REVIEW
OF THERMAL IMAGING TECHNOLOGY

Krzysztof Chrzanowski

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Author's Preface

Thermal imagers are the most important electro-optical imaging systems used in defense/security applications. These imagers are also extremely important for a series of civilian applications to enable non-contact temperature measurement. Therefore, thermal imaging has received a lot of attention from scientific community world wide. There has been published tens of thousands of scientific papers related to this technology. There are also dozens of books or review papers devoted to thermal imaging. However, available books/review papers on thermal imaging technology concentrate on specific applications of this technology, physics of thermal imaging, design of specific blocks of these imagers, or other narrow aspects of this technology.

This book is unique because it makes an attempt to present a review of complete, wide area thermal imaging technology and to present answers for fundamental questions related to this technology:

1. how thermal imagers are designed/manufactured,
2. how are built blocks of thermal imagers,
3. how thermal imagers available at world market can be technically divided,
4. what are basic rules of characterization of thermal imagers,
5. what are future technical trends for thermal imaging.

The author hopes that this review of modern thermal imaging technology will help readers to understand both design and manufacturing of thermal imagers, sophisticated situation on international thermal imaging market and potential future technical trends.

The author is CEO of one of manufacturers[1] of equipment for testing thermal imagers. He is also a scientist – university professor[2] - working in field of thermal imaging for over three decades. Both jobs have enabled to accumulate a lot of practical knowledge in field of thermal imaging and this know-how has been used to write this book.

As a CEO of a commercial company the author manufactures and sells company products. However, as a scientist the author believes in a concept of free sharing of scientific knowledge in form of open access literature. Therefore this open access book is a gift of the author to a wide international community of people interested in this fascinating technology.

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.

August 2024 Krzysztof Chrzanowski

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1. Introduction

Thermal imagers are electro-optical imaging systems that generate images of the observed targets of typical Earth temperatures using mainly thermal radiation emitted by these targets. They have found numerous applications in both defense/security sector (military, border guards, police, etc.) and civilian sector (industrial non-contact temperature measurement, automotive industry, non-destructive thermal testing, tests of electrical power lines, building industry, medical applications, fire rescue etc.). Civilian market of thermal imagers is growing (especially automotive industry) but still defense&security market dominates.

Thermal imagers are considered as the most important imaging technology used in defense&security applications. They are crucial to enable operation at night and difficult atmospheric conditions. This technology is also extremely important for earlier listed civilian applications.

Technology of thermal imaging has been transformed from an exotic novelty in the 1970s to fully mature technology that enables mass manufacturing. In commercial terms thermal imaging has become a multi-billion USD industry.

Thermal imaging has received a lot of attention from scientific community worldwide. There has been a huge interest of scientists in this technology that resulted in publication of thousands of scientific papers. Google Scholar offers over 5560 publications when searching this library using keyword thermal imaging [1]. Number of such publications related to thermal imaging can be multiplied if similar keywords (infrared imaging, thermal imagers, thermography) are used. Digital Library of SPIE generates also thousands of publications on o thermal imaging technology [2].

Analysis of this huge literature shows that a series of review papers on thermal imaging has been published [3-13]. There are also available books that present at least partial review of thermal imaging technology [14-21]. In addition, there are educational sections of websites of manufacturers of thermal imagers developed with aim to educate potential customers [22-23]. Further on, information on thermal imaging can be found on many educational websites prepared by scientists [24-27]. Finally, there are excellent reviews of physics and technology of IR FPA image sensors (or about wider term infrared detectors) used in thermal imagers as the critical block [28-32]. The latter papers include also sections that describe thermal imaging technology, too.

However, in spite of high number of scientific papers there are significant limitations of available literature on thermal imaging technology.

First, great majority of available review papers on thermal imaging do some review on specific application areas of thermal imaging (papers on medical applications are especially numerous). There is not a single paper that try to make a review of total thermal imaging technology. Further on, sections in books that describe design of thermal imagers are generally outdated or concentrate only on radiometric imagers.

Second, majority of available literature concentrates on physics/technology of IR detectors and present non complete view of thermal imaging technology.

Third, there is a chaos in terminology of thermal imaging used in different publications that makes difficult to understand these papers by incomers to this technology.

Fourth, available literature does not present practical manufacturing models used to manufacture thermal imagers available on the international market.

Fifth, there is not proposed division of thermal imagers offered on the market using clear technical criterion that could be used to segregate these imagers in some logical order.

Sixth, there is no comparison to other imaging technologies like VNIR cameras (visible-near infrared) from designer point of view.

Seventh, there is difficult to find clear rules for characterization of thermal imagers.

Eight, it is easy to find literature on future trends of IR FPA technology but there is no literature trends in wider thermal imaging technology.

In such a situation, the aim of this book is to carry out a review of thermal imaging technology in a way that could eliminate, or at least reduce these drawbacks.

Chapter 2 presents chaotic situation in terminology of thermal imaging. This clarification can help especially for newcomers to this technology.

Chapter 3 presents basic physics of thermal imaging. Main physical phenomenon (radiation laws, atmosphere transmission) needed to understand physics of thermal imaging are discussed.

Chapter 4 presents historical division of thermal imagers into three generations. Comparison of modern staring imagers to human eye imaging systems is discussed, too.

Chapter 5 presents unique, easy to understand models of manufacturing thermal imagers. Stages of manufacturing using different models are discussed, too.

Chapter 6 can be considered as the most important chapter of this book. It presents detail description of main blocks of thermal imagers: IR FPA sensor, FPA controller, IR objective, imager housing, and optional block. Design rules for these block are discussed, too.

Chapter 7 presents methods of image enhancement that play important role in work of thermal imagers. Methods for reduction of spatial noise in video image generated by thermal imagers, correction of blind pixels, regulation of imager temperature span, and improvement of resolution/sharpness of video image generated thermal imagers are discussed.

Chapter 8 presents commercial division of thermal imagers. This division of thermal imagers is based on criterion of intended market/application used by top world manufacturers.

Chapter 9 presents technical division of thermal imagers according to seven technical criterion proposed by the author: 1)image sensor cooling, 2)imager spectral band, 3) radiometric calibration, 4)form of output image, 5)operational range, 6)radiometric measurement capabilities, 7)integration with imaging/laser sensors.

Chapter 10 presents basis of characterization of thermal imagers. First, characterization general concept and a long list of performance parameters of thermal imagers is presented. Later, most popular/most important parameters are discussed in detail.

Chapter 11 presents future trends of thermal imaging. In detail, ten technical trends has been discussed:

1. Automotive thermal imagers,
2. Long life, small weight, low power cooled thermal imagers based on HOT photoelectric IR FPAs,
3. High sampling thermal imagers based on ultra small pixel IR FPAs,
4. Ultra high image resolution thermal imagers based on large IR FPA sensors,
5. Fusion thermal imagers,
6. Renaissance of cooled LWIR thermal imagers for military applications,
7. Super-range thermal imagers,
8. Folded thermal imagers,
9. Space thermal imagers for Earth observation,
10. Moderate performance, mass production, low cost thermal imagers.

Chapter 12 presents short summary of previously discussed chapters of this book.

Finally, chapter 13 presents list of abbreviations used in this book.

2. Terminology of thermal imaging

Thermal imaging is a mature technology known for about six decades (origin in 1960s). However, in spite of a relatively long history there is still no internationally accepted terminology standard (or globally accepted book/scientific paper) that could regulate terminology of technology of thermal imaging.

