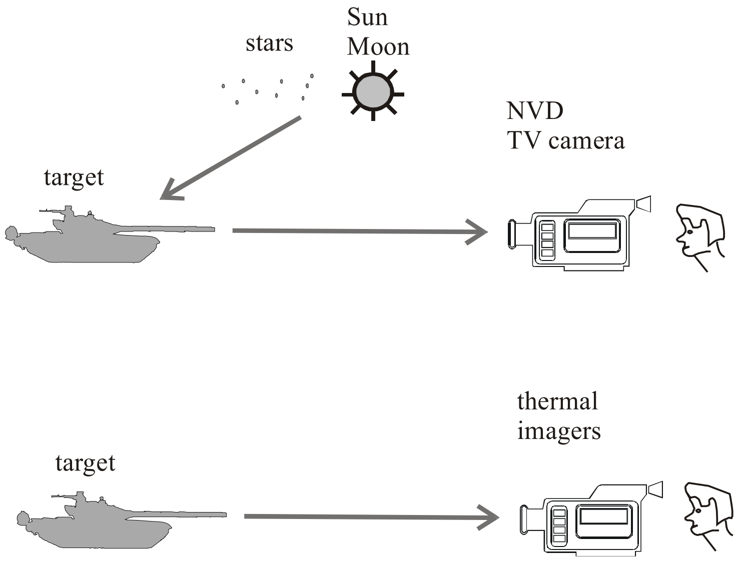


Fig. 1.6. Principle of work of night vision devices, TV cameras and thermal imaging systems.

Night vision devices and TV cameras are sensitive to a visible range and near infrared radiation up to about 1 μm because the Sun, the Moon, and stars emit mostly in visible and near infrared spectral bands. Thermal imaging systems use medium and far infrared range from about 3 μm to about 15 μm because targets of typical temperatures on the Earth emit mostly in this spectral band. Because spectral sensitivity band of I2Ss and TV cameras at least partially overlaps the spectral band of a human eye images generated by NVD or TV cameras are similar to the images generated by human sight. Thermal imaging systems are truly infrared imaging systems that generate images that significantly differ from the images generated by human sight.

1.4 Concept of testing

Sets of technical data used in specifications of E-O systems to describe their characteristics vary significantly. However, in general, all these sets can be divided into three groups: physical (mechanical, electrical) characteristics, environmental characteristics, and performance characteristics.

Measurement methods of physical and environmental characteristics of electro-optical systems do not differ significantly from measurement methods of the same characteristics of other type of photonic systems. The test methods can be found in numerous literature and will not be discussed in here. We are to concentrate on a measurement of performance characteristics.

Quality of the output image is the most important criterion for evaluation of operation of electro-optical imaging systems. We cannot objectively judge an imaging system (thermal camera, NVD, TV camera) looking on the image of a typical scenery. Quality of the image can be bad for some people but still acceptable for others. As shown in Fig. 1.7 we cannot determine whether the right image is acceptable or not without proper testing.

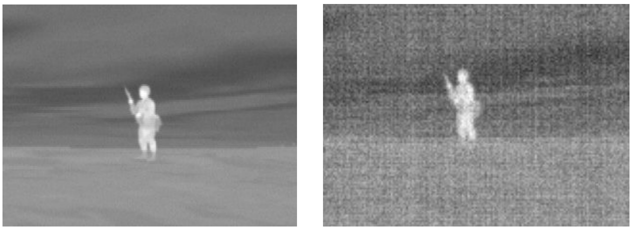


Fig. 1.7. Image of the same target obtained using two thermal cameras.

An imaging system cannot be properly evaluated on the basis of the image of a typical scenery but it can be properly evaluated on the basis of the image of some standard targets (4-bar targets, square targets, circle targets, slit targets, different types of resolution targets, sine targets etc.) projected by a measuring system (target projector) to the tested imaging system. Using proper measuring systems and having a knowledge about radiometric and photometric parameters of the emitted radiation we can measure parameters that describe precisely performance of different infrared imaging systems: thermal cameras, NVD, and different types of TV cameras.

In spite of the same general testing concept, there are significant differences between the apparatus for testing far infrared imaging systems (thermal imaging

systems) and the apparatus for testing visible/near infrared systems (NVD, TV cameras).
Photometric methods developed visible range are used also for near infrared range, when radiometric methods based on temperature control are needed for far infrared range.

List of differences in the test methods for testing the far infrared systems and the test methods for testing visible/near infrared systems is presented in Table 1.1.

Table 1.1. Basic differences between apparatus for testing far infrared systems and apparatus for testing visible and near infrared systems.

	Testing thermal imagers	**Testing NVD and TV cameras**
source of radiation	low temperature black-body	high temperature bulb
method of radiation measurement	measurement of radiator temperature	measurement of light quantities
type of projector optics	reflective	typically refractive
units of radiation	standard temperature units or radiometric units	photometric units
targets	transparent patterns (holes) in metal sheets	non transparent patterns on transparent glass sheets

1.5 Terminology

In spite of a relatively long tradition of IR systems still there are no internationally accepted terminology standards in most areas of this technology. At present, only terminology related to quantities of infrared radiation and detectors of this radiation has been relatively well standardized in the International Lighting Vocabulary published by the International Lighting Commission CIE and the International Electrotechnical Commission CIE in 1987[15]. However, there are vast areas of the infrared technology where terminology is not standardized mostly due to the fact that scientists and engineers of completely different background work nowadays in infrared technology. It results in situation when different authors use different terminology in scientific papers, manuals and catalogs making them difficult to understand even for professionals. Such a situation is particularly difficult for newcomers to this technology and non-native English speakers. Some examples will be discussed next.

Firstly, we will start with the term "electro-optical system" used quite often in this chapter. This popular mostly in USA and Asia term, is used in this book but the terms "optoelectronic systems" or "optronic systems" have the same meaning and are quite often used in literature, too. Next, the term "electro-optical system" in general refers to any system that uses optical radiation: infrared radiation, visible radiation and ultraviolet radiation. We used this convention and classified thermal cameras, night vision devices, TV cameras as electro-optical systems. However, it must be remembered that in many literature sources "electro-optical systems" are understood as only night vision devices technology or technology of manufacturing any electronic element sensitive to optical radiation.

Secondly, an imaging system based on image intensifier tube technology is typically called night vision device (NVD) but in some international military standards is called "image intensifier system" [29,30]. At the same time we must remember that logically thermal imagers and high sensitivity TV cameras are also night vision devices because they enable nigh vision.

Thirdly, if we make a review of literature dealing with infrared technology then we find that there are at least eleven different terms used as synonyms of the term "thermal camera": thermal imager [19], thermograph [31], thermovision [23], FLIR [9], thermal imaging devices [25], infrared imaging radiometer [8], thermal viewer [1], thermal video system [32], infrared camera [18], thermal imaging device [24]. If we analyze the Internet resources we can easily find even more synonyms of the term "thermal camera".

Fourthly, the most surprising thing is that actually even the term "infrared radiation" or division of IR radiation is not standardized. There was presented in the International Lighting Vocabulary considered nowadays as the international primary authority on terminology in radiometry the range of optical radiation a proposal of division of optical radiation (see Table 1.2) but not as compulsory division but only as a recommended division. Additionally, in case of visible radiation, due to human diversity, only approximate limits were given. Further on, what is the most important, these recommendations are not accepted in most communities working in the field of optical radiation due to many, mostly historical reasons.

Table 1.2. Division of optical radiation recommended by the CIE.

Name	Wavelength range
UV-C	0.1 μm - 0.28 μm
UV-B	0.28 μm - 0.315 μm
UV-A	0.315 μm - 0.4 μm
VIS	approximately 0.36-0.4 μm to 0.76 -0.8μm
IR-A	0.78 μm - 1.4 μm
IR-B	1.4 μm - 3 μm
IR-C	3 μm - 1000 μm

Confusion in area of limits and further division of sub-ranges of optical radiation is particularly clear in case of infrared radiation range. A dozen or more proposals on division of infrared range have been published in the literature. Precise division of the infrared radiation is particularly important for any book on thermal imagers. Therefore for the purpose of this book a precise division of infrared radiation shown in Table 1.3 will be used.

The division shown in Table 1.3 is based on the limits of spectral bands of commonly used infrared detectors. Wavelength of 1 μm is a sensitivity limit of popular Si detectors used in TV imagers. Similarly, 3-μm wavelength is a long-wave sensitivity limit of PbS and InGaAs detectors used in near SW IR imagers. Wavelength of 6 μm is a sensitivity limit of InSb, PbSe, PtSi detectors and HgCdTe detectors optimized for 3-5 μm atmospheric window used in medium-wave thermal imagers. Finally, 15-μm wavelength is a long-wave sensitivity limit of HgCdTe detectors optimized for 8-12 μm atmospheric window or non-cooled detectors with long-wave filter used in long wave thermal imagers.

Table 1.3. Division of infrared radiation used in this book.

Name	Wavelength range
near infrared NIR	0.78 μm - 1 μm
short wave infrared SWIR	1 μm - 3 μm
mid-wave infrared MWIR	3 μm - 6 μm
long-wave infrared LWIR	6 -15 μm
very long-wave infrared VLWIR	15 μm - 1000 μm

It is possible to present many more examples of a certain chaos in the terminology related to electro-optical systems. The aim of the author of this book is to use the precisely defined and strictly kept terminology in all book chapters. However, the reader must be aware that in a situation of general chaos in terminology related to electro-optical imaging systems it is difficult to achieve this aim and there can be some inconsistency in terminology used in the book.

1.6 Basic metrological terms

Testing electro-optical imaging systems practically means to measure the parameters of these systems. A measurement is a non-accurate operation. Measurement results always differ from the true value of the measured quantity. Equality of the measurement result and the true value of the measured quantity is an exceptional incident and we do not know when such an incident occurs.
It is recommended for the test teams to be familiar with some basic metrological terms.

Accuracy of a measurement result can be only estimated. It can be done using classical error theory or modern uncertainty theory.
Classical error theory proposes so called limit error as a measure of measurement accuracy. Models that can be used for determination of limit errors can be found in many books dealing with metrology.
Uncertainty theory proposes the uncertainty as such a measure of accuracy of measurement results [16]. Rules for evaluation of uncertainty in measurement are presented in the "Guide to the expression of uncertainty in measurement" [10] published in 1993 by five main international metrological organizations: the Interna-

tional Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), the International Organization of Legal Metrology (OIML), and the International Bureau of Weights and Measures (BIPM). Additional comments can be find in Refs. 6 and 11.

The terms "accuracy", "error", “systematic error”, “random error”, "uncertainty" and “limit error” apparently seem to be easily understood intuitively. However, in practice these terms are often a source of confusion as it is possible to find radically different definitions in different literature sources. Therefore, let us define them clearly now to prevent any possible misunderstanding.

The *International Vocabulary of Basic and General Terms in Metrology* commonly abbreviated VIM, published jointly by the mentioned above seven international metrological organizations, can be considered as the present day most important international standard [16]. Definitions of five mentioned above terms according to the VIM are presented below.

Accuracy of measurement [VIM3.5] - closeness of the agreement between the result of a measurement and true value of the measurand,
where the “measurand” is a specific quantity subject to measurement[1].

Error (*of measurement*) [VIM 3.10] - result of a measurement minus the value of the measurand.

Random error [VIM 3.13] - result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.

Comment: By means of statistical analysis it is possible to estimate the random error.

Systematic error [VIM 3.14] mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus the value of the measurand.

Comment: The systematic error equals to error minus random error. Similarly to earlier defined terms "measurand" and "error" it cannot be fully known; it can be only estimated.

Uncertainty (of measurement) [VIM 3.9] - a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could be reasonably attributed to the measurand (the parameter mentioned above is usually a standard deviation or a given multiple of it).

The term "limit error" is not included into the VIM. However, on the basis of analysis of the Ref. 10 it can be defined as presented below

Limit error - a range around the result of the measurement in which the true value of the measured quantity is located with high value of probability.

From analysis of the presented above definitions we can draw three basic conclusions.

[1] Because the term "measurand" is relatively new and still not accepted widely in literature, the term "measured quantity" will be used in the rest of this book.

First, that “accuracy” is only a qualitative concept that should not be associated with numbers. This means that we should not specify instrument accuracy as equal to a certain number as it is unfortunately a common practice so far. We are allowed according to the VIM to say only that accuracy is good, bad etc.

Second, the defined, according to the VIM, term "error" is a perfect measure of measurement accuracy. However, this true error of measurement is always unknown because the true value of the measured quantity is unknown. The same can be said about its component: the systematic error. Let us temporarily call the term “error” as the “true error” to make a better distinction with the term “limit error”.

Third, two other measures of measurement accuracy: the uncertainty and limit error of the result of a measurement may be evaluated. These two measures of measurement accuracy are useful for users of measuring instruments who know only the instrument indication and want to estimate accuracy of the measurement result. Guidelines on evaluation of uncertainty of measurement results are presented in the mentioned earlier "Guide to the expression of uncertainty in measurement", guidelines on evaluation of limit error – in numerous metrology handbooks.

To summarize, the uncertainty is nowadays the measure of measurement accuracy recommended by international metrological organizations and there are quite clear rules how the uncertainty of measurements should be calculated. However, the problems in consistent use of these recommendations are that these recommendations are often ignored by international community working in the field of electro-optical metrology due to different reasons.

1.7 Structure of the book

As it was stated in Section 1.2, electro-optical imaging systems can be divided into three basic types: night vision devices, TV cameras, and thermal imagers. This book is devoted to the problems of testing and evaluation of thermal imagers.

There are many myths about thermal imagers. The conflicting opinions about performance of these modern and fascinating imaging systems are given. It is also known that quality of thermal imagers offered on the market vary significantly. The only way to be sure about quality of the interesting imagers is to test them and evaluate test results.

Nowadays, testing thermal imagers is very important for many people involved in thermal imaging technology due to several reasons.

Firstly, thermal imagers are still quite expensive. A the same time, the number of thermal imagers used in surveillance applications by military, police, border guards, rescue teams etc. is increasing quickly. Thermal imagers are often purchased within big tenders of total value over one million EUR. There are sometimes doubts whether the offered or delivered thermal imager fulfill technical specifications of the tender. Results of testing thermal imagers offered in such tenders are very important for decision makers.

Secondly, a number of thermal imagers used in automotive industry increases quickly. It is still the beginning of a long process but even now the automotive industry is one of the most important application areas of thermal imagers. The main criterion for the automotive thermal imager is its cost but image quality is still important and proper testing is needed.

Thirdly, a price of infrared focal plane areas (IR FPA) decreased significantly during the last decade. It is particularly true in case of non-cooled IR FPAs. Due to this reason the number of manufacturers of thermal imagers has increased significantly. The only ways for these new manufacturers to be sure about real quality of their products is to test them and compare test results with the parameters of thermal imagers offered by their competitors.

Fourthly, the competition on the market of thermal imagers is strong. Good market position can be reached and kept only if an imager of good ratio quality to price is delivered. In order to keep stable and known quality, the extensive and accurate testing during production line is needed. Further on, semi-automatic testing of thermal imagers during a production process can speed up the process and reduce costs.

Fifthly, quality of thermal imagers, similarly to any other systems, deteriorates with time. Having proper measuring sets we can select thermal cameras that do not fulfill requirements at the end of the guarantee's period and replace them for the new ones.

It is possible to find additional reasons why the proper testing of thermal imagers is needed. However, even the arguments presented earlier show importance of testing thermal imagers for a wide community of people connected with thermal imaging technology.

Testing thermal imagers is quite well standardized and there is rich literature on subject of testing and evaluation thermal imagers. There are several standards that regulate testing thermal imagers [28,2,3,17], valuable books that provide a lot of useful information in testing and evaluation thermal imagers [12,13,14], and hundreds of scientific papers on this subjects like sample Refs. 5,27,26,4,7,22. However in spite of available standards, valuable books and numerous literature less experienced test teams meat a lot of problems to carry out their tasks due to different reasons.

First, testing thermal imagers is a very difficult task. Extended knowledge from different areas like physics, optics, electronics, thermal sciences, precision mechanics, metrology and practical experience with thermal imagers are needed to carry out effectively testing of modern thermal imagers.

Second, some important questions about test methods and precise requirements on test equipment are not answered or it is difficult to find a proper answer in numerous literature on subject of testing thermal imagers.

Third, freely detailed technical literature available from manufacturers of equipment for testing thermal imagers is rare and sometimes compiled in a way to show superiority of their own equipment over the equipment offered by competitors.

This book consists of seven chapters. Chapter 1 is already read introduction of this book where the concept of electro-optical imaging systems, human sign properties, division of electro-optical imaging systems, terminology of E-O systems, basic metrological terminology were introduced.

Thermal imagers employ the phenomenon of thermal radiation create thermal image of the scenery being observed. Therefore, the whole Chapter 2 "*Thermal radiation*" is devoted to the discussion about properties of thermal radiation. Firstly, quantities and units of this kind of radiation are presented. Next, basic laws are discussed. The laws describe only a phenomenon of thermal radiation emitted by an ideal type of objects, i.e., blackbodies. Therefore radiant properties of real materials are also discussed to enable us the analysis of radiation emitted by real materials. Further on, the influence of the atmosphere on propagating radiation is discussed. Finally, rules of source/receiver flux calculations are presented.

In Chapter 2, a short review of thermal imaging technology is presented. Different generations of thermal imagers are discussed. Some technical details of design of thermal imagers are shown. Finally, main applications of thermal imagers are presented.

Chapter 3 is devoted to definitions and measurement principles of numerous characteristics of thermal imagers. At first, the characteristics are divided into several main groups and later the definitions and each group is analyzed.

In Chapter 4, modern equipment for testing thermal imager is discussed. At first, several different types of test systems are presented. Next, all major modules of test systems for testing thermal imagers are presented and analyzed. Conclusions about requirements for these modules are shown, too.

In Chapter 5, procedures of measurement of main characteristics of thermal imagers are discussed. MRTD measurement procedure was discussed in detail due to its subjective, manual characters. Measurement procedures of other parameters like MTF, responsivity function, and noise parameters (NETD, FPN, non uniformity,1/f, 3D noise components, NPSD) were presented shortly due to semi-automatic measurement character of their measurement and possible differences of measurement techniques using equipment from different manufacturers.

In Chapter 6, comments on requirements on test equipment of the Stanag 4349 standard are presented. The comments can be useful for laboratories that implemented quality systems according to ISO/EN standards and need to prove that their test system fulfill requirements of this well known standard.

Finally, in Chapter 7 short guidelines for buyers of equipment for testing thermal imagers are given. The guidelines can be useful for scientific/manufacturing centers that analyze possibility of purchase of such test equipment.

1.8 References

1. Anderson D.; M1A2 tank commander's independent thermal viewer optics: optics design perspective, Proc. SPIE Vol. 1970, p. 128-138, Systems-Oriented Optical Design, Thomas U. Kampe; Joseph H. Oberheuser; Eds. Publication Date: 8/1993.

2. ASTM standard E 1213-2002 “Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems”
3. ASTM standard E 1311-99 “Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems”
4. Bryant Paul, Grigor Jack, McHugh Stephen; White Steve, Performance comparison of reflective and emissive target projector systems for high-performance IR sensors, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XIV, SPIE Vol. 5076, p. 242-249, 2003.
5. Driggers Ronald, Hodgkin Van A., Vollmerhausen Richard, O'Shea Patrick, Minimum resolvable temperature difference measurements on undersampled imagers, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XIV; SPIE Vol. 5076, 2003.
6. EA-3/02, The Expression of Uncertainty in Quantitative Testing (previously EAL-G23), European Cooperation for Accreditation, 1996
7. Forrai David; Bertke Stephen; Fischer Robert; Back Thomas, Test techniques for high performance thermal imaging system characterization, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XVII, SPIE Vol. 6207, 2006.
8. Griffith B. et al., Buildings research using infrared imaging radiometers with laboratory thermal chambers, Proc. SPIE Vol. 3700, p. 502-513, Thermosense XXI, Dennis H. LeMieux; John R. Snell; Eds., Publication Date: 3/1999
9. Gruben J. et al., Scene-based algorithm for improved FLIR performance, Proc. SPIE Vol. 4030, p. 184-195, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XI, 2000.
10. Guide to the expression of uncertainty in measurement, International Organisation for Standarisation-International Electrotechnical Commission-International Organisation of Legal Metrology-International Bureau of Weights and Measures, TAG 4/WG 3, 1993.
11. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297, 1994
12. Holst G.C., Electro-Optical Imaging System Performance, SPIE, 2005.
13. Holst G.C., Infrared Imaging System Testing, Vol.4, Chapt. 4 in The Infrared & Electro-Optical Systems Handbook, Michael C. Dudzik ed, SPIE 1993..
14. Holst G.C., Testing and evaluation of infrared imaging systems, JCD Publishing Company 1993.
15. International Lighting Vocabulary, CIE Publ. No. 1 7.4, IEC Publ. No. 50(845) (1987).
16. International Vocabulary of Basic and General Terms in Metrology, International Organisation for Standarisation, 1993.
17. ISO 15529, Principles of measurement of modulation transfer function (MTF) of sampled imaging systems, 1999.
18. Miller J., L., An introduction to infrared cameras, 1999 The photonics design and applications handbook, Laurin Publ. Co, p. 133-139, 2000.
19. Pruchnic et al., Design, analysis, and testing of collimators used for testing low-resolution thermal imagers, Proc. SPIE Vol. 2743, p. 337-348, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing VII, Gerald C. Holst; Ed. Publication Date: 6/1996
20. Qin Y. et al. , Novel quantitative NDT method for composite structures, Proc. SPIE Vol. 3173, p. 274-278, Ultrahigh- and High-Speed Photography and Image-based Motion Measurement, Donald R. Snyder; Andrew Davidhazy; Takeharu Etoh; C. Bruce Johnson; James S. Walton; Eds. Publication Date: 12/1997
21. Rodgers A.L., Surveillance and target acquisition systems, Brassey's Battlefield Weapons Systems&Technology Vol.VII, Brassey's Publishers Ltd., 1983.
22. Fourier Ron, Accuracies in FLIR test equipment, 7th Mtg in Israel on Optical Engineering, SPIE Vol. 1142, pp.109-117, 1991.

23. Saginov, L., Influence of spectral characteristics of IR (8-12 μm) photodetectors on thermovision system parameters, Proc. SPIE Vol. 4340, p. 305-307, 16th International Conference on Photoelectronics and Night Vision Devices, Anatoly M. Filachev; Ed., 11/2000.
24. Schwalm R., Design solutions for thermal imaging devices in military vehicles , Proc. SPIE Vol. 2736, p. 259-270, Enhanced and Synthetic Vision 1996, Jacques G. Verly; Ed. Publication Date:5/1996
25. Schwalm R., Design solutions for thermal imaging devices in military vehicles , Proc. SPIE Vol. 2736, p. 259-270, Enhanced and Synthetic Vision 1996, Jacques G. Verly; Ed. Publication Date:5/1996
26. Sousk Stephen; O'Shea Patrick; Hodgkin Van, Measurement of uncooled thermal imager noise, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XVI Conference, SPIE Vol. 5784, p.301-308, 2005.
27. Sousk Stephen; O'Shea Patrick; Hodgkin Van, Uncertainties in the minimum resolvable temperature difference measurement, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XV Conference, SPIE Vol. 5407, p.1-7, 2004.
28. STANAG 4349, Measurement of minimum resolvable thermal difference (MRTD) of thermal cameras, 1995
29. STANAG No. 4348, Definition of nominal static range performance for image intensifier systems, 1988.
30. STANAG No. 4351, Measurement of the minimum resolvable contrast (MRC) of image intensifiers,1987.
31. Thermographic Terminology - Supplement 2 to Acta Thermographica, 1978.
32. Zhu D. et al., Temperature measurement of gas flow with high temperature and speed using thermal video system, Proc. SPIE Vol. 3783, p. 373-379, Optical Diagnostics for Fluids/Heat/Combustion and Photomechanics for Solids, Soyoung S. Cha; Peter J. Bryanston-Cross; Carolyn R. Mercer; Eds.10/1999.

2 Review of thermal imagers

Thermal imagers are imaging systems that generate images of the observed scenery using thermal radiation emitted by the scenery. These numerous imaging systems can be divided into several different groups.

First, according to a method of creation of two-dimensional image of the observed scenery, thermal imagers can be divided into two distinct groups: thermal cameras and imaging thermal scanners.

Second, according to application area, thermal imagers can be divided into two groups: surveillance thermal imagers and measurement thermal imagers.

Third, according to a spectral band, thermal imagers can be divided into two (optionally three) groups: MW(mid-wave infrared) thermal imagers and LW (long-wave) imagers. Sometimes SW (short wave) thermal imagers are added too.

Fourth, according to technology of IR detector (IR FPA), thermal imagers can be divided into at least three different generations.

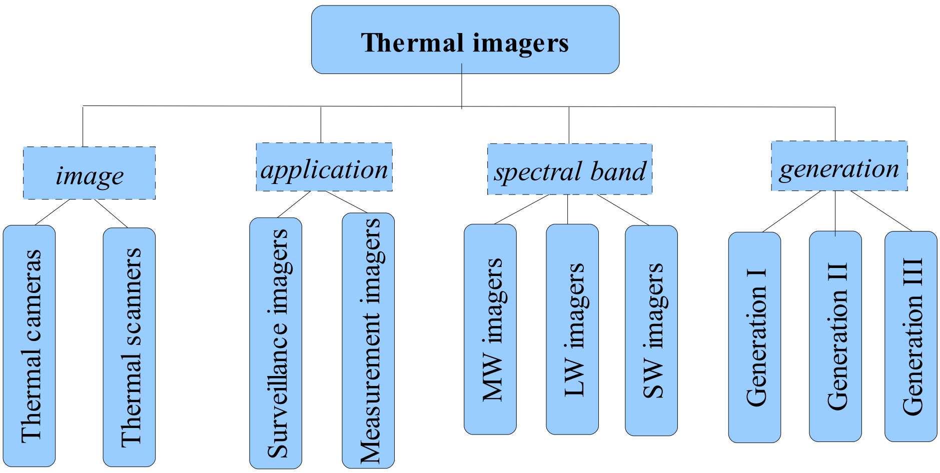


Fig. 2.1. Classification of thermal imagers.

2.1 Thermal cameras versus thermal scanners

Thermal camera is a thermal imaging system that enables us creation of a two-dimensional thermal image of the observed scenery independently whether the system or objects are movable or stationary ones.

Imaging thermal scanner is a thermal imaging system that provides creation of a two-dimensional thermal image of the observed scenery only when the scanner or the objects are moving.

Thermal cameras represent probably over 99% of all existing thermal imagers. Imaging thermal scanners are almost exclusively airborne systems used for reconnaissance applications because they offer very wide field of view (standard 120º) in contrast to the thermal cameras offering field of view not wider than about 30º. Because of distinct differences in design of these two types of thermal imaging systems and narrow specialized market, the imaging thermal scanners are very expensive systems. Due to mass application of thermal cameras their prices are significantly lower. There exist numerous literature on both imaging thermal scanners and on thermal cameras. We can here only mention that detail presentation of a design of thermal cameras was presented in Refs: 6,7,12,11,10 and detail discussion on a design of imaging thermal scanners in Ref. 5.

As we mentioned earlier, thermal cameras are the most numerous group of thermal imagers. Practically, almost all thermal imagers are thermal cameras. Therefore both review of thermal imagers and later analysis of test methods in next chapters is mostly limited to thermal cameras. Next, the terms "thermal imager" and the term "thermal camera" will be used as equivalent terms.

2.2 Applications of thermal cameras

According to their applications, thermal imagers can be generally divided into two basic groups: surveillance thermal cameras and measurement thermal cameras. The surveillance thermal cameras are mostly used in military applications for observation of a battlefield in darkness or in difficult atmospheric conditions by creating the relative temperature distribution of the terrestrial scenery being observed.

The measurement thermal cameras are used for civilian applications in industry and science; mostly for non-contact measurement of temperature distributions on the surface of the tested objects. Nowadays, the borderline between these two groups becomes more fluid as there are some cameras that can be used for both observation and measurement applications. However, this situation is still an exception from the rule as most surveillance cameras do not have capabilities to measure temperature of the observed objects and the image quality of the measurement systems is inferior to the image quality of the observation thermal cameras.

Image quality is the most important criterion for performance evaluation of surveillance (military) thermal cameras. In case of measurement (commercial) thermal cameras, the situation is more complicated.

Applications of measurement thermal cameras can be divided into two general groups: the applications that require only relative temperature measurement and the applications that require absolute temperature measurement. Although the same cameras can be typically used in both applications there are different criteria of assessment of camera suitability for these two groups of applications. If the camera is used in applications when only relative temperature measurement is needed, like in non-destructive thermal testing (NDTT), then the quality of the thermal image of the tested object is usually the most important criterion like in the case of the surveillance thermal cameras. If the measurement thermal camera is used in applications when an absolute temperature measurement is needed, then accuracy of temperature measurement results is the most important criterion.

2.3 Spectral band

Objects of typical earth temperatures emit radiation mostly in the spectral region from about 3 µm to about 15 µm. Thermal radiation emitted by these objects dominate over the radiation reflected by them at this spectral range because the radiation emitted by sun, moon, stars and typical artificial sources is weak for wavelengths over 3 µm. There are two „atmospheric windows" in the above mentioned range: the 3-5-µm window and the 8-12-µm window. Therefore there are two main types of thermal imaging systems: the middle-wave MW systems using the 3-5-µm window and the long-wave LW systems using the 8-12-µm window and rarely available commercially SW systems of spectral band located within 1-3-µm range.

MWIR spectral band and LWIR spectral band differ substantially with respect to background flux, scene characteristics, temperature contrast, and atmospheric transmission under diverse weather conditions. Factors which favor MWIR band are: higher contrast, superior clear-weather performance (favorable weather conditions, e.g., in most countries of Asia and Africa), higher transmittance in high humidity, and higher resolution due about 3 times smaller optical diffraction. Factors which favor LWIR band are: better performance in fog and dust conditions, winter haze (typical weather conditions, e.g., in West Europe, North USA, Canada), higher immunity to atmospheric turbulence, and reduced sensitivity to solar glints and fire flares. The possibility of achieving higher signal-to-noise (S/N) ratio due to the greater radiance levels in LWIR spectral range is not persuasive because the background photon fluxes are higher to the same extent, and also because of readout limitations. Theoretically, in staring arrays charge can be integrated for full frame time, but because of restrictions in the charge-handling capacity of the readout cells, it is much less compared to the frame time, especially for LWIR detectors for which a background photon flux exceeds the useful signals by orders of magnitude.

To summarize, in general, the LWIR band is preferred for high performance thermal imaging because of its higher sensitivity to ambient temperature objects and its better transmission through mist and smoke. However, the 3-5 mm band may be more appropriate for the hotter object, or if sensitivity is less important than contrast. Also additional differences occur; e.g. the advantage of MWIR band is smaller diameter of the optics required to obtain a certain resolution and that some detectors may be operated at higher temperatures (thermoelectric cooling) than it is usual in the LWIR band where cryogenic cooling is required (about 77 K). Therefore there is no definite, always valid answer which type of thermal imagers (MW thermal imagers or LW thermal imagers) should be preferred. Both types of thermal imagers have certain advantages and disadvantages.

2.4 Generations of thermal imagers

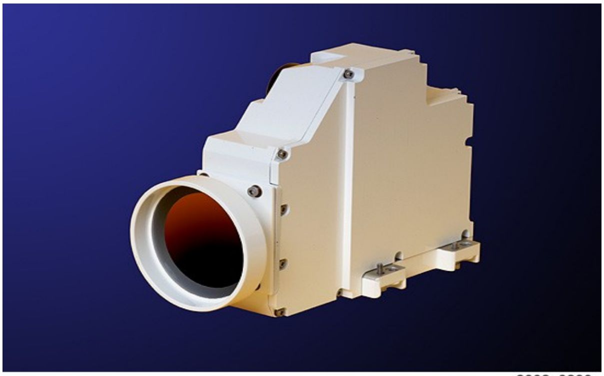
Thermal cameras are generally divided into three generations. Scanning cameras built using discrete detectors, simple non-multiplexing photoconductive linear arrays (typically PbSe, InSb or HgCdTe) of elements number not higher than about one hundred, or the SPRITE detectors are the first generation thermal cameras. They usually operate in 8-12-μm spectral range, use the optics of F/2-F/4 number, and are characterized by temperature resolution NETD about 0.2 K. Small quantities of first generation thermal cameras were introduced as military equipment in the 1970s, more in the 1980s. Thousands of these systems are still in military services, spare part will be available for many years. The US common module HgCdTe arrays that employ 60, 120 or 180 photoconductive elements are the prime example of Gen 1 thermal cameras.

Fig. 2.2. Exemplary Gen 1 thermal camera: LORIS (courtesy of FLIR Inc.).

Scanning cameras built using linear or 2D focal plane arrays (FPA) of elements number higher than about 100 but lower than about 10000 are the Gen 2 thermal cameras. Temperature resolution NETD of these cameras is improved up to the level of about 0.1 K. They are also characterized by smaller weight and size and improved reliability. The 1980s is a period when most modern army forces started to use the second generation thermal cameras. The cameras of this generation are presently majority of all military thermal cameras. New version of these FPAs offered in a form of a single chip fully integrated with readout electronic are even now an attractive solution for many observation applications. Thermal cameras built using these improved linear FPAs are often termed Gen 2+. Temperature resolution NETD of Gen 2+ can be improved up to the level of about 0.05 K. Typical examples of these systems are HgCdTe multilinear 288×4 arrays fabricated by Sofradir both for 3–5-μm and 8–10.5-μm bands with signal processing in the focal plane (photocurrent integration, skimming, partitioning, TDI function, output preamplification and some others).

Third generation cameras are non-scanning thermal cameras build using 2D array detectors (cooled FPA based on InSb, HgCdTe, QWIP technology or non-cooled FPAs based on microbolometer or pyroelectric/ferroelectric technology) that have at least 10^6 element on the focal plane. These staring arrays are scanned electronically by circuits integrated with the arrays. These readout integrated circuits (ROICs) include, e.g., pixel deselecting, antiblooming on each pixel, subframe imaging, output preamplifiers, and some other functions. The opto-mechanical scanner is eliminated and the only task of the optics is to focus the IR image onto the matrix of sensitive elements.

Fig. 2.3. Exemplary Gen 2 thermal camera: Sophie (courtesy of Thales Optronique).



2002 0280

Fig. 2.4. Exemplary cooled Gen 3 thermal camera: Catherine XP (courtesy of Thales Optronique).

Third generation thermal cameras have been offered since the beginning of the 90s to compete with their predecessor. First, they have been offered as cooled MWIR cameras (using InSb or HgCdTe technology) sensitive in 3-5-µm atmospheric window in situation when for most geographic conditions LWIR thermal cameras are desirable. Cooled LW IR Gen 3 thermal cameras based on QWIP technology started to be commercially available at the end of the 1990s. Almost at the same time non-cooled thermal cameras based on microbolometer and pyroelectric/ferroelectric technologies became fully commercially available. Image quality of non-cooled thermal cameras is inferior to image quality offered by cooled cameras but is good enough to be used in many short and medium range applications. Due to a 2-4 times lower price than equivalent cooled systems, the number of non-cooled thermal cameras is growing rapidly in both military and commercial applications.

Parameters of thermal cameras from the same generation can vary significantly. Therefore it is not possible to form a single table enabling accurate comparison of parameters of thermal cameras from different generations. Table 2.1 was created on the basis of a review of the parameters of different observation thermal cameras offered during the last 30 years but should be treated as an estimation of the sophisticated situation on the market.

Table 2.1. Typical parameters of thermal cameras.

No	Examples	temperature resolution NETD [K]	image resolution	cooler type	mass [kg]
Gen 1	60,120 pixels CMT (US common modules) 8,14 pixels CMT SPRITE (US, UK common modules)	0.2	250×190	-liquid nitrogen -Joule Thomson - Stirling	> 20
Gen 2	94×4 pixels CMT (Ophelios) 288×4 CMT (Synergy, Catherine, Sophie, Iris)	0.1	640×288	-Stirling Joule-Thomson	> 4
Gen 3	320×240 HgCdTe MWIR (Opal, Spike, Matiz) 320×240 QWIP LWIR (Thermovision 2000, Catherine QWIP) --------------------------------- 640×512 HgCdTe MWIR (High Definition POD) ---------------------- 320×240 ferroelectric (Lion 320×240 bolometric (Elvir)	0.05 ---------- 0.15-0.3	320×240 640×480 (micro-scanning) ----------------- 640×512 -------------- 320×240	Stirling --------- Stirling ------------ uncooled	> 2

Fig. 2.5. Exemplary non-cooled Gen 3 thermal camera: ELVIR (courtesy of Thales Angenieux).

As we can see in Table 2.1, the Gen 2 thermal cameras are characterized by significantly better thermal and spatial resolution that the Gen 1 thermal cameras. This means that quality of the image and sensitivity offered by the latter cameras is significantly inferior. However, situation is not so clear if we compare Gen 2 and Gen 3 cooled thermal cameras. Thermal sensitivity of Gen 3 cooled thermal cameras is usually at least slightly better that of thermal resolution of Gen 2 cameras. However, image resolution of modern Gen 2 thermal cameras is superior to image resolution of typical Gen 3 cameras based on 320×240 FPA, particularly in a horizontal direction. This inferiority of Gen 3 cameras can be eliminated by the use of microscanning technique, that can improve, up to two times, image resolution in both horizontal and vertical directions. However, the disadvantage of microscanning technique is the higher production costs and reduced reliability. The inferiority of image quality offered by typical Gen 3 thermal cameras in comparison to Gen 2 cameras can be fully eliminated if 640×512 or bigger FPAs are used.

A generation number is not connected strictly with image quality; it is more connected with mass, dimensions, manufacturing costs and reliability of the thermal camera. The generation number suggest rather potential of the detector module but does not describe quality of a thermal camera. Next, in order to evaluate properly thermal cameras, not only image quality (detection, recognition and identification ranges) but also other factors like mass, dimensions, resistance to harsh environmental conditions, ergonomics must be taken into account. Further on, there are, on the market, thermal cameras integrated with additional modules like GPS, laser range finder, goniometer, day light TV camera and laser pointer. These additional modules can significantly increase capabilities of a thermal camera. To summarize, evaluation and comparison of thermal cameras is a complicated and risky task that requires to take into account a set of factors that could vary, depending on the final user needs.

Fig. 2.6. Sophie MF – thermal camera integrated with laser range finder, goniometer, day light TV camera and laser pointer (courtesy of Thales Optronique).

Detectors used in Gen 1, Gen 2 and partially Gen 3 of thermal cameras require cooling, typically to the temperature equal to 77 K. First thermal cameras were cooled using dewar coolers. The dewar cooler is essentially a “ vacuum bottle” filled with a coolant. Different liquid gases can be used as coolants. However, liquid nitrogen is used as a coolant in almost all dewars used in practice.

The cryogenic cooling is characterized by a few significant disadvantages like necessity to have a source of liquid nitrogen supply readily available, limited working time of the dewar after filling, and necessity to keep quasi-horizontal position of the thermal camera. Therefore later cooled thermal cameras employ Stirling coolers, or rather rarely Joule-Thomson coolers.

The Stirling cooler is fundamentally a closed-cycle compression-expansion refrigerator with no valves; instead, it incorporates a regenerator. The regenerator is a tube of porous material that has low thermal conductivity to maintain a temperature gradient and high heat capacity to act as an efficient heat exchanger. Typical Stirling coolers operate with a sealed charge of helium, which is mechanically compressed and then allowed to expand near the dewar cold finger. This expansion cools the detector , and the helium is then “recycled” through cooler’s compressor.

The Stirling coolers can cool the detector to the required temperature , usually after 3-5 minutes from the turn on. These coolers require recharging and service by the cooler manufacturer after a fixed period of time; typically after about 1000-10000 hours. Size and mass of these coolers depend on required cooling power. The power of about 0.2-0.6 W is enough to cool a small single detector but a few times higher is needed to cool an array FPA.

The Joule-Thomson cooler is an open cycle cooler that converts pressurized gas (typically nitrogen, argon, CO_2) to cryogenic liquid gas. High pressure gas is cooled by expansion at the throttle valve, flows back through the counter-current heat exchanger and precools the incoming gas until the gas is liquefied as it leaves the throttle valve. Because Joule-Thomson coolers require the supply of pressurized gas they are rarely used in thermal cameras but they are typically used in IR guided seekers where the required working time is relatively short.

Both Stirling coolers and Joule-Thomson coolers are relatively expensive components that represent a significant portion of cost of a whole thermal camera. Therefore it was highly desirable to eliminate these components as it has been done recently by introduction of non-cooled FPA based on microbolometer and pyroelectric/ferroelectric technologies. However, please note that so-called non-cooled FPAs usually require temperature stabilization and thermoelectric coolers are usually used in the non-cooled thermal cameras.

The thermoelectric coolers employ the effect of Peltier that makes possible to generate the temperature changes using current flows in a circuit consisting of two dissimilar conductors. A big disadvantage of the thermoelectric coolers is their non-ability to cool detectors down to very low temperatures; temperature difference of not more than about minus 50–70°C relative to ambient temperature can be achieved. However, low cost of these coolers is their big advantage in sharp contrast to expensive Stirling coolers and Joule-Thomson coolers.

Apart from the MWIR thermal cameras and the LWIR thermal cameras there are also SWIR cameras of a spectral band located within the spectral range 1-3 μm. It is questionable whether the SWIR cameras are thermal cameras as in this spectral range the reflected radiation dominates over the emitted radiation for the objects of temperatures below about 100°C. However, let us treat them as a group of thermal cameras because of very similar design to MWIR and LWIR thermal cameras.

At present, the SWIR cameras are only a marginal group of thermal cameras. The SWIR cameras have been commercially available on the market for no more than a decade. This situation originated the fact that the SWIR range has not been an interesting range for both military and civilian applications for many decades. Due to dominance of the emitted thermal radiation and the atmospheric windows, military agencies were interested mostly in the MWIR and LWIR ranges. Because of sensitivity range of human sight and well developed silicon technology the civilians were interested in the visible and NIR ranges.

This lack of significant interest created the situation when up to the middle of the 1990s no well matured technology of detector arrays for SWIR range was available [1]. Currently, this vacuum is occupied by InGaAs arrays and the SWIR cameras have found a number of applications. The SWIR imagers are quickly gaining popularity in surveillance market due to higher image resolution than MWIR/LWIR thermal imagers and better performance at limited visibility conditions than typical TV cameras based on silicon CCD/CMOS technology. At the same time SWIR imagers have proved to be useful in telecommunication sector enabling accurate coupling of optical fibers working at 1.53 μm; and in museums for painting reflectography.

2.5 Technology trends

Thermal imaging is one of the technologies of paramount importance for military&security sector. Thermal imaging has found also numerous applications in a civilian sector. Therefore it is not strange that there is a lot of efforts to improve existing technologies of manufacturing thermal imagers and to develop new technologies.

We can distinguish several trends in thermal imaging technology

1. Low cost low/medium resolution non-cooled thermal imagers
2. High-resolution cooled thermal imagers of improved surveillance capabilities
3. Dual band thermal imagers
4. Multi-sensor systems

Technology of non-cooled thermal imaging experienced very rapid growth during the last decade [13]. Parameters of non-cooled imagers improved so much that nowadays non-cooled imagers dominate on the market of short range surveillance thermal imagers in both military and civilian applications. The critical factor on this market is a price. Therefore now, the technology efforts concentrate on decrease in manufacturing costs but still keeping or even improving the image quality and reliability. Critical areas are two modules of non-cooled thermal imagers: infrared focal plane area and infrared optics.

The top end non -cooled thermal imagers offer 680x480 image resolution and are directed mostly towards more demanding military applications. Non-cooled thermal imagers of 320x240 image resolution are typically targeted to general surveillance and radiometric applications (security sector, automotive industry, non-contact temperature measurements, etc.). Imagers of 160x120 or lower resolution are targeted to mass applications in low-cost intruder detection systems or as non-contact imaging thermometers.

Technology of cooled thermal imagers is for the last decade under the pressure from non-cooled technology. Because of a need to use expensive cooler module, the cooled technology is inherently more expensive that non-cooled technology. Because of this situation, manufacturers of cooled thermal imagers concentrate on market of long/medium range surveillance imagers or on applications that require dynamic surveillance of high speed scenarios. The efforts go into four directions. First, reducing costs of manufacturing of II and III Gen thermal imagers of medium resolution (up to 640x480). Second, development of high resolution thermal imagers of image quality comparable to quality of images offered by High Definition Television (minimal image resolution 1280x720 pixels is needed) [9,14]. Third, development of multi-band cooled imagers capable to employ spectral phenomenon as an effective tool in both surveillance and measurement applications [4,3]. Fourth, development of polarization-sensitive thermal imager to further improve the capabilities of cooled technology [2,8].

An increasingly noticeable trend appeared on the market to integrate thermal thermal imagers with other imaging and non-imaging sensors. Such integrated multi-sensor surveillance systems (thermal imager, TV camera, laser range finder) have been used for quite a long time in airborne applications. Nowadays, however, modern airborne imaging systems consist of more sensors: high resolution four-FOV thermal imager (or two thermal imagers), wide-FOV color TV camera, ultra narrow FOV color TV camera, LLLTV camera, laser range finder, laser pointer, laser designator, laser illuminator [14]. Next, ground portable thermal imagers are more frequently integrated with additional modules like GPS, laser range finder, goniometer, day light TV camera, and laser pointer. In some airborne, naval or ground applications, thermal imagers are integrated with classical radars or millimeter-wave radars. In all cases, such integration significantly increases capabilities of thermal imagers.

2.6 References

1. Baronti S. et al., Multispectral imaging system for the mapping of pigments in works of art by use of principal-component analysis, Applied Optics, 37, 1299-1309 (1998).
2. Beekman Daniel W.; Van Anda James B, Polarization-sensitive QWIP thermal imager, Infrared Detectors and Focal Plane Arrays VI Conference, SPIE Vol. 4028, 2000.
3. Bell W. Randy; Weber Paul G., Multispectral Thermal Imager: overview, Algorithms for Multispectral, Hyperspectral, and Ultraspectral Imagery VII Conference, SPIE Vol. 4381, 2001.
4. Breiter Rainer et al; Portable sequential multicolor thermal imager based on a MCT 384x288 focal plane array, Infrared Technology and Applications XXVII Conference, SPIE Vol. 4369, 2001.
5. Campana Stehen B. ed., *The Infrared & Electro-Optical Systems Handbook*, Vol. 5: Passive Electro-Optical Systems , Chapt. 1 Infrared Line Scanning Systems , SPIE (1993).
6. Campana Stehen B. ed., *The Infrared & Electro-Optical Systems Handbook*, Vol. 5: Passive Electro-Optical Systems , Chapt. 2 Forward Looking Infrared Systems, SPIE (1993).
7. Campana Stehen B. ed., *The Infrared & Electro-Optical Systems Handbook*, Vol. 5: Passive Electro-Optical Systems , Chapt. 3 Staring Sensor Systems, SPIE (1993).
8. Cocle Olivier; Rannou Christophe; Forestier Bertrand; Jougla Paul; Bois Philippe F. , QWIP compact thermal imager: Catherine-XP and its evolution, Infrared Technology and Applications XXXIII Conference, SPIE Vol 6542, 2007.
9. Dahlberg Anders G. M., High-resolution QWIP thermal imager for AFV upgrade, Infrared Technology and Applications XXX Conference, SPIE Vol. 5406, 2004.
10. Holst Gerald C., Common Sense Approach to Thermal Imaging, SPIE Vol: PM86, 2000.
11. Kaplan Herbert, Practical Applications of Infrared Thermal Sensing and Imaging Equipment, SPIE Vol: TT75, 2007.
12. Kruse Paul W., Uncooled Thermal Imaging Arrays, Systems, and Applications, SPIE Vol. TT51, 2001.
13. Manning Paul A. et al., Silicon foundry microbolometers: the route to the mass-market thermal imager, Infrared Technology and Applications XXX Conference, SPIE Vol. 5406, 2006.
14. Star Safire HD QWIP thermal imaging equipment - operator manual, FLIR Inc., P/N 4100070, 2006.

3 Parameters of thermal imagers

Thermal imagers generate images that can be seen by humans and it is possible to evaluate a thermal imager using human sight. However, it is surprisingly difficult even for an expert to precisely evaluate thermal imagers only by looking on images of typical scenery. Measurement of a series of parameters is needed in order to accurately evaluate tested thermal imagers.

Parameters are quantitative physical measures of thermal imagers. The measurement is typically done in laboratory conditions but generally parameters of thermal imager enable an expert to predict how this imager will perform under real observation conditions.

Characterization of thermal imagers is relatively well standardized [1,2,15,18,19,27]. There exists also a numerous literature on a subject of testing thermal imagers [3,9,12,13,14,17,21,23,25,26,31]. On the basis of the mentioned above literature, parameters that describe performance of thermal cameras can be, in general, divided into eight groups:

1. Subjective image quality parameters .
2. Response parameters .
3. Noise parameters .
4. Image resolution parameters .
5. Geometric parameters .
6. Accuracy parameters .
7. Spectral parameters .
8. Operation parameters .

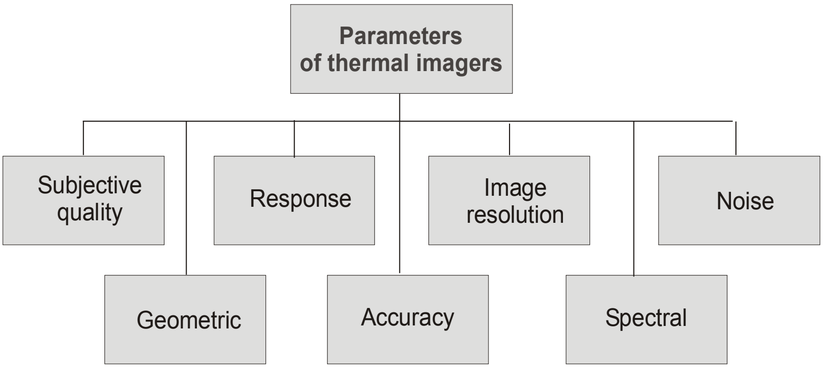


Fig. 3.1. Division of parameters of thermal imagers.

Subjective image quality parameters give information about ability of the system: thermal camera – human observer to detect, recognize, and identify targets at different scenarios.

Response parameters give information about response of the thermal camera to variable size or variable temperature targets.

Noise parameters - about noise that limits camera sensitivity detecting low contrast targets.

Image resolution parameters carry out information about camera ability to perceive small details of high contrast images.

Geometric parameters give information about geometrical relations between the target and its image.

Accuracy parameters give information about accuracy of non-contact temperature measurement using thermal cameras.

Operational parameters provide information about position of the observed target or position of human eye necessary for proper operation of the camera.

Finally, spectral parameters provide information about camera responsivity versus wavelength.

Subjective image quality parameters, response parameters, noise parameters, image resolution parameters, and geometric parameters give us general information about performance of thermal cameras in surveillance applications. Accuracy parameters are vital to evaluate thermal cameras for measurement applications. Operational parameters provide information about some practical aspects of work with both types of thermal cameras.

Table 3.1. Performance parameters of thermal cameras.

No	**Subjective image quality parameters**	**Response parameters**	**Noise parameters**	**Image resolution parameters**
1	MRTD (minimum resolvable temperature difference)	Responsivity function	NETD (noise equivalent temperature difference)	- Number of pixels (lines) - IFOV (instantaneous field of view) - DAS (detector angular substance)
2	MDTD(minimum detectable temperature difference)	SiTF(signal transfer function)	FPN (fixed pattern noise)	- MTF(modulation transfer function)
3	Auto MRTD	- Dynamic range - Saturation level	Non-uniformity	- CTF (contrast transfer function) - EIFOV (effective instantaneous field of view) - limiting resolution
4	TOD (triangle orientation discrimination)	SRF (slit response function)	$1/f$ noise	PVF (point visibility factor)
5	MTDP (minimum temperature difference perceived)	ATF (aperiodic transfer function)	3D noise model (nine components)	- measurement spatial resolution - imaging spatial resolution
6			NPSD (noise power spectral density)	subjective parameters based on resolution targets

No	Accuracy parameters	Geometric parameters	Operational parameters	Spectral parameters
1	"accuracy" (Minimal Error)	Field of view	Focus range	Spectral sensitivity function
2	NETD – Noise Equivalent Temperature Difference (Noise Generated Error)	Magnification	Eye distance	
3	Temperature stability	Distortion	Diopter settings	
4	Slit Response Function	Image rotation		
5		Boresight alignment		

Attention: there is no correlations between parameters from different groups having the same number. Numbering was used only to make easier identification of different parameters.

Accuracy parameters are necessary to evaluate commercial thermal cameras to be used as non-contact thermometers. They are useless in case of thermal imagers to be used in surveillance applications.

Measurement of operational parameters of thermal cameras does not differ significantly from a measurement of the same parameters of other visual imaging systems. There is the same situation in case of spectral parameters. Therefore both operational parameters and spectral parameters will not be discussed here.

3.1 Subjective image quality parameters

Thermal cameras are imaging systems used to enhance human ability to see in darkness and poor visibility conditions. Parameters of subjective image quality perceived by humans are considered as the most important parameters of surveillance thermal cameras from the point of view of the user who wants to have the highest ranges of detection, recognition and identification of targets of interest.

MRTD is a measure of ability to detect and recognize targets on a non-uniform background. MDTD is a measure of human ability to detect targets on uniform background.

The real targets of interest are usually located on non-uniform backgrounds and MRTD is considered as the most important measure of surveillance (often military) thermal cameras.

3.1.1 MRTD

The MRTD is a subjective parameter that describes ability of the imager-human system for detection of low contrast details of the observed object. It is a function of a minimum temperature difference between the bars of the standard 4-bar target and the background required to resolve the thermal image of the bars by an observer versus spatial frequency of the target.

Generally, MRTD is measured by determining the minimum temperature difference between the bars of the standard 4-bar target and the background required to resolve the thermal image of the bars by an observer for 4-bar targets of different dimensions (spatial frequency). The measurement results of an exemplary long range military thermal camera are shown in Fig. 3.4.

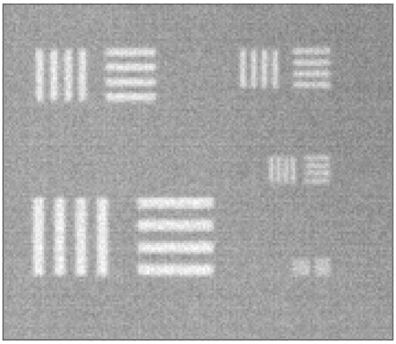


Fig. 3.2. Image of five 4-bar targets of different spatial frequency at the same temperature difference.

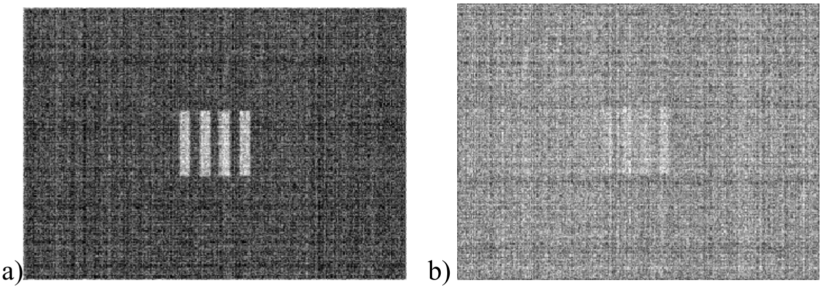


Fig. 3.3. Image of 4-bar target at two different temperature differences.

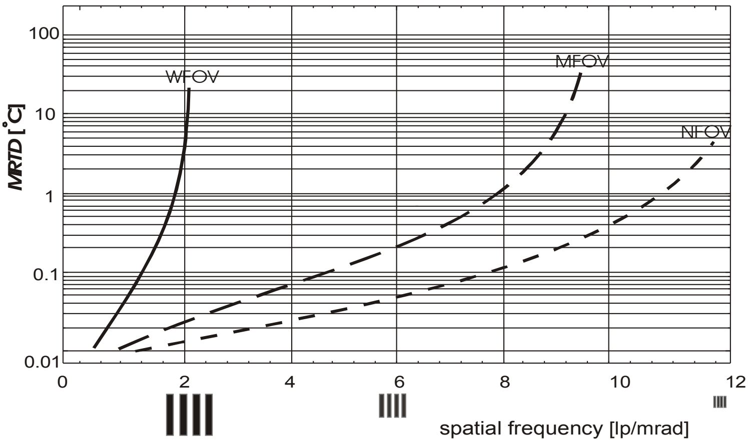


Fig. 3.4. MRTD of exemplary thermal camera of three different field of view.

Classical MRTD is a subjective parameter that takes the observer into account. This subjectivity and time consuming measurements cannot be accepted in high volume production environment where, so-called, AutoMRTD is preferred.

AutoMRTD is a test methodology that proposes a quick objective method to measure MRTD of a thermal camera using an algorithm presented below.

1. Measure MRTD, NETD (noise equivalent temperature difference) and MTF (modulation transfer function) of a large sample of thermal cameras.
2. Calculate average MRTD, NETD, MTF for the tested sample cameras.
3. Next, calculate the coefficient function K(ν) as

$$K(\nu)=\frac{MRTD(\nu)\cdot MTF(\nu)}{NETD} \tag{3.1}$$

4. Calculate new objective MRTD of any new tested thermal camera using the following formula:

$$MRTD_{auto}(\nu)=\frac{K(\nu)\cdot NETD}{MTF(\nu)} \tag{3.2}$$

In order to determine objective $MRTD_{auto}$ it is required to measure only two objective parameters: NETD (noise equivalent temperature difference) and MTF (modulation transfer function). Measurement of both MTF and NETD is fast and semi-automatic. Therefore the measurement time needed to determine objective $MRTD_{auto}$ is much shorter than the time needed to measure the classical subjective MRTD. However, because determination of K(ν) requires testing of many thermal cameras (at least 20–30) then the objective $MRTD_{auto}$ can be determined only in case of large production lines. In case of typical tests of small quantities of different thermal imagers only classical subjective MRTD can be measured.

Nowadays classical MRTD is considered as the most important parameter of thermal imagers and MRTD is typically used for range predictions for real targets. However, it was reported many times that the MRTD concept, when applied to undersampled imagers, generates incorrect range predictions; particularly detection range. The biggest problem is low accuracy of performance modeling over Nyquist frequency.

There are at least three competing solutions to eliminate the mentioned above limitation of MRTD concept and to improve accuracy of range prediction.

The DMRT (Dynamic MRTD) is an MRTD variation method that assumes that the bar pattern is moved relative to the sampling lattice with optimum speed (about ¼ pixel per frame). This measurement way enable for human eye to integrate over various phase positions of the 4-bar target and the the target is perceived at spatial frequencies significantly higher than Nyquist frequency. However, this artificial movement of the target during measurement creates conditions that are drastically different than conditions during static observation. Dependence of the test procedure (movement speed) on sensor characteristics is another big drawback of the DMRT method.

There are however two real rivals of classical MRTD as the figure of merit of thermal imagers.

Triangle Orientation Discrimination (TOD) threshold as an alternative to MRTD method to characterize performance of thermal imagers [3]. The TOD method proposes to use a series of triangle targets for characterization of thermal imagers.

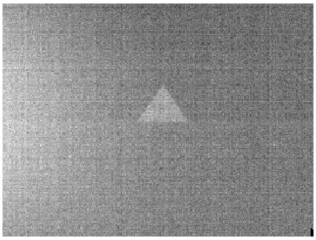


Fig. 3.5. Image of a triangle target during testing thermal imager using TOD method.

The TOD method has a number of theoretical and practical advantages over the MRTD method. The method is based on an improved test pattern, a well-defined observer task, a solid psychophysical measurement procedure, and generates more accurate and more comparable results from different measuring teams than in case of classical MRTD. It is also possible to convert TOD measurement results to MRTD characteristics. However mathematical conversion algorithm is not simple. Next, TOD method was invented several decades after introduction of the MRTD concept. Further on, the classical MRTD test method has been already implemented in several widely disseminated military standards. Therefore, probability that the TOD method shall be widely accepted by international community is rather low in spite of potential advantages of this test method.

Minimum Temperature Difference Perceived (MTDP) parameter is a new figure of merit to evaluate quality of modern undersampled thermal imagers [29]. MTDP is a temperature difference at which four, three or two bars can be resolved by an observer with the test pattern at the optimum phase position. Using MTDP concept, imager performance over Nyquist frequency can be still analyzed and a significant drawback of classical MRTD is eliminated. At the same time MTDP uses much of MRTD concept (the same 4-bar target, the same test equipment) and it is easy for people familiar with MRTD concept to understand and accept MTDP concept. Next, MTDP concept was implemented in TRM3 - a well know model for performance evaluation of thermal imagers [30]. Therefore MTDP has a real chance to become in future the main figure of merit of thermal imagers if gets support from any international standard.

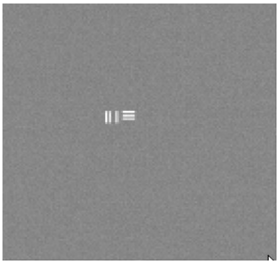


Fig. 3.6. Image of a four bar target during MTDP measurement.

3.1.2 MDTD

The MDTD is a subjective parameter that describes ability of the imager-human system for detection of small size targets. It is a function of a minimum temperature difference between the circular target and the background required to detect the target by an observer versus inverse spatial size of the target.

The MDTD is measured by determining the minimum temperature difference between the target and the background required to detect the thermal image of a target, for targets of different spatial dimensions.

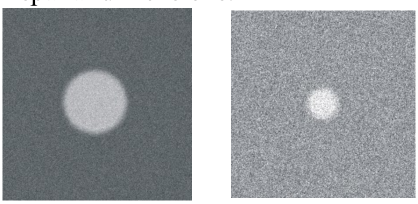


Fig. 3.7. Images of two circular targets of different angular sizes

The measurement results of an exemplary thermal camera are shown in Fig. 3.8.

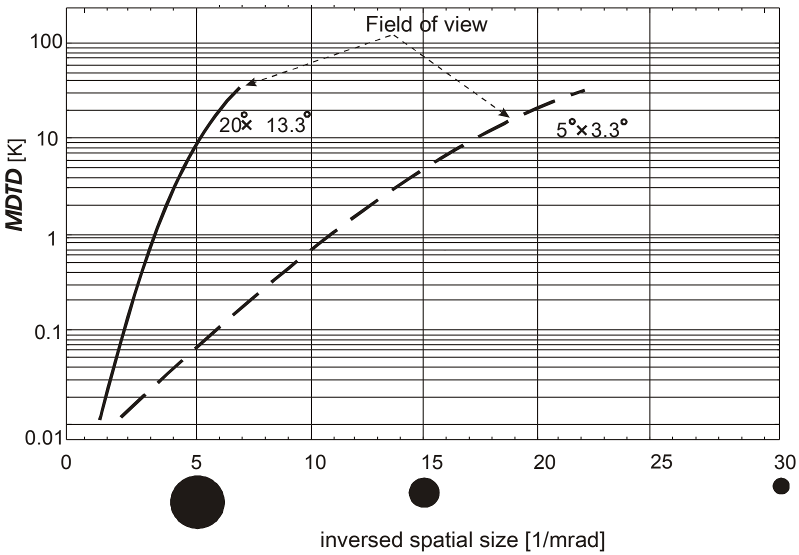


Fig. 3.8. MDTD of exemplary thermal camera.

3.1.3 Evaluation of ranges of effective surveillance

Detection, recognition and identification ranges of a target of interest are the prime criterion for evaluation of most surveillance thermal cameras.

It is possible to measure directly detection, recognition, and identification ranges of a target of interest and to evaluate the tested thermal camera on the basis of the test results. However, it is a risky solution. The ranges vary with observation conditions (atmosphere, background) and it is relatively easy to manipulate with the detection, recognition and identification ranges at real conditions if the observation conditions are not very precisely specified. Next, it is difficult to compare test results of different thermal cameras tested at different time periods and at different observation conditions.

It is possible to calculate theoretically the detection, recognition, and identification ranges of any target (man, tank, truck) using simulation computer program based on mathematical models of thermal cameras [22,30]. However, the safest way to evaluate surveillance thermal cameras is to measure MRTD of this thermal imager and calculate the detection, recognition, and identification ranges of a standard NATO target using methodology proposed by this standard: STANAG 4347, Definition of nominal static range performance for thermal imaging systems, 1995. The standard defines precisely parameters of the standard target, standard atmospheric conditions and presents a way to calculate the detection, recognition and identification ranges of the standard target on the basis of the MRTD function of the tested thermal camera. Two well known computer models that enable calculations of performance ranges for thermal imagers (NVTherm or TRM3) use algorithms that can be treated as modified versions of the method proposed by the STANAG 4347.

The detection, recognition, and identification ranges of the standard NATO target are potentially a good criterion to be used in requirements on surveillance thermal imagers. It is apparently a good idea to present requirements on a surveillance thermal imager by presenting requirements on the performance ranges (Table 3.2). However, in order to calculate the performance ranges of a thermal imager we must know its MRTD function. Therefore a more common way to specify requirements on surveillance thermal cameras is to present requirements on MRTD characteristic in a form shown in Table 3.3.

Table 3.2. Exemplary requirements on surveillance thermal camera using a concept of performance ranges.

Field of view	Detection range [km]	
	Good transmission ($\sigma = 0.2$)	Bad transmission ($\sigma = 1$)
Wide field of view	2.7	2
Narrow field of view	7	3
	Recognition range [km]	
Wide field of view	1.1	0.9
Narrow field of view	3.1	2

Table 3.3. Exemplary requirements for MRTD function of a long range surveillance thermal camera.

Spatial frequency [mrad^{-1}]	MRTD [°C]	
	field of view	
	wide (about 10°)	narrow (about 3°)
0.5	<0.1	
1	<0.38	<0.1
1.5	<2	
2		<0.18
3		<0.4
4		<1
5		<6

Attention: These are only exemplary MRTD values

To summarize, we can say that MRTD is the most important characteristic of thermal cameras from the point of view of the user who wants to have the best ranges of detection, recognition, and identification of targets of interest. Having known MRTD functions of different thermal cameras we can calculate the ranges of detection, recognition of the standard NATO target and compare their performance (only thermal cameras of almost the same field of view should be compared). Therefore proper specifications of a thermal camera should specify precisely maximal values of MRTD function at a set of spatial frequencies. Then, the measured MRTD values must be lower than the values in the specifications if the camera is to pass the test.

Now, let us discuss the way to calculate the detection and recognition ranges on the basis of the measured and known MRTD function of the tested thermal camera using the recommendation from STANAG 4347. The summary of the recommendations is shown in Table 3.4.

Table 3.4. Target parameters, atmosphere conditions and resolution criteria specified in the standard STANAG 4347.

Target		Atmosphere		Resolution criteria (according to 50% probability)	
size	Rectangle : 2.3×2.3 m	transmission law	$\tau(R) = e^{-\sigma R}$ R- distance in km σ - coefficient	detection	1 line pair/target
temperature difference	ΔT_o = 2 K (related to blackbody temperature of 288 K)	σ - at good atmospheric condition	0.2 km^{-1}	recognition	3 line pair/target
		σ - at limited atmospheric condition	1 km^{-1}	identification	6 line pair/target

In details, the detection, recognition and identification ranges of the standard NATO targets can be calculated using the below presented algorithm.

1. Convert MRTD characteristic into a new one by changing variable from spatial frequency ν [mrad^{-1}] to the range R [km] using the following formulas

   $_{Ardent}$ [km] = 2.3 ν [mrad^{-1}],

   $_{Rec}$ [km] = 2.3/3 ν [mrad^{-1}],

   R_{id} [km] = 2.3/6 ν [mrad^{-1}].

2. Calculate decrease in the initial temperature difference ΔT (it was assumed that initial ΔT_o = 2 K) between the target and the background due to limited atmospheric transmission

$$\Delta T(R) = \Delta T_0 \cdot e^{-\alpha \cdot R} \quad . \tag{3.3}$$

3. Determine the respective nominal static ranges as the intersections of ΔT(R) and the converted MRTD functions.

Let us to practice using this algorithm by calculation of the detection ranges of the standard NATO target using a thermal camera of MRTD function shown in Fig. 3.9. The calculation results are shown in Fig. 3.10 and we can conclude that the detection ranges are the following:

- 7.2 km at good atmospheric transmission,
- 2.8 km at limited atmospheric transmission.

Calculation of the recognition and identification ranges can be done in the same manner.

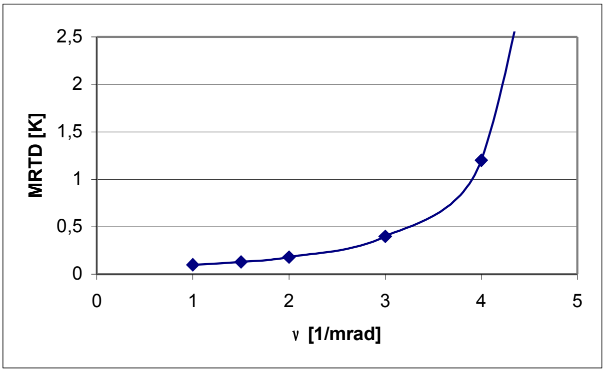


Fig. 3.9. Original MRTD measurement results.

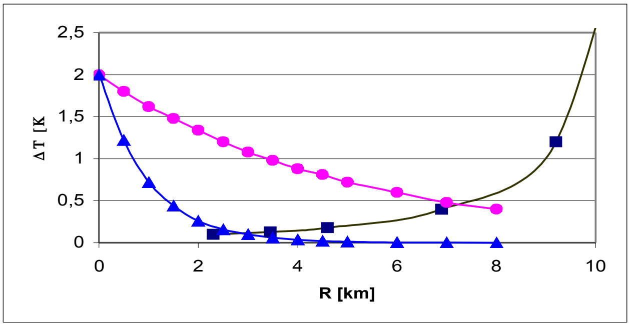


Fig. 3.10. Converted MRTD function (for detection range) and the functions $\Delta T_o[R]$ at different atmospheric conditions (rectangles – MRTD values, circle – $\Delta T_o[R]$ at good transmission, triangles – $\Delta T_o[R]$ at bad transmission).

As we see algorithm provided by the STANAG 4347 enables to determine detection, recognition, and identification ranges of the standard target using the tested thermal cameras by doing only several non-complicated mathematical operations. The performance ranges of tested thermal camera in case of other targets of known parameters (temperature difference and size of equivalent rectangle) can be also determined using the same algorithm. The calculations can be carried out even using a simple calculator but can be speed up by using several available computer programs optimized for the task of calculation of performance ranges of thermal cameras.

3.2 Response parameters

Response parameters give us information about system response to variable temperature targets or to the variable size targets.
There are three commonly used response parameters of thermal cameras:

1. Responsivity function,
2. ATF (Aperiodic Transfer Function),
3. SRF (Slit Response Function).

Responsivity function is the system response to a large target of variable temperature. It provides information on gain, linearity, dynamic range and saturation level. The signal transfer function (SiTF) is the linear part of the responsivity function.

Aperiodic transfer function (ATF) is defined as a normalized dependence of system response to a variable size square (circular) target. It provides information on system ability to detect small targets.

Slit response function (SRF) is defined as a normalized dependence of system response to a variable size slit target. It provides information on system ability to detect long narrow targets.

3.2.1 Responsivity function

Responsivity function is a function of an output signal (screen luminance, or electrical signal) versus target temperature (absolute or relative) in case of a large, constant size target (Fig. 3.11, Fig. 3.12). It can be characterized by three digital parameters: SiTF, saturation level, and dynamic range that are determined on the basis of measurement results of the responsivity function.

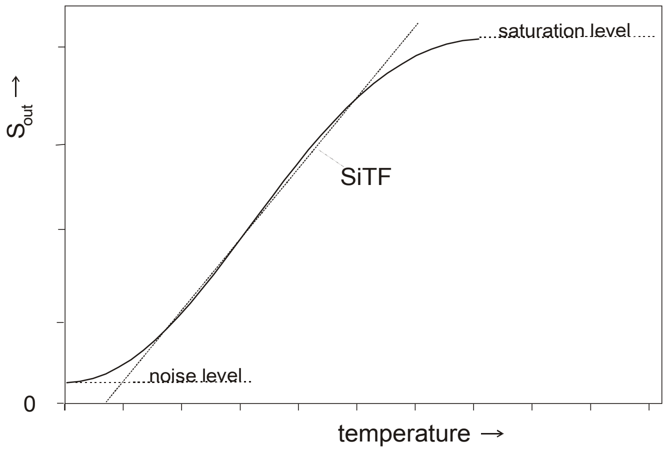


Fig. 3.11. Responsivity function of a DC coupled thermal camera.

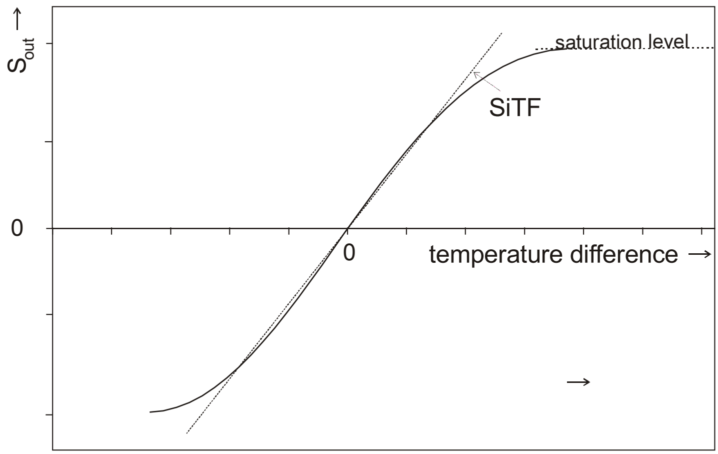


Fig. 3.12. Responsivity function of a AC coupled thermal camera or DC coupled camera with AGC (automatic gain control).

The responsivity function is usually S shaped.
The signal transfer function SiTF or the responsivity is the linear part of the responsivity function. It is calculated as tangent of the angle between linear part of the responsivity function and the temperature axis (the slope of the linear part).
The saturation level is the upper part of the responsivity function.
Dynamic range is the ratio of the maximum measurable input signal and the minimum measurable input signal.

$$Dynamic\ Range = \frac{maximum\ measurable\ input\ signal}{minimum\ measurable\ input\ signal} \tag{3.4}$$

The situation is rather unclear what are really these two measurable input signals. There are at least two different definitions of the dynamic range parameters used in specifications of thermal cameras.

First, the dynamic range is defined as a ratio of temperature difference generating the output signal equal to 95% (or 90%, or 100%) of the saturation level value to the temperature resolution of the tested camera. It is typically assumed that the temperature resolution is equal to NETD of the tested camera.

$$\textit{dynamic range}\,(1) = \frac{\Delta T_s}{NETD}$$

where ts is temperature difference generating the signal that equals 95% (90% or 100% depending on literature source) of the saturation level.

Second, the dynamic range is defined as a ratio of the upper value to the lower value of the temperature difference when the deviation between the response function RF(ΔT) and its linear approximation is within specifications

$$\textit{dynamic range}\,(2) = \frac{\Delta T_h}{\Delta T_l}$$

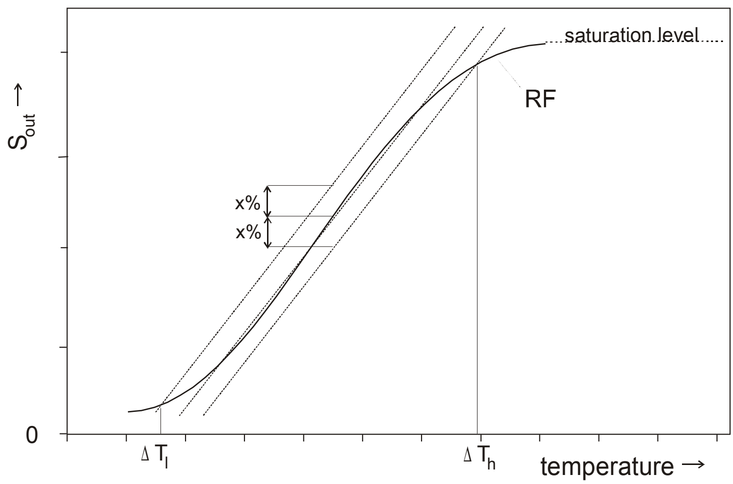


Fig.3.13. Determination of the dynamic range using the linearity range concept.

3.2.2 Aperiodic Transfer Function

Thermal camera can detect small targets of angular size smaller than its instantaneous-field-of-view (IFOV). The latter parameters is calculated as a detector (single pixel) angular substance. The output signal generated by such a small size target depends on the target area. For an ideal thermal camera, the signal is proportional to the target area when the target area is smaller than IFOV; the signal does not depend on the target area when the target area is bigger than IFOV (Fig. 3.14).

Aperiodic transfer function (ATF) is the dependence of a normalized function of the output signal (voltage, current, digital) on a variable size circular (square) target. The difference between the ideal and real ATF is caused by the image blur generated by optical and electronic systems. Therefore the target transfer function (TTF) calculated as the ratio of the real ATF to the ideal ATF provides useful information about this phenomenon.

The point visibility factor (PVF) is a point of TTF function determined for the conditions when the target area approaches zero. The PVF is also sometimes termed the en squared energy (EE), or en squared power (EP) or blur efficiency.

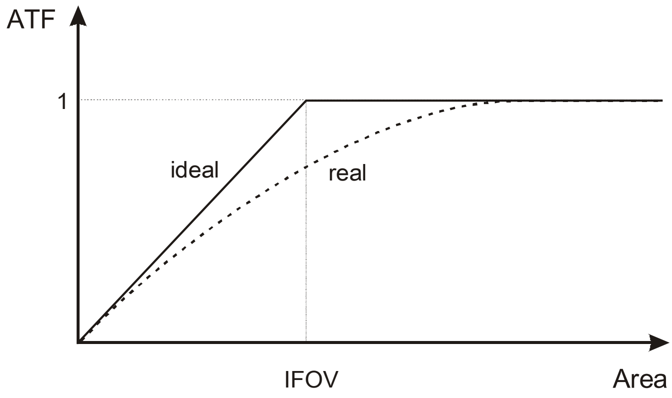


Fig. 3.14. Ideal and real aperiodic transfer function (ATF).

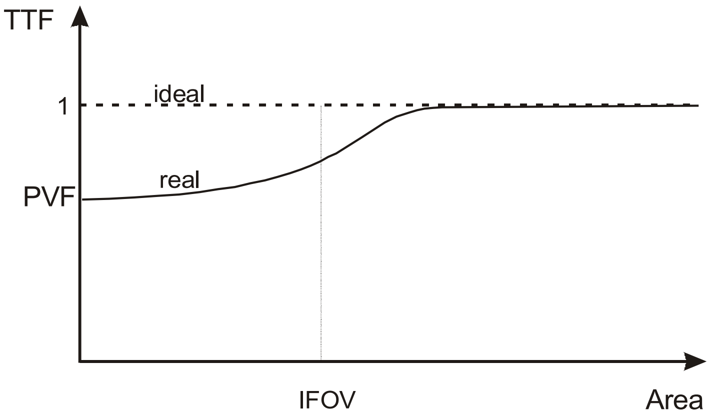


Fig. 3.15. Target transfer function.

3.2.3 Slit Response Function

The SRF is defined as a function of the signal generated by a slit versus width of the slit normalized to the signal generated by a very wide slit. The SRF can be treated as one dimensional ATF.

SRF generally provides directly information on the system ability to detect long narrow targets. The SRF function is used as a base to determine so called measurement resolution and imaging resolution. The latter parameters shall be discussed later.

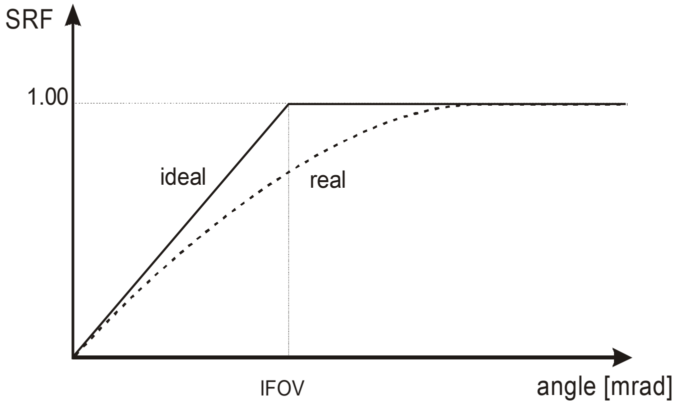


Fig. 3.16. Slit Response Function.

3.3 Noise parameters

Noise is a phenomenon that can significantly decrease image quality and limit system ability to detect low contrast targets. Noise parameters are very important performance measures of thermal cameras.

Noise present in thermal images can be in general divided into two groups: temporal noise and spatial noise. The temporal noise refers to temporal variations of the signals generated by detector pixels during observation of an uniform target: variations of the signal in a single line for case of scanning cameras or frame to frame variations of pixels signals for case of staring cameras. The spatial noise refers to differences between the signals generated by different pixels during observation of an uniform target that does not change from frame to frame. Both types of noise have its own noise power spectral density (NPSD).

Noise is a complex phenomenon, difficult for characterization. In general, we can find in literature three different noise analysis approaches to characterize the noise phenomenon present in thermal images:

1. Three dimensional noise model where the noise is divided into eight components. Visualization is in form of multi-dimensional images or numbers.
2. Noise phenomenon is characterized by a single parameter presented as a number.

3. Noise phenomenon is characterized by four parameters presented in form of numbers.

3.3.1 3D noise model

The 3D noise model is based on the concept of the D_i directional averaging operators that allow the mathematical derivation of eight noise components from the noise data set [8]. The operators average the data in the direction indicated by the subscripts.

Let us assume that a sequence of images generated by the tested imager was captured. Then, the captured data can be presented in form of 3D array N_{TVH} (Fig. 3.17). The *T*-dimension represents time or the framing sequence. The *H*-dimension and *V*-dimension give spatial information. In case of staring systems, *m* and *n* indicate the pixel location; in case of scanning systems, *m* refers to a pixel location but *n* refer to time or sample number in a digitized analog signal. Names of each components and information provided by each component are presented in Table 3.5. The noise components are calculated by converting the 3D array into a series of 2D or 1D arrays. The conversion formulas are presented in Table 3.6.

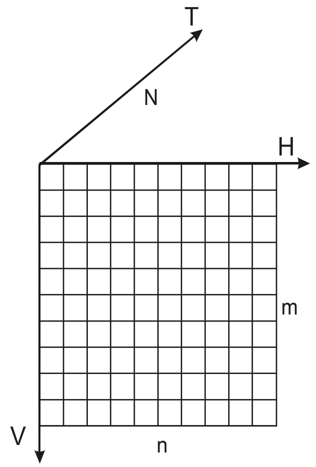


Fig. 3.17. Three dimensional noise model coordinate system: *m*-row number, *n*-column number, *N*-frame number.