The author prefers to define thermal imagers as electro-optical imaging systems that generate images of the observed targets at typical Earth temperatures using mainly thermal radiation emitted by these targets. It should be noted that to become thermal imager the system must fulfill at the same time three conditions:

1. electro-optical imaging system (conversion of optical image to electrical image and optional inverse process)
2. the system must be able to generate images of the targets at typical Earth temperatures (from about 250 K to about 330 K)
3. thermal radiation must dominates in spectral band of the imaging system.

This definition indirectly indicates spectral band of thermal imager. It is the band from about 3 μm to about 15 μm, because thermal radiation dominates in this spectral band.

There are at least ten different terms that are used in literature to name imaging systems capable to do thermal imaging:

1. thermal imager [33-36],
2. thermal camera [37-38],
3. thermal imaging camera [39-40]
4. FLIR [41-42],
5. thermovision camera [43-44],
6. thermographic camera [45-46],
7. infrared imaging radiometer [47-48],
8. thermal imaging system [49-50],
9. thermal viewer [51-52],
10. thermal video system [53-55].

In author opinion the names nos 2-10 are basically synonyms of the basic name: thermal imager. In some cases (nos 6-8) the names refer to subgroup of thermal imagers. However, authors of different literature sources believe in significant differences between imaging systems with names from this list and increase this terminology chaos.

In order to shorten discussion let us discuss only terminology proposed by popular Wikipedia website. This website defines four terms:

1. thermography [56],
2. thermal imaging camera [57],
3. thermographic camera [58],
4. FLIR [59].

The thermography section mentions at beginning that the term thermography is a synonym of the term thermal imaging used in this book. Further on, this section defines also infrared thermography (IRT) as a process where a thermal camera captures and creates an image of an object by using infrared radiation emitted from the object in a process. This definition has a clear drawbacks that according to it all infrared imaging systems (including NIR cameras or SWIR imagers) can be treated as thermography/thermal imaging. It makes no sense as NIR cameras cannot see thermal radiation emitted by typical targets. This conclusion is also generally valid for SWIR imagers. Further on, there are also some fragments of this definition that fit only for thermal imagers used in industrial applications when thermal imaging covers also surveillance/military applications.

Further on, the thermal imaging camera section presents in reality only thermal imagers optimized to be used by firefighters. A thermal imaging camera (colloquially known as a TIC) is defined as a type of the thermographic camera used in firefighting. Practically it means that Wikipedia recommends only very narrow meaning of the term thermal imaging camera that is commonly used to describe practically any type of device capable to do thermal imaging.

Finally, the thermographic camera section defines thermographic camera as a device that creates an image using infrared (IR) radiation, similar to a normal camera that forms an image using visible light. Instead of the 400–700 nanometre (nm) range of the visible light camera, infrared cameras are sensitive to wavelengths from about 1,000 nm (1 micrometre or μm) to about 14,000 nm (14 μm). In opinion of the author this definition is wrong for two reasons. First, it is not mentioned that thermal radiation is to be used to create output image. Second, it suggest that even non cooled SWIR cameras sensitive in 1-1.7 μm band can be treated as thermographic cameras in situation when such imagers cannot see targets of typical Earth temperatures.

Finally, the FLIR section of Wikipedia defines Forward-looking infrared (FLIR) as systems typically used on military and civilian aircraft that use a thermographic camera that senses infrared radiation. It means that FLIR systems are airborne thermal imagers. However, practically the term FLIR is used in literature to describe non-airborne thermal imagers, too.

Further on, terminology used by main manufacturers of thermal imagers mainly ignore Wikipedia recommendations. For example, according to website of Teledyne-FLIR (probably the world biggest manufacture of thermal imagers) the term thermographic camera describe only a narrow group of radiometric thermal imagers used for industrial non contact temperature measurement when according to Wikipedia this term describes almost all types of thermal imagers including even firefighting imagers.

To summarize, review of literature on thermal imaging shows that due to lack of terminology standards or other semi-standard documents there is a nearly total terminology chaos. The same imaging system can be called using different names. What is even more important the same system that offers thermal imaging can be named in different ways, too. Different authors use different terminology in scientific papers, manuals and catalogs making them difficult to understand even for professionals. Lack of standardization of terminology of thermal imaging is one of biggest obstacles to understand this technology, especially for newcomers to this technology.

3. Basic physics of thermal imaging

Optical radiation (light of wavelength from about 100 nm to about 1 mm) is typically divided according to wavelength on different spectral ranges: infrared, visible and ultraviolet. The infrared range is further divided into: near infrared NIR (0.78-1 µm), short wave infrared SWIR (1-3 µm), mid-wave infrared MWIR (3-6 µm), long-wave infrared LWIR (6-15 µm), and far infrared FIR (15-1000 µm).

However, it should be also noted that radiation in all these spectral bands can be divided on criterion of origin into two groups:

1. thermal radiation,
2. non-thermal radiation.

Thermal radiation is radiation generated by all sources at temperature higher over absolute zero that is governed by Planck law. Non-thermal radiation is radiation generated by all non-thermal phenomenons: lasers, electroluminescence, photo luminescence, cyclotron/synchrotron radiation, etc.

Almost all optical radiation met at Earth conditions is thermal radiation. It should be noted that solar light (including visible range) is actually thermal radiation emitted by ultra high temperature emitter in form of Sun. The same is with moonlight that is actually thermal radiation from Sun reflected by the moon.

Thermal radiation emitted by targets of typical Earth temperatures from about -40ºC to about 80ºC dominates in medium-wave infrared and long-wave infrared (the spectral range from about 3 µm to 15 µm) over radiation emitted by sun, moon, stars, and sky. Totally inverse situation exists in visible, near infrared range and short infrared range (VIS-SWIR band – wavelengths below 3 µm) where thermal radiation emitted by Earth targets is almost not existing. Therefore radiation of targets of interest that are typically under surveillance (humans, mechanical vehicles, ships, aircraft) is emitted in MWIR-LWIR spectral bands when the same targets reflect optical radiation in VIS-SWIR spectral bands (Fig. 1).

Due to these reasons the term thermal radiation is typically understood as radiation emitted by targets of typical Earth temperatures at MWIR-LWIR spectral bands.

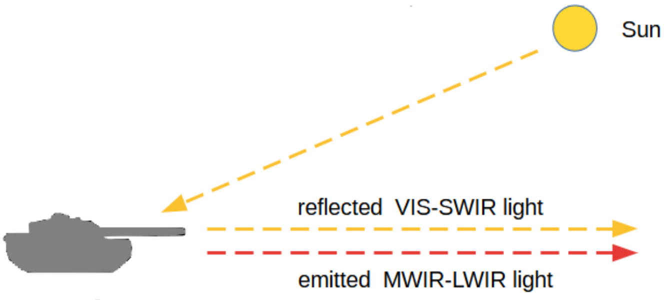


Fig. 1. Optical radiation generated by targets of interest incoming to imaging system

Thermal radiation emitted by targets of interest is attenuated by atmosphere between target and thermal imager. Atmosphere transmission depends on many factors (distance, humidity, temperature, altitude, weather conditions) but for any case it can be said that atmosphere transmits relatively well only in two so called atmospheric windows: MWIR window (about 3-5 µm) and LWIR window (about 8- 2 µm). It should be noted that inside MWIR window there is an internal absorption band (about 4.15-4.35 µm). Typical transmission spectrum is shown in Fig. 2.