It is possible to get detail information about the nature of a noise phenomenon by the analysis of a sequence of the images generated by the tested thermal camera using the 3D noise model and this model is often used by manufactures of thermal cameras. On the other hand, the 3D noise model due to long series of parameters is complicated and this model is very rarely used by users of thermal cameras who prefer simple solutions. Because of these customer demands for simplicity, even manufacturers rarely publish data using the 3D noise model.

Table 3.5. Noise components of the 3-D noise model.

	3D component	Number of elements	Comments	Information
1	S_{VHT}	$m \times n \times N$		Random 3-D noise
2	S_{VH}	$m \times n$	each pixel is averaged over N frames	2D spatial noise
3	S_{HT}	$n \times N$	each column is averaged over m pixels	temporal column noise (rain): variations of mean column brightness with time
4	S_{VT}	$m \times N$	each row is averaged over n pixels	temporal row noise (streaking): variations of mean row brightness with time
5	S_V	m	each row is averaged over n pixels and N frames	spatial row noise: variations of mean row brightness that do not depend on time
6	S_H	n	each column is averaged over m pixels and N frames	spatial column noise: variations of mean column brightness that do not depend on time
7	S_T	N	each frame is averaged over $m \times n$ pixels	frame to frame brightness variation (flicker)
8	S	1	each frame is averaged over $m \times n$ pixels and N frames	average brightness of the frames in the sequence

Table 3.6. Conversion formulas.

3D TVH array to 2D VH array	3D TVH array to 2D TH array	3D TVH array to 2D TV array
$S_{VH}(i,j) = \frac{\sum_{k}^{N} S_{TVH}(i,j,k)}{N}$ i can vary from 1 to n - horizontal	$S_{HT}(j,k) = \frac{\sum_{i}^{m} S_{TVH}(i,j,k)}{m}$ j can vary from 1 to m – vertical	$S_{VT}(i,k) = \frac{\sum_{j}^{n} S_{TVH}(i,j,k)}{n}$ k can vary from 1 to N – temporal
3D TVH to 2D TV array	2D TV array to 1D V array	2D TH array to 1D T
$S_H(j) = \frac{\sum_{k}^{N} \sum_{i}^{m} S_{TVH}(i,j,k)}{m \cdot N}$	$S_V(i) = \frac{\sum_{k}^{N} \sum_{j}^{n} S_{TVH}(i,j,k)}{n \cdot N}$	$S_T(k) = \frac{\sum_{i}^{m} \sum_{j}^{n} S_{TVH}(i,j,k)}{n \cdot m}$
3D TVH to a single number		

3.3.2 Single parameter approach

If we look into technical data offered by manufacturers of most thermal cameras we find a parameter called “thermal sensitivity”, “thermal resolution”, “temperature resolution” or “ NETD” that provide information about noise of the thermal camera. The parameter mentioned above has different names but usually means noise equivalent temperature difference (NETD). The problem is that different definitions and different measurement techniques of NETD are used in literature.

According to its classical definition, NETD is defined as the blackbody temperature difference between a target and its background required to produce a peak-signal-to-ems-noise ratio of unity at a suitable point in the output electrical channel. This definition was developed at the time when all thermal cameras were the scanning thermal cameras. Although the definition does not state it clearly, NETD is a metric of only high frequency temporal noise along the video line (Fig.3.18). Low frequency temporal changes are corrected (Fig. 3.19) before the NETD measurement. Next, NETD typically gives no information about the spatial noise between different video lines.

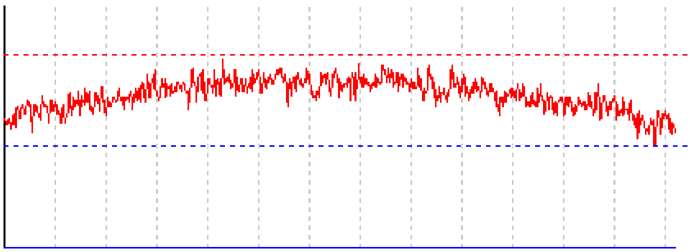


Fig.3.18. Signal profile of a video line.

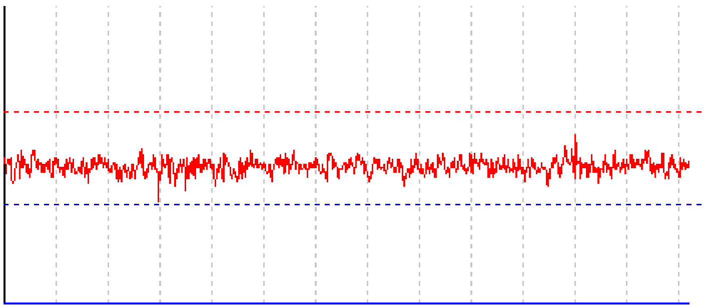


Fig. 3.19. Signal profile of a video line after low frequency trends correction.

NETD can be calculated as

$$NETD = V_n \cdot SiTF \qquad (3.5)$$

where $_V$ is ems value of noise in the signal line, SiTF is the Signal Transfer Function of the tested thermal camera. $_V$ can be presented in different signal units: digital levels, volts, etc. However, as long as SiTF is expressed as a ratio of the same unit divided by K, then NETD is calculated in Kelvin degrees.

As it was presented above, the situation with NETD parameter as a metric of a noise phenomenon is relatively clear in case of scanning thermal cameras. It is a measure of high frequency temporal noise in a single line.

Situation is much more complicated in case of array thermal cameras. Different definitions of NETD are often used. NETD is still defined as a blackbody temperature difference between a target and its background required to produce a peak-signal-to-ems-noise ratio of unity. A sequence of images of uniform target is typically used as raw data for NETD calculations. However, the difference depends on the way how to calculate this ems noise.

NETD can be calculated in case of staring thermal cameras using different methods.

First, ems noise can be calculated as a standard deviation of temporal variation of a signal of a single pixel. NETD is now a measure of only temporal noise of a single pixel.

Second, ems noise can be calculated as a standard deviation from temporal and spatial variations of signals from a group of pixels. NETD is now a measure of total noise (both temporal and spatial noise components).

Third, ems noise can be calculated as a standard deviation from temporal and spatial variations of signals from a group of pixels but after correction of spatial noise. NETD is now a measure of average temporal noise for a group of pixels.

Both three methods can be used with or without correction of low frequency trends. This means that depending if we use the correction or not, then NETD can be a measure of only high frequency noise or of a measure of full bandwidth noise.

To summarize, NETD can be treated as a useful metric of a noise phenomenon but only if it is precisely known how it was measured; without this knowledge NETD data can be very misleading. The differences in NETD values, get using different calculation methods, can be very significant. NETD measured using the first method can be several times lower than NETD measured using the second method. This situation is particularly drastic in a field non-cooled thermal cameras when the total noise is typically a several times higher than its temporal component.

3.3.3 Four parameters approach

Noise phenomenon is too sophisticated to be precisely characterized by a single parameter like NETD. Even if it is clearly defined how NETD was determined we get too little information about the noise phenomenon. Two thermal cameras can have the same NETD (defined using any of different methods presented earlier) but a human eye will immediately notice big differences in images generated by these thermal cameras. On the other hand, as it was stated earlier, 3D noise model, using eight components for precise characterization of a noise phenomenon, is too sophisticated to be commonly accepted and used. It seems that in this situation a middle way, when the noise is characterized by a set of three/four parameters, is an optimal solution.

Four parameters approach is based on the assumption that the noise present in images generated by thermal cameras can be generally divided into two groups: temporal noise and spatial noise. Next, each group can be further divided into low frequency noise and high frequency component.

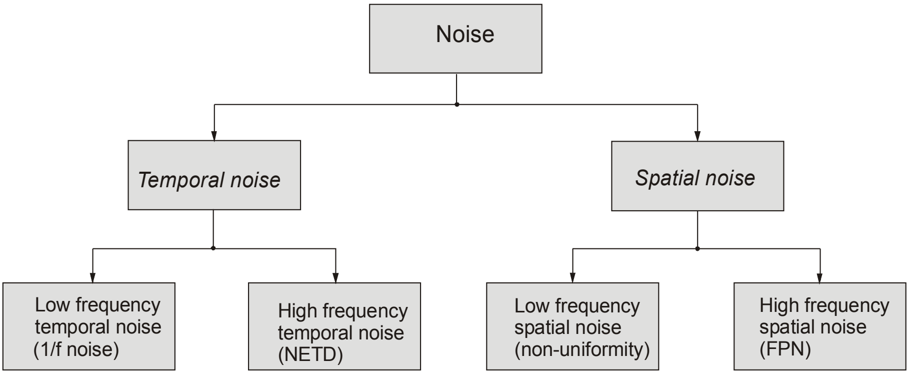


Fig. 3.20. Types of noise.

Temporal noise generates temporal variation of intensity of camera pixels even when target radiation does not change in time.
Spatial noise generates spatial variations of intensity of camera pixels even in case of uniform target filling the camera field of view.

Low frequency temporal noise generates slow temporal variations of intensity of camera pixels. This noise component creates an effect called $1/f$ noise. The latter component is noticeable if we capture and compare the images generated by the camera, separated by a relatively long period of time (say at least a dozen or more minutes). We can see in Fig.3.21 that some groups of pixels in the second or the third frame are clearly darker or brighter in comparison to the first frame.

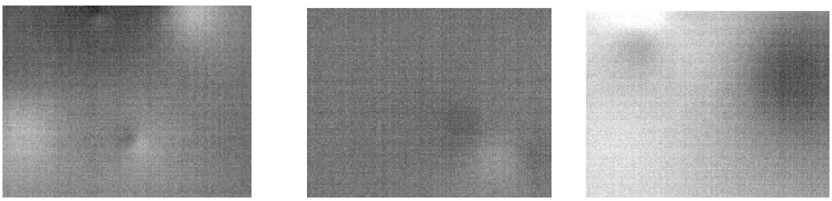


Fig.3.21. Images of uniform target captured at long intervals.

High frequency temporal noise generates fast temporal variations of the intensity of camera pixels. If we refer to original interpretation of NETD in older scanning thermal cameras then NETD can be considered as a measure of this high frequency temporal component of the total noise. High frequency temporal component is clearly noticeable if we capture and compare several neighbor images generated by the tested thermal camera. We can see in Fig. 3.22 that the pixels intensity depends on a frame number, in spite of the fact that they are neighbor frames and time intervals between them are very short (1/60 s in NTSC video system; or 1/50 s in PAL video systems).

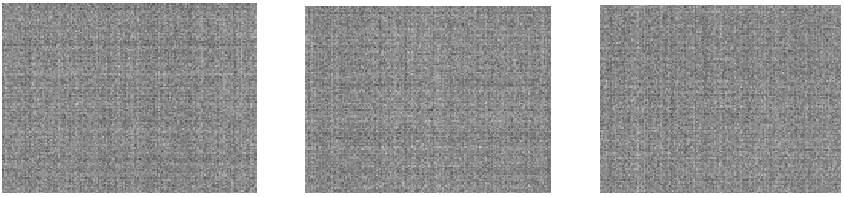


Fig. 3.22. Three neighbor images of uniform target generated by a thermal camera of dominant high frequency temporal noise.

Low frequency spatial noise generates slow spatial variations of the intensity of camera pixels. This noise component creates an effect that is called non-uniformity. If low frequency spatial noise component is significant then it is noticeable if we capture and compare several neighbor images generated by the tested thermal camera. We could notice, present in every frame, low frequency spatial trend that does not depend on a frame number and the frames are almost identical (Fig. 3.23)

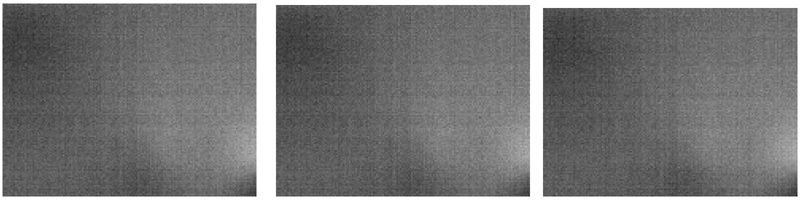


Fig. 3.23. Three neighbor images of uniform target generated by a thermal camera of dominant low frequency spatial noise.

High frequency spatial noise generates fast spatial variations of the intensity of camera pixels. This noise component creates an effect that is called Fixed Pattern Noise. If high frequency spatial noise component is strong then it should be clearly noticeable if we capture and compare several neighbor images generated by the tested camera. We could notice the high frequency spatial trend, present in every frame, that does not depend on the frame number and the frames are almost identical (Fig. 3.24).

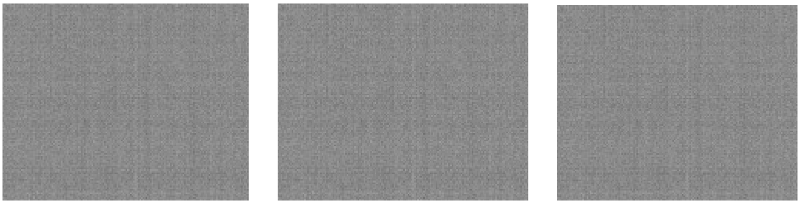


Fig. 3.24. Three neighbor images of uniform target generated by a thermal camera of dominant high frequency spatial noise.

It is usually considered that the frequency of 150 kHz for NTSC video or 186 kHz for PAL video systems is the border between the high and the low frequency components. It is possible to separate low frequency temporal and spatial components from the total noise using suitable low pass filter (or high pass filter) in a video channel.

Another more convenient method to separate different noise components is to capture a series of images generated by the tested thermal camera when its field of view is filled by an uniform target. The captured data created 3D patio-temporal array. It is possible then to calculate the measures of all four noise components by carrying out the data filtering using low/high digital filters.

Calculation method of four noise components from 3D patio-temporal array depends on answer on a question what is dominant type of noise of thermal camera: ergodic noise or non-ergodic noise.

If the thermal camera is a source of ergodic noise then the detectors are considered as statistically dependent noise sources. The same average ems will be measured if the average is calculated from n different detectors, or the same ems noise of the same detector is the measured n times. Then, ems noise can be calculated as

$$\sigma = \sqrt{s_{ave}^2} = \sqrt{\frac{s_1^2 + s_2^2 + \ldots + s_n^2}{n}} \, , \tag{3.6}$$

where s_i^2 is the variance of noise from i-detector or from the same detector but measured i time; n is the number of detectors or indicator how many times were recorded the data from the same detector.

If the thermal camera is non-ergodic then the detectors are considered as independent noise sources. Each detector is statistically a different noise source. Then ems noise is calculated as

$$\sigma = s_{ave} = \frac{s_1 + s_2 + \ldots + s_n}{n} \, . \tag{3.7}$$

Scanning thermal cameras can be considered to some degree as ergodic systems. Staring thermal cameras are usually non-ergodic systems. In order to simplify the analysis let us assume that the tested camera is non-ergodic as staring thermal cameras dominate the market. Anyway, the consequences of non-fulfilling this assumption are not really significant because the differences between ems noise values calculated using two presented earlier formulas are usually quite small (below 2%).

Now, we will present the methods that can be used to measure all four noise components.

1/*f* noise

1. Capturing several tens of group of frames separated by a long time interval. Each group is treated as a 3D noise array. There are *n* such 3D noise arrays, where *n* is the number of captured groups of frames.
2. Averaging operation of frames within the each group. A group of frames (3D noise array) is replaced by a single averaged frame. High frequency temporal noise component is eliminated or at least reduced. New 3D array is created that carried information only about low frequency temporal noise.
3. Calculations of 1/*f* noise of a single pixel as a standard deviation of temporal variation of intensity of this pixel.
4. 1/*f* noise of an analyzed group of pixels (or the whole thermal image) is calculated as an average of 1/*f* noise of all pixels included into the analyzed group.
5. Calculated 1/*f* noise in digital level units is converted into the 1/*f* noise in temperature units

$$1/f\ \text{noise}\,[^\circ\text{C}] = \frac{1/f\ \text{noise}\,[\text{digital levels}]}{\text{SiTF}}\ . \tag{3.8}$$

6. 1/*f* noise can be also expressed as a percentage of average signal of the analyzed area or as a percentage of NETD.

1/*f* noise component is noticeable only if we analyze temporal trends in frames of a long video sequence; say at least a few minutes. The 1/*f* effect is not noticeable in short video sequences. Generally 1/*f* noise creates an effect of slow variations of brightness of pixels of images generated by thermal cameras. In other words, the 1/*f* noise creates slow temporal changes of spatial noises: FPN and non-uniformity.

1/*f* noise has directly no influence on image quality perceived by a human observer. Therefore 1/f noise is typically omitted in noise analysis of thermal cameras and this parameter is rarely measured. NETD, FPN, and non-uniformity are considered as a basic trio noise parameters and are commonly measured.

NETD

1. Capturing a short video sequence of thermal images generated by the tested thermal imager (if the number of captured video frames is no

more than about one hundred we can assume that $1/f$ effect is negligible). 3D noise array is created.
2. NETD of a single pixel is calculated as a standard deviation of temporal variation of intensity of this pixel with time.
3. NETD of an analyzed group of pixels (or the whole thermal image) is calculated as an average NETD of all pixels included in the analyzed group.
4. Calculated NETD in digital level units is converted to the NETD in temperature units

$$NETD\,[^\circ\mathrm{C}] = \frac{NETD\,[\text{digital levels}]}{\mathrm{SiTF}} \tag{3.9}$$

FPN

1. Capturing a short video sequence of thermal images generated by the tested thermal imager.
2. Averaging operation of the captured frames. A group of frames is replaced by a single frame (temporal noise component is eliminated or at least reduced).
3. High-pass frequency filtering operation on the average frame.
4. FPN of an analyzed area (or the whole thermal image) is calculated as a standard deviation of spatial variation of intensity of different pixels within the analyzed area.
5. Calculated FPN in digital level units is converted to the FPN in temperature units:

$$FPN\,[^\circ\mathrm{C}] = \frac{FPN\,[\text{digital levels}]}{\mathrm{SiTF}}\ . \tag{3.10}$$

6. FPN can be also expressed as a percentage of average intensity of the analyzed area or as a percentage of NETD.

Non-uniformity

1. Capturing a short video sequence of thermal images generated by the tested thermal imager.
2. Averaging operation of the captured frames. A group of frames is replaced by a single frame (temporal noise component is eliminated or at least reduced).
3. Low-pass frequency filtering operation on the average frame.
4. Non-uniformity NU of the analyzed area (or the whole thermal image) is calculated as a standard deviation of spatial variation of intensity of different pixels within the analyzed area.
5. Calculated NU in digital level units is converted to the NU in temperature units:

$$NU\,[^{\circ}\mathrm{C}] = \frac{NU\,[\text{digital levels}]}{\mathrm{SiTF}} \quad . \tag{3.11}$$

6. FPN can be also expressed as a percentage of average intensity of the analyzed area or as a percentage of NETD.

High frequency temporal noise expressed by NETD is usually a dominant noise component in cooled thermal imagers. High frequency spatial noise expressed as FPN is typically a dominant noise component in non-cooled staring thermal imagers. Low frequency spatial noise (non-uniformity) is typically much lower in cooled thermal imagers than in non-cooled thermal imagers. Examples of possible measurement results are shown in Table 3.7. Please note, however, that these are only the examples and within each technology test results can vary significantly. Next, measurements are usually done immediately after the imager internal calibration and therefore the non-uniformity measurement results are lower than during real work.

Table 3.7. Examples of measurement results of noise components of different thermal imagers.

Imager type	NETD [°C]	1/*f* [°C]	FPN [°C]	NU [°C]
cooled scanning	0.1	0.04	0.07	0.08
cooled array	0.05	0.05	0.03	0.1
non-cooled array	0.12	0.09	0.15	0.3

3.4 Image resolution parameters

Image resolution parameters carry out the information about imager ability to perceive small details of high contrast images. There is a lot of confusions in literature in this area because many parameters are used to expressed this ability. Generally, parameters that represent thermal imagers ability to perceive small details (resolution) can be in four groups:

1. Parameters based on basic specifications of the IR FPA module (number of detectors, pixel dimensions) used in thermal imager.
2. MTF (modulation transfer function) and derivative parameters.
3. Parameters based on imager response to point sources or slit sources.
4. Parameters based on subjective human ability to resolve some patterns.

3.4.1 Parameters based on specifications of the IR FPA

Infrared focal plane arrays are hearts of thermal imagers. Therefore it is not strange that some IR FPA parameters like number of detectors, number of lines, -detector angular size parameters called IFOV or DAS) are often used to describe performance of thermal imagers.

The first parameter is the total number of detectors of a two-dimensional IR FPA sensor and it is used to describe resolution of staring thermal cameras.

The second parameter is the total number of vertical lines of a linear IR FPA. This parameter is used to describe resolution of scanning thermal cameras.

IFOV (instantaneous field of view) or DAS (detector angular substance), in spite of different names, are the same parameter defined as angular dimension of a single pixel of the IR FPA used in the thermal camera

$$\text{DAS [mrad]}=a[\mu\text{m}]/f'[\text{mm}], \quad (3.12)$$

where a is the pixel linear dimension and f' is the focal length of the optics. Please note, however, that a pixel horizontal dimension can differ from a pixel vertical dimension. Therefore there can be a difference between a horizontal resolution, and a vertical resolution of thermal cameras.

It is very easy to get these simple data about the IR FPA sensor and the optics used in a thermal imager. Therefore not only manufacturers but also most community involved in infrared technology like to express imager resolution using parameter based on FPA sensor (Table 3.8).

Table 3.8. Specifications of exemplary IR FPAs and calculated resolution of thermal cameras.

No	FPA	Pixel dimension [μν]	Optics focal length [mm]	Number of detectors/ Number of lines	DAS
1	320×256 HgCdTe LWIR cooled	30×30 m	50 mm	81920 pixels	0.6 mrad
2	288×4 HgCdTe LWIR cooled	28×25 m	50 mm	288 lines	0.56 mrad (horizontal) 0.5 mrad (vertical)
3	640×512 HgCdTe MWIR cooled	15×15 m	50 mm	327680 pixels	0.3 mrad
4	320×240 LWIR non-cooled	45×45 m	50 mm	76800 pixels	0.9

Resolution parameters based on FPA specifications can be misleading due to different reasons.

There are cases when a thermal camera built using IR FPA sensor of smaller pixel number can generate sharper image than a thermal camera built using IR FPA sensor of higher detector number. This means that poor 640x480 pixel staring thermal camera can produce worse image that good 320x240 pixel thermal camera, although such a situation occurs rather rarely.

Next, when DAS is equal to x mrad, it does not mean that we will be able to resolve 4-bar targets of bar width that equals x mrad. There can be cases when we will not be able to resolve even 4-bar targets of bar width three times bigger than the DAS.

Therefore the resolution parameters based on IR FPA specifications should be treated as indicators of imager theoretical ability to resolve small details. More pixels in FPA sensor mean that thermal cameras built using this sensor should theoretically resolve smaller details. However, practically it is not always true. The same is with DAS or IFOV parameters. Lower values of DAS (IFOV) are welcome but they do not always indicate improvements in thermal camera ability to resolve small details.

3.4.2 MTF and derivative parameters

MTF (modulation transfer function) is a function of the contrast of image of a sine pattern at a given spatial frequency generated by the tested camera relative to a contrast of an image of sine pattern at spatial frequency equal to zero. Spatial frequency is typically measured per cycles (or line pairs) per a unit angle or a unit length (in case of thermal cameras MTF in line pairs per millionaires [LP/mrad] or in inverted millionaires [$mrad^{-1}$])[2] (see Fig.3.25).

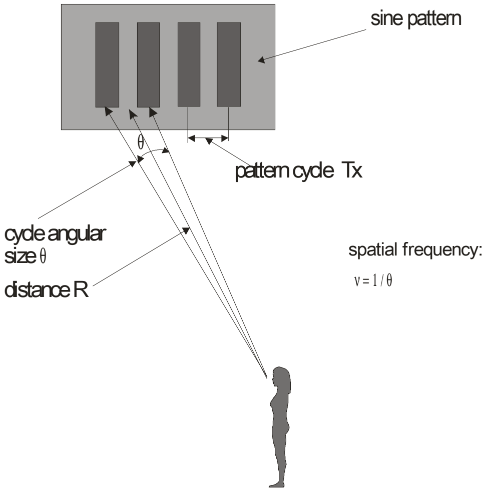


Fig.3.25. Graphical interpretation of spatial frequency.

Images of several sine patterns of different spatial frequency generated by a thermal camera of MTF presented in Fig. 3.26 are shown in Table 3.9.

[2] Attention: TV resolution is measured in line widths instead of pairs, where there are two line widths per pair, over the total height of the display

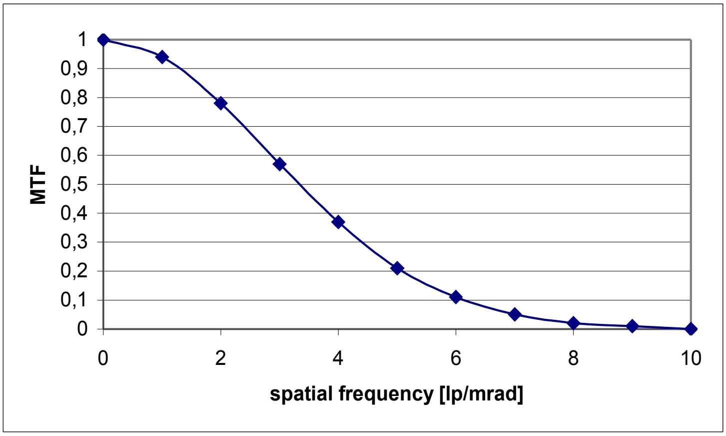
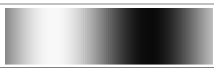
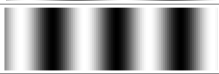
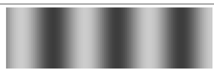
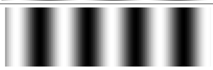
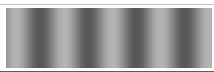
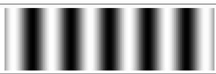
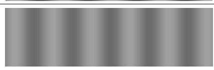
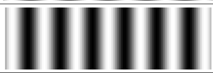
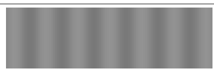
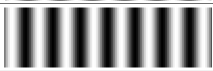
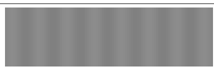
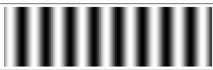
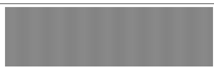
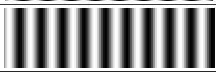
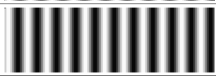


Fig. 3.26. Exemplary MTF.

Table 3.9. Images of sine patterns generated by a thermal camera of assumed MTF function.

Frequency [LP/mrad]	MTF	Original pattern	Image
1	0.94		
2	0.78		
3	0.57		
4	0.37		
5	0.21		
6	0.11		
7	0.05		
8	0.02		
9	0.01		
10	0.0		

From mathematical point of view MTF is defined as

$$\text{MTF}(\nu) = \text{C}(\nu)/\text{C}(\nu = 0)\,, \tag{3.13}$$

where $C(\nu = 0)$ is the contrast of image of the sine pattern at near zero frequency.

The contrast of the image of the sine pattern is defined as

$$C(\nu) = \frac{I_{max}(\nu) - I_{min}(\nu)}{I_{max}(\nu) + I_{min}(\nu)}\,, \tag{3.14}$$

where

$_{Max}$ is the maximum intensity for a pattern of spatial frequency ν ("white peak") and $_{Min}$ is the minimum intensity for a pattern of spatial frequency ν ("black valley").

The relationship between MTF function and contrast of a sine target creates the possibility of determination of MTF by measurement of contrast of series of sine targets of different spatial frequencies.

Measurement of MTF using sine targets is an oldest, classical MTF measurement technique. However, this measurement method is time consuming because measurement of contrast must be done for a series of sine targets. At the same time this method is also an expensive one, particularly in case of thermal cameras. Manufacturing sine targets is difficult and costly even in case of visible targets when a sine target is created by deposition of a layer of spatially variable transmittance over a transparent glass. It is technically possible to manufacture sine filters for far infrared range but it is so difficult and costly technology that MTF of thermal imagers is never measured using sine targets method.

Contrast transfer function (CTF) can be treated as a substitute of MTF that can be measured using targets that are simpler to manufacture. CTF is defined in the same way as MTF with an exception that a square wave pattern is used instead of a sine wave pattern. The CTF values are usually higher than the MTF values. The difference between MTF and CTF is usually not great. Next, it is much easier to measure CTF than to measure MTF. Therefore, several decades ago CTF was typically used instead of MTF to evaluate thermal cameras. However, nowadays CTF is rarely measured because in present era of computer technology and image processing MTF function can be easily measured by capturing images of some standard targets and using mathematical apparatus of Fourier transform.

MTF can also be defined as the magnitude of a complex function Optical Transfer Function:

$$OTF(\nu) = MTF(\nu)\ \exp\left(\mathrm{i}\, PTF(\nu)\right)\,, \tag{3.15}$$

where OTF is Optical Transfer Function, MTF is Modulation Transfer Function, and PTF is a function called Phase Transfer Function that represent the change in phase position as a function of spatial frequency[3].

A perfect optical system would have MTF of unity at all spatial frequencies, and PTF equal to 0 at all spatial frequencies. In case of real imaging systems, MTF always decreases to zero at some spatial frequency. The shape of MTF function gives precise information about imager ability to produce sharp images.

In most imaging systems PTF is not significant and therefore it is usually assumed that OTF equals MTF. Therefore MTF, not OTF, is typically used as a measure of quality of imaging systems.

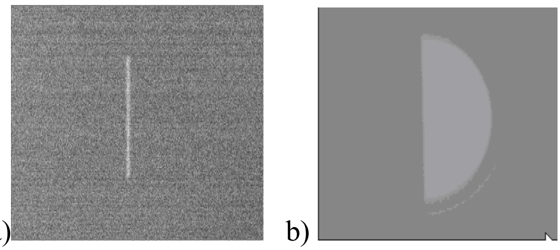
Modern measurement methods of MTF of thermal imagers are based on relationships between MTF function and two other functions (LSF and ESF):

$$MTF(\nu)=\text{Magnitude }\{F[LSF(\text{x})]\}, \tag{3.16}$$

$$MTF(\nu)=\text{Magnitude }\{F[\text{derivative from } ESP(\text{x})]\} \tag{3.17}$$

where F is the Fourier transform operator, LSF (line spread function) is one directional distribution of the flux in the image of an ideal line-like target, ESF (edge spread function) is one directional distribution of flux in the image of an ideal edge-like target.

Measurement of MTF of thermal imagers is usually carried out on the basis of captured images of two types of targets: narrow slit target or edge target (Fig. 3.27). When an image of one of these targets is captured and digitized then later MTF is calculated using formula (3.16) or formula (3.17). Practically measurement of MTF is not as simple as formulas (3.16) and (3.17) suggest due to necessity to use noise correction algorithm but these formulas present the principle of modern measurement of MTF of thermal cameras.



a) b)

Fig. 3.27. Images captured during MTF measurement a)image of a narrow slit target, b)image of an edge target.

[3] If case of a linear PTF, only simple lateral displacement of the image is observed. Non-linear PTF can adversely affect image quality. An extreme case is a phase shift of 180º produces a reversal of image contrast.

MTF function is an excellent criterion of image quality of thermal cameras. However, interpretation of a curve is more complicated than interpretation of simple numerical parameters. Next, graphical presentation of MTF function was difficult several decades ago when computers were rarely used. Therefore several numerical parameters based on MTF function were proposed in the past to characterize thermal cameras. Nowadays, these numerical parameters are rarely used but still it is useful to know these five numerical parameters related to MTF function:

1. Equivalent frequency (equivalent line number or equivalent bandwidth) N_e,.
2. Half frequency HF,
3. Effective resolution ER,
4. Effective instantaneous field of view EIFOV,
5. Limiting resolution LR.

First, the equivalent frequency N_e is defined as

$$N_e = \int_0^\infty MTF^2(\nu)d\nu \quad , \tag{3.18}$$

where N_e is the equivalent frequency (called also equivalent line number or equivalent bandwidth). N_e is presented using spatial frequency units. The equivalent frequency N_e concept is based on Shade criterion [24], who stated that perceived image quality can be described using the formula (3.18).

Second, the effective resolution ER is defined as

$$ER = \frac{1}{2 \cdot N_e} \quad . \tag{3.19}$$

The effective resolution is presented using angle units (in case of thermal cameras typically millionaires are used).

Third, experiments have shown that perceived image sharpness is closely related to the spatial frequency where MTF is 0.5. This means that the spatial frequency at which MTF drops to 0.5 can be a good indicator of imager quality. This frequency is called the half frequency HF. It is expressed in spatial frequency units.

Fourth, the effective instantaneous field of view EIFOV is defined as

$$EIFOV = \frac{1}{2 \cdot HF} \quad , \tag{3.20}$$

EIFOV is presented in angle units (typically in millionaires).

Fifth, the limiting resolution is defined as spatial frequency at which MTF equals from about 0.02 to 0.05. The definition is based on the fact that humans usually cannot distinguish high contrast sine pattern at frequencies where MTF drops below the level 0.02–0.05. Exact value of the limiting MTF level depends on the observer.

As we can see, determination of these five numerical parameters related to MTF function is quite easy when the latter function is known. However, nowadays in era of computer technology when it is easy to measure, present and store MTF function it is better always to use MTF function as original data. The numerical parameters listed earlier should be used only for comparisons of thermal cameras of different MTF functions when we need to have a simple numerical criterion of comparison.

3.4.3 Parameters based on imager response to point/slit sources

There are three numerical parameters of image resolution that are based on imager response to point/slit sources:

1. Point visibility factor PVF,
2. Measurement spatial resolution MSR,
3. Imaging spatial resolution ISR.

Point visibility factor PVF is defined as normalized centre pixel signal caused by a point source. It is calculated as ratio of the centre pixel signal to the sum of signals generated by the point source in both the centre pixel and the neighbor pixels:

$$PVF = \frac{\text{center pixel signal}}{\text{sum of all pixels}} . \tag{3.21}$$

PVF can be determined using the four step algorithm presented below:

1. Capture an image of a uniform background (Frame 1).

100	100	100	100	100
100	100	100	100	100
100	100	100	100	100
100	100	100	100	100
100	100	100	100	100

Fig. 3.28. Exemplary signal distribution of uniform background image.

2. Capture an image of a point source on the uniform background (Frame 2).

100	100	100	100	100
100	108	130	109	100
100	130	210	128	100
100	120	131	109	100
100	100	100	100	100

Fig. 3.29. Exemplary signal distribution of point source image.

3. Calculate a new frame as the difference of Frame 1 and the Frame 2.

0	0	0	0	0
0	8	30	9	0
0	30	110	28	0
0	20	31	9	0
0	0	0	0	0

Fig. 3.30. Signal distribution after background frame removal

4. Calculate PVF using the formula (3.21). [4]

Both the measurement spatial resolution MSR and the imaging spatial resolution ISR are Slit Response Function related parameters. The measurement spatial resolution MSR is defined as angular slit dimension for which Slit Response Function (SRF) of the tested thermal camera is equal to 0.99. The imaging spatial resolution ISR is defined as angular slit dimension for which the Slit Response Function (SRF) of the tested thermal camera is equal to 0.5.

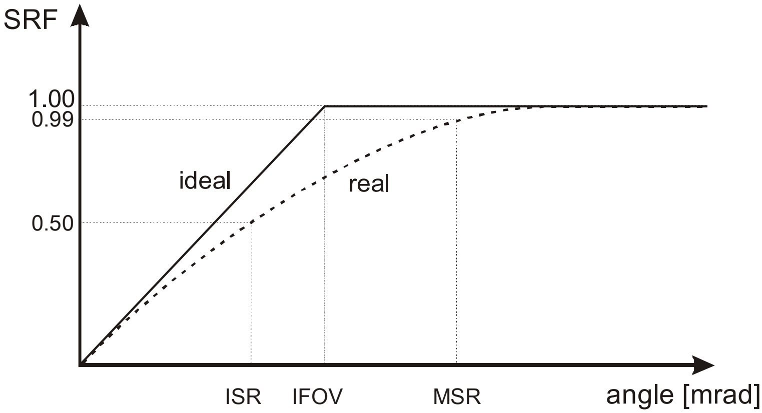


Fig. 3.31. Graphical definitions of MSR and ISR.

The imaging spatial resolution (ISR) is typically found among the parameters of older scanning thermal cameras. ISR is a good measure of camera ability to create a thermal image of small targets. However, this parameter does not give information whether the size of the tested object is high enough to assure negligible influence of this size on measurement results during non-contact temperature measurement. The information is provided by the measurement spatial resolution (MSR). When angular size of the tested object is higher than the measurement spatial resolution, then we can assume that influence of the size of this object on the temperature measurement results is negligible. We can say in other words that if the angular size of the tested objects varies, but is always higher than MSR, then the output temperature will be the same. However, the MSR is usually a few times higher than ISR and manufacturers often prefer to present only the values of the second parameter.

3.4.4 Subjective parameters based on resolution targets

There are myriads of resolution patterns developed during last century to measure resolution of optical instruments, and later to measure resolution of image intensifier systems or television cameras. The USAF 1951 target, the EIA

[4] In the presented above exemplary case we get PVF=0.4.

Resolution Chart 1956, the NBA 1963A Resolution Target can be considered as the most popular targets from this group. These resolution patterns can be potentially also used to characterize resolution of thermal cameras. However, there are some technical problems that make difficult direct use of commercially available resolution targets.

Typical resolution targets offered on the market [32] are manufactured using two techniques: a) translucent targets (chrome pattern on glass substrate), b) opaque targets (printed black pattern on mylar/high quality paper).

The problems is that typical glass substrate does not transmit in spectral bands of thermal imagers. Next, emissivity of printed patterns can be similar to emissivity of the mylar/paper. These reasons create a situation when thermal cameras do not see typical resolution targets and such targets cannot be used for testing thermal cameras.

A new type of USAF 1951 targets was recently introduced on commercial market: so called “the Clear Optical Path USAF target”[32]. Such targets are manufactured from an extremely thin electroformed nickel substrate. Since there is no glass in the pattern area, light travels only through air, eliminating chromatic and absorption issues and can be potentially used for testing thermal imagers. However, the targets are characterized by too low emissivity (about 0.7-0.8) in comparison to typical IR targets of emissivity over 9.96. Next, the reflectivity of such targets is not very high (about 0.7-0.8) and the targets absorb radiation emitted by the blackbody located behind the target in systems for testing thermal imagers. This radiation can change temperature distribution on the surface of the new type USAF 1951 target. Because of these reasons the "Clear Optical Path USAF targets" should not be used for MRTD measurement of thermal cameras. However, these targets can be used for relative comparison of resolution of different surveillance thermal cameras.

3.5 Accuracy parameters

So far we have discussed parameters useful for testing and evaluation of surveillance thermal cameras. In case of this type of thermal cameras, image quality is the most important figure of merit. However, in case of measurement (commercial) thermal cameras high quality thermal image is useful but accuracy of non-contact measurement of temperature is more important.

There are two types of errors of a temperature measurement with thermal cameras: the external errors and the intrinsic errors [4]. Here, we will present parameters of measurement thermal cameras that describe camera performance when only the intrinsic errors are present. Such a situation occurs when emissivity of the tested object is close to unity and a distance camera-object is short. Then, the external errors due to unknown emissivity, reflected radiation and limited atmospheric transmittance can be treated as negligible.

Manufactures of measurement thermal cameras often state a parameter called “accuracy” that is measured as a range around the true object temperature T_{ob} in

which the output temperature T_{out} is located when the external sources of errors are negligible. Typical values of this parameters are: ±1% of the output temperature T_{out} but not less than ±1 °C for scanning thermal cameras, or ±2% of the output temperature T_{out} but not less than ±2 °C for staring thermal cameras.
The term "accuracy", according to the international metrological organizations, is only a qualitative concept that should not be associated with numbers [11]. Therefore the name "accuracy" is improper for formal metrological terminology. However, there are more serious limitations of usefulness of the "accuracy" parameter.

The "accuracy" parameter could potentially enable determination of the intrinsic uncertainty of a measurement thermal camera. Assuming a uniform distribution dispersion of a true temperature within the limits, determined by the "accuracy" parameter, we can write [10]

$$intrisic\ accuracy = \frac{accuracy}{\sqrt{3}} \quad . \qquad (3.22)$$

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

Manufacturers state very rarely at what ambient temperature the "accuracy" was measured. However, typical practice is that the "accuracy" is measured at laboratory conditions when ambient temperature is equal to about 23°C.

During real measurements, the environment temperature can vary significantly within wide limits from about –20 °C to about 40°C. Changes of the environment temperature can have significant effect on the measurement results due to several reasons. First, radiation emitted by the optical elements of the camera depends directly on temperature of these elements and indirectly on temperature of the environment. Second, variation of the environment temperature can cause variation of the detector temperature. Third, changes of the environment temperature cause direct changes of the temperature of the electronic blocks and indirect changes of the gain and the offset of these blocks.

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

There are also several parameters presented in the catalogs of measurement thermal cameras that give some indications about intrinsic errors of thermal cameras: thermal sensitivity, IFOV, and rarely MRTD or MDTD.

Thermal sensitivity called also “thermal resolution”, “temperature resolution” or “ NETD” that provides information about the influence of noise in electrical channel on the measurement errors. It was shown in Ref. 6 that NETD equals the standard deviation of the output temperature dispersion caused by noise of the system. Therefore, the NETD can be treated as a good estimation of uncertainties due to system noise.

However, we must remember that the NETD depends on an object temperature. It is typically measured only for one fixed value of this temperature usually close to 30°C and can be a few times higher for object temperatures at the lower limit of available temperature range close to –20°C.

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

Manufactures of measurement thermal cameras present also MRTD or MDTD functions or values of MRTD/MDTD functions measured for a case of large targets (low spatial frequency).

If the thermal camera is only to be used for non-contact temperature measurement on surfaces of the tested objects, then MRTD and MDTD parameters are practically useless because it is impossible to connect these parameters with the measurement errors of the thermal camera. However, MRTD and MDTD can be useful figure of merits if the cameras are to be used in non-destructive thermal testing (SAARS testing that can be treated as a part of NDTT technology). Image quality is then as important as the accuracy of temperature indications [5,7].

If the information provided by manufacturer is not enough and want to get more knowledge about possible performance of a measurement thermal camera then it is recommended to measure a set of four parameters:

1. Minimal error ME.
2. Noise generated error NGE.
3. Temperature stability TS.
4. Measurement spatial resolution MSR.

As it was discussed in Ref. 4 this set of four parameters is sufficient for characterization of measurement thermal cameras.

The minimum error ME is defined as a range around the output temperature T_{out} in which the true temperature T_{ob} is located when the measurements are carried out in the conditions identical with the conditions during calibration of the thermal camera. The calibration conditions exist when the tested object is a sufficiently large blackbody, the distance between the tested object and the thermal camera is short in order to have negligible influence of limited transmittance of the atmosphere, environment temperature is of typical laboratory range 18°C–25°C, the object is located in the center of the system field of view, measurements are carried out for the shortest temperature span of the thermal camera, and averaging the effect of a dozen or more of measurement results is used. Practically, the minimal error *ME* is an equivalent of the "accuracy" parameters presented in data sheets of measurement thermal cameras.

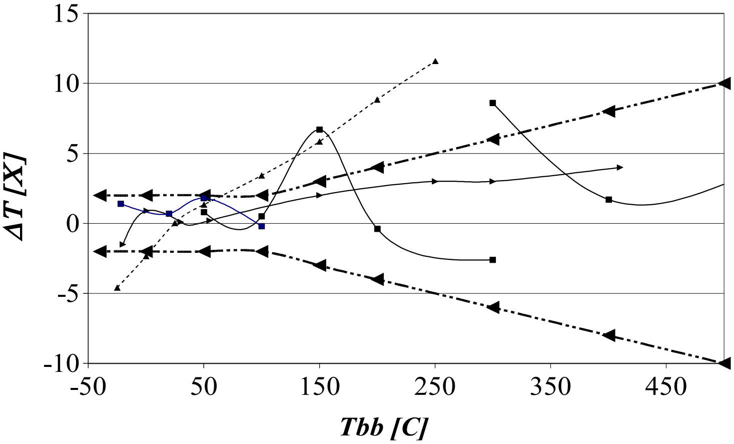


Fig. 3.32. Exemplary measurement error ME of several thermal cameras (squares – camera 1, triangles – camera 2, circles– camera 3, plus signs – limits according to "accuracy" parameter.

The noise generated error NGE is defined as the standard deviation of the output temperature dispersion caused by the system noise. As it was shown in Ref. 6, NGE equals NETD in case of typical thermal cameras (systems of single spectral band). NGE theoretically decreases with an object temperature. Practically, as we can see in Fig. 3.33 it does not always occur due to different reasons. One of them are neutral filters used to extend camera temperature measurement range that cause significant suppression of the signal coming to the detectors and increase in NGE (NETD) value.

The temperature stability TS is defined as a range in which the results of measurements, carried out at different environment temperatures, are located. As we see in Fig. 3.34 this parameter can provide crucial information to estimate ability of tested thermal camera to carry out accurate temperature measurement at real environmental conditions.

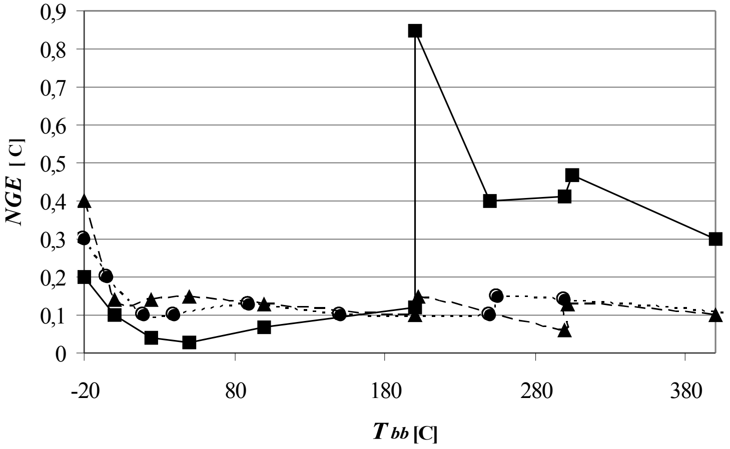


Fig. 3.33. Exemplary NGE measurement results of several thermal cameras.

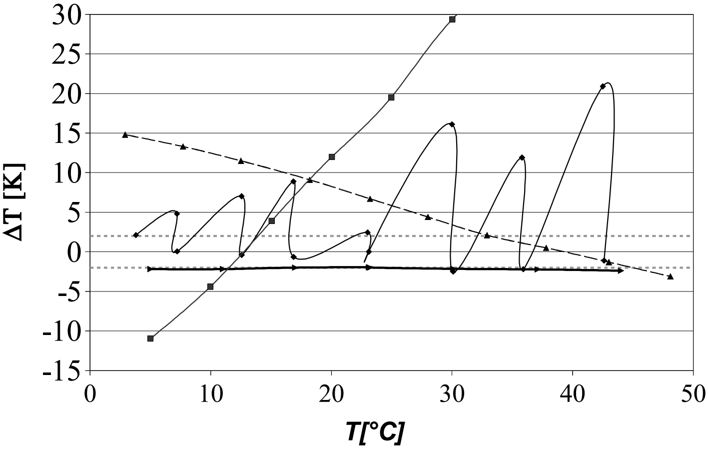


Fig. 3.34. Exemplary temperature stability TS of several thermal cameras (the errors of temperature measurement ΔT of a blackbody of the temperature T_{bb} = 90°C with a few thermal cameras at different temperatures of the environment T).

The measurement spatial resolution MSR is defined as the minimum angular dimension of the tested object when there is still no influence of limited size of this object on temperature measurement results. The MSR parameter is typically measured as the angular slit dimension when the slit response function SRF equals 0.99.

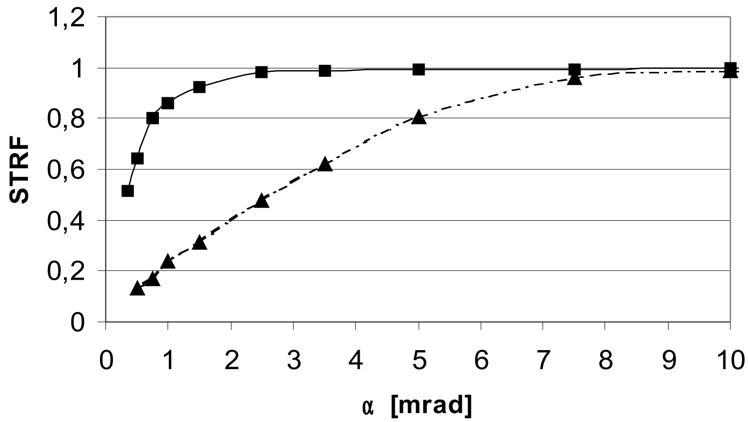


Fig. 3.35. Slit Temperature Response Functions of two exemplary thermal cameras.

As we can see in Fig. 3.35, there can be big differences between measurement resolution MSR of different measurement thermal cameras present on the market. MSR of the first thermal camera shown in Fig. 3.35 equals 3.5 mrad in situation when the MSR of the second camera equals 10 mrad. The first thermal camera can be used for accurate temperature measurement of the targets of size as small as 3.5 mrad, the second- as small as 10 mrad. Therefore is always recommended to carefully check MSR value of a measurement thermal camera before trying to make measurement of temperature of small targets.

3.6 Summary

Over forty parameters of thermal imagers were presented in this chapter. The task of measurement of all these parameters is a very time consuming task even in case of a single thermal imager. Fortunately, probability that a reader of this book will be forced to measure all the parameters presented in Table 3.1 is low, even if the reader is a test professional. Most people actively involved in testing thermal imagers do not even know definitions and test methods of most parameters of thermal imagers shown in Table 3.1. The list of parameters commonly measured during tests of thermal imagers is much shorter than list of parameters discussed in this chapter due to several reasons.

First, MRTD gives information about both temperature sensitivity of tested thermal imagers and about its spatial resolution. At the same time MRTD is the only parameter of thermal imagers presented in several internationally recognized test standards. Therefore, there are some test teams that limits tests of surveillance thermal imagers to measurement of only this parameter. Other subjective image quality parameters like MDTD, TOD, MDTP are measured rarely.

Second, measurements of response parameters are typically limited to measurement of SiTF parameter because it is the only response parameter that is needed to carry out measurement of important noise parameters.

Third, nine components of 3D noise model give the most detail information about noise present in images generated by tested thermal imagers. However, the concept of 3D noise model is not simple and the information provided by this parameter is not easy for interpretation. Therefore almost all users of thermal imagers and majority of manufacturer test teams prefer measurement of more simple parameters like NETD, FPN, non-uniformity.

Fourth, a long series of image resolution parameters are MTF related parameters. If MTF function is measured we can determine almost all other image resolution parameters. Therefore it is logical that the tests of thermal imagers are typically limited to measurement of only MTF function.

Fifth, parameters used to characterize surveillance thermal imagers differ from parameters used to characterize measurement thermal imagers. Therefore typical test teams that specialize in testing surveillance thermal imagers do not need to know definitions and test methods of parameters of measurement imagers like accuracy, NGE, thermal stability, MSR.

Sixth, performance of thermal imagers do not depend significantly on spectral parameters. At the same time these parameters do not typically vary with time. Therefore the spectral parameters are only rarely measured by test teams of manufacturers of thermal imagers; very rarely - by users of these imagers.

To summarize, detail knowledge about all parameters of thermal imagers discussed in this chapter is not needed for both the users and the manufacturers of thermal imagers. Optimal set of parameters to be measured depends on potential use of measured parameters.

In case of users of surveillance thermal imagers the tests are generally carried out to verify potential performance of tested imagers. Due to direct relationship of MRTD parameter and ranges of effective surveillance the tests are often limited to measurement of this parameter. For manufacturers of thermal imagers the aim of the tests is not only to verify performance of the imagers but also to find weak spots of the tested imager that could be potentially improved. At the same time such tests should be carried out with high speed due to time restriction of typical production line. Therefore MRTD measurement is done only for sample imagers in situation when measurement of MTF, NETD, FPN, non uniformity, FOV is carried out at production line.

In case of both surveillance thermal imagers and measurement thermal imagers three different test levels can be proposed: basic, typical, expanded (Table 3.10).

The basic test level can be recommended for users of thermal imagers who are beginners to this technology and are looking for simple methods to verify quality of thermal imagers they purchased or to be purchased.

Table 3.10. Recommended sets of parameters of thermal imagers.

Type of thermal imagers	Test level	Recommended set of parameters
Surveillance imagers	Basic	MRTD
	Typical	MRTD, MTF, SiTF, NETD, FPN, non-uniformity, distortion, FOV
	Expanded	MRTD (or Auto MRTD), MDTD, MTF, responsivity function, NETD, FPN, non-uniformity, distortion, FOV, 3D noise, NPSD, PVF
Measurement imagers	Basic	Minimum Error (“accuracy”)
	Typical	Minimum Error (“accuracy”), NGE, SRF, MRTD
	Expanded	Minimum Error (“accuracy”), NGE, SRF, MRTD, temperature stability

The typical test level is recommended for more advanced users of thermal imagers who want to have detail information about thermal imagers due to different reasons. One of such typical reasons is the possibility of estimation of performance deterioration of tested thermal imagers in order to predict their life time and to create optimal plan of repairing these imagers.

The typical test level is also recommended for manufacturers of thermal imagers who are looking for a test system needed both to verify final quality of manufactured imagers and to get information needed to optimize manufacturing of thermal imagers at production line.

The expanded test level is recommended generally for advanced manufacturers (or R&D) teams who want to get very detail information about tested thermal imagers in order to make design improvements. This test level is particularly recommended if the tested imager is to be used not only for classical surveillance task (surveillance using human observers) but also as a module of automatic target recognition system.

3.7 References

1. ASTM standard E 1213-2002 “*Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems*”
2. ASTM standard E 1311-99 “*Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems*”
3. Bijl Piet, Valeton J, Guidelines for accurate TOD measurement, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing X, SPIE Vol. 3701, 14-25, 1999.
4. Chrzanowski K., Evaluation of commercial thermal cameras in quality systems, Optical Engineering, Vol. 41, No. 10 (2002)

5. Chrzanowski K., Park S.N., Evaluation of Thermal Imagers For Non-Destructive Thermal Testing Applications, Infrared Physics and Technology, 42 (2) 101-105 (2001).
6. Chrzanowski K., Szulim M., A measure of influence of detector noise on temperature measurement accuracy with IR systems, Applied Optics, 37, 5051-5057 (1998).
7. Chrzanowski, J. Fischer, W. Wrona, *Testing of Thermal Imagers For Non-Destructive Thermal Testing Applications, ASTM Journal of Testing and Evaluation*, 28, 395-402 (2000).
8. D'Agostiono, Webb C., 3-D Analysis Framework and measurement methodology for infrared systems noise, Infrared Imaging Systems: Design, Analysis, Modeling and Testing, SPIE Vol. 1448, 110-121, 1991.
9. Driggers Ronald G, Van A. Hodgkin, Vollmerhausen Richard H., O'Shea Patrick , *Minimum resolvable temperature difference measurements on undersampled imagers*, Proc. SPIE Vol. 5076 Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XIV; 2003.
10. *Guide to the expression of uncertainty in measurement*, International Organisation for Standarisation-International Electrotechnical Commission-International Organisation of Legal Metrology-International Bureau of Weights and Measures, TAG 4/WG 3, 1993.
11. *International Vocabulary of Basic and General Terms in Metrology*, International Organisation for Standarisation, 1993.
12. Holst G.C., *Infrared Imaging System Testing*, Vol.4, Chapt. 4 in The Infrared & Electro-Optical Systems Handbook, Michael C. Dudzik ed, SPIE 1993..
13. Holst G.C., *Testing and evaluation of infrared imaging systems*, JCD Publishing Company 1993
14. Holst G.C., *The Infrared & Electro-Optical Systems Handbook*, Vol.3: Electro-Optical System Design, Analysis, and Testing, Chapt. 4, pp. 206-207, SPIE (1993).
15. ISO 15529, *Principles of measurement of modulation transfer function (MTF) of sampled imaging systems*, 1999
16. Jaccobs E., Dynamic MRTD simulation, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XI, SPIE Vol. 4030, pp.70-76, 2000.
17. Lloyd J., *The Infrared & Electro-Optical Systems Handbook*, Vol.3: Electro-Optical System Design, Analysis, and Testing, Chapt. 1,SPIE (1993).
18 MIL-I-24698(SH), Infrared thermal imaging systems, Department of Defense USA (1988).
19. MIL-STD-1859: Thermal Imaging Devices, Performance Parameters Of, 1983.
20. MIL-T-49381 Test Set, Thermal sight TS-3681/VSG, USAERADCOM (1980)
21. Miller Scott J., Backer Brian S., Kohin Margaret, Alonso Pascual, Whitwam Jason T. , Test methods and technology for uncooled imaging systems, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XV,SPIE Vol. 5407, 30-37, 2004.
22.Night Vision Thermal Imaging Systems Performance Model, User's Manual & Reference Guide, U.S Army Night Vision and Electronic Sensors Directorate, AMSEL-RD-NV-MS-SPMD, 2001.
23. Pieper R., Cooper A., Celik M., Kenter Y., Objective MRTD experimental measurements compared with predictions based on the visibility model, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XIV, SPIE Vol. 5076, p. 196-207, 2003.
24. Schade O. (1948). Electro-optical parameters of television systems. 1. parameters of vision and visual systems. *RCA Review*, 9: 5-37.
25. Sousk S., O'Shea P., Van Hodgkin A., Measurement of uncooled thermal imager noise, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XVI, SPIE Vol. 5784, 301-308, 2005
26 Sousk S., O'Shea P., Van Hodgkin A., Uncertainties in the minimum resolvable temperature difference measurement, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XV, SPIE Vol. 5407, p. 1-7, 2004.

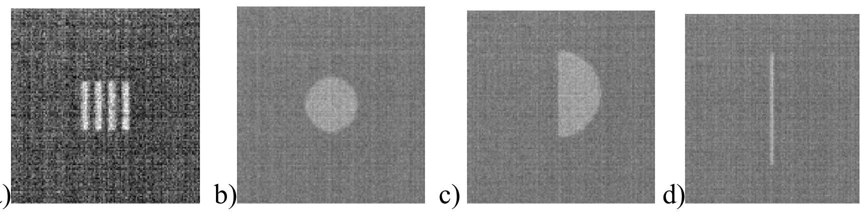
27. STANAG 4349, *Measurement of minimum resolvable thermal difference (MRTD) of thermal cameras*, 1995.
28. Webb C., Holst G., Observer variables in minimum-resolvable temperature difference, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing III, SPIE Vol. 1689, 1992.
29. Wittenstein W., Minimum temperature difference perceived—a new approach to assess undersampled thermal imagers, Opt. Eng., Vol. 38, 773, 1999.
30. Wittenstein W., Thermal range model TRM3, Infrared Technology and Applications XXIV, SPIE, Vol. 3436, p. 413-424, 1998.
31. Wood L., Laboratory Bench Analysis of Thermal Imaging Systems, Opt. Eng., 15, G193-G197 (1976).
32. www.edmundoptics.com

4 Test equipment

Some information about structure and requirements on equipment for testing thermal imagers can be found in international standards that regulate testing thermal imagers [1,2, 17,19]. However, real value of this information is rather limited due to small size of these standards, lack of many important details, some out-dated recommendations. More useful information can be found in some specialized literature sources like Refs. 10,11. However, the most valuable information about test equipment can be get from analysis of real test systems offered by manufacturers of equipment for testing thermal imagers [24,26,29,30,32]. Here in this chapter conclusions from such an analysis are presented. Due to limitations in information access most detail technical information refers directly to test equipment from a single manufacturer: Inframet [30]. However, there are no basic differences in test systems from different manufacturers; only minor technical details. All properly working test systems, independently of the manufacturer, should generate the same measurement results. Therefore the information about equipment for testing thermal imagers presented in this chapter should be generally valid for all test systems available on international market.

4.1 Types of test systems

The task of a test system for testing thermal imagers is to generate images of some standard static targets of precisely known shape, dimensions and temperature. These images can be projected to the tested thermal imager by the test system or viewed directly by the tested imager. In both cases the tested imager generates distorted copies of the original targets images. Next, the images generated by the tested imagers are evaluated and important characteristics of the tested imagers are determined.



a) b) c) d)

Fig. 4.1. Images of standard targets used during testing thermal imagers a)4-bar target, b)pinhole target, c)edge target d)slit target.

Technically we can formulate four basic requirements on a test system for testing thermal imagers:

1. Ability to simulate targets of different geometrical shape (needed to measure different parameters of thermal imagers),
2. Ability to regulate precisely angular size of simulated targets (in order to simulate changes of distance at real conditions),

3. Ability to regulate precisely temperature difference of the simulated target in comparison to background temperature (needed in order to simulate variable contrast of thermal targets at real observation conditions),
4. Ability to simulate targets located at distance bigger than minimal focus distance of the tested imager (typical work conditions).

The requirements mentioned above can be fulfilled by several types test systems built using three different test principles:

1. variable target test systems (Fig. 4.2, Fig. 4.3),
2. variable distance test systems (Fig. 4.4,Fig. 4.5, Fig. 4.8),
3. variable target/distance test system (Fig. 4.6, Fig. 4.7).

The variable target test systems(Fig. 4.2, Fig. 4.3) project images of targets fixed to a rotary wheel using an reflective collimator as an image projector. The tested thermal imager is located at the output of IR collimator and the target is located at the collimator input (the focal plane). The distance between the target and the tested imagers is very short. The distance is typically no more than about 4 meters if we analize the optical ray way and the distance is usually not within the focusing range of typical surveillance thermal imagers. However, due to use of the collimator as an image projector the imager "sees" the target as a very long distance object that is within imager focusing range. Next, a series of targets is fixed to rotary wheel. By rotating the wheel it is possible to exchange quickly targets. By changing target dimensions the changes of distance are simulated.

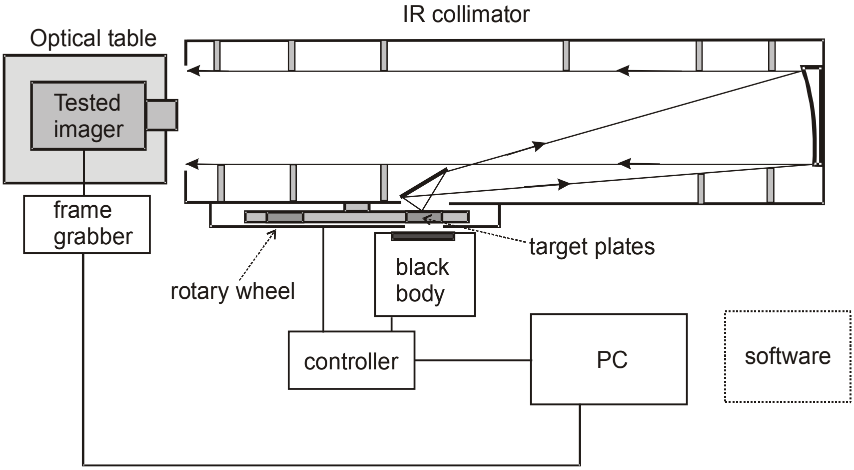


Fig. 4.2. Diagram of the variable target test system (image projector).

Fig. 4.3. Photo of the DT 1500 variable target test system (courtesy of Inframet www.inframet.com)

The variable distance test systems (Fig. 4.4,Fig. 4.5) generate a thermal image at the plane of the target fixed to a large area blackbody. The tested thermal imager sees this image directly and generates a distorted copy of the image generated by the test system. Because the variable distance systems do not use a collimator during the tests then the distance between the target of the test system and the tested imager must be long enough to have the measuring system within the focusing range of the tested imager. This means that the test system must be always located at distances longer than the minimal focus distance of the tested imager. In case of surveillance thermal imagers the latter value vary from about 5 m to about 50 m. This means that the tests cannot be carried in small rooms but should be carried out in the field or at indoor conditions using long corridors.

The size of the targets simulated by variable distance test systems must be big enough to enable simulation of big objects (low spatial frequency 4-bar targets) when the distance test system-tested imager is equal to minimal focus distance of the tested imager. Practically this means that due to long distance between tested imager and the test system (from about 5 m to about 50 m) large area blackbodies and large IR targets (sizes over 200 mm in most cases) are needed for variable distance test systems. Therefore both blackbodies and targets used for variable distance test systems are several times bigger than blackbodies/targets needed for typical variable target test systems (sizes between about 50 mm to 100 mm).

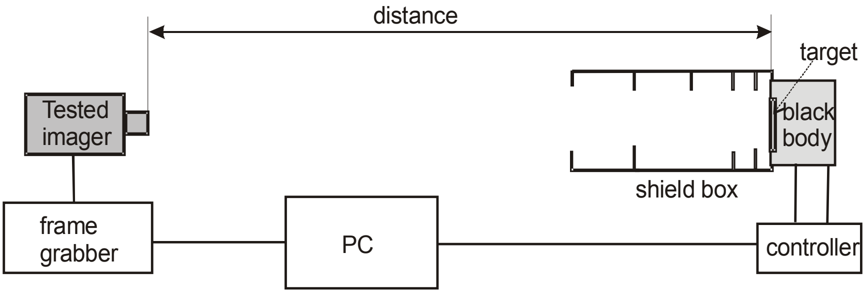


Fig. 4.4. Diagram of the variable distance measuring system.

Fig. 4.5. Photo of the LAFT mobile variable distance test system (courtesy of Inframet www.inframet.com).

The variable target/distance test systems (Fig. 4.6, Fig. 4.7) are practically the variable target test systems without an IR collimator to project a thermal image generated by a set: target/blackbody. Because there is no collimator and the generated thermal image must be seen directly by the tested thermal imager then the distance tested imager - test system must be bigger than minimal focus distance of the tested imager. At the same time typical commercially available rotary wheels are adapted to use target of small size (typical diameter about 50 mm) and the distance target-imager must be short if typical imager is to "see" small details of the target. This creates situation when only thermal imagers of short minimal focus distance can be tested using the variable target/distance test systems. Commercial thermal imagers are designed for observation of short distance targets (minimal focus distance is typically about 0.5m) and such imagers can always be tested using the discussed group of test systems. However, most surveillance (military type) imagers design for observation of long distance targets cannot not be tested using the variable target/distance test systems due to much longer minimal focus distance (typically over 5m). When the distance imager-target is over the minimal focus distance of the imager then we cannot carry out parameters of measurement procedures that require simulation of big targets.

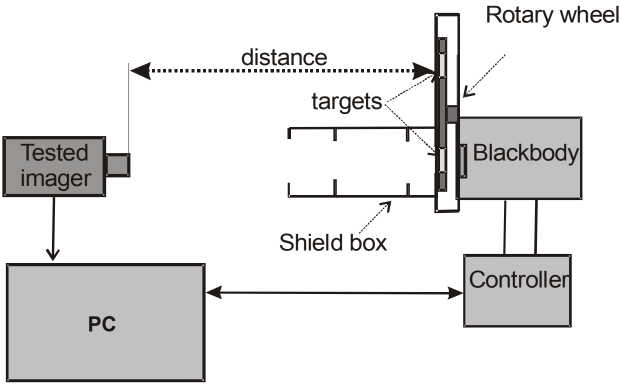


Fig. 4.6. Diagram of the variable target/distance measuring system.

Fig. 4.7. Photo of the SAFT variable target/distance measuring system.

All three types of earlier presented types of test systems posses some advantages and disadvantages.

The variable target test systems (or variable target projectors) of configuration shown in Fig. 4.2 can be considered as classical systems for testing thermal imagers. Due to high thermal inertia, use of baffles in the collimator, motorized rotary wheel, and the fact that they are mostly used in laboratory conditions they are characterized by very good stability and measurement accuracy.

Any thermal imager is able to focus on optical infinity distance simulated by the collimator. Therefore all types of thermal imagers (surveillance or commercial, short distance of long distance) can be tested using these test systems (on condition that the aperture of the imager optics is smaller then output aperture of the collimator). Big size of these systems (mostly due to the use a collimator) is main drawback of the variable target test systems. Even in case of smaller collimators it is difficult to use such a test system outside laboratory due transport problems and necessity to align tested imager with the collimator output.

The variable distance test systems of configuration shown in Fig. 4.4 represent a class of test systems of much more compact design than in case of variable target systems. Collimators and rotary wheels are eliminated. Because of small size and mass these systems are excellent measuring tools at field/depot applications when number of parameters to be measured is limited. They can be packed in a large suitcase and easily transported to any location. Therefore, these test systems are very good tool for comparison of quality of different thermal imagers offered by different manufacturers. Next, it is possible to test thermal imagers from some distance, and as a consequence, the thermal imager can be tested without removing it from the mechanical carrier (tank or helicopter). Further on, several thermal imagers can be tested at the same time using a variable distance test system (Fig. 4.8). Another advantage of variable distance systems is the fact that there is no limitation on aperture of the tested cameras (in case of the previously discussed group (image projectors) the aperture of the tested thermal camera must be at least about 10% smaller than aperture of the IR collimator).

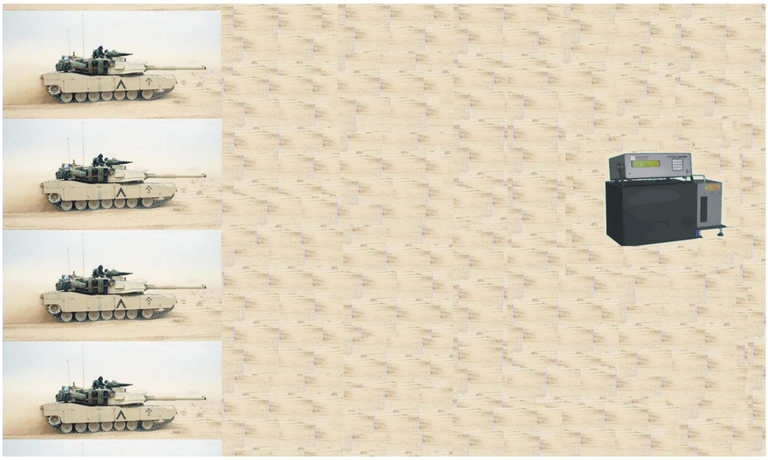


Fig. 4.8. Concept of group testing using variable distance test system.

Low offset phenomenon is another big advantage of variable target test systems. In case of variable target test systems it was is possible to measure directly targets temperature because the targets are movable parts. Only indirect temperature measurement methods are possible. This indirect temperature measurement method is one of the biggest source of creating the so called "offset" of blackbody indication of differential temperature. In case of variable distance test systems the target temperature can be measured directly or at least the temperature sensor has a very good thermal contact with the target plate. Therefore the offset of variable distance test systems is much smaller than in case of variable target test systems. Next, the offset is more stable if measurements are done at relatively stable ambient temperature (the system is not exposed to sun, wind, ambient temperature changes are slow).

There are also several serious disadvantages of variable distance test systems. First, large blackbodies and large targets and needed. This makes speed of regulation of blackbody temperature significantly lower than in case of smaller blackbodies used by variable target test systems. There also technical problems to assure required high thermal uniformity and temporal stability of bigger blackbodies. Second, large rooms or corridors are needed if the tests are to be carried out in indoor conditions. It is not so easy to find a 50-m long corridor that is sometimes needed to test a surveillance thermal imager. Third, the test system requires some kind of protection against environmental condition (wind, rain, sun) if they are to be used at outdoor conditions. Fourth, expanded tests (measurement of a long series of parameters) of thermal imagers can be done using the variable distance test systems but the test procedures are not as user friendly as in case of the variable target test systems.

The variable target/distance test systems represent a mixture of two earlier presented test concepts.

Their main advantage is lower costs and lower mass due to elimination of the collimator in comparison to variable target test systems. The disadvantage is the fact that the systems can be used only for testing thermal imager of very short minimal focus range like typical commercial (measurement) thermal imagers.

Summary comparison of the presented three groups of test systems for testing thermal imagers is presented in Table 4.1.

Table 4.1. Comparison of different types of test systems.

	Variable target test systems	Variable distance test systems	Variable target/distance test systems
Design structu-re	IR collimator, rotary wheel, small blackbody, set of small IR targets, PC, frame grabber, software	large blackbody, set of large targets, shield box, portable PC, frame grabber, software	rotary wheel, small blackbody, set of small IR targets, shield case, PC, frame grabber, software
Advanta ges	classical mature design, high measurement accuracy, all types of thermal imagers can be tested	compact design, possibility to use outside laboratory, low cost	lower cost than in case of variable test system, compact design
Dis-advanta ges	difficulties to use outside laboratory, limitation on aperture of optics of the tested imager, high cost	Large rooms/corridors needed for indoor application, non-convenient in case of expanded tests	suitable only for imagers of short focus distance

On the basis of earlier presented analysis of features of three different types of test systems the recommendations on optimal application are presented in Table 4.2 .

Table 4.2. Recommended application area of different types of test systems.

	Recommended applications	Not-recommended applications
Variable test system	expanded testing of surveillance thermal imagers at laboratory conditions	tests at field conditions
Variable distance test systems	Simplified tests of portable thermal cameras at indoor conditions using long corridors Simplified tests at field conditions	expanded tests of surveillance thermal imagers
Variable target/distance test system	tests of measurement (commercial) thermal imagers	tests of long range surveillance imagers

4.2 Blocks of test system

First thermal imagers were designed for military applications to enable observation of long distance targets. Minimal focus distance of these imagers was often more than 100 m. Therefore testing of such imagers was possible only using variable target test systems that used a collimator as an image projector. Now, due to presence on the market of a large number of thermal imagers designed also for short distance surveillance or for non-contact temperature measurement it is often possible to use other two types of test systems (variable distance systems or variable target/distance systems) for testing modern thermal imagers. However, the classical variable target test system is typically the preferred choice. It can be estimated that over 90% of systems used all over the world for testing thermal imagers are variable test systems. At the same type the other two types of test systems can be treated as simplified versions of the variable target test system. Therefore, from now we will concentrate only on variable target test systems and will discuss in detail only blocks of these test systems.

The variable target test systems are built from the following blocks:

1 Collimator,
2 Blackbody,
3 Rotary wheel,
4 Set of targets,
5 PC,
6 Frame grabber,
7 Test software.

A set of the standard targets (metal sheets with holes) is fixed to the rotary wheel placed at the focal plane of the collimator. One of the targets is within the field of view of the collimator (we can call it the active target). The differential blackbody is located close behind this target. The temperature distribution on the target surface and the blackbody is projected by the collimator to the tested thermal camera and image of the active target is generated by the tested imager. Next, the image is evaluated by an observer or the image captured and analyzed with help of specialized hardware/software module.

4.2.1 Collimator

Collimators are typical elements of laboratory set-ups used for testing thermal imaging systems. The function of the collimator is to generate a thermal image closely resembling the thermal scene at the target plate located at collimator focal plane.

4.2.1.1 Collimator structure

Reflective two mirror collimators built using an off-axis parabolic collimating mirror and a smaller directional flat mirror represent a typical design of the collimator to be used in systems for testing thermal imagers. The reflective collimators like the collimator of diagram shown in Fig. 4.9 dominate the market because of several reasons:

1. Very high manufacturing costs of large size infrared refractive objectives needed to built refractive collimators,
2. High polychromatic aberrations of the refractive collimators. Non-existence of polychromatic aberrations in case of reflective collimators,
3. Wide spectral range of reflective collimators.

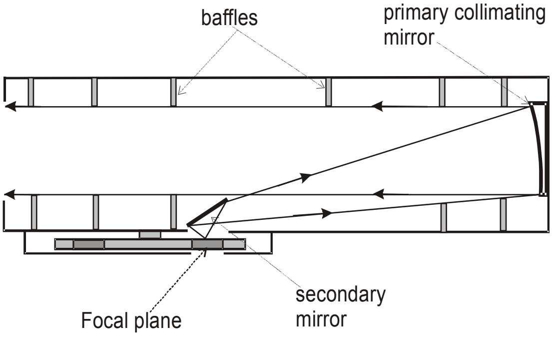


Fig. 4.9. Diagram of typical reflective off-axis collimator.

Mirrors used in reflective collimators are almost always front-surface mirrors of configuration shown in Fig. 4.10 and the back-surface mirrors are excluded from further discussion. The front-surface mirrors consist of three basic elements: substrate, reflective film and protective layer.

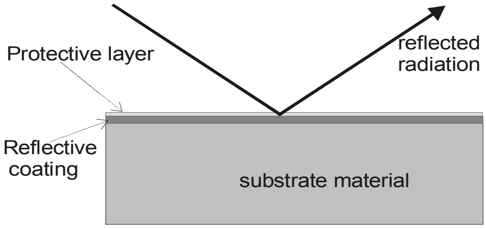


Fig. 4.10. Front-surface mirror.

4.2.1.2 Requirements

The task of the collimator is to project with negligible distortion an image of temperature distribution on the target plate located at the collimator focal plane into direction of the tested thermal imager. The condition on negligible distortion can be fulfilled only when certain requirements on four parameters of IR collimators:

1. Resolution,
2. Aperture,
3. Spectral range/transmittance
4. Thermal properties

are fulfilled.

A. Resolution

According to a popular myth the function of the collimator is to generate a parallel ray beam in direction of the tested imager. Practically, the collimator does not generate a single parallel ray beam; it generates an infinite number of parallel ray beams in different directions. The true task of the collimator is to generate a thermal image closely resembling the temperature distribution at the target plate located at collimator focal plane. In its ultimate form, an ideal collimator would be capable of generating a radiation pattern that exactly reproduces the real temperature distribution of the target plate. However, such quality is unattainable. Instead, a practical design condition should be adopted, based on the requirement that the collimator spatial resolution should match the spatial resolution capabilities of the tested thermal imager. We should remember that collimators of too low quality can become a source of significant measurement errors; collimators of too high quality can unnecessarily increase cost of the test system.

Manufacturers of IR collimators use different ways to characterize performance of these optical instruments and there is a confusion in area of evaluation methods.

First, accuracy of manufacturing of the collimating mirror is often presented as a collimator parameter [35]. Values of proclaimed surface accuracy of mirrors used to built IR collimators vary in quite wide range from about $\lambda/2$ to $\lambda/12$. However, manufacturing accuracy of the mirrors is not very useful as criterion of overall quality of collimators for testing thermal imagers.

Generally, perfect mirrors do not necessary mean that the collimator generates a perfect image. Very precise alignment of these two collimator mirrors is required to obtain the maximal theoretically possible performance. Next, precision, zero thermal-expansion optical and mechanical elements must be used in collimator design. Further on, even small imperfections of mirrors coating or simply dust can degrade quality of images projected by the collimator. Finally, we must remember that the off axis parabolic mirrors are aberration free only at their focus point; not for entire area of the target located at the focal plane. Practically this means that information about mirror manufacturing accuracy does not give precision information about overall collimator performance. Practically, increasing manufacturing accuracy of the collimating mirror does not always increases the collimator performance but always increases manufacturing costs of the collimator.

Second, collimator manufacturers often claim that the collimator is diffraction limited [25,27,34]. This claim suggests that the collimator is perfect. Practically such a claim can be very misleading.

Let us look on the diffraction limited target frequency values for typical collimators produced by a calculator available at a website of one of manufacturers of equipment for testing thermal imagers [28].

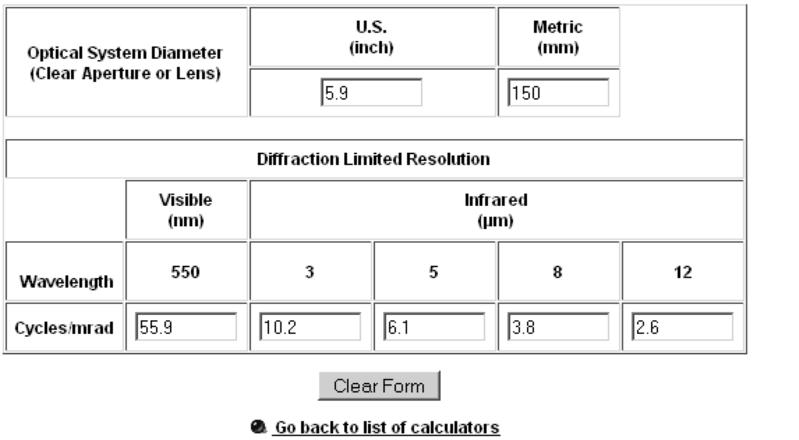


Fig. 4.11. Window of a calculator of diffraction limits[5].

The diffraction limits of several collimators calculated using this website calculator are shown in Table 4.3.

Table 4.3. Diffraction limited target frequency values (in lp/mrad) for collimator of different optical apertures.

Aperture / Wavelength	100 mm	150 mm	200 mm	250	300 mm
5µm	4.1	6.1	8.2	10.2	12.3
12 µm	1.7	2.6	3.4	4.3	5.1

[5]http://www.electro-optical.com/eoi_page.asp?h=Diffraction%20Limits

As we can see in Table 4.3 values of diffraction limited target frequencies of typical collimators are low; actually very low. Table 4.3 suggests that resolution of even big collimators (aperture about 250 mm) during tests of LW thermal imagers is below 5 lp/mrad due to diffraction limit of the collimator. This means that using typical off axis reflective collimators for projecting images of targets of frequencies over 5 lp/mrad we should always get blurred images of these targets generated by the tested LW thermal imagers. Such situation should occur even if the tested imagers is perfect because the collimator is the limiting factor. It is not true as the author of this book tested some long wavelength thermal imagers that generated sharp images of targets of frequency over 10 lp/mrad; clearly over the suggested diffraction limit of the collimators.

The situation described above is possible because the manufacturer [28] used to calculate the values of limited target frequency v_{max} using the most pessimistic formula met in literature. The limited target frequency v_{max} is calculated generally using this formula:

$$v_{max}[1/\text{mrad}] = \frac{D[\text{cm}]}{x \cdot \lambda\,[\mu\mu\text{m}} \tag{4.1}$$

where: D is the collimator aperture, λ is the wavelength, and x is the coefficient. The manufacturer [28] used the coefficient x equal to 2x2.44= 4.88 in a situation when it is possible to find literature sources where the x coefficient equals one. Therefore the values of diffraction limited target frequencies presented in Table 4.3 are so low. The practical consequence of using formula (4.1) or the web calculator [28] is very big relaxation of requirements on so called "diffraction limited" collimator. Even collimator built using poorly manufactured and poorly aligned mirrors can be treated as so called "diffraction limited collimator".