Further on, it should emphasized that average spectral exitance of typical targets is much higher in LWIR spectral band comparing to MWIR spectral band. In detail this ratio is approximately 24 times for targets of typical lab temperature 20°C. This ratio clearly indicates that even if both atmospheric windows can be used for thermal imaging then MWIR imagers of much higher sensitivity are needed to compensate much weaker radiance in this spectral band. In addition, due higher non-linear relationship between temperature and radiometric signal, electronics of MWIR imagers must be designed to accept variable intensity input radiometric signal of much higher dynamic comparing to LWIR imagers.

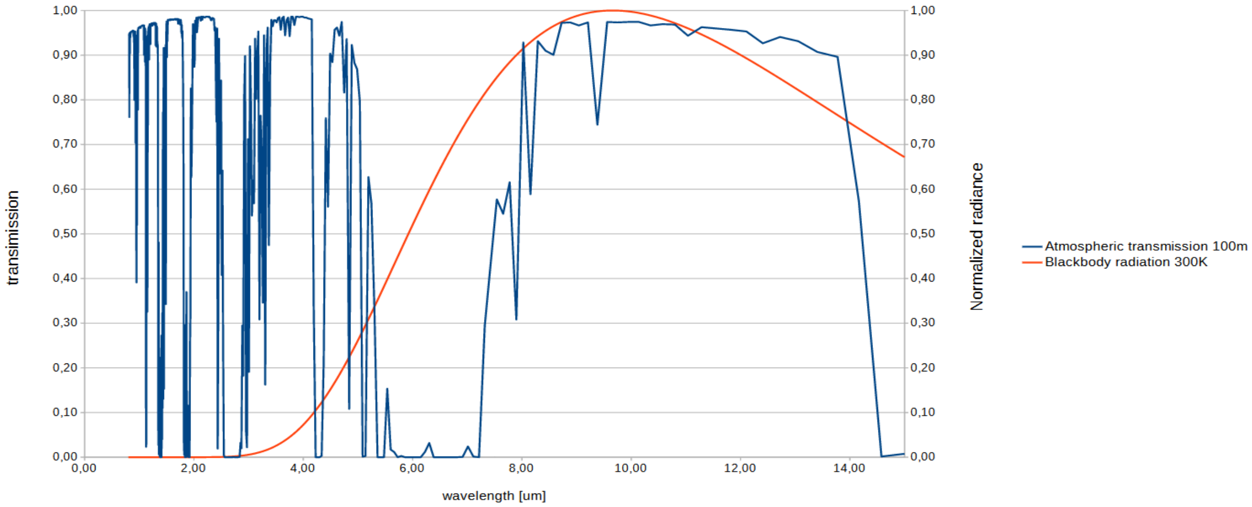


Fig. 2. Approximate transmission of atmosphere at distance of 100 m and relative spectrum of typical target at 300 K temperature.

Finally, it should be noted that due to longer wavelength, diffraction blur of LWIR optics is about 2.5 times bigger comparing to diffraction blur of MWIR optics assuming the same optics aperture. It means that it is possible to design MWIR imagers with smaller optics comparing to LWIR imager of the same spatial resolution.

4. Generations of thermal imagers

Details of long history of thermal imaging are not needed to understand present day and potential future of this technology. However, historical division of thermal imagers on generations shall be discussed here because this historical division is needed to understand present day technology.

Historically, thermal imagers have been generally divided into three generations.

First generation are two directional scanning imagers. They are built using an image sensor with so low pixel number that two-direction scanning is needed. The image sensor can be in different forms: discrete detector, simple non-multiplexing photo-conductive linear arrays (typically PbSe, InSb or HgCdTe) of elements number not higher than about one hundred, or the SPRITE detectors. These imagers usually operated 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. Nowadays, first generation camera can be treated as totally extinct group of thermal imagers.

Second generation thermal imagers are one directional scanning imagers. They are built using a linear image sensor with so high pixel number that only one-direction scanning is needed. In detail, Gen.2 scanning cameras are built using linear arrays of line-elements number higher than about 100 but lower than about 612. Temperature resolution NETD of these cameras is improved up to the level of about 0.1 K.

Thermal cameras built using improved multi-linear FPAs can be treated as a subgroup of Gen.2 imagers and are called Gen 2+ imagers. Temperature resolution 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 (presently Lynred) both for 3–5 µm and 8–10.5 µm bands with signal processing/enhancement in the focal plane (photocurrent integration, skimming, partitioning, TDI function, output preamplification and some others). Gen. 2+ imagers are characterized by smaller weight and size and improved reliability.

A significant portion of military thermal cameras used world wide are Gen.2/Gen.2+ thermal imagers but their volume share is decreasing. However, Gen 2+ imagers are still manufactured due to a number of advantages: low cooling power consumption, single chip fully integrated with readout electronic, small size, reliable scanner.

Third generation imagers are non-scanning thermal cameras build using 2D array detectors with number of pixels at sufficient level to eliminate need for mechanical scanning. 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 only task of the optics is to focus the IR image onto the image sensor. Image sensors of different technologies are used: cooled FPA based on InSb, HgCdTe, QWIP technology or non-cooled FPAs based on microbolometer or pyroelectric/ferroelectric technology. Gen 3 thermal imagers dominate present day market as share of Gen.2+ is rather marginal.

It can be surprising that block structure of Gen 3 staring imagers is similar to block structure of human eye (Fig. 3). IR objective is equivalent to eye lens. Both generate image of scenery of interest. FPA controller electronic is equivalent to system built from nerves and brain. Both blocks convert optical image into electrical signals and do some image processing. This comparison can help to understand work concept of thermal imagers.

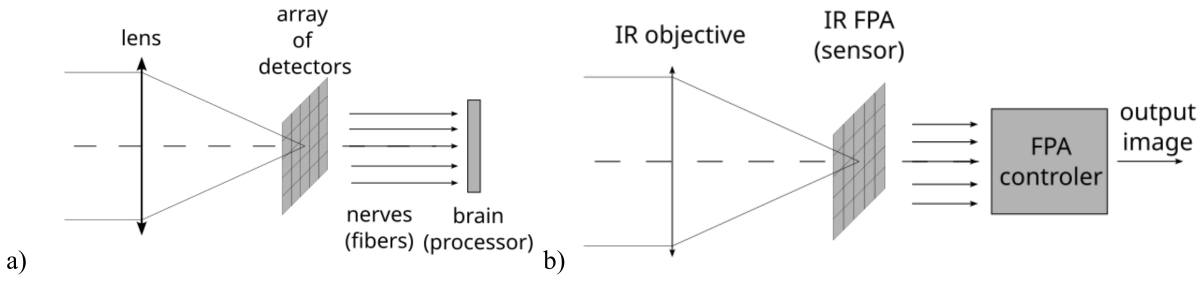


Fig. 3. Block diagrams of two systems: a) human eye, b)staring thermal imager

To summarize, modern thermal imagers are built using IR FPA image sensors capable to generate 2D thermal image without need for any mechanical scanning. Due to lack of scanning system design of thermal imagers is much easier comparing to situation several decades ago.

At present presented earlier division of thermal imagers into three generations is almost obsolete because great majority of thermal imagers offered on the market are Gen 3 staring imagers.

The aim of this book to be a practical guide to present day/future thermal imaging technology. Therefore previous generations (Gen1 and Gen2) of thermal imagers shall not be analyzed.

IR FPA sensor is the main block of Gen 3 thermal imagers. Now, it should be emphasized that IR FPA image sensors are also divided on three generations [29-30].

Gen.1 – linear arrays for scanning thermal imagers (popular in period 1990-2000 but nowadays are rarely manufactured),

Gen.2 – typical two-dimensional arrays for staring thermal imagers (manufacturing technology up to about 2020 year is considered as typical),

Gen. 3 – IR FPAs that provide enhanced capabilities such as ultra high numbers of pixels, ultra high speed, ultra low thermal resolution, multicolor functionality, and/or other on-chip signal-processing functions comparing to typical IR FPAs. Gen.3 specifications are not fully defined and there are discussions on this subject.

It should be noted that the presented divisions of thermal imagers and IR FPA sensor produce confusing results because Gen 3 thermal imagers are typically is built using Gen.2 IR FPA image sensors.

5. Models of manufacturing thermal imagers

In some simplifications it can be said that thermal imager is actually as a sum of four main blocks (IR FPA image sensor (integrated with cooler in case of photon sensors), FPA controller, optical objective, imager housing, power supply) and several optional blocks: shutter, display, ocular lens (Fig. 4). Therefore the ways to manufacture thermal imagers can be classified according to method to produce these blocks. In detail, manufacturing thermal imagers can compared to building a system using a series of modules that can be purchased from third parties (easier solution) or developed internally (more difficult solution).

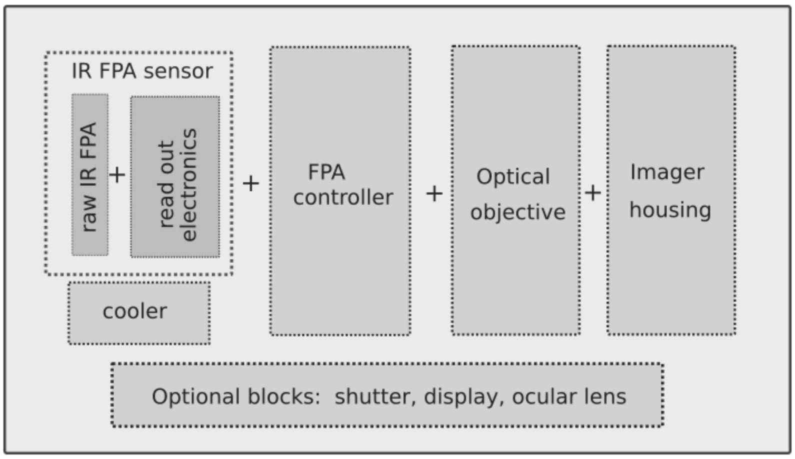


Fig. 4. Graphical concept of building thermal imagers

In detail, there is also a fifth main block of thermal imager: power supply. It is an electrical block that delivers electric power to other blocks of thermal imager: IR FPA sensor, FPA controller and IR objective. However, from design point of view there are no differences between power supply of thermal imager and general purpose power supplies of similar wattage. Therefore this block shall be omitted in further discussion.

IR FPA image sensor is the most important and most difficult to manufacture block of thermal imagers. However, it is a typical situation that manufacturers of thermal imagers purchase them from third parties or from separate entities within large corporations. Therefore it can be assumed that IR FPA sensor needed to develop thermal imager is to be purchased. The same can be said about the optional blocks. They can be easily acquired on the market at relatively modest price.

The inverse situation is in case of the fourth block: the imager housing. This is a wide term that describes mechanical block that keeps all electronics and optics of thermal imager at proper locations.

This block is typically manufactured according to mechanical documentation developed by the manufacturer of thermal imagers. Therefore this way to procure of this block can be treated as internal manufacturing.

In such a situation different ways of manufacturing thermal imagers can be defined on basis of method to procure the two critical blocks:

1. FPA controller,
2. IR objective.

These blocks can be procured in two ways: purchase from third party – coded as 0, or internal manufacturing – coded as 1. That gives us four models of manufacturing thermal imagers (Table 1).

Table 1. Models of manufacturing thermal imagers (0-purchased block, 1-internal manufacturing

Model of manufacturing	IR FPA sensor	FPA controller	Optical objective	Imager housing	Optional blocks
Integrator	0	0	0	1	0
Mixed 1	0	1	0	1	0
Mixed 2	0	0	1	1	0
Internal manufacturing	0	1	1	1	0

There are two limit models of manufacturing of thermal imagers:

1. integrator model (code 00010) where both two main blocks are purchased from third parties,
2. Advanced manufacturing model (code 01110), where both two main blocks are manufactured internally.

In first case, thermal imagers are built using a six step algorithm:

1. Purchase of thermal camera core (IR FPA image sensor integrated FPA controller). The sensor is integrated with a cooler in case of cooled IR FPAs sensors.
2. Purchase of IR objective optimized for a thermal imager to be designed,
3. Purchase of optional blocks (shutter, display, ocular lens if needed),
4. Development of an imager mechanical case capable to combine all blocks of thermal imager to be designed.
5. Mechanical/electronic/software integration of the imager body with the camera core, optics, and the optional blocks.
6. Imager calibration in range determined by manufacturer of the camera core.

This way of building thermal imagers looks very easy. However, in spite of this apparent design simplicity, the process of manufacturing of thermal imagers using the integrator model is quite difficult and risky in spite of the fact that the critical blocks are purchased from third parties.

First, there are commercial/technical risks with purchase of blocks needed to design thermal imagers. The main challenge is IR FPA sensor. Number of manufacturers of IR FPA sensors is very limited and these sensors are considered as dual use products. Therefore there are some export limitations. In addition, some IR FPA manufacturers have rules to sell best image sensors only for their strategic customers. Therefore, purchase of high grade IR FPA sensor is often a difficult and risky task.

Second, there are similar risks with other main blocks. Basically, business experience, technical know-how and ability to test equipment purchased modules is needed to ensure acquire high quality blocks needed to built high performance thermal imagers.

Third, many rules related to integration of blocks and calibration/noise corrections of complete thermal imagers must be well understood to manufacture high performance thermal imagers. All purchased blocks can be perfect and still is possible to manufacture poor performance thermal imager.

In second case, thermal imagers are built using an eight step algorithm:

1. Purchase of IR FPA image sensor in form of a raw IR FPA sensor integrated with read-out electronics (ROIC).
2. Development of FPA controller block.
3. Integration of the IR FPA sensor with the FPA controller block to form thermal camera core (thermal imaging module).
4. Development of an IR objective optimized for a thermal imager to be designed,
5. Purchase of optional blocks (shutter, display, ocular lens),
6. Development of an imager housing capable to combine all blocks of thermal imager to be designed.
7. Mechanical/electronic/software integration of the imager housing with the camera core, optics and the optional blocks.
8. Expanded imager calibration (noise correction, contrast/brightness settings, image sharpness improvements).

As we can see there are two main differences comparing to previously analysed integrator model:

- FPA controller block and IR objective are developed internally,
- Expanded calibration of thermal imager.

This new way to acquire FPA controller block and IR objective does not give warranty that final thermal imager will be technically better, and commercially more profitable comparing to imagers manufactured using integrator model. However, use of the advanced manufacturing model create potential to develop thermal imagers that are technically more advanced and can be sold at higher price.