As we can see defining collimator quality using the diffraction limit as a reference is a risky solution because the diffraction limits can be defined in different ways. Next, this approach is also logically wrong. We must remember than collimator is always used as a module of a system. The tested thermal imagers is a module of the same system, too. Aperture of the tested imagers is always smaller than the aperture of the collimator. This means that quality of the final image generated by the tested thermal imager is degraded by imager aberration blur, imager diffraction blur and collimator aberration blur. Therefore resolution of the collimators used in real test systems is truly limited only by aberration effects.

Third, interferometric methods are typically used for quality checking of mirrors. These methods are also sometimes used for aligning components of reflective off axis collimators and for characterization of overall collimator quality. In opinion of the author of this book, the interferometric methods are useful during aligning process but present misleading results when we want to evaluate overall collimator quality. The data presented in this form: “wavefront accuracy of the collimator output= λ/8 at 630 nm” suggest a perfect collimator capable to project perfect images not only in infrared range but also in visible range. Practically this information is truly valid only in case of spot targets where the small spot is located exactly at the collimator focus or in case of the center point of bigger test patterns. In case of low F-number off-axis parabolic collimators image quality of projected big targets or targets located outside the collimator focus can be much lower that the interferometric data suggest.

To summarize, mirrors accuracy, diffraction blur or collimator wavefront accuracy should not be used as criteria of collimator quality. They all can be misleading parameters. These parameters should be treated as indicators of possible collimator quality. However they are not the parameters that would give warranty about quality of collimator at user hands. Collimators should be characterized using a parameter called spatial resolution that depends on aberration blur and this parameter should be measured at final user facilities.

Such a precise condition on quality of IR collimator was proposed in Ref. 5. The collimator spatial resolution v_{col} was defined as the frequency of the smallest bar pattern projected by the collimator that the observer is able to recognize. The resolution of the tested imager was defined as the Nyquist frequency v_N that determines thermal imager theoretical limit.

It was shown in Ref. 5 that to have collimator influence on degradation of image generated by tested thermal imager negligible then the collimator resolution v_{col} must be at least 5 times better than the thermal imager resolution v_N

$$v_{col} \geq 5 \cdot v_N \ . \tag{4.2}$$

The spatial resolution v_N defined as Nyquist frequency of the thermal imager can be calculated using data provided by the manufacturers using this formula

$$v_N [mrad^{-1}] = \frac{N}{2 \cdot FOV[mrad]} \ , \tag{4.3}$$

where N is the number of pixels in horizontal (or vertical) direction of FPA used in imager design, FOV is imager field of view in horizontal (or vertical) direction.

The spatial resolution of the collimator v_{col} cannot be calculated but it can be measured. It can be done using a measurement method that was proposed in Ref. 5. The method is based on an idea to carry out measurement of collimator spatial resolution in visible spectral range because geometric aberrations of typical reflective IR collimators do not change with a spectral range. It is also extremely important that the measurements should be carried out not only when the resolution targets located exactly in the collimator focus point but in several position located within a circle around the focus point. It is suggested that the diameter of such the circle should be at least 14 mm (the area wide enough for a typical multi-pattern target). If such tests are carried out then we get information about real capabilities of tested collimator to project high quality images.

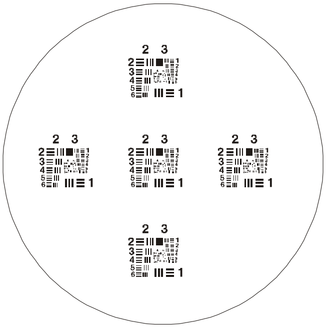


Fig. 4.12. Multi-USAF 1951 target recommended for measurement of resolution of collimators.

Experiments carried out by the author of this book with infrared collimators used in different test systems[6] showed that the center spatial resolution of these collimators varied significantly from about 30 lp/mrad to over 300 lp/mrad. The reasons for this significant dispersion of resolution of infrared collimators are different: aging processes, manufacturing errors of the mirrors, alignment errors, deterioration of coating properties, dust on mirror surfaces etc. Now, let us check if such collimators can be used as important blocks of measuring systems for testing thermal imagers. We can easily calculate the minimal acceptable collimator resolution using formula (4.2) and some basic data of several thermal imagers.

The calculation results are shown in Table 4.4. We can make two basic conclusions from the data presented in this table.

First, the requirements on spatial resolution of IR collimators significantly depend on a field of view of the tested thermal imagers . The requirements are very low in case of imagers working in wide field of view mode but they are many times higher in case of the same imagers working in narrow field of view mode.

Second, in case of testing short/medium range thermal imagers the collimators of resolution at 25 lp/mrad can be considered as acceptable. Collimators of resolution about 50 lp/mrad enable to carry out tests of all short/medium range thermal imagers and majority of long range thermal imagers. Please note that such collimators are acceptable even in case of LW IR imagers of very narrow FOV built using very large optics (240 mm) like Thermovision 2000 (FLIR Inc). Reflective collimators of spatial resolution in the region 70-100 lp/mrad are recommended for testing long range imagers of very narrow field of view designed using very large optics and 640x480 (or higher) resolution FPA.

To summarize, we can say that manufacturing of collimators for testing short/medium range thermal imagers of wide/medium field of view is relatively easy; manufacturing good collimators for testing medium/long range thermal imagers of narrow field of view much more difficult as the required spatial resolution

[6] Attention: The warranty period of most of the tested collimators expired but the collimators are used usually many time over the warranty period.

of the collimator is several times higher. However, a real challenge in field of reflective collimators is not to design a collimator to be used for testing typical surveillance thermal imagers as listed in Table 4.4 but to design a collimator to be used for testing space CCD cameras. The requirements on spatial resolution of collimators for testing such CCD cameras are at least five times higher than for collimators to be used even for testing best thermal imagers. Design of collimators for testing space imagers is a true technical art where many small details like type of mirror mount are of utmost importance and there are special requirements on room where the collimator is to be used. In case of collimators for testing thermal imagers the situation is much easier but still it is always recommended for users of collimators to calculate required spatial resolution of the collimator using formula (4.2) and to verify this condition by practical tests to be sure that the collimator projects the images of proper quality during tests of thermal imagers.

Table 4.4. Requirements on spatial resolution ν_{col} of IR collimators to be used in testing different thermal imagers.

Thermal imager	FOV (HFOVxVFOV)	FPA	ν_N [lp/mrad] (horizontal)	Required ν_{col} [lp/mrad]
Elvir (Thales Angenieux)	FOV: 8°x6° (140mrad x105mrad)	320×256	1.14	5.7
Thermovision 2000 (FLIR Inc)	WFOV: 25°x18° (436x314 mrad)	320×240	0.37	1.85
	MFOV: 6°x4.32° (105x75.3mrad)		1.52	7.6
	NFOV: 0.98°x0.71° (17.1x12.4mrad)		9.36	46.8
Matiz long range (SAGEM)	WFOV: 6.53°x4° (114x69.8mrad)	640×480 (micro-scanning)	2.8	14
	NFOV: 1.36°x0.91° (23.7x15.9mrad)		13.5	67.5
Ultra 275C (FLIR Inc)	WFOV: 18°x13° (314x227mrad)	320×240	0.5	2.5
	NFOV: 4°x2.89° (69.8x50.4mrad)		4.6	23
TV camera for space program	FOV = 1.6°	4000 pixel linear CCD detector,	70	0

HFOV- horizontal Field Of View VFOV – vertical Field Of View

B. Aperture/Focal length

Collimator aperture is the diameter of the maximal ray beam that can be generated by the collimator when a point source is used. It is strictly needed for proper testing that a collimator aperture must be bigger than a diameter of the optics of the tested thermal camera. It is recommended that the collimator aperture should be at least 10% bigger than the diameter of the optics of the tested thermal camera. If this condition is not fulfilled then additional errors of measurement of parameters of thermal cameras are generated.

Diameters of optics used in modern thermal cameras varies greatly: from 10-30 mm diameter objectives typically used in commercial thermal cameras up to 200-250 mm diameter objectives used in some ultra long range surveillance thermal cameras. Therefore only big collimators of apertures of about 300 mm can be used for testing all thermal cameras available on the market. However, bigger collimator means also more expensive, more bulky instrument. At the same time we should remember that thermal cameras of optics diameter of over 130 mm are very rarely met (no more than about 1% of the market, probably much less). We can expect also some problems when testing thermal cameras of wide field of view with small optics (like commercial thermal cameras) using big collimator of long focal length. Even the biggest targets can be small for the tested imager and measurement of MRTD at low spatial frequency cannot be carried out. .

Therefore it seems that collimators of aperture of about 150-200 mm represent an optimal choice. Such collimators enable testing almost all thermal cameras available on the market. In case when test area is limited to cameras of small aperture then smaller aperture collimators can be used (aperture of about 100mm).

F-number (ratio of focal length to aperture) of collimating mirrors used in IR collimators vary from about 5 (low F-number collimators) to about 12 (high F-number collimators). This means that focal length of collimators of the same aperture but of different F-number will vary significantly. For example, in case of 150-mm aperture collimators of variable F-number from 5 to 12 the focal length varies from 750 mm to 1800mm.

There are advantages and disadvantages of both types of the collimators. Low F-number collimators are characterized by small size that enables to decrease dimensions of the complete test system. However, thermal stability of low F-number collimators is lower than in case of high F-number collimators. Next, manufacturing mirror accuracy is usually better in case of high F-number mirrors. However, the most important disadvantage of low F-number collimators are significant geometrical aberrations that occur for off-axis spots (Fig. 4.13). This means that they project a perfect image of a small spot 4-bar target located in the center of a collimator field of view but an image of several 4-bar targets located outside the center can be blurred.

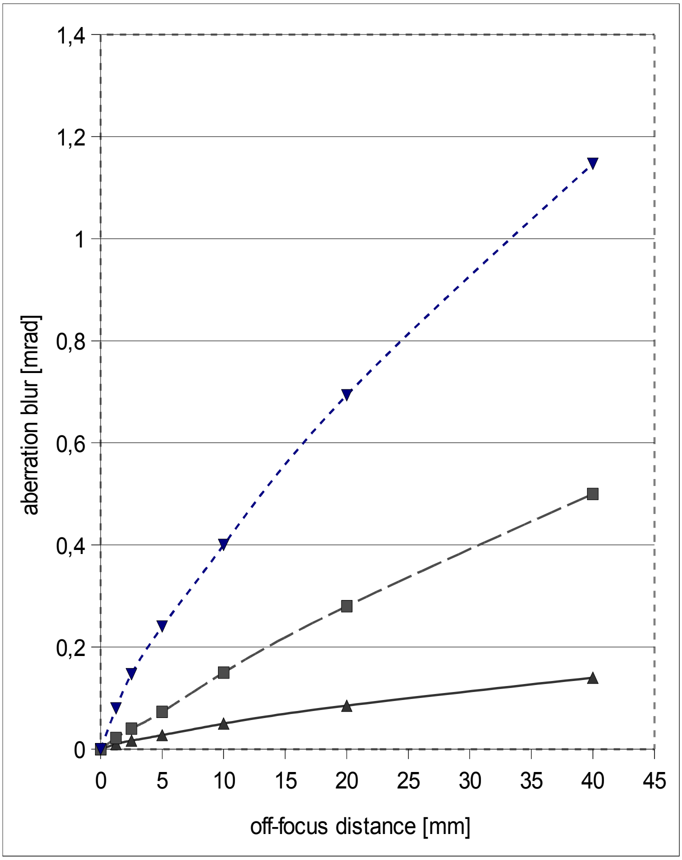


Fig. 4.13. Aberration blur versus off axis distance for several reflective off axis collimators of 150mm aperture and different F-number (F=5 - triangles down, F=6.6 - squares, F=10 - triangles up)[7].

To summarize, if small size and mass is important then low F-number collimators of short focal length should be preferred. If high quality of the images projected by the collimator in its entire field of view is important then high F-number collimators of long focal length are recommended. However, in most cases when the requirements on collimator spatial resolution are not high then both low F-number collimators and high F-number collimators can project images of sufficient quality and the test results get using both two types of collimators are the same.

C. Spectral range/transmittance

IR collimator must projects thermal radiation emitted by the blackbody and targets located in its focal plane at least within the spectral range of the tested

[7] Aberration blur was calculated as a angular diameter of a rectangle detector getting 71% energy of a ideal point source.

thermal imager. This means that spectral range of IR collimator must cover at least two spectral bands used in thermal imaging: MWIR band (3-5 μm) and LWIR band (8-14 μm); preferable also the third band: SWIR band (1-3 μm). Therefore we can conclude that for testing thermal imagers we need collimators of a spectral range that covers at least the region from 3 μm to 15 μm, preferably from 1 μm to 15 μm. If the collimator is to be used also for testing visible imaging systems then the collimator is required to project radiation in the spectral range from 0.4 μm to 15 μm.

Spectral range of the reflective collimators is determined by coatings of the mirrors. Metallic coatings are typically used as reflective coatings in IR mirrors. There are three types of most often used metallic coatings: aluminum, silver and gold. All three types offer high reflectivity over about 95% in the spectral range of interest: 1-15 μm. As it was discussed earlier all mentioned above coatings need some kind of dielectric overcoat that arrests the oxidation process or improves its mechanical properties.

Gold offers consistently very high reflectance (about 99%) from about 0.8 μm to about 50 μm. . Silver offers slightly lower reflectance (about 97%) but broader spectrum from 0.3 μm to over 20 μm. Aluminum coatings are characterized by lower average reflectivity (about 95%) and a certain reflectivity drop in near infrared. From the other point of view the aluminum coatings are characterized by the best durability and the lowest costs. Additionally, reflectance of aluminum coatings increases with a wavelength. Practically, there is only a slight difference in 3-15 μm spectral region between aluminum mirrors or gold mirrors but only in case of collimating mirrors, where a mirror surface is nearly perpendicular to the incoming beam. Silver/gold coated flat mirrors working at about 45 deg angle are characterized by much better reflectance than their aluminum equivalents, particularly about 10 μm wavelength.

To summarize, several guidelines on coating of mirrors for IR collimators can be formulated.

1. Aluminum coated primary collimating mirrors is the best option due to high reflectance and very good durability.
2. Aluminum coated secondary flat mirrors are not a good choice due to possible low reflectance of this coating at a wavelength of about 10 μm when working at 45° angle. If the test area is limited to testing thermal cameras then gold coating of the secondary mirror is the best option; if the collimator is to be used to test both thermal imagers and visible/near infrared cameras then protected silver coating for secondary flat mirror is the best option due to nearly uniform high reflectance in both visible and infrared range.

D. Mirror thermal properties

There are four materials that are most often used in mirrors fabrication: optical crown glass, low-expansion borosilicate glass (LEBG), synthetic fused silica and Zerodur.

The material for mirror fabrication should be chosen on the basis of four parameters: coefficient of thermal expansion, cosmetic surface accuracy, surface accuracy, and material cost.

Optical crown glass (often BK7 type) is an old and low cost material for mirrors. Crown glass has a relatively high coefficient of thermal expansion and is employed when thermal stability is not a critical factor. We must remember that mirror surfaces can be distorted or even damaged when subjected to wide temperature changes. Therefore low-thermal expansion substrate materials are critical to successful performance of imaging reflective optical systems to be used at different ambient temperatures.

Low-expansion borosilicate glass (LEBG) known by the Corning brand name - Pyrex - is well suited for high quality front-surface mirrors designed for low optical deformation under thermal shock. Pyrex coefficient of thermal expansion is lower than in case of optical crown glass.

Synthetic fused silica has a very low coefficient of thermal expansion. Fused silica mirrors can be polished to extreme accuracies, thereby minimizing wavefront distortion and scattering.

Zerodur is a unique glass-ceramic material whose thermal expansion is almost zero. This stability is essential in diffraction limited systems where the optical figure must not vary under thermal changes.

Parameters of the described earlier materials used for mirrors substrates are shown in Table 4.5. As we can see the best material for the substrate of mirrors seems to be Zerodur due to negligible thermal expansion and ultra high surface accuracy. However, Zerodur is also the most expensive material of the four analyzed materials. Surface mirrors accuracy at the level of over $\lambda/12$ is needed only in rare applications of testing optics for space applications. In case of collimators for testing thermal imagers surface accuracy at the level of $\lambda/8$ can be considered as acceptable. Therefore we can conclude that if the collimator is to be used at highly variable ambient temperature conditions (field conditions) then the collimators mirror should be made from Zerodur, or at least from Pyrex. In case of laboratory conditions when the ambient temperature is almost stable then all optical materials mentioned earlier are acceptable, but due to lower cost mirrors made from Pyrex or from optical crown glass should be preferred.

Table 4.5. Comparison of four materials used for mirror substrates

Material	Coefficient of thermal expansion/°C	Typical cosmetic surface quality	Typical surface accuracy	Cost
Optical crown glass (commonly BK7 type)	10^{-5}	80-50	λ/4-λ/12	low
Pyrex	$5\ 10^{-6}$	60-40	λ/4 ÷λ/10	moderate
Synthetic fused silica	$8\ 10^{-7}$	60-40	λ/10 ÷λ/20	high/modera te
Zerodur	$4\ 10^{-7}$	60-40	up to λ/20	high

4.2.2 Blackbody

Blackbody is an ideal body that completely absorbs whole radiant energy striking it and, therefore, appears perfectly black at all wavelengths. The radiation emitted by such a body when heated is referred to as blackbody radiation.

A perfect blackbody has an emissivity equal to unity. Emissivity of real technical blackbodies is close to unity. There are generally two methods to design technical blackbodies of emissivity nearly equal to unity.

First method is to manufacture a cavity in a block of material of high thermal conductivity (mostly metal alloys) and regulate temperature of this block using a heating/cooling element. Emissivity of cavity blackbodies is typically over 0.995 even when emissivity of the cavity walls is much lower (about 0.5-0.8). Most medium, or high temperature blackbodies are designed using the cavity concept. Typical commercially available cavity blackbodies are characterized by relatively small emitting aperture about 1 inch aperture and quite high temporal inertia.

Second method is to put a layer of high emissivity material over a flat metal element of regulated temperature. Some special black paints of emissivity equal to 0.97 are put over blackbody emitters. The latter elements are manufactured from high conductivity metals (usually copper). It is possible to use the second method to achieve bigger emitting apertures then using the first method. The blackbodies designed using the second methods are called area blackbodies. The area blackbodies are also characterized by lower temporal inertia than the cavity blackbodies due to smaller mass. However, due to lack of high emissivity coatings resistible to high temperatures the area blackbodies can be used only at low temperatures (typically the maximal temperature is no more than 400°C).

The emitting area of the blackbodies used in systems for testing thermal imagers must be bigger than the target plates. This creates requirement that emitting area must be typically at least equal to about 50 mm. Next, blackbody for the test systems should simulate objects of rather low temperature to simulate typical observation condition. Further on, both positive and negative temperature differences (between the target and the blackbody) are needed during testing thermal imagers. Because of these requirements thermoelectric area blackbodies dominate among blackbodies used in systems for testing thermal imagers.

Thermoelectric area blackbody is an blackbody that uses Peltier element for temperature control of the emitting element. Peltier element (Peltier module) is a semiconductor-based electronic component that functions as a small heat pump. By applying a low voltage DC power source to a Peltier element (called also often TEC(thermoelectric cooler because of its ability to cool) heat will be moved through the element from one side to the other. One face of the element will be cooled while the opposite face simultaneously is heated. Consequently, a thermoelectric element may be used for both heating and cooling by reversing the polarity (changing the direction of the applied current). This ability makes TECs highly suitable for precise temperature control applications as well as where space limitations and reliability are paramount. Due to ability to heat or cool relative to ambient temperature, the thermoelectric blackbodies are usually called differential blackbodies.

There are a few important advantages of differential blackbodies that made this type of blackbodies an ideal choice for testing modern thermal imagers.

First, standard temperature range of differential blackbodies from about -25°C to about +75°C overlaps the temperature range needed during tests of surveillance thermal imagers. Second, it is possible by careful design to develop differential blackbodies of excellent temperature resolution (0.1 mK), stability (1 mK) and uniformity (10 mK). Third, these blackbodies are characterized by low mass and low temporal inertia in contrast to cavity blackbodies for the same temperature range (typically liquid based blackbodies or pipeline blackbodies). All these features created situation when differential thermoelectric blackbodies are practically the only type of blackbodies used by manufacturers of professional test systems for testing surveillance thermal imagers. Please note however, that the cavity blackbodies are frequently used in testing accuracy of commercial thermal imagers to be used for non contact temperature measurements due to wider temperature range at high temperatures.

4.2.2.1 Design

Differential blackbodies to be used as components of test systems are offered by different manufacturers [24,26,30,32,29]. Now we will discuss in details design of a differential blackbody offered by one of manufacturers [30] but the conclusions will be generally valid for all high performance differential blackbodies present on the market.

The blackbodies offered on the commercial market are typically built from two blocks: the radiator block and the controller block. The diagram of the radiator block is shown in Fig. 4.14. As it can be seen this block is built from: the radiation emitter, the Peltier element, two temperature sensors (the sensor of temperature of the radiation emitter and the sensor of temperature of the front wall), the cooling radiator integrated with the fans, the electronic module, and the block case.

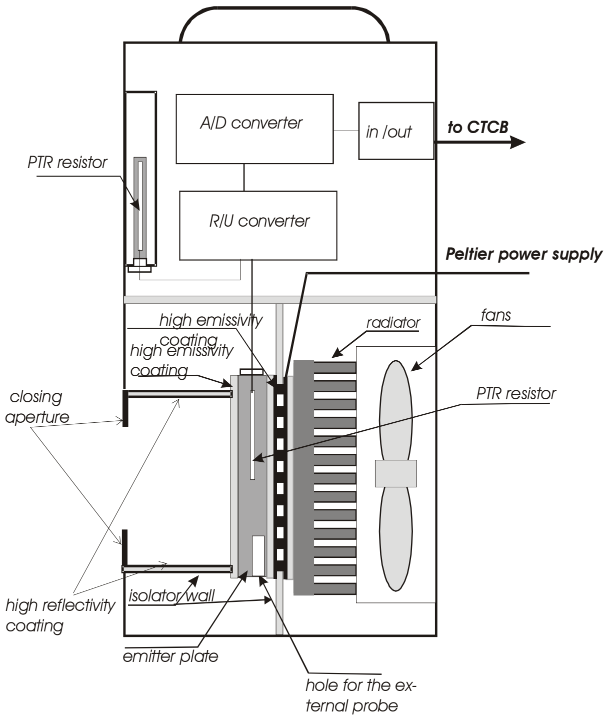


Fig. 4.14. Construction of the radiator block.

The radiation emitter is manufactured as a sandwich of several metal plates fixed together. The plates are manufactured from material of high thermal conductivity in order to achieve very good temperature uniformity on the surface of the emitter. The front side of the emitter plate is painted using a special high emissivity coating. This technique enables to achieve emissivity of the emitter plate equal to 0.97±0.01. Emissivity of the emitter plate can be improved up to 0.985 using additionally so called the micro-cavities technique when an array of small micro-cavities is created in the surface of the emitter.

Two high quality platinum resistance thermometers (PRT resistors) are placed in a hole drilled in the emitter plate and in the hole drilled in the front wall of the of the RTCB radiator. The task of the second sensor is to measure the ambient temperature.

The PRT resistors are characterized by high linearity, temporal stability and the high temperature coefficient α. Due to good thermal contact of the PRT resistor with the emitter plate or with the front wall it is possible to measure accurately temperature of the emitter plate and temperature of the front wall (or further of the rotary wheel when the wheel is connected to the radiator block). Because of temporal inertia effect the measurement is typically done with frequency not higher than 1 Hz. Next, due to fixing of the PRT resistors in high thermal conductivity material the influence of the effect of resistor self heating on its resistance is minimized. Further on, the emitter was placed inside a cavity made from low thermal conductivity material in order to minimize influence of air random vortexes on temperature distribution on the surface of the emitter

The back side of the emitter plate is closely attached to the Peltier thermo-element of temperature dependent on the applied voltage. It is possible to heat or cool the emitter applying proper voltage. The other side of the Peltier thermoelement is closely attached to the cooling radiator equipped with fans. The task of the cooling radiator is to dissipative quickly the heat from the Peltier element.

Measurement of temperature of the emitter plate and temperature of the front wall is done by measurement of temperature dependent resistance of the PRT resistors. The resistance is converted to voltage using a resistance bridge made from resistors of high linearity, temporal stability and temperature stability. Next, the output signal is amplified using a low noise preamplifier with corrected temperature drift. Finally the analogue voltage is converted to digital signal using 24-bit A/D converter and that digital signal is sent to the controller.

The controller block consists of three basic modules: micro-controller no 1, micro-controller no 2, and power supply module.

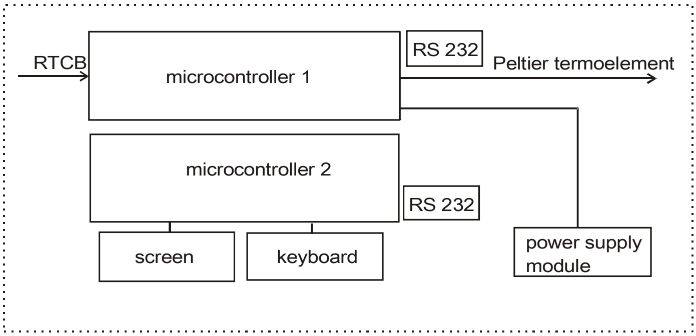


Fig. 4.15. Block diagram of the controller block.

There are 3 basic functions of the micro-controller no 1. First, it enables communication with the radiator block, with PC computer through RS 232 port, and with the micro-controller no 2. Second, the micro-controller no 1 converts values of the output voltage into values of temperature. Third, the micro-controller no 1 controls, through the D/A converter, the voltage applied to the Peltier thermoelement in the radiator block.

The micro-controller no 2 controls the keyboard and enables the user to set the required absolute or relative temperature. Next, the micro-controller 2 controls the screen and enable visualization of current and required values of temperature of the emitter plate, or the temperature difference between the emitter temperature and the front wall temperature.

Task of the power supply module is to power the micro-controller 1 module, the micro-controller 2 module and the Peltier thermoelement and analog electronic module of the radiator block.

a) b)

Fig. 4.16. Photo of the TCB-2D blackbody a) RTCB radiator block b) CTCB controller block (courtesy of Inframet).

The main task of the controller is to control and stabilize absolute or differential temperature of the emitter in the radiator block. Stabilization is a temperature control process of the emitter with aim of achieving its stable temperature equal to the value set by the user. Temperature control of the emitter plate is done via precision control of the voltage applied to the Peltier element.

The easiest way to shorten time necessary to achieve the stable temperature of the emitter plate is to decrease thermal capacity of the emitter plate. However, lower thermal capacity means also lower thermal uniformity of the emitter and therefore the only reasonable way to shorten stabilization time is to optimize control algorithm of the voltage applied to Peltier element. Classical PID (proportional-integral-derivative) algorithm can be used for this voltage control. However due to its low speed a combination of DMC (Dynamic Matrix Control) and PID algorithm is used often in controllers of differential blackbodies. All data required by these algorithms are determined on the basis of statistical analysis of measurement results obtained during experimental trials.

Before the blackbody can work properly it must be calibrated. Calibration of the blackbody is a process when the relationships between temperature of the sensors and output voltages generated by the temperature sensors are determined. The calibration process is carried out using an external temperature probe inserted to a hole in the emitter plate close to the temperature sensors. High quality certified external temperature meter of temperature resolution 1 mK and stability 2 mK (or better) is used during calibration.

The relationship between temperature and voltage is typically determined at at least 10 temperature points. Later the measurement data is interpolated using a high degree polynomial and the calibration function is generated in a form of a table. Values of the calibration table are saved in EPROM memory what enables easy editing during cyclic recalibration.

Practically all blackbodies offered for testing thermal imagers can be at least optionally controlled from PC via RS232 port or USB2.0 port. This way of communication between the PC and the blackbody is more convenient than using controller keyboard as the user has at his disposal a large keyboard, a mouse and a monitor of the PC instead of a small keyboard and a small screen of the blackbody controller. Next, the control software enables the user also visualization and recording temperatures versus time and recalibration of the blackbody.

The presented above description, block diagrams and photos refer precisely to old model of blackbodies offered by Inframet [30]. New models from this company look a different but basically the work concept is the same as presented earlier.

4.2.2.2 Requirements

Temperature resolution NETD of modern cooled thermal cameras can be as low as about 10 mK. Temperature resolution NETD of uncooled thermal cameras is worse (typically about 100 mK) but is improving rapidly. If we want to test accurately thermal imagers then we need blackbodies of temperature resolution a dozen or more times better than imager temperature resolution (NETD). Temperature resolution of 10 mK is acceptable in case of non-cooled thermal cameras. However, if cooled thermal imagers are to be tested then blackbodies of 1 mK resolution are needed. In some extreme cases when imager MRTD at low frequency range is below 10 mK then even 0.1 mK resolution is useful.

Differential temperature range ±10°C at 25ºC ambient temperature can be considered as acceptable during tests of typical surveillance thermal imagers. However, wider temperature range is useful when testing commercial measurement thermal imagers. It can be estimated that absolute temperature range from 0°C to 100°C fulfills typical requirements for temperature range needed for testing surveillance thermal imagers and partially the requirements on blackbodies for testing commercial thermal imagers[8].

Theoretically it is possible to use gray bodies during tests of thermal cameras and later to correct influence of difference between emissivity of the real blackbody and emissivity of an ideal blackbody on condition that the emissivity of the real blackbody is not lower than 0.9 due to problems with reflected radiation. However, a better option is to use real blackbodies of emissivity close to one when almost no correction is needed, particularly during differential measurements. Therefore emissivity not less than 0.97 (or higher) is considered nowadays as a standard requirement.

[8] Temperature range of some measurement thermal cameras goes over 1000°C and cannot be covered using thermoelectric blackbodies.

Measurement of some characteristics is carried out for both positive and negative contrast. Later the results are averaged. Theoretically this approach enables full correction of systematic errors of measurement process (mostly caused by offset phenomenon). However, practically this correction works properly only when blackbody does not change its temperature with time. Practically this means that blackbodies of high temporal stability are recommended. Blackbodies of temporal stability not worse than ±3 mK are usually acceptable but there are cases when temporal stability at level ±1 mK is needed.

Non-uniformity of temperature distribution on surface of the blackbody emitter should not influence the measurement results. The requirements on non-uniformity are the highest during measurements of subjective characteristic like MRTD. The observer should not notice any non-uniformity on blackbody surface during MRTD measurement. Temperature difference during MRTD measurements is usually not higher than 5°C and therefore it is usually considered that non-uniformity is acceptable if it is below 10 mK at 5°C.

Tests of thermal cameras can be quite time consuming; particularly MRTD measurements. Therefore blackbody speed (stabilization time) is an important parameter because long settling time means long lasting tests. There is no strict limits on settling time but it is convenient if blackbody temperature stabilize at time no longer than about 1 minute in case of small (about 50 mm diameter) blackbodies or 90 s in case of bigger blackbodies of a size more than 100 mm.

Due to relative nature of measurement of most characteristics of surveillance thermal imagers accuracy of absolute temperature of the blackbody emitter is not a crucial parameter. Even significant errors of differential temperature measurement are fully eliminated, or at least significantly reduced, when measurements are carried out first for positive contrast targets and later – for negative contrast targets.

Blackbody accuracy is important during calibration process of measurement (commercial) thermal cameras when the blackbody is used as a reference standard. Absolute accuracy of modern commercial thermal cameras is typically ±2% or ±2°C (whichever higher) in camera temperature range. Accuracy of blackbodies should be at least ten times better. Therefore it seems that temperature errors of blackbodies at a level of ±0.2% or ±0.2°C should be considered as acceptable. If the manufacturer can deliver blackbodies of better accuracy it should be welcome.

Table 4.6. Summary requirements on blackbodies

Parameter	Acceptable	Recommended
Temperature resolution	10 mK-for testing non-cooled imagers 1 mK – for testing cooled III gen imagers	1 mK – typical situation 0.1 mK – extreme cases
Absolute Temperature range	15°C ÷ +35°C at +25°C ambient temperature	0°C ÷ +100°C – typical situation -15°C ÷ +100°C – extreme situation
Differential Temperature range	-10°C ÷+10°C at +25°C	–25°C ÷ + 75 °C – typical situation –40°C ÷ + 75 °C – extreme situation
Emissivity	≥ 0,96	≥0.97
Settling time ±10ºC step (seconds)	120s (at ±10 mK level)	60s (at ±10 mK level
Uniformity	±20 mK for ±5°C temperature range ±150 mK for ±30°C temperature range	±10 mK for ±5°C temperature range ±100 mK for ±30°C temperature range
Stability	±20 mK- non cooled imagers	±2 mK – typical situation ±1 mK– extreme situation
Absolute uncertainty	±0.2% or ±0.2°C	(T-25°C)*2+15 [mK] – blackbody exceeding real requirements

4.2.3 Rotary wheel

The task of rotary wheel is to enable speedy exchange of the target to be projected by the collimator or to be observed directly by the tested thermal imager. This task can be also done by horizontal or vertical sliders with a set of different targets. However due to simplicity, the rotary wheels are used typically to exchange the targets in systems for testing thermal imagers.

Two basic types of rotary wheels are available on the market: manual rotary wheels or motorized rotary wheels. A touch of human hand can change slightly temperature of the wheel. In situation when modern thermal imagers are becoming extremely sensitive any such temperature variation can cause some measurement errors. Therefore motorized rotary wheels are recommended when testing high sensitivity thermal imagers.

Next, air flow can cause some variations of target temperature. This effect can be reduced if the wheel with targets is put inside a closed enclosure that eliminates exchange of air inside/outside the wheel block.

Number of holes for the targets can vary. However, there are usually 6 to 12 holes for targets in the wheel. The wheels are usually covered with a black, high emissivity coating. The requirements on coating are similar like in case of the targets.

Requirements on positioning accuracy are not high in case of typical tests of thermal imagers. Slight angular variations of position of the image projected by the collimator has no influence on measurement results of parameters of thermal imagers. It is enough if positioning repeatability of the wheel is not worse than about 1 mm. However there are some tests of thermal imagers used for automatic target recognition tasks when much better positioning repeatability close to 0.1 mm level is required.

Fig. 4.17. Photo of a motorized rotary wheel and differential blackbody (courtesy of Inframet).

During tests of thermal imagers, we need to know temperature of the blackbody radiator and temperature of the target. Temperature of the blackbody radiator is typically measured using a small temperature sensor inserted to a hole in the radiator. This direct contact measurement method cannot be used to measure temperature of the targets because the targets are rotating.

One solution to solve the problem is to use a sliding temperature sensor that slightly touches the active target and measures its temperature. However, that direct contact of the sensor with the target, when the latter is moving generates some heat and this effect creates additional measurement error.

Another solution is to measure target temperature indirectly. The sensor is attached to the rotary wheel. If there is good thermal contact between the targets and the rotary wheel then difference between target temperature and wheel temperature is negligible and target temperature can be indirectly measured.

Both the target plates and the rotary wheel should be put inside an enclosure that would reduce influence of conditions in a test room on temperature of the wheel with the targets. We must keep in mind that variations of ambient temperature in test rooms are often at level of several Kelvins in a period of a dozen minutes. If similar variations of temperature of the target wheel occur then accurate measurement of parameters of thermal imagers is not possible.

To summarize, we can present the following requirements on the rotary wheels:

1. Manufactured from high thermal conductivity material.
2. Good thermal contact between targets and the wheel where the targets are fixed.
3. Preferably motorized type.
4. Easy and speedy target exchange.
5. The targets should be protected against influence of external conditions on their temperature.
6. Positioning repeatability at level about 1 mm (typical tests) or about 0.1 mm (automatic targets recognition tests).

4.2.4 Targets

Targets for testing classical visible/near infrared imaging systems are manufactured by creating opaque or semi-transparent coatings on transparent glass substrate.

When a diffuse light source is put behind the target then the tested visible camera sees a "target" formed by the coating on an uniform bright background (in case of positive contrast targets). The visible targets can be also manufactured by precise printing of images of different shape on high quality paper. However, these two techniques are rarely used to manufacture targets for testing thermal imagers because it is difficult to determine and to control temperature distribution on the surface of such targets. Additionally typical glasses poorly transmit radiation over 3 micrometers. Therefore infrared targets for testing thermal imagers are manufactured using a different technology.

Targets for testing thermal imagers are usually manufactured by creating precision holes of different shapes in metal sheets. When a blackbody is put behind such a target, the tested thermal camera sees a "target" of shape determined by the holes on an uniform background. The apparent temperature of this "target" is equal to blackbody temperature; the apparent temperature of the background is equal to the temperature of the real target plate.

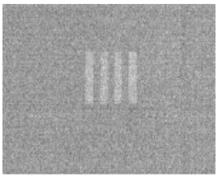


Fig. 4.18. Image of a 4-bar target (generated by a tested imager during MRTD measurement).

Fig. 4.19. Photo of a multiply 4-bar target used for MRTD measurement from two sides.

In order to achieve high thermal uniformity on the surface of the target, the targets are manufactured by cutting the desired holes in a thick metal sheet of high thermal conductivity (typically copper alloys). Next, one side of the targets is coated using a special high emissivity black coating. This side of the target should look into the direction of the IR collimator (or in the direction of the tested thermal camera). The second side of the target is coated using a high reflectivity coating in order to minimize influence of the blackbody thermal radiation on the target plate temperature. The targets are typically fixed to the rotary wheel or directly to the blackbody.

The targets manufactured using the technology described earlier are called "emissive targets". There is also another type of the infrared targets called "reflective targets". Both sides of such targets are covered using high reflectivity coatings. When such targets are mounted to a rotary wheel in a collimator based test system then a tested imager will see through target holes a blackbody behind the active target and collimator enclosure[9] reflected by the target reflective surface. If a second blackbody is located inside the collimator then we can achieve a situation when both target temperature and the background temperature can be independently regulated (Fig. 4.20).

If the targets are properly manufactured and properly used then both two types of targets should generate the same test results. However, the "emissive targets" are preferred because collimators used in the test system optimized for reflective targets shown in Fig. 4.20 are more expensive than typical collimators (collimating mirror of ultra low F-number and big off axis distance is needed). Therefore the reflective targets are met rather rarely when testing thermal imagers; mostly in case of collimators of modified design with improved baffling.

[9] The tested imager can see also itself reflected on the surface of the reflective target.

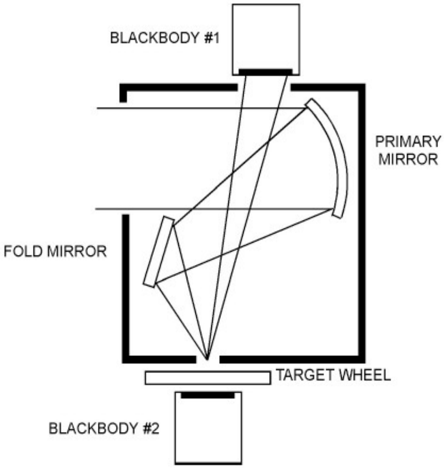


Fig. 4.20. Block diagram of test system optimized for use of reflective targets and two blackbodies [3]

Targets of different shape are manufactured to enable measurement of different parameters of thermal imagers. We can distinguish at least fourteen shapes of IR targets:

1. Four-bar targets.
2. Pinhole targets.
3. Square targets.
4. Slit targets.
5. Interlace targets.
6. Edge targets.
7. Alignment targets.
8. Double 4-bar targets.
9. Multiple 4-bar targets.
10. Multiple pinhole targets.
11. Abingdon cross targets.
12. Distortion targets.
13. Grey scale target.
14. Silhouette targets.

Drawings of these targets are shown in Fig. 4.21 and their description in Table 4.7.

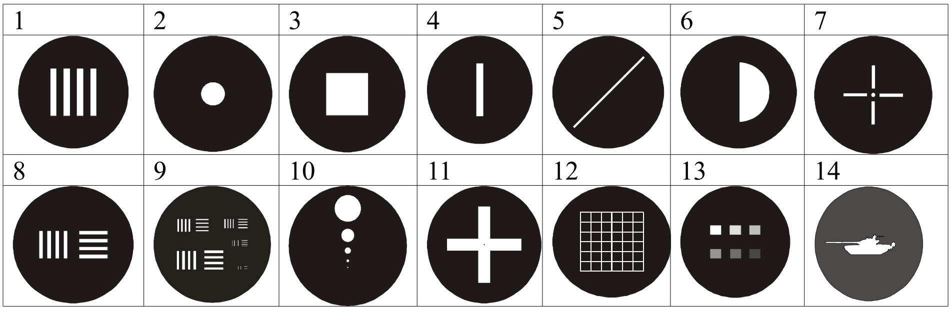


Fig. 4.21. Drawings of different types of IR targets

Table 4.7. Application area of different types of IR targets

No	Target type	Description	Application	Comments
1	4-bar	single 4-bar pattern (7:1 bar proportions) cut in metal sheet	MRTD	-a set of targets with various spatial frequencies is needed to measure MRTD characteristic -it is necessary to rotate targets to measure both vertical and horizontal MRTD
2	pinhole target	circular pattern cut in metal sheet	MDTD	-a set of targets with various size is needed to measure MDTD characteristic -small pinhole target is needed during PVF measurement
3	square target	single square pattern cut in metal sheet	ATF or SiTF, NETD, FPN (option)	- a set of square targets for ATF measurement - single square target for SiTF, NETD, FPN measurement (old technique)
4	slit target	single long slit cut in metal sheet	SRF, MTF	-a set of slit targets of different width is needed to measure SRF -single very narrow slit target for MTF measurement
5	interlace target	single long, narrow slit pattern cut in metal sheet skewed by 45º	scanning adjustment, dead channels	needed to check interlace scanning adjustment, as well as to identify strapped or dead channels in scanning imagers. These effects appear in a form of deviations from the ideal smooth diagonal line.
6	edge target	a half-moon of sharp smooth edge pattern cut in metal sheet	ESF, MTF	ESF (edge spread function) is measured directly. MTF is calculated on the basis of measured ESF.
7	alignment target	patterns of pinhole-and-cross combinations	boresighting, focusing and alignment	different sizes are needed depending on imager field of view
8	double 4-bar target	double 4-bar pattern (vertical and horizontal 4-bar pattern)	MRTD	it is possible to shorten measurement time of MRTD because both horizontal 4-bar patter and vertical 4-bar patterns are seen at the same time
	Multiple 4-bar targets	multiple 4-bar patterns of different size cut in a single metal sheet	MRTD	cost-effective solution for MRTD measurements when test are to be carried out at 2-3 frequencies. A single multiple 4-bar target with several 4-bar patterns can replace a series of 4-bar targets with a single pattern.
10	multiple pinhole	multiple circular patterns of different diameter cut in a single metal sheet	MDTD	cost-effective solution for MDTD measurements. A single multiple pinhole target with several pinhole patterns can replace a series of pinhole targets with a single pattern.