There are two main reasons for such higher potential. First, higher knowledge about manufactured FPA controller and IR objectives enables better optimization of these blocks. Second, higher quality critical blocks due to quality control and possibility to select best units for internal use. Third, lack of limitations on image enhancement methods that exist in case of integrator model.

The advanced manufacturer model creates new opportunities but it is also much more difficult comparing to integrator model. Therefore this model is mainly used by large companies capable to master both advanced electronics needed to manufacture FPA controller, advanced optics needed to manufacture the IR objective, and advanced software needed to develop high efficiency methods to enhance output image. It can be estimated that only about 25% of market of thermal imagers are imagers using advanced manufacturing model. Share of integrator model can be estimated at about 25% and the rest of market (50%) for mixed models.

Methods of design thermal imagers based on IR FPA image sensors presented above are similar to method of design of VNIR cameras based on silicon image sensors (mainly CMOS sensors). However, market price of thermal imagers is typically at least over 10 times higher comparing to price of VNIR cameras of comparable output image resolution due to a number of both commercial and technical reasons:

1. IR FPA sensors used at thermal imagers are much more expensive comparing to CMOS sensors used in VNIR cameras (price ration over about 10 times in case of non cooled IR FPAs and over about 50 times in case of cooled IR FPAs).
2. Majority of CMOS sensors are integrated with advanced digital ROIC and can generate at their output standard digital video image. ROICs of IR FPA. sensors generate non-standard video images.
3. IR optics used in thermal imagers is much more expensive comparing to VNIR optics. The main reason is high cost of optical materials for MWIR/LWIR band comparing to low cost glasses for VNIR band.
4. IR optics must correct effects not met in VNIR band: Narcissus effect, high veiling glare.
5. IR optics (refractive index) is more sensitive to ambient temperature and this dependence must be corrected by proper athermal design.
6. Spatial noise of IR FPA sensors is much higher comparing to spatial noise of CMOS sensors and therefore special image processing/enhancement electronics capable to reduce this noise is needed (Fig. 5).
7. Special mechanics is needed in thermal imagers due to special requirements: mechanical shutter, heat dissipation.
8. VNIR cameras represent fully matured mass manufacturing technology. Thermal imaging is still a beginner level technology.

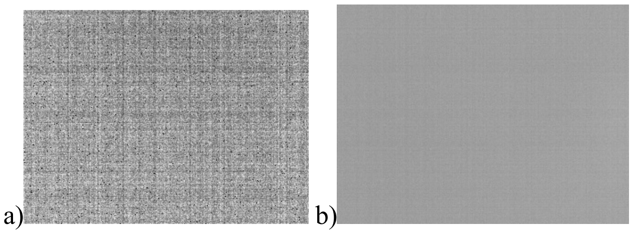


Fig. 5. Exemplary raw image from two image sensor: a)uncooled LWIR FPA, b)CMOS sensor for VNIR band

6. Blocks of thermal imagers

As stated earlier thermal imagers are built by mix of purchase and/or internal manufacturing of four main blocks of critical importance (IR FPA sensor, FPA controller, IR objective and imager body) and some optional blocks and later combining these blocks to form a thermal imaging system. Therefore, these blocks shall be discussed in details in next sections in order to allow basic understanding of rules of designing of thermal imagers. In addition, methods of image enhancement that are of critical importance of thermal imaging shall be discussed, too. Finally comparison of design challenges versus VNIR cameras is presented.

6.1 IR FPA image sensor

IR FPA image sensors offered on the market are imaging chips built by combining array of optical detectors sensitive to thermal radiation (typically MWIR or LWIR bands) with an integrated circuit specifically designed for reading electrical signals from this array of detectors. The detector array and the read-out integrated circuit (ROIC) are typically manufactured as two separate entities that are hybridized together using advanced interconnection methods (typically indium bumps). The idea is presented in Fig. 6.

The task of detector array (sometimes called raw IR FPA) is conversion of optical signals coming to the detectors to an array of electrical signals. The main function of ROIC is to work as multiplexer capable to capture array of electrical signals and to generate a serial video signal that contains all the useful information about array of electrical signals. ROIC can also optionally amplify, digitize input electrical signals.

It should be noted that ROICs are electronic circuits optimized for specific detector arrays. Further on, ROICs can differ depending on required features of serial video signal. Therefore ROICs used for manufacturing of different IR FPA sensors offered on the market differ a lot.

Finally, it should be emphasized that ROICs should be treated only as a first stage of electronics needed to built thermal imager that is capable to generate electronic image in one of standards of electronic video image.

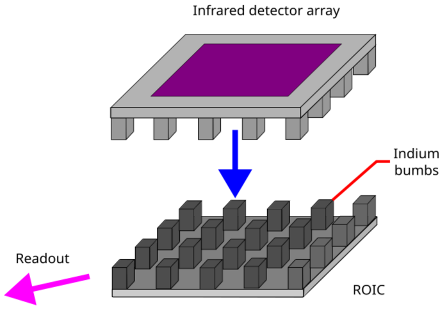


Fig. 6. Graphical concept of hybridization of detector array with ROIC

There are myriad of IR FPAs sensors used to manufacture thermal imagers. These imaging sensors can be divided using six main criterion:

1. Sensor type (work concept)
2. Sensor cooling
3. Sensor spectral band,
4. Sensor output image (resolution/sensor size),
5. Maximal frame rate of output image,
6. ROIC type.

This division of IR FPAs shall be presented in next sections.

6.1.1 Types of IR FPA sensors

Depending on work concept of discrete IR detectors the IR FPA sensors can be divided into two main groups, shown in Fig. 7:

1. photon (photoelectric) FPAs
2. thermal FPAs.

Photon FPAs are built using detectors that absorb incoming light and generate output electrical signal (voltage, current) proportional to number of incoming photons.

Thermal FPAs are built using detectors that absorb incoming light (mainly in MWIR-LWIR spectral bands) and change their temperature. The change of temperature generates a change of other physical property that can be electrically detected.

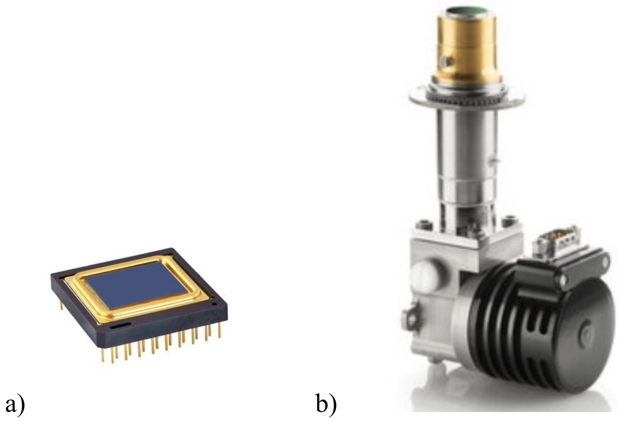

a) b)

Fig. 7. Photos of two IR FPA sensors: a)uncooled PICO640GEN2™ from Lynred Inc., b)SCORPIO IDCA block (MWIR sensor integrated with a cooler) from Lynred Inc

Over last three decades scientific centers have developed about a dozen of types of photon FPAs or photon discrete detectors for potential use in photon FPAs. However, so far only three types have already found mass applications in manufacturing thermal imagers and can be considered as fully mature technologies:

1. HgCdTe FPAs
2. InSb FPAs
3. QWIP FPAs.

In detail, the list of types of photon FPAs that are commercially available has been recently expanded with so called HOT FPAs. However, the latter image sensors are market novelty. Only small numbers of thermal imagers has been manufactured using these new image sensors. Therefore HOT FPA sensors shall be discussed in details later in section 11.2 dealing with future of thermal imaging.

It can be roughly estimated that thermal imagers built using HgCdTe FPAs represent at least 80% of total volume of photon thermal imagers that have been manufactured worldwide. Percentage of thermal imagers built using InSb FPAs can be estimated at level about 18%. Finally, market volume share of QWIP FPAs can be estimated at level about 2%.

HgCdTe FPAs are imaging sensors built using an array of semiconductor photodiodes made from HgCdTe. It is a chemical compound of cadmium telluride (CdTe) and mercury telluride (HgTe) that enables to achieve a tunable bandgap of spectral band covering a longer part of SWIR range, MWIR range and LWIR range. Therefore, these FPAs can optimized to sense MWIR radiation or LWIR radiation. Near perfect detectivity is the greatest advantage of this type of IR FPAs. However, these imaging sensors are prone to problems with poor image uniformity, and temporal stability in form of slowly fluctuating spatial noise.

InSb FPAs are imaging sensors built using an array of semiconductor photodiodes made from InSb. It is a crystalline compound made from mixture of indium (In) and antimony (Sb). In contrast to HgCdTe InSb it is a semiconductor with narrow gap that cannot be tuned. Therefore, InSb FPAs can be used only in thermal imagers sensitive in MWIR spectral range. These FPAs offer similar performance as HgCdTe FPAs optimized for MWIR band but detectivity of the InSb FPAs is typically slightly lower.

QWIP FPAs are imaging sensors built using array of optical photoconductors based on the quantum well principle. In detail, these are special optical detectors where a narrow bandgap semiconductor layer is between two layers of wide bandgap. Incoming photons are absorbed by the quantum well layer generating an electric current. QWIP detectors are commonly made using gallium arsenide. Spectral band of QWIP FPAs is typically optimized to cover the shortwave part (from about 7.5 μm to about 9.5 μm) of LWIR band. QWIP FPAs are characterized by near perfect image uniformity, stability, and pixel operability but sensor detectivity is at modest level.

As stated earlier, thermal FPAs employ thermal detectors based on concept of change of their temperature due to incoming radiation.

There are four main types of thermal detectors:

1. thermocouples and thermopiles that use the thermoelectric effect,
2. pyroelectric detectors that produce pyroelectric voltage when irradiated,
3. Golay cells that employ thermal expansion,
4. bolometers that works as special material of temperature-dependent electrical resistance.

However, virtually all thermal FPAs are built as array of microbolometers using the latter work concept. The microbolometer can be considered special miniaturized, ultra small version of bolometer detector. Design of microbolometers is based on a simple concept of thermally isolated absorber that changes its resistance when irradiated. Thermal FPA is built by creation of an array of microbolometers encapsulated under a vacuum with ROIC electronics.

Situation on a market of thermal IR FPA image sensors is similar to earlier described situation on the market of photon IR FPA image sensors. There have been reported a series of technologies/materials that can be potentially used to manufacture thermal FPAs. However, practically the market is dominated by two types of thermal FPAs

1. sensor manufactured using vanadium oxide (VOx)
2. sensors manufactured using amorphous silicon (a-Si).

There are conflicting claims in literature but basically both VO_x and a-Si technologies offer similar performance. Other silicon derivatives, such as silicon-germanium (a-SiGe, poly-SiGe, and a-$Ge_xSi_{1-x}O_y$) have shown promise in the recent years [60] but still market situation has not changed.

6.1.2 Sensor cooling

All three types of mature photon IR FPAs discussed in previous section need cryogenic cooling (temperatures below about 80K) to achieve proper performance needed for work in thermal imagers. Detectivity of these three mature photon FPAs (HgCdTe, InSb, QWIP) is very poor (especially in LWIR band) when FPA sensor is at typical laboratory temperature. Even more, detectivity is still at a modest level when temperature is above earlier mentioned cryogenic limit. In detail, detectivity improves several magnitudes when detector is cooled from the ambient temperature to the temperature below about 80 K. Therefore in order to achieve high detectivity (10^{11} cm $Hz^{0.5}$ W^{-1} for MWIR detectors or about $2x10^{10}$ cm $Hz^{0.5}$ W^{-1} for LWIR detectors) these photon FPAs must work at cryogenic temperatures. Therefore, all mature photon FPAs discussed in previous section are offered integrated to Stirling coolers (see Fig. 7b) or rarely integrated to liquid nitrogen dewars (scientific research). For this reason photon FPAs are commonly called cooled FPAs.

However it should be noted that so called HOT FPAs mentioned in previous section as market novelty can work at higher operating temperature about 150 K and need use of smaller, low power Stirling cooler.

Some level of cooling or at least temperature stabilization of microbolometric FPA can improve performance of these image sensors (much lower temporal drift of spatial noise). Therefore, significant portion of old microbolometric FPAs was equipped with miniaturized Peltier cooler. However, this solution made sensor bulky and increased power consumption. It was also soon discovered temporal drift of spatial noise can be compensated using image enhancement methods run by software of FPA controller. Therefore practically all modern microbolometric FPAs do not use any mechanism for cooling or stabilization of their temperature and operate typically at near ambient temperatures. In such situation thermal FPAs are typically called uncooled IR FPAs.

6.1.3 Sensor spectral band

As presented in Section 3 there are two atmospheric windows in thermal imaging spectral band: MWIR band and LWIR band. Therefore, it is natural that virtually all thermal imagers used world wide work in one these spectral band. However, choice of spectral band is not always for all IR FPA sensors.

HgCdTe FPA can be optimized for work in MWIR band (or subband) or in LWIR band. In detail, such FPAs can be optimized to be sensitive in both of these spectral bands.

InSb FPA cannot be optimized for work in LWIR band. This material enables to manufacture IR FPA sensors sensitive only in MWIR band.

QWIP FPA can theoretically be optimized for work in any part of spectral range from about 3 µm to about 20 µm. However, practically QWIP FPAs are typically sensitive in shorter part of LWIR band: from about 7.5 µm to about 9.5 µm.

Situation in case of uncooled FPA is different. Here we have situation that physics favors LWIR band: targets of typical Earth temperature emit mainly radiation in LWIR spectral band. Therefore, the typical uncooled FPAs are optimized spectrally (absorption spectral curve, window transmission) for LWIR range.

It is technically not difficult to manufacture MWIR FPAs (absorption spectral curve and window transmission optimized for MWIR band) but such FPAs are characterized by poor temperature resolution NETD (at least twenty times worse comparing to performance of uncooled LWIR FPAs). Therefore, the rule is that practically all uncooled FPAs are LWIR FPAs and all uncooled thermal imagers are LWIR imagers.

6.1.4 Resolution/pixel size of IR FPA image sensor

IR FPA image sensors generate spatially digital image of resolution specified by a table in form of number of rows x number of columns and by size of a single pixel. This rule is valid in case of any types of IR FPA (even in case of analog output FPAs).

History of staring thermal imagers (Gen 3 imagers) is basically a history of improvement of spatially discrete image generated by IR FPAs: more pixels and smaller pixels. Improvement of image resolution and decreasing of pixel size has been the main aim of R/D teams since appearance of first staring IR FPAs sensor at end of 1980s.