11	Abingdon cross target	single Abingdon cross pattern cut in metal sheet	testing tracking systems	targets are used to evaluate the effectiveness of image processing algorithms in presence of noise.
12	distortion target	set of narrow lines creating multiple square pattern	distortion	to evaluate linear and angular displacements due to distortion effect
13	gray target	set of small squares of different transmittance	response function	can speed up measurement of response parameters
14	silhouette target	silhouette pattern resembling real targets	evaluation of surveillan-ce ranges	targets are used for evaluation of surveillance ranges of real targets

A process of cutting holes in metal sheets necessary to manufacture IR targets looks simple. However, practically it is quite difficult to manufacture proper IR targets that can fulfill presented below requirements.

1. High thermal uniformity of temperature distribution on target surface. The uniformity of the temperature distribution on the target plates should be a few times better than MRTD or MDTD values obtained with these targets. In order to fulfill this requirement the targets should be manufactured from material of high thermal conductivity. Copper or copper alloys are acceptable but steel sheets should be avoided. Next, the metal sheets cannot be too thin as thin sheets are characterized by low thermal conductance even if manufactured from proper material. It seems that 0.3-0.5 mm can be considered as minimal thickness of metal sheets for target manufacturing even in case of copper sheets.
2. High accuracy of pattern manufacturing. If there are significant differences between area of the bars in 4-bar targets, then accuracy of MRTD measurement is reduced because spatial frequency of such a target is determined with some error. In general, the following tolerances are recommended: 2% for patterns of minimal dimension over 1 mm and 4 % for patterns below 1 mm but over 0.3 mm, and 8% for pattern below 0.3 mm.
3. High emissivity of the target side surface facing the tested imager. The target emissivity should be the same as the blackbody emissivity to avoid situation when the target is seen not due to temperature difference but due to emissivity difference. Therefore target emissivity should be at least 0.97 to resemble ideal blackbody surface.
4. High reflectivity of the target side surface facing the blackbody. Targets should be polished or coated to get reflectance of at least 0.9 in order to eliminate influence of blackbody temperature on target temperature.

As we can see in Table 4.7 the list of types of infrared targets is quite long. However, a typical set of targets for testing surveillance thermal imagers is rather short:

1. A set of six to twelve 4-bar targets (for MRTD measurement),

2. Edge target (for MTF measurements),
3. Distortion target (for distortion/FOV measurement).

The set of 4-bar targets is built typically from several single targets (bigger patterns) and several double 4-bar (smaller patterns). Single big 4-bar targets are used because simply there is no space for double patterns in the target plate if the 4-bar pattern is big.

The edge target is typically preferred over slit target during MTF measurement. There are several advantages of edge targets but one of most important is the fact that several slit targets are needed for testing different thermal imagers in situation when a single edge target can be used for measurement of MTF of any thermal imager.

The distortion target is used for measurement of distortion. The distortion effect in thermal imagers of narrow/medium field of view is usually small, almost negligible. However, the same target can be used also for measurement of imager field of view. It is important to measure the latter parameter because only when we known field of view there is any sense to compare MRTD characteristics of several thermal imagers.

It may be surprising for some readers that square targets are not included in this basic set of IR targets. The square targets were traditionally used for several decades during measurement of NETD of thermal imagers. However, it should be noted that these targets were used to measure NETD of scanning thermal imagers using oscilloscopes. Nowadays, frame grabbers are typically used instead of oscilloscopes. Next, staring thermal imagers are typically tested instead of scanning imagers. Finally, modern software enables analysis of any part of images generated by thermal imagers. Therefore the rectangle targets are not strictly needed for measurement of noise parameters. These targets are needed for measurement of ATF but it is a rather rarely measured characteristic.

Other types of IR targets listed in Table 4.7 are needed in case of extended tests of thermal imagers or when by use of multi-pattern targets we want to speed up test procedure. Applications of these targets are presented in the same table.

4.2.5 Image acquisition/analysis module

Image acquisition/analysis module is built from the following blocks: PC, frame grabber (video card), and test software. It is practically a specialized PC to carry out tasks needed in testing thermal imagers. The module should enable acquisition of the output signal from the tested thermal imager, analysis of the captured images, and semi-automatic determination of important characteristics of thermal imagers.

4.2.5.1 PC

In general, PC should enable processing of the input data from the frame grabber, and calculation and visualization of characteristics of thermal imagers. Practically, all modern PCs can handle such tasks.

4.2.5.2 Frame grabber

Almost all surveillance thermal imagers generate output images in form of analog video electrical signal: PAL standard or NTSC standard. However, more and more thermal imagers generate output images in form of digital signal: Fire Wire, USB 2.0, Camera Link, GigE, LVDS. Especially the latter three standards (Camera Link, GigE, LVDS) are popular for designers of high resolution/high speed thermal imagers.

The task of a frame grabber (video card) is to capture sequences of images generated by tested thermal imager. The ideal frame grabber should accept input data in all typical electronic standards: PAL, NTSC, Fire Wire, USB 2.0, Camera Link, GigE, LVDS. Next, it is critical that there should be no noticeable degradation of image quality caused by the frame grabber. Please note that most low cost frame grabbers are designed with the aim to be used in applications where quality of the captured images is not critical but compression ratio is the most important parameter.

Each frame grabber device should provide a proper software driver, which should contain routines compatible with one of existing, commonly used APIs (Application Programming Interfaces). Image acquisition applications (software modules) are based on such standards as e.g. TWAIN, or more native to Microsoft's operating systems interfaces as DirectShow, or WIA (Windows Image Acquisition). Main functionality of image acquisition software module is to get image from video capture device in form of separate frames or – in most cases – in form of video sequence. Such collection of image data can be passed on for further processing and analysis.

4.2.5.3 Test software

There are four tasks of test software used in systems for testing thermal cameras:

1. Remote control from PC of the test system hardware (blackbody, rotary wheel).
2. Acquisition of the output images generated by the tested thermal camera.
3. Software support during measurement of subjective parameters: MRTD, MDTD.
4. Semi-automatic measurement of objective parameters of tested thermal imager.

The tasks mentioned above can be handled in different way by different computer programs. Here we will formulate basic requirements and recommendations for test software.

1. Easy to learn, graphical method for control of blackbody temperature and position of rotary wheel.
2. Tools for software support during MRTD/MDTD measurements:
   a) Storing test conditions (type of tested imagers and its serial number, test date, ambient temperature, collimator transmittance, target frequencies),

b) Calculation of target frequencies in lp/mrad using user inserted data of bar width in mm,
c) Automatic inserting current blackbody temperatures to the test table at temporal points determined by the user,
d) Correction of influence of two test parameters (ambient temperature and collimator transmittance) on MRTD/MDTD measurement results,
e) Presentation of measured MRTD/MDTD in graphical form or tables.
f) Generally the software should limit requirements on the user only to make decision whether he recognize the 4-bar pattern and carry out all data analysis, visualization and recording.

3. Ability to cooperate with different types of frame grabbers capable to capture video signals of different standards. Software should enable capturing images with no compression, or using compression methods that would not degrade in noticeable way quality of the captured sequence of images[10].
4. Test software should enable semi-automatic measurement of most important parameters of surveillance thermal imagers: noise parameters, SiTF, MTF, distortion, distortion, FOV.
5. Test software should enable measurement of most important parameters of measurement thermal imagers: accuracy, NETD, and SRF.

To summarize, good test software should guide the user through the measurement process and minimize possible errors. This requirement can be fulfilled by semi-independent software modules designed to support measurement of specific characteristic that make the user to carry out steps of the measurement algorithm and give the user precise instructions about the measurement steps.

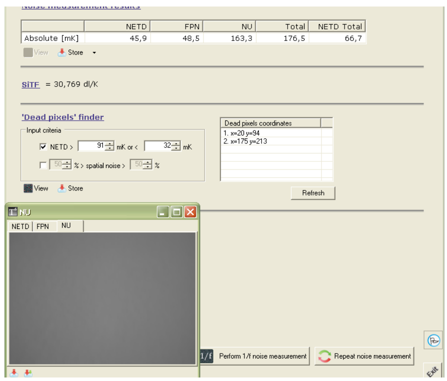


Fig. 4.22 Exemplary noise window of test software.

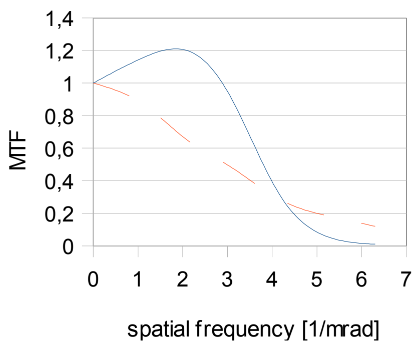


Fig. 4.23 MTF of two different thermal cameras.

[10] Typical commercial video capturing software was developed with the aim to capture and record long video sequences using as least as possible memory on hard disk. Therefore such software often degrades image quality of the captured images and this degradation can influence measurement results.

4.2.6 Optional blocks

It is impossible or at least very difficult to carry out testing thermal imagers without such blocks of the test system like: collimator, blackbody, rotary wheel, set of targets, PC, frame grabber, and test software. There are also some blocks that are not strictly needed but still can be useful.

4.2.6.1 Temperature chamber

Thermal imagers are usually tested at laboratory conditions in a situation when they are expected to work properly at extreme ambient temperatures. It is a commonly forgotten truth that parameters of thermal imagers can vary significantly with ambient temperature. This dependence or in other words imager temperature stability can be measured by placing the tested imager inside a temperature chamber of variable ambient temperature and then by measuring imager characteristics. There are two methods to measure temperature stability: the first by putting to the chamber both the imager and the blackbody, the second – by putting to the chamber the imager and using a chamber with a transparent window. The latter method is more convenient for the test crew.

There are many commercially available temperature chambers on the market. However, they are typically not optimized for testing thermal imagers: they are too big, have too high thermal/temporal inertia, and the chambers often are not equipped with infrared transparent windows. Therefore it is recommended to use for testing thermal imagers small temperature chambers of low thermal inertia equipped with an infrared transparent window. Temperature range of the temperature chamber should fit to the temperature range of the environment where the tested imager is to be used. Such a temperature chamber can be also very useful during calibration process (spatial noise correction) during manufacturing process.

4.2.6.2 Optical table

Special expensive anti-vibration optical tables are not generally needed as a place where the test equipment is to be located. The required accuracy of alignment of the test system is much lower than accuracy of alignment of some laser systems or holographic equipment. In most cases the test equipment can be properly aligned on any large, heavy and stable wooden (stone, metal) table. However, special care should be taken during testing long range thermal imagers of very narrow field of view. Vibration of the table can influence image quality of the image from the tested imager and can distort measurement results. In this case it is recommended to use expensive optical anti-vibration tables or to use modified typical tables with additional vibration damping parts.

4.3 Manufacturing/R&D support equipment

So far we have discussed in detail systems for testing thermal imagers understood generally as final, ready products. The tests using presented earlier test systems deliver a lot of information useful to verify final quality and to localize weak points of manufactured thermal imagers that should be improved. However other types of test equipment are needed for manufacturing thermal imagers and for research&development projects. Before a thermal imager is ready for final tests, several important operations must be carried out:

1. Correction of spatial noise.
2. Calibration of measurement thermal imagers.
3. Boresighting to a reference optical/mechanical axis.

4.3.1 Correction of spatial noise

Image generated by modern IR FPA sensors, particularly non-cooled sensors, is typically very noisy. Spatial noise is the dominant type of the noise. Correction of spatial noise is needed to obtain a clear image generated by thermal imagers.

There are many algorithms that are used to correct spatial noise in thermal imagers. However, they are generally based on a concept of IR FPA module/thermal imager looking into an internal/external uniform radiation source (Fig. 4.24). We can say that in order to correct spatial noise we must create a data array that records values of this noise at different ambient temperatures and at different input signal levels.

Practically, such data array is determined by putting a tested IR FPA module or tested thermal imager, located at a very short distance to an area blackbody, to a temperature chamber; and by recording images at different chamber temperature, for different blackbody temperature, and for different imager settings (gain, level, etc). This operation provides primary data base used for spatial noise correction. Recalibration of thermal imagers using internal mechanical chopper provides only additional secondary data base.

Some manufacturing teams carry out corrections of spatial noise on the basis of data obtained during tests of IR FPA modules; others carry out corrections of spatial noise on the basis of data get during tests of complete thermal imagers. The first case is more convenient because smaller blackbodies and smaller temperature chambers of low power and low thermal inertia can be used. In the second case bigger blackbodies and bigger temperature chambers must be used, but the test conditions resemble well work conditions of real thermal imagers and better effectiveness of correction of spatial noise can be achieved.

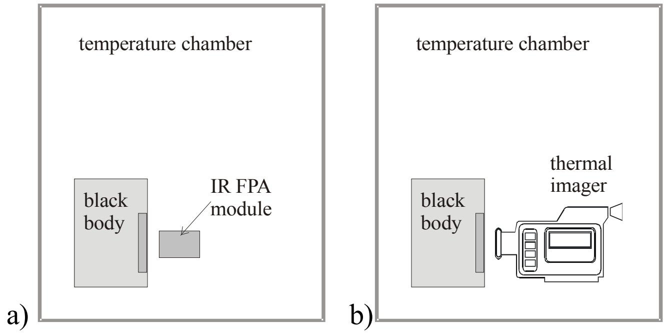


Fig. 4.24. Typical concept of correction of spatial noise.

From test hardware point of view two basic test modules are needed to carry out measurement of spatial noise of tested thermal imager: a temperature chamber and an area blackbody.

The task of these two modules is to simulate real environmental conditions of work of the tested imager/IR FPA module. Therefore the requirements vary depending on geographic region but let us propose requirements on these two modules that make them suitable for testing thermal imagers supposed to work in any climatic conditions.

Table 4.8. Requirements on temperature chamber.

Parameter	Requirement
Temperature range	-30ºC to +60ºC
Temperature uniformity	better that ±0.5ºC
Volume	Optimized to number of imagers to be tested at the same time
Temperature regulation speed	Full temperature range below 45 minutes

Table 4.9. Requirements on blackbody.

Parameter	Requirement
Blackbody emitter size	-at least 10% bigger than diameter of optics of tested imager -at least four times bigger than size of IR FPA sensor
Work ambient temperature range	-30ºC to +60ºC
Differential temperature range	–10°C÷+40°C
Absolute temperature range	-40ºC to 80ºC

As we can see in Table 4.9, the requirements on blackbody to be used for correction of spatial noise of thermal imagers differ significantly from requirements on blackbodies to be used in typical test systems that were discussed in Section 4.2.2. We must remember that generally typical test systems are designed to work at laboratory conditions in a situation when the tests of spatial noise are done in extreme temperature conditions. Therefore there are big differences in requirements on work temperature and on absolute temperature range. Next, there are also some differences in requirements on size of the blackbody emitter. In case of typical test systems a blackbody of emitter size equal to 50x50 mm can be considered as sufficient because the holes in the targets are typically smaller than about 40 mm. The blackbodies that are to be used in temperature chambers they must be bigger than diameter of the optics of tested imager. Optics of a diameter of about 100 mm is commonly met in many non-thermal imagers. Therefore blackbodies of a size at least about 125 mm can be considered as acceptable for spatial noise tests of majority of thermal imagers.

Theoretically it is possible to use one big blackbody both for testing calibration (spatial noise correction) of surveillance imagers and for typical tests of thermal imagers. However, such compromise solution is not convenient for the user due to necessity of manual moving heavy blackbody, test speed is reduced, and finally blackbody reliability can deteriorate, too. Therefore it is recommended to use two specialized blackbodies: a smaller blackbody as a module of a system for testing thermal imagers, and bigger blackbody for spatial noise correction.

4.3.2 Calibration of measurement thermal imagers

Calibration of measurement thermal imagers is a process where relationship between temperature of a blackbody and output signal generated by tested imager is determined for different settings of the imager. The calibration principle is simple: the imager is looking into a blackbody located in its field of view as shown in Fig. 4.25.

The environmental requirements on measurement thermal imagers are not as harsh as such requirements on surveillance imagers. Next, due to some design differences the influence of ambient temperature on image generated by measurement imagers is not as significant as in case of surveillance imagers. Therefore it is recommended to carry calibration of measurement thermal imagers at several ambient temperatures using a temperature chamber but this recommendation can be treated as an optional one.

Calibration of measurement thermal imagers could be potentially carried out using a typical system for testing surveillance thermal imagers when the tested measurement imagers is looking into the blackbody via the collimator. However practically blackbodies from systems for testing surveillance imagers can be used only for partial calibration of measurement thermal imagers. The absolute temperature range of typical blackbodies used for testing surveillance range (from

0ºC to 100ºC) is too narrow for calibration of measurement thermal imagers designed for non-contact temperature measurement of targets of temperature variable from about -20ºC to about 300ºC (sometimes up to 1000ºC).

There are on the market some differential blackbodies of extended temperature range from about -15ºC up to about 150ºC-180ºC [24,30]. Such blackbodies can be used for calibration, even more for recalibration, of measurement thermal imagers optimized for temperature ranges no more than only slightly bigger than the absolute temperature range of these blackbodies. However, upper limit of temperature range of most thermal imagers is typically much higher than 180ºC. Therefore several blackbodies of wide combined temperature range are needed to carry calibration of most measurement thermal imagers.

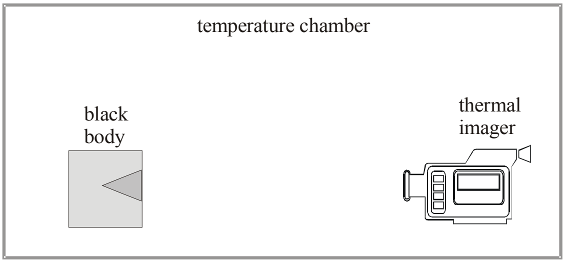


Fig. 4.25. Concept of calibration of measurement thermal imagers.

4.3.3 Boresighting to a reference optical/mechanical axis

Boresighting is a process to align optical axis of a single system or a series of optical or electro-optical systems with a certain reference optical axis or mechanical axis.

Basically the aim of boresighting of a thermal imager is to achieve a situation when:

a) optical axis of the thermal imager is parallel to axis of other electro-optical surveillance systems (the case when the thermal imager is a part of a bigger multi-sensor surveillance system),

b) optical axis of the thermal imager is parallel to a reference mechanical axis.

In other words the aim of boresighting process is to achieve a situation when:

a) all subsystems of bigger electro-optical imaging systems are looking into the same point (assumption: the distance is hundreds times bigger than the focal length of the optics of the subsystems),

b) an imaging system (the thermal imager) is looking at a point of exactly known coordinates relative to the reference mechanical axis).

When the boresighting process is not carried out properly we can get a situation when:

a)the thermal imager generates an image of a slightly different area that the area seen on the image produced by the TV camera (the two images are slightly displaced); laser range finder can measure a distance but not to the point marked on the image generated by the thermal imager,
b) the thermal imager generates an image of the target of interest but we cannot determine accurate relative/absolute coordinates of the target.

Boresighting of thermal imagers can be done using special versions of systems for testing thermal imagers or using specialized systems optimized for boresighting task.

There are generally three types of systems for boresighting of thermal imagers or multi-sensor surveillance systems.
The first systems are based on a concept of a collimator generating output beam in direction of exactly known angular coordinates.
The second systems are based on a concept of an additional imaging sensor fixed to a reference mechanical axis looking into direction of the test collimator.
The third systems use an additional imaging sensor fixed to a reference mechanical axis looking into infinity target (real target at long distance).

Boresighting process is generally outside area of interest of this book and shall not be discussed further. More detailed information about equipment for boresighting of thermal imagers can be obtained from manufacturers of equipment for testing thermal imagers who can optionally deliver also boresighting equipment.

4.4 References

1. ASTM standard E 1213-2002 "*Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems*"
2. ASTM standard E 1311-99 "*Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems*"
3. Bryant P., Grigor J., McHugh S., Performance comparison of reflective and emissive target projector systems for high-performance IR sensors, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XIV, SPIE Vol. 5076, pp.242-249, 2003.
4. Chrzanowski K., J. Fischer, W. Wrona, Testing of Thermal Imagers For Non-Destructive Thermal Testing Applications, ASTM Journal of Testing and Evaluation, 28, 395-402 (2000).
5. Chrzanowski K., Evaluation of IR collimators for testing of thermal imaging systems, Optoelectronics Review, 1/2007.
6. Chrzanowski K., Lee H.C., Wrona W., A condition on spatial resolution of IR collimators for testing of thermal imaging systems, Optical Engineering., 39 (5), 14137-1417 (2000).
7. Chrzanowski K., *Evaluation of commercial thermal cameras in quality systems*, Optical Engineering, Vol. 41, No. 10 (2002).
8. Digital Signal Processing Application with the TMS320 Family, *Theory, algorithms and implementations*, Vol.2, Texas Instruments, 1990, 570-573.
9. *Guide to the expression of uncertainty in measurement*, International Organisation for Standarisation-International Electrotechnical Commission-International Organisation of Legal Metrology-International Bureau of Weights and Measures, TAG 4/WG 3, 1993.
10. Holst G.C., *Testing and evaluation of infrared imaging systems*, JCD Publishing Company (2008).

11. Holst G.C., *The Infrared & Electro-Optical Systems Handbook*, Vol.3: Electro-Optical System Design, Analysis, and Testing, Chapt. 4, pp. 206-207, SPIE (1993).
12. Holst G.C., *Infrared Imaging System Testing*, Vol.4, Chapt. 4 in The Infrared & Electro-Optical Systems Handbook, Michael C. Dudzik ed, SPIE 1993.
13. International Lighting Vocabulary, CIE Publ. No. 1 7.4, IEC Publ. No. 50(845) (1987).
14. ISO 15529, *Principles of measurement of modulation transfer function (MTF) of sampled imaging systems*, 1999
15. Li .X. *An investigation into the stability of industrial platinum resistance thermometer*, Hart Scientific
16. Lloyd J. M., *The Infrared & Electro-Optical Systems Handbook*, Vol.3: Electro-Optical System Design, Analysis, and Testing, Chapt. 1,SPIE (1993).
17. MIL-STD-1859: Thermal Imaging Devices, Performance Parameters Of, 1983.
18. Driggers R., Van Hodgkin A., Vollmerhausen R., O'Shea P., *Minimum resolvable temperature difference measurements on undersampled imagers*, Proc. SPIE Vol. 5076 Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XIV; 2003.
19. STANAG 4349, *Measurement of minimum resolvable thermal difference (MRTD) of thermal cameras*, 1995.
20. Tavener J.P., *Common errors in industrial temperature measurement*., Isotech Journal of Thermometry Vol.6 No.2 1995, 20–27.
21. The Photonics Handbook, Book 3, p. H398-H404, Laurin Publishing Co. (1993).
22. Walker R., *Achieving 0.25mK uncertainty with an integrated-circuit resistance thermometer readout.*, Hart Scientific.
23 Wood L., Laboratory Bench Analysis of Thermal Imaging Systems, Opt. Eng., 15, G193-G197 (1976).
24. www.ci-systems.com
25. www.ci-systems.com/eo/flir/mets.asp
26. www.eoi.com
27. www.electro-optical.com/datashts/collimtr/collimat.htm
28. www.electro-optical.com/eoi_page.asp?h=Diffraction Limits
29. www.hgh.fr
30. www.inframet.com
31. www.inframet.com/testing_infrared_imaging_systems.htm
32. www.sbir.com
33. www.optikos.com
34. www.sbir.com/stc_collimators.htm
35. www.sorl.com/productline/oaps/offaxisparabolas.htm

5 Test procedures

Methods of testing thermal imagers do not depend on test equipment used for measurements. There are many similarities in procedures of measurement of parameters of thermal imagers using test equipment from different manufacturers but there are also some differences, particularly resulting from the fact that nowadays most of these measurements are supported using specialized software [8,10]. Therefore in this chapter, the simplified test procedures independent of software of test equipment will be presented. These simplified test procedures refer directly to equipment manufactured only by one of manufacturers of test equipment (Inframet www.inframet.com) as only this equipment was at disposal of the author. However, the presented in this chapter test procedures should be valid also for test equipment from other manufacturers.

Over twenty parameters of thermal imagers can be measured to characterize accurately tested thermal imagers. Here in this chapter, we are to discuss measurement procedures of only a small but the most important group of parameters of thermal imagers; MRTD, MTF and noise parameters (NETD, FPN, non-uniformity, 1/f noise, 3D noise components, NPSD).

The main emphasis was put on measurement of MRTD due to two basic reasons. First, MRTD is considered as the most important parameter of thermal imagers and it is commonly measured by both user of thermal imagers and by manufacturers of these imagers. Second, in spite of apparent simplicity the measurement of MRTD is difficult and it is easy to make errors in measurement procedure that can significantly reduce accuracy of the test results.

It is highly probable that a test team capable to carry out accurately MRTD measurement of modern thermal imagers shall have no problems to carry out measurement of other parameters of thermal imagers.

5.1 MRTD

MRTD is considered as the most important parameter of thermal imagers. MRTD measurement is both simple and difficult. Simple because the decisions are made by humans; no tools for recording and processing electronic images are needed. Difficult because many sources of possible measurement errors exist.
A classical subjective measurement of MRTD is a time consuming process. The measurement can be shortened by using semi-automatic MRTD measurement method. However, the latter one can be used practically only by manufacturers. In order to carry out semi-automatic MRTD measurement, it is necessary to carry out first classical MRTD measurement of a few imagers of the same type in order to determine correction coefficients. The coefficients are valid only for just this type of thermal imagers. This requirement makes the semi-automatic MRTD measurement attractive only when large number of imagers of the same time is to be tested.

5.1.1 Test team

MRTD is a subjective measurement when decision about test results is made by a human observer. It is natural that there is some variability of human sight within human population. In order to correct this variability, both standards and specialized literature recommend to carry out MRTD measurement by several (at least three observers) and then to average test results [1-4]. In this way, the variability of results get by different test teams should be theoretically eliminated. Practically, differences between MRTD measurement results of the same thermal imager obtained by several test teams at the level as high as 50% are quite common [2,3].

There are two basic reasons for this situation. First, differences in test equipment, detection criterion, observation conditions, and in a measurement procedure used during testing. Second, training level of the test crew. There is a general tendency that observers who spend hundreds of hours working with thermal imagers are well adapted to typical noisy thermal images and they get better results and the results are more stable. Therefore it is highly recommended to carry out MRTD measurement only by test teams employing people who are so-called "qualified MRTD observers". The latter ones are the people having no medical problems with their eyes and who passed special training where they became familiar with MRTD measurement. They made exemplary MRTD tests for at least dozen or more hours and then repeatability of their test results and their ability to detect and recognize low contrast targets in noisy environment was confirmed. The training of qualified MRTD observers should be done using a series of different real market thermal imagers. Such training can be also supported using computer simulators[11].

During real work, the observation time is quite often limited. The observer must hurry up to detect and recognize the target he is looking for in the scenery. However, it is commonly accepted that during MRTD tests the observer is allowed unlimited (in reasonable range) viewing time. It improves little test results in comparison to the limited-time test conditions.

5.1.2 Detection criterion

It is generally accepted in literature that the observer can consider that he "sees" the 4-bar pattern when he is able to count four separate bars. The bars do not to be seen all the time. They can be covered by temporal and spatial noise but still the observer must be sure that he can recognize all four bars. The bars can be distorted. One or two bars can be wider than the others but still the observer must be able to recognize separately four bars.

[11] VIRTEST computer program freely available from www.inframet.com website can be used for training.

5.1.3 Test environment

Observation conditions like ambient illumination, ambient temperature can significantly influence measurement results. It is generally considered that ambient illumination conditions during the MRTD tests should be similar to normal working condition of the tested thermal imager. Next, the recommended ambient temperature by the test standrds is 20 ±2°C. If tests are carried out at different temperatures, then the test results should be corrected.

Influence of two factors on measurement results should be taken into account and corrected: ambient temperature and transmittance of the optical channel between imager and the test system. Ambient temperature depending on exact value can both decrease or increase MRTD measurement results. Limited transmittance always increases measurement results.

Influence of ambient temperature on measurement results can be corrected by multiplying the measurement results by a certain correction coefficient *cor.* In case of non-cooled thermal imagers (it can be assumed that imager noise does not depend on ambient temperature), the coefficient can be determined using the following formula:

$$cor\left(T_{ba}\right) = \frac{\int_{\Delta\lambda} \frac{\partial M(\lambda, T_{ba})}{\partial T_{ba}} sys(\lambda) d\lambda}{\int_{\Delta\lambda} \frac{\partial M(\lambda, T_{ba(s)})}{\partial T_{ba(s)}} sys(\lambda) d\lambda} , \tag{5.1}$$

where T_{ba} is the ambient temperature for which the measurements were made, $T_{ba(s)}$ is the standard background temperature, $M(T,\lambda)$ is the spectral exitance at the temperature T and the wavelength λ, $sys(\lambda)$ is the imager relative spectral sensitivity, and $\Delta\lambda$ is the imager spectral band.

In case of cooled thermal imagers (it is assumed that BLIP detectors of ambient temperature depending on noise are used) the coefficient *cor* can be determined using this formula:

$$cor\left(T_{ba}\right) = \sqrt{\frac{\int_{\Delta\lambda} \frac{\partial M(\lambda, T_{ba})}{\partial T_{ba}} sys(\lambda) d\lambda}{\int_{\Delta\lambda} \frac{\partial M(\lambda, T_{ba(s)})}{\partial T_{ba(s)}} sys(\lambda) d\lambda}} . \tag{5.2}$$

If we assume that the reference ambient temperature equals 20°C, then for typical thermal imagers of the 3-5 μm and the 8-12 μm spectral bands, the correction coefficient *cor* can be presented as shown in Fig. 5.1.

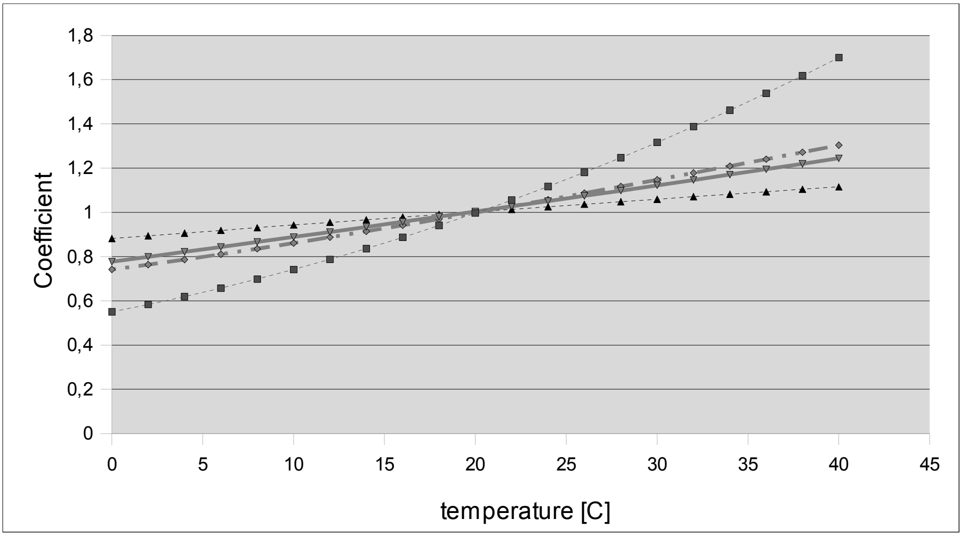


Fig. 5.1. The correction coefficient *cor* for typical thermal imagers of the spectral bands 3-5 µm and the 8-12 µm: *squares – non-cooled 3-5 µm; rhombus - non-cooled 8-12 µm; triangle up - cooled 8-12 µm; triangle down - cooled 3-5 µm)*.

Using the values of the coefficient *cor* shown in Fig. 1.1 and Table 1.1 it is theoretically possible to correct MRTD measurement results when measurements were carried out at a range of ambient temperatures from 0°C to 40°C. However, the real thermal imagers fulfill relatively well assumptions taken to derive formulas for the coefficient *cor* only in the range from about 10°C to about 30°C. Therefore it is recommended not to carry out MRTD outside this temperature range.

Influence of transmittance of the optical channel can be corrected by multiplying the results by a value of transmittance of the channel. In case of a variable target test system, the distance between the test system and the imager is very short, influence of atmosphere on radiation propagation is negligible, and transmittance of the optical channel is equal to collimator transmittance.

Values of collimator transmittance can vary quite significantly from about 0.85 to about 0.96. Next, collimator transmittance depends on a spectral range. Because of this significant variability, the user should always get information from manufacturer about collimator transmittance in the spectral range of interest.

The correction is done using the formula presented below:

$$MRTD_{cor} = MRTD_m \ \ \tau_{col} \, , \tag{5.3}$$

where $MRTD_{cor}$ is the corrected MRTD, $MRTD_m$ is the original measurement result, and τ_{col} is the transmittance of the collimator.

In case of variable-distance test systems there is no collimator in the optical channel but the distance imager-test system is longer. In typical conditions when

the distance is below about 100 m and measurement is done at good atmospheric conditions we can consider that atmospheric transmittance is almost unity and does not carry out any corrections. However, when the measurement is done at longer distances or at poor atmospheric conditions then atmospheric transmittance should be calculated and its influence on measurement results corrected.
The correction is done using the formula presented below

$$MRTD_{cor}= MRTD_m \quad \tau_a , \tag{5.4}$$

where τ_a is the atmospheric transmittance.

Table 5.1. The correction coefficient *cor* for typical thermal imagers of the spectral bands 3-5 µm and the 8-12 µm at different ambient (background) temperature.

Temperature T_{ba}	**Non-cooled 3-5 µm**	**Non-cooled 8-12 µm**	**Cooled 3-5 µm**	**Cooled 8-12 µm**
0	0.55	0.78	0.74	0.88
2	0.58	0.8	0.76	0.89
4	0.62	0.82	0.79	0.91
6	0.66	0.84	0.81	0.92
8	0.7	0.87	0.84	0.93
10	0.74	0.89	0.86	0.94
12	0.79	0.91	0.89	0.95
14	0.84	0.93	0.91	0.97
16	0.89	0.96	0.94	0.98
18	0.94	0.98	0.97	0.99
20	1.0	1.0	1.0	1.0
22	1.06	1.03	1.03	1.01
24	1.12	1.05	1.06	1.03
26	1.18	1.07	1.09	1.04
28	1.25	1.1	1.12	1.05
30	1.32	1.12	1.15	1.06
32	1.39	1.15	1.18	1.07
34	1.46	1.17	1.21	1.08
36	1.54	1.2	1.24	1.09
38	1.62	1.22	1.27	1.1
40	1.7	1.24	1.3	1.12

5.1.4 Targets

MRTD is a continuous function of temperature difference on target spatial frequency. However, MRTD is measured only at several points. The results are later approximated and MRTD curve is presented.
It is typically considered that MRTD should be measured at at least three measurement points that area located at three spatial frequency ranges: low, medium,

and high. In case of staring thermal imagers the frequency of the smallest target (the highest frequency) should be about the Nyquist frequency. The latter one can be calculated as 1/(2 IFOV).

Three measurement points is the minimal number. It is recommended to carry out measurements at more points. Practically it means that for testing a set of different thermal imagers available on the market a set of at least twelve 4-bar targets is needed.

Next, if the specifications of the tested imager present its MRTD values it is recommended to carry out measurements at exactly the same spatial frequencies as reported in the specifications.

Spatial frequency of 4-bar patterns is calculated as

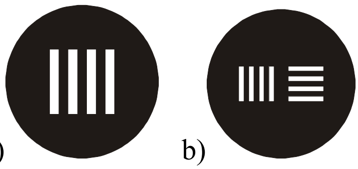
v [lp/mrad]=f' [m]/(2 a [mm]) - in case of variable target test systems,

v [lp/mrad]=R [m]/(2 a [mm]) - in case of variable target test systems,

where v is the spatial frequency of the 4-bar target, f' is the focal length of the collimator, R is the distance between the test system (target plane) and the imager (optics plane), and a is the width of a single bar in the 4-bar target.

Spatial frequencies of exemplary targets used in several variable target systems and in a variable distance system are shown in Table 5.2-Table 5.3. In the first case it was assumed that a series of 4-bar targets of a bar width variable from 0.1 mm to 4 mm and variable collimator focal length from 1 m to 3 m were assumed. In the second case it was assumed that the variable distance test system uses two 4-bar patterns: bigger 10 mm bar; smaller 4 mm bar.

International standards recommend to carry out MRTD measurements using targets with a single 4-bar pattern [1-4]. The target can be rotated to have the bars in horizontal, vertical or other position. The aim of this is to help the observer to concentrate and make his task easier because he can expect to find only one 4-bar pattern on a uniform background and there are no other objects that can distract attention of the observers. However, practical experience of the author shows that placing two 4-bar patterns (one vertical 4-bar pattern and one horizontal 4-bar pattern) do not reduce significantly accuracy of MRTD measurement but speeds up measurement process as within one process both horizontal MRTD and vertical MRTD can be determined. Therefore it is recommended to use double 4-bar targets in MRTD measurement process, particularly when differences between horizontal MRTD and vertical MRTD are expected.



a) b)

Fig. 5.2. Two 4-bar targets: a)single 4-bar pattern b)double 4-bar pattern

Table 5.2. Spatial frequencies of exemplary series of 4-bar targets in case of four variable target test systems of different collimator focal length *f'*

bar width [mm]	spatial frequency [1/mrad]	spatial frequency [1/mrad]	spatial frequency [1/mrad]	spatial frequency [1/mrad]
	f'=1000 mm	*f'*=1500 mm	*f'*=2000 mm	*f'*=3000 mm
4.00	0.13	0.19	0.25	0.38
3.36	0.15	0.22	0.30	0.45
2.83	0.18	0.27	0.35	0.53
2.38	0.21	0.32	0.42	0.63
2.00	0.25	1500	0.50	0.75
1.68	0.30	0.45	0.60	0.89
1.41	0.35	0.53	0.71	1.06
1.19	0.42	0.63	0.84	1.26
1.00	0.50	0.75	1.00	1.50
0.84	0.60	1500	1.19	1.79
0.71	0.70	1.06	1.41	2.11
0.59	0.85	1.27	1.69	2.54
0.50	1.00	1.50	2.00	3.00
0.42	1.19	1.79	2.38	3.57
0.35	1.43	1500	2.86	4.29
0.30	1.67	2.50	3.33	5.00
0.25	2.00	3.00	4.00	6.00
0.21	2.38	3.57	4.76	7.14
0.18	2.78	4.17	5.56	8.33
0.15	3.33	1500	6.67	10.00
0.13	3.85	5.77	7.69	11.54
0.10	5.00	7.50	10.00	15.00

Table 5.3. Spatial frequencies (in lp/mrad] of two 4-bar patterns as a function of the distance *R* between the imager and the variable distance test system and the width of target bar *a*

R[m]	*a*=10 [mm]	*a*=4 [mm]	*R* [m]	*a*=10 mm	*a*=4 [mm]	*R* [m]	*a*=10 [mm]	*a*=4 [mm]	*R* [m]	*a*=10 [mm]	*a*=4 mm
1	0.05	0.125	19	0.95	2.375	37	1.85	4.625	60	3	7.5
2	0.1	0.25	20	1	2.5	38	1.9	4.75	62	3.1	7.75
3	0.15	0.375	21	1.05	2.625	39	1.95	4.875	64	3.2	8
4	0.2	0.5	22	1.1	2.75	40	2	5	66	3.3	8.25
5	0.25	0.625	23	1.15	2.875	41	2.05	5.125	68	3.4	8.5
6	0.3	0.75	24	1.2	3	42	2.1	5.25	70	3.5	8.75
7	0.35	0.875	25	1.25	3.125	43	2.15	5.375	72	3.6	9
8	0.4	1	26	1.3	3.25	44	2.2	5.5	74	3.7	9.25
9	0.45	1.125	27	1.35	3.375	45	2.25	5.625	76	3.8	9.5
10	0.5	1.25	28	1.4	3.5	46	2.3	5.75	78	3.9	9.75
11	0.55	1.375	29	1.45	3.625	47	2.35	5.875	80	4	10
12	0.6	1.5	30	1.5	3.75	48	2.4	6	82	4.1	10.25
13	0.65	1.625	31	1.55	3.875	49	2.45	6.125	84	4.2	10.5
14	0.7	1.75	32	1.6	4	50	2.5	6.25	86	4.3	10.75
15	0.75	1.875	33	1.65	4.125	52	2.6	6.5	88	4.4	11
16	0.8	2	34	1.7	4.25	54	2.7	6.75	90	4.5	11.25
17	0.85	2.125	35	1.75	4.375	56	2.8	7	95	4.75	11.875
18	0.9	2.25	36	1.8	4.5	58	2.9	7.25	100	5	12.5

**R* – distance, a=10 mm – width of a single bar of the bigger pattern; a=4 mm – width of a single bar of the smaller pattern

Multiple 4-bar targets can speed up measurement process even more. However, the use of these targets is more risky due to not verified influence on measurement accuracy in situation when the observer sees several patterns at the same time. Next, parabolic off axis collimator are theoretically aberration-free but only for on-axis point. Images of 4-bar patters located outside the target center can be distorted noticeably in case of collimator of low F-number. Therefore, the multiple 4-bar targets should be used only when short measurement time is critical.

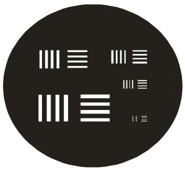


Fig. 5.3. Multiple 4-bar target

Rotation of the pattern bars always influence test results. The worst results we can get when the rotation angle is about 45°. However, the standards and specialized literature recommend to carry out the measurements for two cases: vertical bars (so called horizontal MRTD) and horizontal bars (so called vertical MRTD) and to average results. In case of staring thermal imagers the difference between horizontal MRTD and vertical MRTD is usually small. Totally inverse situation is in case of scanning thermal imagers. Horizontal MRTD is usually significantly better (50% or more) than vertical MRTD (Fig. 5.4). Therefore it is necessary to be very careful with a target position when testing scanning thermal imagers. A simple 90º rotation is enough to change drastically test results.

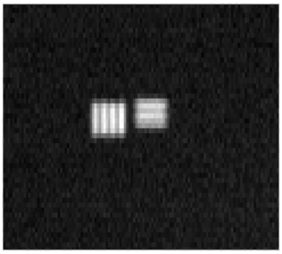


Fig. 5.4. Image of double 4-bar target generated by a scanning thermal imager.

5.1.5 Offset

International standards recommend to carry out MRTD measurements first for positive patterns, later for negative pattern, and finally to average results [1-4]. The aim of this recommendation is to correct influence of offset effect on MRTD measurement results. Offset exists when minimal positive temperature difference (set by the blackbody controller) needed to recognize positive 4-bar pattern of low frequency target is not equal to minimal negative temperature difference needed to recognize negative 4-bar pattern of the same target. We can also less accurately say that offset exists when the observer can recognize 4-bar pattern in situation when the blackbody controller indicates differential temperature equal to zero. Such a situation generates a constant bias in differential temperature readout.

There is a set of different factors that could create offset: limited accuracy measurement of target temperature using indirect method (the temperature probe is not inserted into the target plate but into the rotary wheel wall), difference of emissivity values of the target plate and blackbody radiator, limited temperature uniformity on the surface of blackbody radiator, etc.

If the MRTD measurement is done only for positive contrast patterns then offset can create significant measurement errors. If the MRTD measurement is done for both positive and negative contrasts, and the results are averaged then influence of the offset on MRTD results is corrected. However, this offset correction method is based on assumption that the offset does not change with time. The time from the moment when MRTD measurement was done for positive contrast to the moment when MRTD measurement was done for negative one can be estimated as 2-4 minutes. Offset can change quite significantly during that time if tests are carried out at room of low stability of ambient temperature and the test system is not protected well against ambient temperature variability.

As we see, the effectiveness of the offset correction method depends directly on temporal stability of the temperature difference between the target and the blackbody; indirectly - on quality of a test system and the environmental conditions in the test room. Therefore it is highly recommended to use for MRTD measurement of modern cooled staring thermal imagers (the highest requirements) only test systems that of highly reduced offset variations. If not, the measurement results at low spatial frequency range shall not be repeatable.

If ofset stability is confirmed then we have an opportunity to speed up measurement process. We can first correct the offset and next carry out MRTD measurements only for positive contrast.

In case of most test systems offset can be easily measured and later eliminated using blackbody controller. It can be measured and later calculated using this formula:

$$offset = (\Delta T_{+} + \Delta T_{-})/2 \quad (5.5)$$

ΔT_{+} is the minimal positive temperature difference when the observer recognizes the target and ΔT_{-} is the minimal negative temperature difference when the observer can recognize the target.

When offset was calculated using the formula presented above the observer should insert offset value into electronic memory of the controller. Then the bias in indications of differential temperature is eliminated and we can consider the test systems as "offset free" at least for some limited time.

5.1.6 Imager settings

Observers are allowed to regulate all imager settings until they consider that they get the best image during MRTD measurement. Here we present several guidelines:

a) set gain (contrast) to maximum (during measurements when low frequency targets are used),
b) set brightness (level) to average position,
c) set edge improvement (electronic boost) off when MRTD is measured at low frequency range,
d) set edge improvement (electronic boost) on when MRTD is measured at medium/high frequency range.

These guidelines should not be treated as "must to do" conditions. There are imagers when at different settings better test results can be get.

There are many thermal imagers with built in display. For such imagers, two display configurations are possible: 1)test are carried out using original imager display; 2)tests are carried out using a special high quality monitor. The first approach is recommended as only then we can get information about real capability of tested thermal imagers.

5.1.7 Static/dynamic images

Classical MRTD definition refers to static targets and MRTD is generally a measure of imager ability to detect, recognize and identify static targets. However, during real work of thermal imagers the image of static targets becomes slightly dynamic due to imager movement (human hands vibration when portable imager is kept; movement or vibration of a tank equipped with a thermal imager etc). Next, the head of the observer is rarely fully static during real work, too. Therefore it looks logically that the observers should be allowed to move slightly both the imagers and their heads during MRTD measurement to simulate real work conditions. It can surprise but minimal movements of the imager can quite significantly improve MRTD measurement results particularly in case of non cooled imager with high fixed pattern noise due to phase effects. In case of staring imagers, when the imager is slowly vibrating it is often easier to detect 4-bar pattern in comparison to situation when the imager is fully stabilized.

5.1.8 Differential temperature steps

Stanag 4349, *Measurement of minimum* resolvable *thermal difference (MRTD) of thermal cameras* that regulates measurement of MRTD of thermal imagers presents precise guidelines about steps of differential temperature that should be used during test procedure (Table 5.4). These recommendations were perfect two decades ago when typical temperature resolution of thermal imagers was about 200 mK. Regulation of differential temperature with 10 mK step is perfectly acceptable for such imagers. However, regulation of differential temperature with 10 mK step is totally not acceptable in case of modern thermal imagers; particularly cooled staring imagers of temperature resolution often below 20 mK. Next, the recommendations about steps for temperature differences over 2°C are useless because this temperature range is not practically used during tests of modern sensitive thermal imagers. Therefore the author updated the table with recommended differential steps to the form shown in Table 5.5.

Table 5.4. Recommended steps of differential temperature during MRTD measurement.

ΔT	step	ΔT	step
below 0.5°C	0.01 °C	1°C – 2.0 °C	0.1°C
0.5°C – 1.0 °C	0.02 °C	2°C – 8.0 °C	0.2°C
1°C – 2.0 °C	0.05 °C	over 8.0 °C	0.4°C

Table 5.5. Updated recommended steps of differential temperature during MRTD measurement.

ΔT	step	ΔT	step
<0.02°C	0.002 °C	0.5°C – 1.0 °C	0.02 °C
0.02°C – 0.1 °C	0.005 °C	1°C – 2.0 °C	0.05 °C
0.1°C – 0.5 °C	0.01 °C	1°C – 2.0 °C	0.1°C

5.1.9 Measurement methods

There are two basic methods to measure MRTD:

1. Keep constant spatial frequency and vary temperature difference,
2. Keep constant temperature difference and vary spatial frequency.

In case of classical test systems (variable target test system), only the first method is possible. In case of variable distance test systems, both methods can be used; but practically the second method is applied.

In case of the first method, in order to measure MRTD at one measurement point spatial frequency is kept constant but temperature difference varies. Practically, this means that a single target is used but the observer regulates temperature difference between the bars and the background until he finds that he can recognize the 4-bar pattern. The procedure is repeated by several observers and then a target is exchanged and measurement of a new MRTD point is carried out.

In case of the second method, in order to measure MRTD at one measurement point, temperature difference is kept constant but spatial frequency varies. Practically this means that the blackbody controller keeps constant temperature difference but the distance between the test system and the tested imager is slowly increased (spatial frequency is increased) until the observer finds that this is the highest distance when he still can recognize the 4-bar pattern. The procedure is repeated by several observers and then new temperature difference is set and measurement of a new MRTD point is carried out.

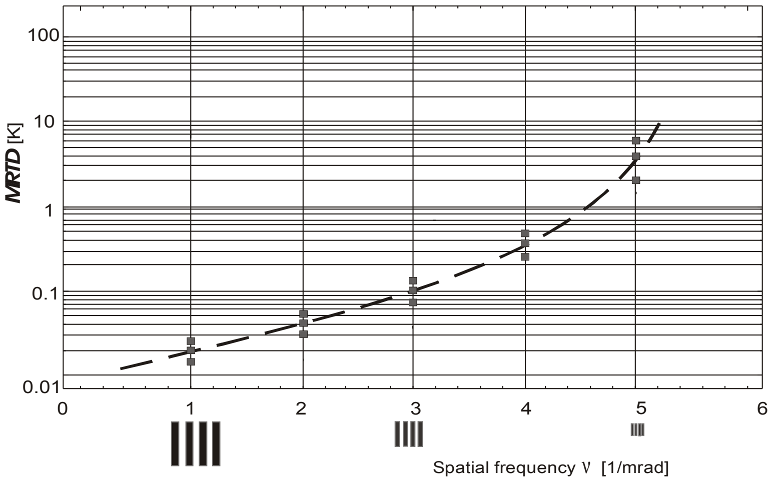


Fig. 5.5. MRTD measurement results of three observers using the constant spatial frequency and variable temperature measurement method.

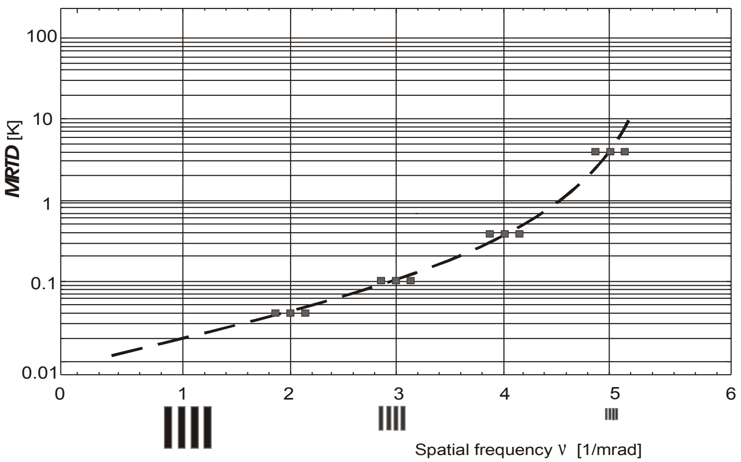


Fig. 5.6. MRTD measurement results of three observers using the constant temperature difference and variable spatial frequency method.

Both methods should deliver the same final MRTD curve. The advantage of the first method is semi-automatic control of the temperature difference and the spatial frequency (target number) using the test software. Next, the variable target test systems that use this method require little space to carry out measurement and the tests can be carried out even in a small room.

The variable-distance test systems require usually manual change of the distance between the imager and the test system. Next, more space is required during the test procedure. A long corridor of 20-50 m length is typically required but in case of tests of long range thermal imagers longer distances are sometimes needed. These requirements create logistical problems for some potential users of test equipment.

There are, however, several serious advantages of the variable-distance test systems. First, the measurement speed is high in case of testing portable thermal imagers or in any case when a distance change can be quick. Second, a big advantage of the variable distance test systems is the possibility of carrying out measurement at any spatial frequency. We must remember, that in case of variable target image projectors measurement or MRTD can be carried out only at spatial frequencies that are equal to spatial frequencies of the set of 4-bar targets the user posses. This latter feature saves a lot of problems and money when it is necessary to test different thermal imagers at different spatial frequencies. Third, the variable-distance test systems can be optionally used at field conditions to enable testing thermal imagers located at their mechanical carriers. Please note however that it is difficult to carry out accurately MRTD measurement at field conditions due to possible influence of environment conditions on measurement results. It is necessary to protect the test system against wind, direct sun, rain, etc. In other words, it is necessary to achieve relatively stable ambient temperature to enable accurate MRTD at field conditions. It is typically done by using some kind of protection of the test equipment: buildings with open window or door, tents, etc.

A. Case of variable target test system

Here a detail procedure for MRTD measurement using a variable target test system is presented.

1. Write down basic test data: imager type, imager serial number, its field of view; date of the test; number and names of the observers; ambient temperature; collimator transmittance; orientation (vertical or horizontal) of the bar pattern.
2. Fix to the rotary wheel a set of 4-bar targets keeping proper bar pattern orientation. Spatial frequencies of the targets should be equal to spatial frequencies of the needed measurement points. The targets should be arranged in the following order: the largest target of the lowest spatial frequency becomes target no 1, the smallest target of the highest spatial frequency gets the highest number on the wheel.
3. Put the tested thermal imager at the output of the collimator. The imager should look into the collimator. Attention: the optics of the imager should be kept as close to the hole in the collimator output wall as possible.
4. Turn on the imager.
5. Turn on the blackbody controller.
6. Wait for at least 15 minutes. Give time for both the imager and the test system to reach thermal equilibrium.
7. Set temperature difference equal of the blackbody controller to 2ºC.

8. Put target of the lowest spatial frequency in the active position (the position when target is located at collimator focal plane and can be seen by the tested thermal imager).
9. Focus the imager until you get a sharp image of the 4-bar pattern.
10. Rotate the imager until the image of the 4-bar pattern is located in the center of imager field of view.
11. Set using the blackbody controller temperature difference equal to zero.
12. Increase slowly (see recommended steps of differential temperature showed in Table 5.5) positive temperature difference until observer I starts to recognize 4-bar patter. Write the current temperature difference value as ΔT_+ to Table 5.7.
13. Decrease slightly the positive temperature difference until the 4-bar pattern disappears.
14. Exchange observers.
15. Increase slowly positive temperature difference until observer II starts to recognize 4-bar pattern. Write the current temperature difference value as ΔT_+ to column 7 of Table 5.7.
16. Decrease slightly the positive temperature difference until the 4-bar pattern disappears. Exchange observers.
17. Increase slowly positive temperature difference until observer III starts to recognize 4-bar pattern. Write the current temperature difference value as ΔT_+ the Table 5.7.
18. Decrease temperature until the observer I starts seeing negative 4-bar target. Typically it is needed to get temperature difference below zero to see negative 4-bar target. However, in case of test systems with a significant offset the negative target can be seen even for positive temperature differences close to zero (see exemplary case in Table 5.7). Write the current temperature difference value as ΔT_- to Table 5.7.
19. Decrease slightly the negative temperature difference until the 4-bar pattern disappears. Exchange observers.
20. Increase slowly negative temperature difference until observer II starts to recognize 4-bar pattern. Write the current temperature difference value as ΔT_- to Table 5.7.
21. Decrease slightly the negative temperature difference until the 4-bar pattern disappears. Exchange observers.
22. Increase slowly negative temperature difference until observer III starts to recognize 4-bar pattern. Write the current temperature difference value as ΔT_- to Table 5.7.
23. Exchange targets using the rotary wheel. Target number 2 should be placed in the active position.
24. Repeat points 8-18.
25. Repeat points 19-20 until the MRTD measurement was done for all 4-bar targets.

26. Calculate MRTD values for each observer as an average from recorded positive temperature differences ΔT_+ and negative temperature differences ΔT_-

$$MRTD = \Delta T = \frac{\Delta T_+ - \Delta T_-}{2} \quad . \tag{5.6}$$

Fill the ΔT columns for each observer in the test results table.

27. Calculate raw measurement MRTDm as an average MRTD from each observer

$$MRTD_m = (\Delta T_1 + \Delta T_2 + ... + \Delta T_n)/n \ , \tag{5.7}$$

where $MRTD_n$ is measurement result for n observer (n=3 in case presented in Table 5.7) . Fill the $MRTD_m$ column.

28. Correct the raw measurement $MRTD_m$ results using this formula

$$MRTD_{cor} = MRTD_m \ cor(T_a) \ \tau_{col} \tag{5.8}$$

where $cor(T_a)$ is the correction coefficient (see Table 5.1) and τ_{col} is transmittance of the collimator. Fill the $MRTD_{cor}$ column.

The procedure presented above enables us to measure MRTD at one orientation.

The exemplary data shown in Table 5.6 and Table 5.7 refer to vertical bar orientation that enabled to measure horizontal MRTD. In order to measure vertical MRTD it is necessary to change orientation of the single 4-bar targets fixed to the rotary wheel on horizontal orientation, and to repeat the earlier presented algorithm and insert the test results to Table 5.8.

Attention: If double 4-bar targets (see Fig. 5.2) are used then both horizontal MRTD and vertical MRTD can be measured at one measurement process.

Table 5.6. Exemplary test conditions.

No	Test conditions	Value
1	Imager name, type, number and field of view	Marico, cooled 8-12 µm, no 232, FOV: 2°x1.5°
2	Number of observers and names	3 (F. Fotell, K. Novak, Y. Russon)
3	Test date	November 12,2006
4	Test place	Factory laboratory no 10
5	Test system type and number	DT 2000 no A12/2005
6	Ambient temperature	16°C (correction coefficient 0.98)
7	Collimator transmittance	0.94
8	Target type and bars position	Single 4-bar pattern, vertical position

Table 5.7. Exemplary table with horizontal MRTD test results.

			Observer I			Observer II			Observer III				
No	*a*	*ν*	ΔT_+	ΔT_-	ΔT_1	ΔT_+	ΔT_-	ΔT_2	ΔT_+	ΔT_-	ΔT_3	$MRTD_m$	$MRTD_{cor}$
1	2,00	0,50	-0,02	0,08	0,05	-0,02	0,08	0,05	-0,03	0,09	0,06	0,05	0,05
2	1,00	1,00	-0,05	0,11	0,08	-0,07	0,13	0,1	-0,09	0,15	0,12	0,1	0,09
3	0,67	1,50	-0,13	0,19	0,16	-0,17	0,23	0,2	-0,22	0,28	0,25	0,2	0,19
4	0,50	2,00	-0,27	0,33	0,3	-0,34	0,4	0,37	-0,37	0,43	0,4	0,36	0,33
5	0,40	2,50	0,47	0,53	0,5	-0,55	0,61	0,58	-0,61	0,67	0,64	0,57	0,53
6	0,33	3,00	-0,77	0,83	0,8	-0,84	0,9	0,87	-0,87	0,93	0,9	0,86	0,79
7	0,29	3,51	-1,47	1,53	1,5	-1,47	1,53	1,5	-1,77	1,83	1,8	1,6	1,47
8	0,25	4,00	-3,17	3,23	3,2	-2,97	3,03	3	-3,47	3,53	3,5	3,23	2,98

a - bar width in mm; *ν* - spatial frequency in lp/mrad; ΔT - temperature difference in °C units; *MRTD* - in °C units

Table 5.8. Exemplary table with vertical MRTD test results.

			Observer I			Observer II			Observer III				
No	*a*	*ν*	ΔT_+	ΔT_-	ΔT_1	ΔT_+	ΔT_-	ΔT_2	ΔT_+	ΔT_-	ΔT_3	$MRTD_m$	$MRTD_{cor}$
1	2,00	0,50	-0,03	0,09	0,06	-0,02	0,08	0,05	-0,03	0,09	0,06	0,06	0,05
2	1,00	1,00	-0,06	0,12	0,09	-0,05	0,11	0,08	-0,09	0,15	0,12	0,1	0,09
3	0,67	1,50	-0,15	0,21	0,18	-0,19	0,25	0,22	-0,27	0,33	0,3	0,23	0,21
4	0,50	2,00	-0,32	0,38	0,35	-0,37	0,43	0,4	-0,52	0,43	0,47	0,43	0,4
5	0,40	2,50	-0,62	0,68	0,65	-0,67	0,62	0,64	-0,77	0,73	0,75	0,72	0,66
6	0,33	3,00	-1,07	1,13	1,1	-1,37	1,43	1,4	-1,37	1,43	1,4	1,3	1,2
7	0,29	3,51	-3,47	3,53	3,5	-3,17	3,23	3,2	-3,37	3,43	3,4	3,37	3,1
8	0,25	4,00	-	-	-	-	-	-	-	-	-	-	-

a - bar width in mm; *ν* - spatial frequency in lp/mrad; ΔT - temperature difference in °C units; MRTD - in °C units

The measurement algorithm presented earlier generated two significantly different MRTD curves: horizontal MRTD and vertical MRTD. This is a typical situation for scanning thermal imagers: horizontal MRTD significantly better than vertical MRTD particularly in high frequency range. In case of staring thermal imagers the differences between horizontal MRTD and vertical MRTD are typically small, sometimes negligible. There is also no rule which MRTD is better for staring imagers.

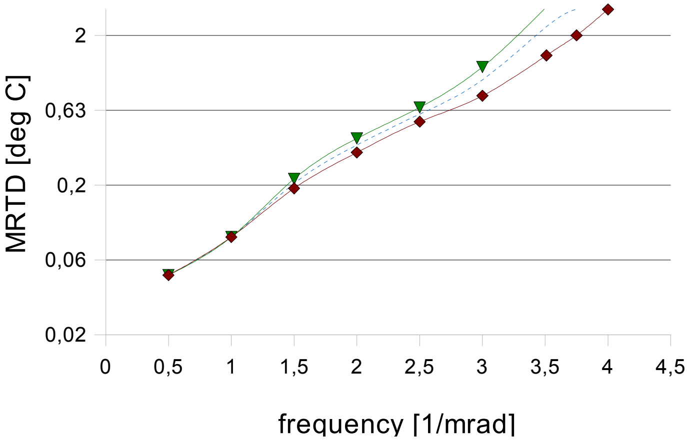


Fig. 5.7. Exemplary horizontal MRTD and vertical MRTD measurement results (squares – horizontal MRTD; triangles – vertical MRTD, no symbols – average MRTD).

There is a question of big importance what to do when there is a difference between horizontal MRTD and vertical MRTD. People usually prefer to get a single MRTD curve instead of MRTD curves. The problem is that we will get slightly different MRTD curves depending on averaging method we choose: to average temperatures or to average spatial frequencies, to use algebraic averaging or geometric averaging. Literature proposals are inconsistent in this matter. The author typically uses frequency averaging using algebraic mean method because this way can be used for all measurement points

$$\nu_{av}=(\nu_h+\nu_v)/2 \,, \tag{5.9}$$

where ν_h is the spatial frequency of horizontal MRTD curve at ΔT level, ν_v is spatial frequency of vertical MRTD curve at ΔT level, ν_{avg} is average spatial frequency of MRTD curve at ΔT level.

The algorithm to calculate average MRTD curve is based on three steps.

1. Determine functions that approximate (interpolate) measured $MRTD_h$ and $MRTD_v$ data. Two functions are obtained: $MRTD_h$ (ν) and $MRTD_v$ (ν).
2. Calculate ν_h and ν_v at several levels of temperature difference ΔT: $MRTD_h$ and $MRTD_v$(ν).
3. Use formula (5.9) to calculate ν_{av} at several levels of temperature difference ΔT.

After carrying out these three-step algorithm the average MRTD can be calculated as in exemplary case presented in Fig. 5.7.

Please note that, other options of calculation of average MRTD are also possible as long as it is clearly stated in the test report what method was used.

The presented earlier in detail classical measurement procedure is time consuming; particularly if imagers of several fields of view are to be tested. For each FOV a separate MRTD curve should be measured; both horizontal MRTD and vertical MRTD. The measurement procedure can be speed up if horizontal MRTD and vertical MRTD could be measured at the same time using the same target. It can be done if a double pattern 4-bar target is used instead of a typical single pattern 4-bar target (Fig. 5.2). Next, the measurement procedure can shorten more if MRTD is measured only for positive contrast targets. Such a solution is acceptable only is the offset is stable and was corrected to a negligible level.

It means that MRTD measurement can be made for positive contrast targets only for test systems of small offset and having additionally some kind of offset monitoring. Generally the test team should be informed about offset temporal changes.

Next, it is always recommended at the beginning of testing a new thermal imager to make offset measurement, correct offset using available software tools, and only then to carry out MRTD measurement for positive contrast targets.

The simplified MRTD measurement algorithm for positive contrast is presented below.

1. Carry out preliminary points 1-6 of the classical algorithm.
2. Set differential temperature to equal zero. Regulate slowly temperature difference around zero. Determine the minimal positive temperature difference when the observer recognizes the target ΔT_{+}. Determine the minimal negative temperature difference ΔT_{-} when the observer can recognize target. Calculate the offset as
$$offset = (\Delta T_{+} + \Delta T_{-})/2 \qquad (5.10)$$
Attention: Both ΔT_{+} or ΔT_{-} can be positive or negative numbers.
Insert the offset value to blackbody software memory (please refer to blackbody operational manual). Blackbody indications are corrected and offset influence is eliminated.
3. Increase slowly (see recommended steps of differential temperature showed in Table 5.5 positive temperature difference until observer I starts to recognize the vertical 4-bar pattern. Write the current temperature difference value as horizontal ΔT_{+} to test results table.
4. Decrease slightly differential temperature until both patterns disappear and then increase it slowly until observer I starts to recognize horizontal 4-bar pattern. Write the current temperature difference value as vertical ΔT_{+} to test results table.
5. Exchange observers.
6. Repeat the previous two points until all observers carried out MRTD measurements for the current target (spatial frequency point)
7. Exchange targets using the rotary wheel for a new target of higher spatial frequency.

8. Repeat points 3-6 until MRTD measurement was done for all targets.
9. Calculate MRTD values for each observer at one spatial frequency as the recorded positive temperature differences ΔT_+

$$MRTD = \Delta T_+$$

Fill the columns of the test results table.
10. Calculate raw measurement $MRTD_m$ as an average MRTD from each observer

$$MRTD_m=(MRTD_1+MRTD_2+...+MRTD_n)/n \quad (5.11)$$

where $MRTD_n$ is the measurement result for n observer. Fill the $MRTD_m$ column.
11. Correct the raw measurement $MRTD_m$ results using this formula

$$MRTD_{cor} = MRTD_m \; cor(T_a) \; \tau_{col} \quad (5.12)$$

where $cor(T_a)$ is the correction coefficient (see Table 5.1) and τ_{col} is transmittance of the collimator. Fill the $MRTD_{cor}$ column.

Table 5.9. Exemplary table with horizontal MRTD test results using the simplified procedure.

			Observer I	Observer II	Observer III		
No	a	v	ΔT_h	ΔT_h	ΔT_h	$MRTD_m$	$MRTD_{cor}$
1	2,00	0,50	0,05	0,05	0,06	0,05	0,05
2	1,00	1,00	0,08	0,1	0,12	0,1	0,09
3	0,67	1,50	0,16	0,2	0,25	0,2	0,19
4	0,50	2,00	0,3	0,37	0,4	0,36	0,33
5	0,40	2,50	0,5	0,58	0,64	0,57	0,53
6	0,33	3,00	0,8	0,87	0,9	0,86	0,79
7	0,29	3,51	1,5	1,5	1,8	1,6	1,47
8	0,25	4,00	3,2	3	3,5	3,23	2,98

a - bar width in mm; v - spatial frequency in lp/mrad; ΔT - temperature difference in °C units; MRTD - in °C units

Table 5.10. Exemplary table with vertical MRTD test results using the simplified procedure.

			Observer I	Observer II	Observer III		
No	a	v	ΔT_v	ΔT_v	ΔT_v	$MRTD_m$	$MRTD_{cor}$
1	2,00	0,50	0,06	0,05	0,06	0,06	0,05
2	1,00	1,00	0,09	0,08	0,12	0,1	0,09
3	0,67	1,50	0,18	0,22	0,3	0,23	0,21
4	0,50	2,00	0,35	0,4	0,55	0,43	0,4
5	0,40	2,50	0,65	0,7	0,8	0,72	0,66
6	0,33	3,00	1,1	1,4	1,4	1,3	1,2
7	0,29	3,51	3,50	3,2	3,4	3,37	3,1
8	0,25	4,00	-	-	-	-	-

The test procedure can be shorten even more if measurements are made by only one, but well trained observer. It is a risky solution but if it was earlier verified that the observer indications are close to group of average indications then the solution can be considered as acceptable.

B. Case of variable distance test system

Variable distance test systems are systems built using a large area blackbody integrated with a large area multi-pattern target surrounded by a special shield. Multi-pattern target can be built using a set of different patterns. However, two double 4-bar patterns shown in Fig. 5.8 are typically used as such multi-pattern targets [8]. The target plate is not changed during measurements and the pattern linear size of these two 4-bar patterns is constant. However, the test team can vary angular size of the 4-bar patterns (spatial frequency of the two patterns) by changing distance between tested imager and test system.

In case of variable distance test systems it is typically acceptable to use simplified measurement algorithm and to carry out vertical/horizontal MRTD measurement only for positive contrast after offset correction at the beginning of the test procedure[12].

[12] Attention: Stable offset must be confirmed before measurement.

Fig. 5.8. Exemplary multi pattern target (black color-holes, white color – metal plate).

It is possible to measure MRTD using a variable distance test system but keeping the same measurement method used by variable target test systems. This means by keeping constant spatial frequency of the target and changing target temperature difference during measurement of a single MRTD point. It is, however, a rather slow measurement procedure. When we change temperature difference of the blackbody we must wait typically about 60 s for temperature difference to stabilize.

If we consider that we need often ten steps or more to find proper temperature difference then we see that measurement of a single MRTD point can take a dozen or more minutes. Therefore, in case of variable distance systems MRTD is typically measured by keeping temperature difference constant but changing spatial frequency (distance) even for a single MRTD point. If we can change the distance quickly then we can save a lot of time by using this measurement method. Therefore this method is highly recommended in case of testing small portable thermal imagers that can be easily moved. In case of testing bigger thermal imagers it is recommended to regulate a distance by changing position of the test system placed on a movable platform. It is preferable if the test system is battery powered.

Due to the presented above advantages of the constant temperature-variable spatial frequency method only for this method will be presented. Next, the measurement are shall be only for positive contrast targets. Further on, to simplify procedure only MRTD test results for targets of vertical orientation are presented.

This simplified MRTD measurement algorithm is presented below.

1. Write down basic test data: imager type, number and its field of view; date of the test; number and names of the observers; ambient temperature. As in the previous case we assume that ambient temperature equals 16°C (correction coefficient 0.98).
2. Calculate spatial frequencies of the 4-bar patterns at different distance imager-test system (or use data provided by the manufacturer of the test system like in the form shown in Table 5.3).
3. Turn on the blackbody controller. Set temperature difference equal to 2ºC (or more).
4. Turn on the imager. Put the imager at a short distance that can be considered as the minimal imager focus distance. To determine this

distance please check imager specifications or simply reduce the distance until the image of the target becomes blurred[13].

5. Wait at least 15-30 minutes to enable both the imager and the test system to work in stable conditions.
6. Correct blackbody offset. Set differential temperature to equal zero. Regulate slowly this temperature around zero and determine the minimal positive temperature difference when the observer recognizes the target ΔT_{+} and the minimal negative temperature difference ΔT_{-} when the observer can recognize target. Calculate offset as

$$offset = (\Delta T_{+} + \Delta T_{-})/2 \qquad (5.13)$$

   Attention: ΔT_{+} or ΔT_{-} can be positive or negative numbers.
   Insert the offset value to blackbody software memory (please refer to blackbody operational manual). Blackbody indications are corrected and offset influence is eliminated.
7. Regulate temperature difference of the test system to get value equal to 12 mK. If the 4-bar pattern cannot be resolved then increase the temperature difference to 25 mK or more (50 mK, 100 mK).
8. Increase gradually a distance between test system and the tested imager to find the longest distance when you can still recognize the 4-bar pattern (two patterns can be used: big or small)
9. Convert the value of the distance in meters to spatial frequency in lp/mrad using Table 5.3.
10. Insert the measured value of the spatial frequency to Table 5.11.
11. Increase temperature difference to 25 mK and repeat points 7-9.
12. Increase temperature difference to 50 mK and repeat points 7-9.
13. Increase temperature difference to 100 mK and repeat points 7-9.
14. Increase temperature difference to 200 mK and repeat points 7-9.
15. Increase temperature difference to 400 mK and repeat points 7-9.
16. Increase temperature difference to 800 mK and repeat points 7-9.
17. Increase temperature difference to 1600 mK and repeat points 7-9.
18. Repeat points 6-17 by the second observer.
19. Repeat points 6-17 by the third observer.
20. Calculate average spatial frequency of the 4-bar target that can be resolved using this formula

$$\nu_{av} = (\nu_1 + \nu_2 + \nu_3)/n\ , \qquad (5.14)$$

   where n means number of observers.
   Fill the suitable column.
21. Correct the raw measurement $MRTD_m$ using this formula

[13] The latter method is recommended because in specifications manufacturers usually repeat requirements developed by military who are not interested in very short distances. Therefore real minimal focus distance is usually a few times lower that value shown in specifications.

$$MRTD_{cor} = MRTD_m \ cor(T_a) \ \tau_a \ , \tag{5.15}$$

where $cor(T_a)$ is the correction coefficient (see Table 5.1) and τ_a is effective atmospheric transmittance (typically equal to one). Fill the suitable column.

When the presented above measurement procedure is carried out we get eight measurement points and shape of MRTD curve determined accurately. Four measurement points can be still considered as satisfactory high number for typical tests. If MRTD of tested imager can be roughly predicted then the number of measurement points can be reduced to three points.

Test results obtained using the presented measurement algorithm are shown in Table 5.11. Please note that the test results shown in Table 5.11 obtained using a variable distance test system are almost the same as test results shown in Table 5.9-Table 5.10 obtained using a variable target test system. Therefore the conclusion is that if properly used then both two types of test systems generate the same test results. It should be also noted that in case of measurement using the exemplary variable test system two 4-bar patterns of different bar width (8 mm and 4 mm) were used. Bigger 4-bar pattern (8 mm bar width) was used during measurement at low frequency points; smaller (4 mm bar width) at high frequency range). This solution was used in order to minimize the distance needed to carry out MRTD measurement at the required spatial frequency range from 0.5 lp/mrad to 4 lp/mrad.

Table 5.11. Exemplary table with vertical MRTD test results obtained using a variable distance test system.

Temperature difference [K]		Spatial frequency [lp/mrad]			
$MRTD_m$	$MRTD_{cor}$	ν_1	ν_2	ν_3	ν_{av}
0.0120	0.0118	x	x	x	x
0.025	0.0245	x	x	x	x
0.05	0.049	0.51	0.5	0.49	0.49
0.1	0.098	1.03	1	0.96	0.96
0.2	0.196	1.55	1.51	1.45	1.45
0.4	0.392	2.06	2.02	1.97	1.97
0.8	0.784	3	2.92	2.95	2.95
1.6	1.568	3.54	3.52	3.4	3.4

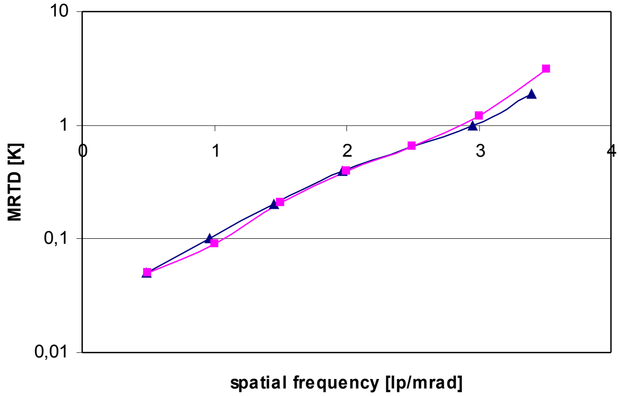


Fig. 5.9. MRTD measurement results obtained using two methods: squares – variable target method, triangles – variable distance method.

5.1.10 Software support

The MRTD is a subjective parameter that describes ability of the imager-human system for detection of low contrast details of the observed object. The human is to make decision when he can resolve the thermal image of the bars. Therefore computer technology is not generally needed during MRTD measurements. However software support can still be useful during MRTD measurements. Most manufacturers of equipment for testing thermal imagers provide also computer programs that help human observer to carry out MRTD measurement.

In detail the tasks of these support programs are following:

1. Recording measurement conditions (imager name or other identification data, number of observers, test date, test place, ambient temperature, collimator transmittance, collimator focal length, test orientation),
2. Calculation of spatial frequency of 4-bar targets in lp/mrad on the basis of known bar width in mm unit,
3. Correction of influence of measurement conditions on test results (correction of influence of ambient temperature and of collimator transmittance)
4. User friendly control from PC of blackbody temperature and position of rotary wheel
5. Presentation of MRTD measurement results in form of tables and graphs.
6. Recording test results.

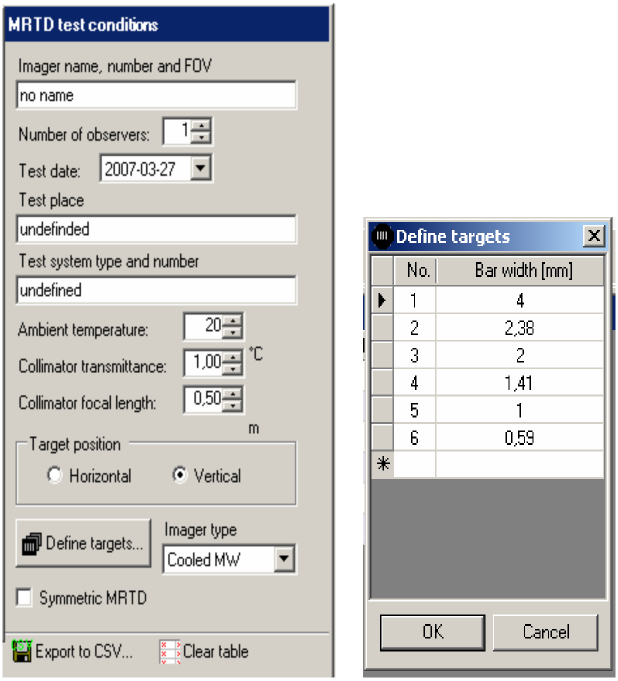


Fig. 5.10. Windows of TCB Control program used for support of MRTD measurement [8].

5.1.11 Interpretation of MRTD measurement results

MRTD tests generate two functions: horizontal $MRTD_h(\nu)$ and horizontal $MRTD_v(\nu)$ that can be graphically represented as two separate curves. MRTD requirements usually do not refer directly to horizontal MRTD or vertical MRTD but to MRTD in general.

As it was mentioned in Section 5.1.9 there is no consensus in specialist literature what averaging method should be used (algebraic mean or geometric mean; temperature averaging or frequency averaging). Literature proposals are inconsistent in this matter. The author typically uses frequency averaging using algebraic sum because this method can be used for all measurement points. However, other options are also possible as long as it is clearly stated in the report what methods was used.

Even when MRTD test results are presented in form of a single curve it is often not easy to decide whether the tested imager fulfills the MRTD requirements or not. Now, let us assume that after measurements we get the average MRTD curve shown in Fig. 5.7. Next, let us consider several versions of requirements on imager MRTD shown in Table 5.12 and find out whether the tested thermal imager fulfills these requirements.

Table 5.12. Exemplary requirements on MRTD of a thermal imager.

frequency[lp/mrad]	**MRTD requirements**			
	Version A	Version B	Version C	Version D
0,5	<0,12°C	<0,02°C	<0,1°C	0,04
1,5	<0,35°C	<0,1°C	<0,25°C	0,16
2,5	<0,95°C	<0,3°C	<0,55°C	0,5
3,5	<3,5°C	<1,3°C	<1,9°C	1,7

Before we decide whether the imager fulfills MRTD requirements we must consider the fact that only measurement result with error (uncertainty) indicator is truly valid measurement data. It is frequently reported in literature that during MRTD measurement variability as high 50% are often cited from laboratory-to-laboratory and 20% at one laboratory [3]. Let us assume this worst case scenario of 50% measurement error. MRTD measurement results (with 50% measurement errors) of the analysed imager and exemplary three versions of MRTD requirements are shown in Fig. 5.11.

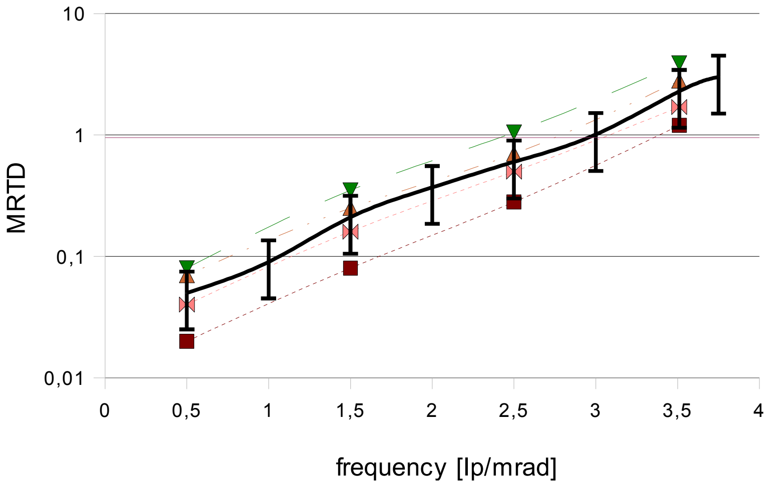


Fig. 5.11. MRTD test results (continuous curve with errors bars) and three different versions of MRTD requirements (version A – triangles down; version B-triangles up; version C-squares, version D-double triangles).