As can be seen in Table 2 there have been a huge progress in IR FPA technology during last 30 years. This sensor change has enabled to make a huge step in design of thermal imagers from very low resolution (160×120) imagers to high resolution (at least 1024×768) imagers. The change is even bigger in case of uncooled thermal imagers. Further on, it should be also noticed that pixel size has decreased from about 45 µm to 12 µm/10 µm level during last three decades.

The consequences are enormous. Sensors with higher number of pixels has enabled to reduce/eliminate spatial sampling effect (human eye sees image as an array of discrete parts. Sensors with smaller pixels have enabled design of thermal imagers with much higher Nyquist frequency (increased DRI ranges of effective surveillance to targets of interest) or keeping the same frequency when using smaller optics of shorter focal length.

Table 2. Approximate date of readiness for mass manufacturing of FPAs of different image resolution/pixel size

Date/ FPA type	1990	2000	2010	2015	2020	R/D level
Cooled	320×240 30 µm	320×240 25 µm	640×480 20 µm	640×480 15 µm	1024×768 10 µm	1280×1024 5 um
Uncooled	RD projects	320×240 35 µm	320×288 25 µm	640×512 17 µm	1024×768 12 um	

This technological race to increase image resolution and decrease size pixel size shall be continued in near future. However, it should be emphasized that pixel size of modern uncooled FPAs (12 µm) is now comparable to mean wavelength of LWIR imagers (10 µm). The difference is still bigger in case of cooled MWIR imagers (pixel size 10um when mean wavelength 4 µm) but still the ratio pixel size is only 2.5 smaller comparing to mean wavelength of MWIR imagers. It means that diffraction effect of imagers optics shall soon become limiting factor in this race.

6.1.5 Maximal frame rate of output image

Maximal frame rate of output image generated by IR FPA sensor is an important parameter that determines if frames of this video image are presented with sufficient speed: negligible temporal latency for human observers or image analysis software. In past it has been commonly accepted that frame rate at level 25-30 FPS is sufficient to generate video image of acceptable speed. Nowadays thermal imagers of frame rate at level of 50-60 FPS are preferred. In some R/D applications when dynamic phenomenons are to be recorded or analysed by software the requirements on frame rate can be in hundreds of frames per seconds. On the other side there are also thermal imagers used for non contact temperature measurement that generate near static images (frame rate at level below 2 FPS).

Maximal frame rate of images generated by IR FPA sensors is limited by two phenomenon:

1. sensor pixel temporal inertia,
2. limited frequency bandwidth of ROIC electronics.

Reason for sensor pixel temporal inertia depends on type of IR FPA sensor.

In case of uncooled microbolometer IR FPA sensors the temporal inertia is due to thermal inertia of microbolometer pixels. In detail, thermal time constant of a microbolometer IR FPA is determined by a ration of thermal mass C and the thermal conductance G between the pixel and its environment. Temporal inertial parameters (time constant and response time at 95% max signal) of present day microbolometer IR FPAs presented in Table 3 shows that these sensors can generate images of negligible latency at frame rate up to 50/60FPS in case of Vanadium oxide VOx sensors or up to 100 FPS in case of Amorphous silicon a:Si sensors.

Table 3. Temporal inertial parameters (time constant and response time at 95% max signal) of two main present day microbolometer IR FPAs [61]

Material	Time constant [ms]	Response time at 95% of max signal [ms]
Vanadium oxide VO_x	15	45
Amorphous silicon a:Si	7	21

In case of cooled photon IR FPA sensors the temporal inertia is due to electric capacitance of the pixel material. However, time constant of photon detectors due to this effect is very short (several nanoseconds) comparing to microbolometer FPAs and therefore sensor temporal inertia of photon IR FPAs can be treated as a negligible factor.

The second limiting factor – frequency bandwidth of analog electronics of ROIC – determines minimal time (inverse frame rate) that ROIC needs to read out signals from all pixels of IR FPA sensors. Therefore maximal frame rate that is possible for a specified ROIC electronics can be approximated using this formula (1)

$$FR=\frac{k\cdot\Delta f}{N_{FPA}}, \qquad (1)$$

where FR is theoretical maximal frame rate, k is the number of analogue outputs of IR FPA sensor, Δf is frequency bandwidth of analogue electronics of ROIC, and NFPA is number of pixels of IR FPA sensor.

The formula (1) shows three ways to increase frame rate

1. increase frequency bandwidth,
2. increase number of output channels),
3. reduce image resolution of IR FPA sensor.

Present day technology limit on ROIC frequency bandwidth is at level about 10 MHz. As can we see in Table 4 simple ROIC with only one output cannot offer proper frame rate (at least over 25/30 FPS) even in case of IR FPAs of modest HD resolution 1024×768 px. Therefore is case of HD resolution IR FPA sensors it is necessary to use ROICs with increased number of channels (up to 8 or more is case of special IR FPA sensors). Another solution is to design analog electronics of higher bandwidth (up to 40MHz or higher). However, it should be also remembered that higher frequency bandwidth/number of output channels increases difficulties in design of FPA controller block that is to cooperate with IR FPA sensor.

Table 4. Maximal frame rate of IR FPA depending on sensor number of pixels and sensor number of output channels for electronics of modest frequency bandwidth at level of 10 MHz

			Maximal frame rate FR		
No of column	No of rows	No of pixels	Channel No =1	Channel No =2	Channel No =4
320	240	76800	130.2	260.4	520.8
384	288	97920	90.4	180.8	361.7
640	480	307200	32.6	65.1	130.2
640	512	327680	30.5	61.0	122.1
1024	768	786432	12.7	25.4	50.9
1280	960	1228800	8.1	16.3	32.6
2560	1920	4915200	2.0	4.1	8.1

6.1.6 ROIC type

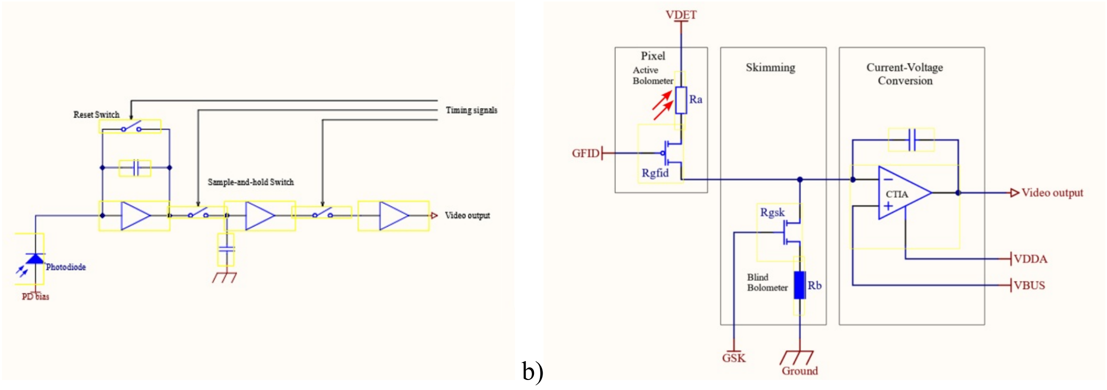
ROIC is an integrated electronic circuit designed for reading signals from pixels of raw IR FPAs. Therefore, it is logical that ROICs can be divided on criterion of parameters of raw IR FPAs they are supposed to cooperate:

1. image resolution (160×120, 320×240, 640×480, 640×512, 1024×768, 1280×1024 and so on)
2. pixel size: 45 µm, 35 µm, 25 µm, 17 µm, 15 µm, 12 µm, 10 µm.
3. physical principle of raw IR FPA to cooperate: 1)photon (photoelectric array) detector, 2)thermal detector (microbolometric array).