It is clear that in case A the tested thermal imager fulfills the MRTD requirements. It is also clear that in case C the tested imager does not fulfill the requirements. There is however a question what should be a proper decision in case B and case D. There is no clear answer what to do in this situation in international standards and literature. Totally different decisions can be taken on the basis of the presented above data:

1. Thermal imager fulfills requirement only in case A. This is the worst scenario for manufacturer but very safe situation for the final user.
2. Thermal imager fulfills requirement in case A, B and D. This scenario assures that no good imager is classified as non-fulfilling specifications but this scenario is very risky for the final user.
3. Thermal imager fulfills requirement in case A, B. Now the risk due to limited accuracy of MRTD measurement method is divided fifty to fifty between the manufacturer and the final user.

The decision which interpretation method should be applied to the MRTD test results should be determined immediately when MRTD requirements are decided. As we see in the example presented earlier not only MRTD measurement results are important but also method of their interpretation.

5.2 MTF

5.2.1 Measurement concept

Modulation Transfer Function (MTF) is a measure of sharpness (or blurring) of images generated by thermal imagers, or in general by any imaging system. There are over a dozen possible methods to measure MTF of imaging systems. However, in case of testing thermal imagers only two measurement methods are typically used.

Method one, an image of a slit target generated by tested imager is acquired , analysed and MTF of the tested imagers is calculated as a module from Fourier transform of Line Spread Function (normalized blur distribution in the image of the narrow slit target)

$$MTF(\nu)=\left|F[\mathrm{LSF(x)}]\right|. \tag{5.16}$$

Method two, an image of an edge target generated by tested imager is acquired, analyzed and later MTF of tested imager is calculated as a module from Fourier transform of the differentiated Edge Spread Function (normalized blur distribution in the image of the edge target)

$$MTF(\nu)=\left|F[\mathrm{ESF'(x)}]\right|. \tag{5.17}$$

Both methods are characterized by some advantages and disadvantages.

A. Slit method

1. Low sensitivity to noise inherent in image to be analysed (+),
2. Measurement result must be corrected depending on width of the slit used for measurement (-),
3. Several slit targets are needed when testing imagers of different field of view (-),
4. High temperature difference (over 10 K or more) is required as assure a clear image of the slit target (-).

B. Edge method

1. High sensitivity to sensitivity to noise inherent in image to be analysed (-),
2. One edge target enables measurement of MTF of any type of thermal imagers (+),
3. Low temperature difference (over 3 K) is required as assure a clear image of the edge target (+),
4. It is technologically easier to manufacture high quality edge target than slit target (+).

Due to lower sensitivity to noise the slit target method was the preferred MTF measurement method in the past. Noways, manufacturers of equipment for testing thermal imagers generally prefer measurement of MTF of thermal imagers using edge target method [8,10]. Therefore only the edge method shall be discussed later in details. However, it should be reminded that the edge method is a modified slit method because differentiated Edge Spread Function equals Line Spread Function.

Finally, we should remember that if properly applied then both two measurement methods should generate the same MTF measurement results.

Typical simplified measurement principle used by most modern test systems for MTF measurement is presented below.

1. Projection of an image of the edge target by the collimator into direction of tested imager.
2. Tested imager generates a blurred copy of projected image of the edge target.
3. Frame grabber captures images generated by the tested imager.
4. Test software using the frame grabber captures images, of the edge target, generated by the tested imager.
5. Test software carries analysis of the captured images, calculates MTF function, and presents the measured data in a graphical form or in form of a table.

Practical implementation of this algorithm is not so simple as there are high requirements on both collimator, target, blackbody, frame grabber and test software that must be fulfilled to generate accurate measurement results:

- Collimator: to generate image of the edge target without any noticeable degradation of image quality
- Blackbody: to generate a stable uniform image of the edge target (requirement on temperature temporal stability and temperature uniformity)
- Edge target: the angular differences between the real edge and the ideal edge must be many times smaller than the angular size of pixel of the tested thermal imager (requirement on manufacturing accuracy of the target edge)
- Frame grabber: to enable capturing image of the edge target generated by the tested imagers without any noticeable degradation of quality of the captured image (requirement on ability to capture images from imagers

generating electronic image signals in different standards: PAL, NTSC, FireWire, USB 2.0, CameraLink, GigE)

- Test software: user friendly software that enables calculation of MTF using advanced algorithms resistible to noise inherent in captured images.

As we can see, typical test systems used for MRTD measurement (built from the following modules: collimator, blackbody, rotary wheel, set of targets, frame grabber, PC, test software) are also used for MTF measurements. The only difference in hardware blocks is that the edge target is used for this measurement instead of typical 4-bar targets.

5.2.2 Measurement procedure

Different manufacturers use slightly different detail measurement procedures of MTF measurement. Here we will present simplified typical MTF measurement procedure.

1. Rotation of the rotary wheel with the targets using the control software until the edge target is in the active position (the target is at the collimator focal plane and can be seen by tested thermal imager). The edge target should be vertical if horizontal MTF is to be measured, horizontal if vertical MTF is to be measured.
   Some manufacturers use also "tilted MTF" measurement method when the edge target is not horizontal or vertical but tilted by 45°. This method can increase measurement accuracy in case when blurring in the analyzed image is very small (smaller than about 3-5 pixels).
2. Setting proper settings of thermal imager: typically Gain to minimal, Level to average.
3. Regulation temperature difference (differential mode) using control software until a clear image of the edge target can be seen. Typically differential temperature in the range from about 2 K to 8 K is used. The contrast of the target should be moderate. It should be avoided situation when bright semi-moon target is very white and background is very dark. The situation when the contrast of the target and background is low should be also avoided. Generally the aim is to get situation when both the target temperature and the background temperature are in the linear range of SiTF function of the tested imager. Some manufacturers offer software tools that enable easy checking of brightness of the target and the background to speed up a process of finding proper contrast of the image of the targets. Situation when we have brightness of the target in the range from about 120 to 150 (grey levels), brightness of the background in the range from about 60 to 90 can be treated as a safe solution.
4. Focusing of tested thermal imager to get maximal sharpness of image generated by the imager. The sharpness can be evaluated subjectively by human eye but use of objective evaluation tool is recommended. Some manufactures of test equipment offer software modules called "Live MTF" or

“Continuous MTF” that enable online measurement of sharpness of edge image generated by the tested imager [8,10]. User is only requested to mark a part of the edge to be analyzed.

Due to significant noise in analyzed images accuracy of “Live MTF” measurement is high and true measurement of MTF must be made later using some noise reduction methods.

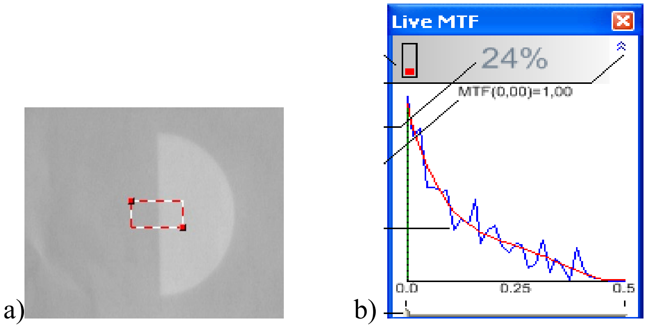


Fig. 5.12. a)Image of the edge target with marked area to be analyzed b)MTF graph.

5. Determination of relationship between image dimension in pixels and true dimension in angular units (mrad). Knowledge about the edge target dimensions and the collimator focal plane is used to find this relationship. This operation is often called Distance Calibration. The operation is carried automatically by software or the user is expected to mark some points on the image generated by the tested imager.
6. Capturing a video sequence of images of the edge target. A series of images is captured in order to reduce temporal noise by simple averaging method. Some test computer programs use also more advanced image processing techniques that can reduce additionally high frequency spatial noise fixed pattern noise).
7. Analyzing the image of the edge target after noise reduction process. MTF of the tested imager is calculated by the test software.
8. Storing the MTF measurement results in form of table, text file, or a graphics.

5.2.3 Interpretation of measurement results

Accurate MTF measurement of thermal imagers is not easy. The same can be said about interpretation of the measurement results as there are several factors that can influence measurement accuracy.

First, measured MTF always depends significantly on proper focusing of tested thermal imager. Therefore, the focusing stage in the MTF measurement procedure should be done very carefully.

Second, MTF measurement results depend often on setting of the tested imager like gain, level or image processing. Therefore, write down always measurement conditions (Gain, Brightness, Image processing features etc) used when MTF measurements were carried out. As we can see in the graph below, MTF of the same imager can be drastically different when measurements are carried out at different imager settings. Therefore please compare several thermal imagers only if the imagers were tested having the same settings.

It is typically recommended to have the following settings during MTF measurement: Gain – minimal, Level – medium. However for low Gain in order to achieve reasonable contrast between the target and the background temperature difference at level over 2 K are needed. There are however on the market cooled IR FPAs that show bigger blurring for such temperature difference (due to crosstalk effect) than for lower temperature difference (below 2 K). For such imagers, it is necessary to use medium Gain level.

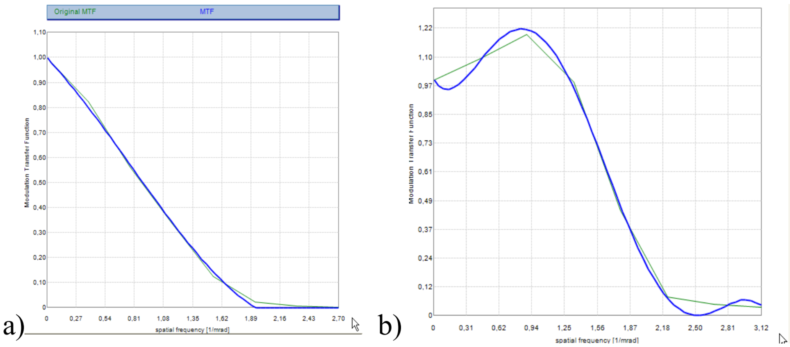


Fig. 5.13. MTF of the same thermal imager: a)Edge enhancement turn off; b)Edge enhancement turn on.

5.3 Responsivity function (SiTF)

Responsivity function is a function of an output signal (screen luminance, or electrical signal) versus target temperature (absolute or relative) in case of large, constant size target. The responsivity function is usually S shaped. The responsivity function depends strongly on imager settings, like level or gain. There is no a single responsivity function that could characterize fully even simple thermal imagers. Measurement of at least several functions is need to get precise information about imager performance at different combinations of gain and level settings.

The responsivity function can be also presented in simpler form of three digital parameters (SiTF, saturation level, and dynamic range) that are determined on the basis of measurement results of the responsivity function. The signal transfer function SiTF (or the responsivity) is the most important parameter from the set of parameters mentioned earlier.

The signal transfer function SiTF is determined on the basis of the linear part of the responsivity function. It is calculated as tangent of the angle between linear part of the responsivity function and the temperature axis (the slope of the linear part). Blackbody temperature in mK is typically treated as the input signal and the screen luminance in digital gray scale levels is treated as the output signal. The formula used for SiTF calculation is shown below

$$SiTF = \frac{(S_2 - S_1)}{(T_2 - T_1)} , \tag{5.18}$$

where S_1 and S_2 are the output brightness of the monitor in grey level units generated by the input target temperatures T_1 and T_2. The values of T_1 and T_2 must be in the linear range of the responsivity function.

Practically, knowledge about responsivity function (or responsivity functions in most cases) is useful for several reasons.

First, analysis of S shape of the responsivity function deliver precise information if the electrical analog video signal is properly set (case of imagers generating output image using PAL, NTSC formats). A situation when output signals in the range from about 0 to 255 are generated by target of temperature in the required temperature range is usually desired. The "required temperature range" depends on geographical regions. If the video signal is not properly set, then imager dynamics can be lower than expected. In other words we can have a situation when image of even very cold targets shall not be truly black and image of a very hot target is not white. It is also possible to have a situation when the imager saturates for temperatures from the required temperature range or the screen brightness is zero also for temperatures of this range.

Second, analysis of captured sequences if images generated by tested thermal imager can deliver information about all noise parameters: NETD, FPN, non uniformity, 1/f, 3D noise model components, NPSD. However these parameters are calculated by test software in digital levels as frame grabbers digitize input analog video images generated by typical thermal imagers. When SiTF is known then noise parameters can be converted from digital level units to more easy to understand temperature units. The following formula is used for this conversion.

$$Noise\,[\mathrm{mK}] = \frac{Noise\,[\text{digital levels}]}{\mathrm{SiTF}\,[\text{digital level/mK}]} . \tag{5.19}$$

Measurement principle of both the responsivity function or its simplified form SiTF is simple.

Tested imager is looking into the blackbody of regulated temperature. Changing blackbody temperature changes brightness of the blackbody image. The task of the test software is to regulate blackbody temperature and to measure brightness of the blackbody image. If temperature regulation span is wide then complete responsivity function is measured. If this span is narrow (and fit properly to the linear range of the responsivity function), then only SiTF is measured.

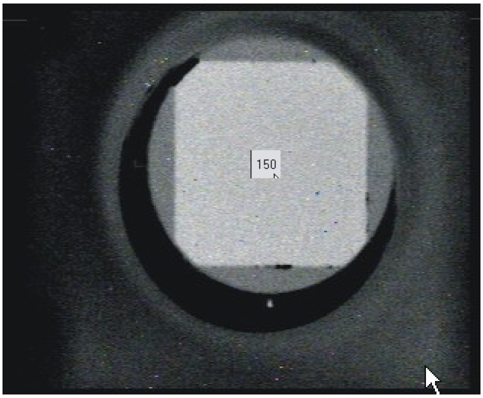


Fig. 5.14. Image of a blackbody during responsivity function measurement (white mark- the area where the brightness is measured).

Typical measurement algorithm of the response function is presented below.

1. Tested imager is looking via collimator into the blackbody of regulated temperature. Changing blackbody temperature changes brightness of the blackbody image. Test software acquires images generated by the tested imager.
2. User marks an area of the blackbody image to be analysed.
3. User determines the temperature regulation range of the blackbody and temperature regulation step to be used during measurement of the responsivity function.
4. The test software carried out measurement of output brightness of the blackbody image for different values of blackbody temperature.
5. The responsivity function is presented in a graphical form and table form.

Temperature [°C]	Brightness
-15	15
-10	16
-5	17
0	20
5	32
10	56
15	80
20	104
25	127
30	150
35	170
40	198
45	220
50	240
55	250
60	253
65	254

Fig. 5.15. A table with exemplary data of measurement of responsivity function (measurements for low gain settings)

5.4 Noise parameters

5.4.1 Measurement concept

The list of noise parameters is quite long: NETD, FPN, non uniformity, 1/f noise, 3D noise model components, NPSD. However measurement of all noise parameters is based on the same concept of capturing a sequence of images generated by tested imager when viewing an uniform target. Such a sequence of images carried out information about temporal noise, spatial noise, and noise frequency spectrum.

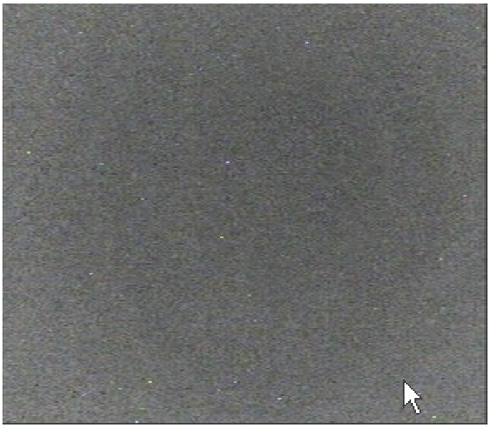


Fig. 5.16. Image of an uniform target used for measurement of noise parameters.

Analysis of only a sequence of images of uniform target can give information about imager noise in gray level units (or in volts in analog electrical signal is analysed) not in temperature units as required. The conversion of noise in gray level units to temperature units can be done only when SiTF is known. SiTF gives information about relationship between input temperature of the target and output brightness of image of this target. Therefore in order to determine noise parameters we must first measure responsivity function (or SiTF) as described in the previous section. Sometimes measurement of SiTF is treated as part of noise measurement procedure and SiTF is presented together with noise parameters.

Manufacturers of equipment for testing thermal imagers use different measurement procedures to measure noise parameters. These differences can generate some differences in test results.

The differences can be divided into two groups:

A. Method of generation of uniform image,

B. Type of output signal generated by the tested imager to be analysed: analog video signal or digital signal.

Uniform image needed for noise measurement can be generated using several methods:

1. Thermal imager is looking into a small active blackbody (temperature regulation possible) used as a part of a typical variable target test system based on off axis collimator.
2. Thermal imager is looking into a big blackbody located within focus range of the tested imager.
3. Thermal imager is looking into a medium size active blackbody (a bit bigger than imager optics) located at very short distance from imager optics.
4. Thermal imager is looking into a passive large blackbody located at short distance to the imager optics.
5. Thermal imager optics is covered using a cap, black cloth or other materials.

Method number one is the most easiest to be used. The needed blackbody is a part of typical test systems. However, field of view of tested thermal imagers is usually much bigger than angular size of image of the blackbody projected by the collimator. Therefore analysis area is limited only to a part of images generated by thermal imagers and measurement using this method generates significantly lower value of spatial noise measurement. Temporal noise is sometimes also lower than true measurement results for full field of view.

The disadvantage of the methods no 2-3 is the fact that an additional large size/medium size blackbody is needed for noise measurement. Another option is that the blackbody used as a part of the variable target test system (if the blackbody size is big enough to cover the imager optics) must be moved to a new position very close to the optics of the tested imager.

For method no 4, a large passive blackbody of non regulated temperature that keeps ambient temperature is needed. An advantage of this method is lower manufacturing costs than in case of methods 2-3.

The method no 5 is the simplest and the cheapest. However, temperature distribution on surface of a such a "ad hoc blackbody" is not uniform. At the same time the temperature distribution is not temporarily stable. Therefore this method generates often non stable test results (particularly spatial noise) and should be avoided. One of earlier discussed methods to generate uniform image should be used.

All thermal imagers of the past and majority of thermal imagers present on the market generate images in form of an analog video signal (PAL/NTSC standard). This means that practically the output image is generated as analog electrical signal. Therefore, in the past the noise of thermal imagers was almost exclusively measured using typical measuring tools for analog electrical signals: the oscilloscopes. The measurements results were obtained in Volts units, and later converted into temperature units.

Frame grabber cards for modern PC units give easy possibility to convert output analog signal from tested thermal imagers into a digital image. Analysis of digital images using modern computer technology is much easier than analysis of analog electrical signals using oscilloscopes (although there are also big improvements in digital oscilloscopes). Therefore nowadays noise parameters are usually determined by analysis of sequence of digital images generated by frame grabbers. However, we should remember that there are still laboratories (mostly manufacturers labs) where the tests of thermal imagers are done by analysis of analog video signal using oscilloscopes. However this method of measurement of noise parameters is rarely used and shall not be discussed later.

5.4.2 Measurement procedure

Measurement of noise parameters of thermal imagers is typically carried out according to the algorithm presented below:

1. Regulation of settings of the tested imager.

   If thermal imagers were truly linear imaging systems then noise parameters would not depend on imager settings like gain or brightness level. However thermal imagers are only quasi linear systems and measured noise parameters depend on setting of the tested imager. The tests are typically done for the following settings: Gain: maximal; Brightness level: medium. However it is not a rule. In any case, the imagers settings (Gain. Level, Image Enhancement) should be written down for future analysis.

   Next, it is critical for successful measurement of noise parameters that the imager setting like Gain/Level should be the same as settings used during measurement of SiTF.

   Further on, it is strictly forbidden to use Auto Gain mode during noise measurements.

2. Regulation of angular position of the tested imager relative to the uniform target (or inverse).
   As it was discussed in previous section, different methods to generate uniform image are used. Therefore position of the tested imager relative to the uniform target (blackbody) can be different. Version one: the imager is looking into the collimator. Version two: the imager is looking into a large blackbody located at some distance within imager focus range. Version three: the blackbody is located just behind the imager optics.
3. Marking area of interest.
   The blackbody that simulates the uniform target typically fills entire field of view of tested imager. However, sometimes some parts of video image generated by the tested imager are not active (black frame around the true active image - see Fig. 5.17). This effect is usually met in thermal imagers using IRFPA modules optimized for resolution of NTSC standard but generating output video image in PAL standard. If such a case occurs then the user must mark area of the active part of the image to be analysed. If not measurement results of spatial noise parameters can be significantly distorted.
4. Capturing of a sequence of images.
   Capturing of a video sequence of images of the uniform target is crucial part of procedure to measure noise parameters. The capturing should be done using high quality analog frame grabbers (case of imagers generating signal in PAL/NTSC standard) that do not distort captured images. The same requirements are also valid for the test software. The compressing algorithms of captured frames should not distort the output images in noticeable way. Most typical frame grabbers and video acquisition software are not useful for the task of capturing images from thermal imagers as these frame grabbers/acquisition software was optimized for a task of capturing images with significant degradation of image quality in order to save disk memory needed for storing long video sequences.
   There is a different situation in case of professional frame grabbers/acquisition software capable to capture digital video images in the following standards: Fire-Wire, USB 2.0, CameraLink, GigE or LVDS.
5. Calculation of noise parameters.
   One of the tasks of computer programs offered by manufacturers of equipment for testing thermal imagers is to do the analysis of the video sequence and calculate the noise parameters. The offered programs differ by the numbers of noise parameters they calculate and by other features.
   On one side, there are computer programs developed only to calculate one parameter (NETD) and to present it in form of a number. On the other side are more advanced computer programs that calculate not only a long series of noise parameters: NETD, FPN, non-uniformity, 1/f noise, 3D Noise components, NPSD; but also bad pixel number, bad pixels location; and provide graphical representation of some noise parameters. The choice in this matter belongs to the user

of the software depending on the requirements on the test system. Exemplary noise measurement results are shown in Fig. 5.18 and Fig. 5.19.
Noise parameters depend on ambient temperature, particularly in case of MWIR thermal imagers. The ambient temperature at which the measurement is carried out can differ significantly from a typical laboratory temperature about 20ºC. In such a case the measurement results should be corrected. Most of computer programs used to support testing of thermal imagers can do this task.

6. Storing noise parameters.
   Storing measurement results is a simple operation for modern software. However practically it is extremely important to enable storing not only the measurement results in form of several numbers but storing measurement results together with all parameters that describe measurement conditions (gain/level/image enhancement settings of the thermal imager; ambient temperature, test date, test place, test team, etc. Such data is very useful if comparison of test results of different imagers is to be made.

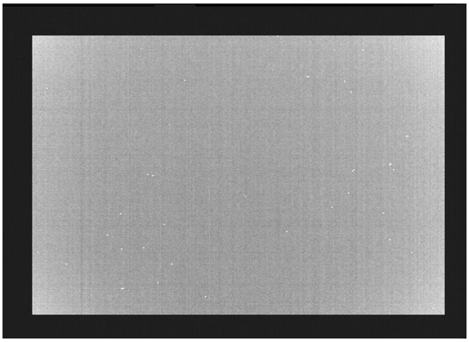
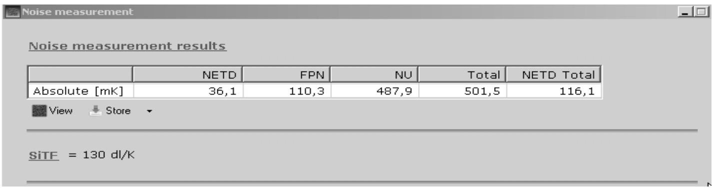


Fig. 5.17. Thermal image with non-active parts.



Noise measurement

Noise measurement results

	NETD	FPN	NU	Total	NETD Total
Absolute [mK]	36,1	110,3	487,9	501,5	116,1

View Store

SiTF = 130 dl/K

Fig. 5.18. Table with three basic noise parameters: NETD, FPN, non-uniformity.

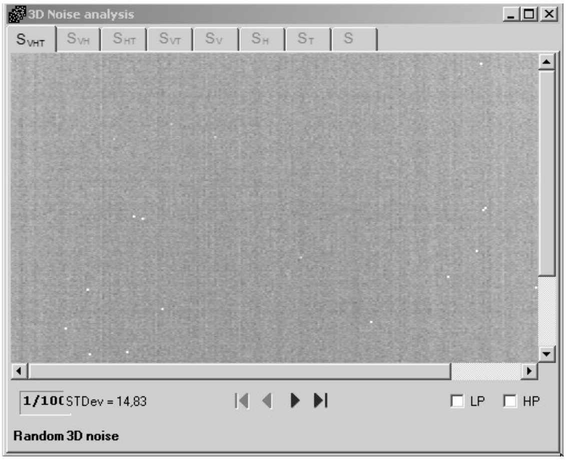


Fig. 5.19. Window of TAS-T program presenting calculation results of VHT components of 3D noise model.

5.4.3 Interpretation of measurement results

There are quite many reasons why interpretation of noise measurement results is often difficult.

First, there are no internationally accepted standards that could regulate measurement on noise related parameters of thermal imagers. There are different recommendations in specialized literature. Therefore there is a certain chaos in measurement of noise parameters. A prime example of this chaotic situation is a situation with the main noise parameter of thermal imagers: the NETD. According to one school NETD is a measure of only high frequency temporal noise, and FPN is a measure of high frequency spatial noise. However according to a second school NETD is a measure of both high frequency temporal noise and high frequency spatial noise. Thus, it is necessary to be very careful in comparison of “NETD” parameter measured by two different test teams.

Second, noise related parameters like NETD, FPN, NU depend on settings of tested thermal imagers; mostly on Gain (contrast) and Level (brightness) but in most cases this relationship is not very strong. However, image processing (like edge enhancement) can change noise measurement results drastically. By pressing the button “Image enhancement” on the imager keyboard the measured noise parameters can be increased even by a factor of two times. Therefore it is recommended to compare several thermal imagers of the same type only if the tests were carried out for the same settings of the tested imagers.

Third, parameters of some IR FPAs used in modern thermal imagers can vary in time. Sometimes such effects are noticeable after a dozen minutes even if the ambient temperature is stable. If ambient temperature varies then stronger variation of noise parameters (NETD, FPN, NU) can be expected. Such a situation most often occurs in case of non cooled imagers, but sometimes occurs also for thermal imagers built using cooled IR FPAs.

Fourth, the noise parameters of thermal imager can vary significantly when the imager heats up even in case of thermal imagers built using IRFPA modules of good temporal stability. Therefore the tests should be started not earlier than after at least 15-30 minutes of work of both the tested imager and the test system. If this condition was not fulfilled then repeatability of test results can be bad.

To summarize, because of inconsistent literature recommendations, inherent dependency of noise related parameters (NETD, FPN, NU) on imager setting and possible temporal variations the user should not expect very good agreement of measurement noise data with data provided by manufacturer or other laboratories. Agreement at the level about 20-30% should be considered as acceptable situation.

5.5 References

1. ASTM standard E 1213-2002 "*Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems*"
2. Holst G.C., *Infrared Imaging System Testing*, Vol.4, Chapt. 4 in The Infrared & Electro-Optical Systems Handbook, Michael C. Dudzik ed, SPIE 1993..
3. Holst G.C., *Testing and evaluation of infrared imaging systems*, JCD Publishing Company 1993.
4. STANAG 4349, *Measurement of minimum resolvable thermal difference (MRTD) of thermal cameras*, 1995.
5. www.ci-systems.com
6. www.eoi.com
7. www.hgh.fr
8. www.inframet.com
9. www.optikos.com
10. www.sbir.com

6 STANAG 4349 requirements

STANAG 4349 present some technical requirements on equipment used for testing thermal imagers. Here, there is presented a table with a list of these requirements and comments about technical capabilities of modern test systems. The comments can be useful for laboratories that implemented quality systems according to ISO/EN standards and which need to prove that their test system fulfill requirements of this well known standard.

Table 6.1. Comments on Stanag 4349.

No	STANAG 4349 requirement	Test equipment
1	4. The MRTD is the minimum temperature difference which allows an observer to resolve a test pattern in accordance with a given criterion. MRTD is a function of spatial frequency of the test pattern.	All manufacturers of test equipment use the same definition of MRTD.
2	NOTE 1: The MRTD measured at a given temperature can be converted to the MRTD at other temperatures, if necessary. The conversion factor depends on the spectral response of the thermal imager and has to be determined in each case.	Test software corrects measurement results depending on ambient temperature and spectral response of tested thermal imager.
3	5.1. The observer shall have normal visual acuity (post-correction defects less than + 0.25 diopters) and good color vision and be experienced in this type of measurement.	Requirement on users of test equipment. This requirement can be fulfilled if proper observers are chosen and trained
4	5.2.The test pattern shall be a plate containing four rectangular slots, forming a square of four bars and three spaces. Length/width ratio of the rectangular slot is 7:1. The space width should be equal to width of the rectangle. The test pattern is positioned in front of a black body, the temperature of which can be varied, giving a temperature difference (at) between the bars and the spaces.	Targets for MRTD measurement are manufactured as a plate containing four rectangular slots, forming a square of four bars and three spaces. Length/width ratio of the rectangular slot is 7:1.Target is fixed to a rotary wheel that is positioned in front of the blackbody.
5	5.2.1. The spatial-frequency of the resolving power measurement targets must be within ±5% of the nominal value.	Point 5.2.1 presents requirements on manufacturing tolerances of 4-bar targets and tolerances of focal length of the

		collimator. Relative uncertainty of spatial frequency of 4-bar targets manufactured by Inframet is 4%. Uncertainty of determination of focal length of IR collimators offered by most manufacturers of test equipment is below 1%.
6	5.2.2. The emissivities of the test pattern and the black body must both be at least 0.95.	Emissivity of TCB series black-bodies is 0.97 ±0.01. Emissivity of typical IR targets offered on the market is 0.97 ±0.01; sometimes >0.98.
7	5.2.3. The blackbody must make it possible to achieve temperature differences of ±10°C. The accuracy must be 0.5% generally, and 0.01°C for ΔTs between 0°C and 2°C.	Typical differential temperature range for blackbodies used in test systems is: -25°C and +75°C (much wider than required). Differential accuracy of blackbodies is not worse than 0.01°C at entire temperature range ±10°C
8	5.2.4. Any variation in temperature across the useful area of the test pattern shall be so small as not to be detectable on the image by the observer	Non uniformity of blackbodies for temperature differences below 5°C is typically below 10 mK and is non detectable for thermal imagers.
9	5.2.5. The measurement temperature is that of the test pattern, which should be 20 ±2°C unless otherwise specified.	This is an requirement to be fulfilled by users of test equipment, not requirement on the test equipment. However, this requirement can be easily fulfilled if air conditioning is used. Next, please note that the standard allows to carry out measurement at ambient temperatures outside this range and to correct the measurement results (4.Note 1)
10	5.3.The transmission losses between the test pattern and the imager and the emissivities of the test pattern and the black body should be known and taken into account when results are calculated.	Transmittance of the collimator, emissivities of blackbody, emissivity of the 4-bar targets are known and they are taken into account by test software when corrected MRTD results are calculated.

11	5.4. In carrying out the measurements, the observer may optimise results by altering both the illumination level in the room and any settings on the imager, adjusting the distance of his eye from the display, and slightly altering the position of the test pattern within the field of view. If a monitor is used it must be of the type normally used with that imager, and it is recommended that, once set up, it should not be adjusted during measurement.	This is an requirement to be fulfilled by users of test equipment, not requirement on equipment.
12	6.1. Starting from an invisible test pattern, the method is based on the determination of the temperature difference (+ or -) required to make the test pattern visible. Owing to limitations in the test equipment, the indicated temperature differences may not be the true temperature differences between test pattern and black body. Therefore the following procedure is recommended to establish the MRTD: starting with the temperatures of the test pattern and black body approximately equal (see Note 2), the temperature of the black body shall increase until the test pattern appears in positive contrast (hot bars). When the observer can just resolve the test pattern, the, temperature difference ($\Delta T+$) is recorded. The black body temperature is then reduced causing the test pattern to disappear, and then to reappear with negative contrast (cold bars). When the observer can just resolve the test pattern again the temperature difference ($\Delta T-$) is recorded (see Note 3). The two measurements must be taken without delay so that temperature drift is avoided (see Note 4). Note 2 : The procedure can be speeded up by starting with a temperature difference between the test pattern and the black body of 0.8 ΔT both for positive and negative contrast.	This is an requirement to be fulfilled by users of test equipment, not requirement on equipment.

<table>
<tr><td>13</td><td>Note 3 : If it can be established that the temperature drift is negligible, both positive and negative contrast measurement need to be made only for the lowest spatial frequencies, in order to determine the “ΔT offset" of the test equipment. This “ΔT offset" is then calculated as the mean of the temperature differences for the positive and negative contrasts (that is“ΔT offset" = 0.5 [“ΔT+” + “ΔT-“], and its value is then subtracted from the temperature differences measured for a single contrast for each of the remaining spatial frequencies in the test run. Positive contrast measurements for these frequencies are recommended.</td><td>Offset is calculated in test software that controls blackbody using the formula recommended in Note 3.</td></tr>
<tr><td>14</td><td>Note 4 : It is proposed that the black body temperature be varied in steps as follows:
<table><tr><td>ΔT</td><td>Proposed step</td><td>ΔT</td></tr><tr><td><0.5 °C</td><td>0.01°C</td><td>2°C to 4°C</td></tr><tr><td>0.5°C to 1°C</td><td>0.02°C</td><td>4°C to 8°C</td></tr><tr><td>1°C to 2°C</td><td>0.05°C</td><td>>8°C</td></tr></table></td><td>Most blackbodies used for testing thermal imagers enable temperature control with 0.001°C steps (much better than required).</td></tr>
<tr><td>15</td><td>6.2. It is recommended that the MRTD be measured with horizontal and vertical orientation of the bars. Any other orientation is optional.</td><td>Most rotary wheels are designed in a way that enables the 4-bar targets to be fixed by the user in vertical orientation or horizontal orientation.</td></tr>
<tr><td>16</td><td>6.3. The criterion to be used for resolution is that it should be possible to see four bars (not just some modulation) on</td><td>This is an requirement to be fulfilled by users of the test equipment, not requirement on the</td></tr>
</table>

	the display, although it is not necessary that all of each of the four bars be visible at the same time.	equipment.
17	6.4. Measurements shall be taken at a minimum of four (4) spatial frequencies distributed approximately uniformly over the useful range of the imager. A minimum of three (3) measurements shall be taken for each pair of contrasts, at each spatial frequency, in each orientation, by each observer. Measurements shall be taken until stable results are observed. A single observer may be used, although multiple observers are recommended.	Manufacturers of test equipment offer typically a series of at least twenty standard 4-bar targets of different spatial frequency. Next, they can optionally deliver custom designed 4-bar targets of spatial frequencies outside the list of standard targets. Such a situation gives users of test system possibility to fulfill requirements of point 6.4 on targets used for MRTD measurement.
18	7.1. If positive and negative contrasts have been measured, the individual MRTD value is $(\Delta T_{+} + \Delta T)/2_{-}$	Test control software uses the formula recommended in point 7.1.
19	7.2 The MRTD results shall be tabulated (see Annex) and plotted on a graph (with a logarithmic .scale for temperature differences and a linear scale for spatial frequencies) for each observer and each orientation. The measurement conditions, values used for calculation and all the results must be shown. Any significant deviation or rejection of results must be explained.	The measurement results can be recorded using the test software in several typical data formats (MS Excel). Later the data can be presented graphically using any software for data presentation.

7 Guidelines for buyers of test equipment

Systems for testing thermal imagers are built from at least six blocks: collimator, blackbody, rotary wheel, set of targets, PC, frame grabber, software. Blocks of the system for testing thermal imagers were presented and discussed earlier. There were also presented requirements on blocks of such test systems.

However, any potential user or buyer of equipment for testing thermal imagers should be reminded that total value of such a test system is much more than a sum of system blocks. One weak block reduces greatly value of a test system. Thus, writing detail requirements on all blocks of a test system optimized for specific applications is an expert task. It is quite easy to make an error on details as there are many parameters that are inter-dependent.

Now, we will present several recommendations for potential buyers/users of systems for testing thermal imagers. If these recommendations not implemented then there is a high probability that the buyer will get a costly test system that is not optimal for his applications.

First, it is recommended for potential buyers of test systems to concentrate more on requirements on the test system than on requirements on blocks of the system. The best way to write safe for the user/buyer requirements on test system is to write a list of required test capabilities of the system understood as a list of parameters to be measured or list of other system functions. It is a common error found in many tender requirements that detail, sometimes not-needed, requirements on collimator, blackbody, rotary wheel are presented but a detail list of parameters that are to be measured is not presented.

Second, equipment for testing thermal imagers is expensive. Therefore take care that your funds are well spent on equipment truly useful in your work. Manufacturers can deliver, or at least should be able, different versions of the same test system of different measuring capabilities and at different price level. Try to find a version of the test system that is optimal for your needs.

Third, testing thermal imagers is difficult even having good test equipment, particularly for newcomers to thermal imaging technology. Test system shall generate measurement results but cannot automatically and properly interpret these results. Such data must be interpreted by human users of test equipment who must do this difficult task. We must remember that test results of a thermal imager often depend on imager settings, environment conditions, test equipment parameters etc. Therefore it is recommended to guarantee in the contract some support from equipment manufacturer covering also help in interpretation of test results.

Fourth, buyers of equipment for testing thermal imagers often forget about problem of recalibration of test systems or rather about the problem of recalibration of some crucial blocks. Costs of frequent recalibration of test equipment can be in long term almost equal to the original cost of purchase of this test equipment. Therefore please check what are recommended recalibration intervals, what is price of recalibration by the manufacturer, and finally, if it is possible to recalibrate the test system in local conditions. In most cases recalibration of such blocks like blackbody or collimator can be done in local metrological centers assuming that some technical information is revealed by the manufacturer.

Sixth, typical twelve month warranty time is quite short. Extended warranty often means well spent funds as such warranty guarantee full manufacturer responsibility in much longer time.

Seventh, you will spend well your time by reading the educational section at websites of manufacturers of test equipment or by reading other available specialized literature. It will be later easier for you to communicate with the manufacturers because you will then know exactly what you need.

Eight, it is possible to built a system for testing thermal imagers by buying some blocks (collimator, blackbody, targets) and developing other needed blocks (rotary wheel, control software, test software). However, it is a risky policy recommended only for technologically advanced scientific/manufacturing centers with deep knowledge of metrology of thermal imaging. Probability of commercial losses due to long time needed for development of such a combined test system, and due to possible technical problems, is high in most cases.

Ninth, systems for testing thermal imagers offered on international market by different manufacturers are generally similar. The differences are created by small technical details. Some of these details are very important: main test capabilities (number of parameters that can be measured) or other system capabilities (accepted standards of output electronic images from thermal imagers, boresighting capabilities, etc). There are also some technical details like dimensions and mass of systems blocks of no real importance for typical applications. Other parameters like blackbody accuracy, blackbody temperature range are important when testing commercial thermal imagers for non contact temperature measurement but not critical when testing surveillance thermal imagers. Further on, if the tests are to be done at laboratory conditions then wide working ambient temperature range offered by one manufacturer is not a real advantage over a system from another manufacturer capable to work only at laboratory conditions. We have a totally different situation if the blackbody from the test system is to be used also in temperature chambers for calibration applications. Therefore it is always recommended to think carefully about requirements on the test system and limit these requirements only to truly needed level. This recommendation is important as equipment characterized by some non typical parameters is often much more costly than typical test system.

To summarize, both cost-effective buying and effective use of systems for testing thermal imagers are difficult tasks. Well educated, properly trained test team is needed in both these tasks.

About Author:

Krzysztof Chrzanowski received his Ph.D., and D.Sc. both in Electronics, from Military University of Technology in Warsaw, Poland. He works currently as Professor in the mentioned above university. He is also CEO of a spin off company: Inframet (www.inframet.com). His main scientific interests include analysis, testing and computer simulation of electro-optical surveillance systems (thermal imagers, night vision devices, TV cameras, laser range finders, multi-sensor surveillance systems), non-contact thermometry and general metrology. He is an author or co-author of over 100 scientific papers and conference communications.

This books presents knowledge of the author on testing thermal imagers that was accumulated during over two decades of scientific work in the field of electro-optical technology interconnected with a series of practical projects. The author hopes that this book can become a practical guide in field of testing thermal imagers for a wide community of people interested in this fascinating technology of thermal imaging.

Krzysztof Chrzanowski received his Ph.D. and D.Sc. both in Electronics, from the Military University of Technology in Warsaw, Poland. He works currently as Professor in the mentioned above university. He is also CEO of a spin off company: Inframet (www.inframet.com). His main scientific interests include analysis, testing and computer simulation of electro-optical surveillance systems (thermal imagers, night vision devices, TV cameras, laser range finders, multi-sensor surveillance systems), non-contact thermometry and general metrology. He is an author or co-author of over 100 scientific papers and conference proceedings.

This books presents knowledge of the author on testing thermal imagers that was accumulated during over two decades of scientific work in the field of electrooptical technology interconnected with a series of practical projects. The author hopes that this book will become a practical guide in a field of testing thermal imagers for wide community of people interested in this fascinating technology of thermal imaging.

ISBN 978-83-61486-81-7