Interpretation of the first two criteria is easy and non need for clarifications. However, situation is different in case of the third criterion: physical principle of IR FPA sensor. Change of physical principle (photon (photoelectric array detector or thermal detector (microbolometric array) generates change in ROIC task and change of ROIC electronics.

Task of ROIC for photon FPA is to accumulate the photocurrent from each pixel. The main element of the photon detector reading circuit is the charge amplifier (Fig. 8a). The photon detector reading circuit integrates the current generated on the detector and presents the value as a voltage. For the operation of the integrated detector matrix reading circuit, additional elements are also necessary, such as a reset switch, latches (sample/hold) and switching systems for reading individual pixels.

The task of ROIC for microbolometer IR FPA is to measure the resistance of a single element (pixel), which changes its resistance depending on the incident radiation. Measurement of resistance is based on a concept of a so called blind bolometer (Fig. 8b). The current flowing through the blind bolometer is integrated and presented as a voltage value. It should be noted that this current also depends on the bias voltages and the resistance of the bolometer compensating for change of ambient temperature.



a) b)

Fig. 8. Input modules of a ROIC: a) ROIC for photon IR FPA, b) ROIC for microbolometer IR FPA

In practice the differences between ROICs for these two types of FPAs are limited to input modules shown in Fig. 8. Other blocks of both types of ROIC from the same manufacturer can be quite similar. However, there are other criterion that generate bigger design changes.

The primary division of ROICs is according to method of reading of signals from raw FPAs that is enabled by ROIC:

1. analogue ROICs – generate analog output signals from pixels,
2. digital (DROIC) - generate digital output signal (additional analog/digital converters at output of typical analog ROIC)
3. digital pixels (DPROIC) ROIC – an advanced method that makes possible simultaneous analogue-to-digital conversion from each pixel. Signals can be measured individually or from a group of pixels to in order to increase reading speed of image sensor.

Integration of raw IR FPA with digital DROIC or even more with digital pixels DPROIC reduces requirements on FPA controller, enable development of ultra miniaturized, lower power and potentially variable speed thermal camera cores. However, development of digital/digital pixels ROICs is extremely difficult and costly (especially for high resolution FPAs). Therefore, great majority of thermal imagers offered on the market are built using IR FPAs that employ analogue ROICs. This rule is especially valid for ROICs used in R/D projects.

6.1.7 Testing IR FPA sensors

Technology of manufacturing IR FPA sensors is very difficult and it is not possible to fully control all factors that influence quality of these sensors. Therefore, it is typical that there is some quality difference between manufactured sensors. Most of manufacturers divide IR FPA sensors on several grades like A, B, C, D that differ on such parameters performance parameters like detectivity, NETD (noise equivalent temperature difference), gain/offset, 1/f noise, dynamic, dead pixels number and location, MTF (modulation transfer function), crosstalk, and relative spectral sensitivity. There is a big performance difference between grades A and D. In such a situation, it is highly desirable to acquire sensors that belong to best grades.

Ability for testing purchased IR FPAs sensors improves position of the buyer and gives higher chance to bargain better IR FPA sensors.

Test of IR FPA sensors carried out by manufacturers of thermal imagers are typically limited to noise/responsivity parameters. These tests are carried out using a test system that irradiates uniformly tested sensor and analyses signal at output of tested IR FPA sensor. This test concept means that near perfect FPA controller is needed to convert raw IR FPA output signal to one standards of video signals. Performance of FPA controller is a subject of common controversies because its poor performance can deteriorate test results.

More expanded tests that include measurement of MTF, cross talk, spectral function are rarely carried out due to high cost of test equipment.

More details on testing IR FPA sensors can be found in specialized literature [62-65].

6.2 FPA controller

6.2.1 Aim of FPA controller

IR FPA image sensors alone are practically useless opto-electronic chips for a number of reasons:

1. typical IR FPA image sensors shall not work at all if not connected to a set of precision bias voltages and clocking generators,
2. raw electronic image generated by IR FPAs sensors is typically very noisy, with dead pixels, and sometimes blurred.
3. IR FPAs sensors cannot generate output electronic video image in one of standards of electronic video image).

Due to these reasons IR FPA sensors are always combined with FPA controller block. These two blocks combined together form so called thermal camera core becomes capable to generate low noise output image in one of standard video formats (Fig. 9).

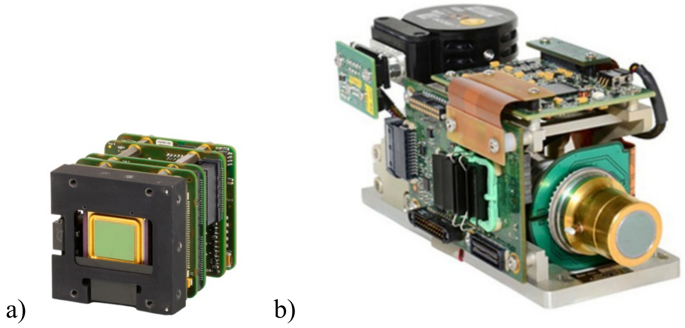


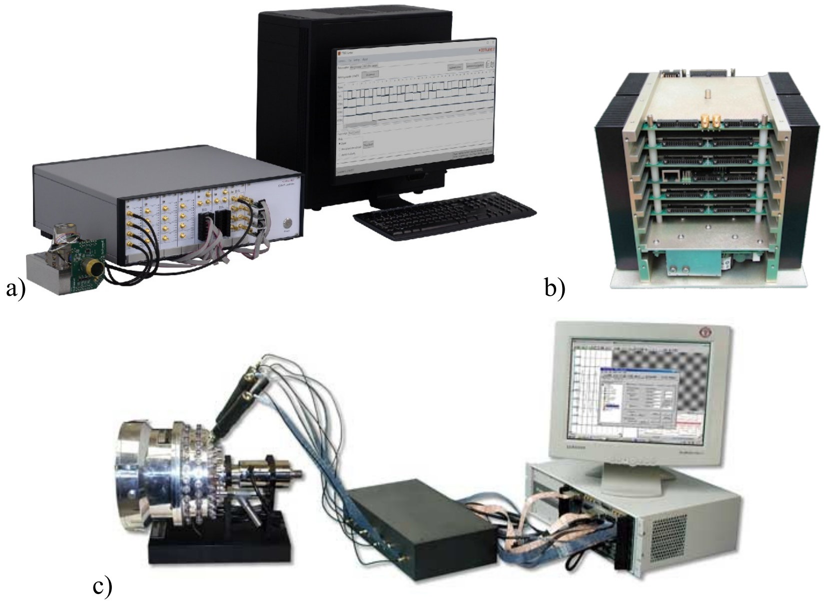
Fig. 9. Photos of two thermal camera cores/modules: a)uncooled XTM+ camera core from Photonis Inc., b)SCORPIO MWIR camera core/module from Lynred Inc

There are hundreds of types of different IR FPA sensors used to built thermal imagers. Therefore it is not surprising that the most important criterion of any FPA controller is number of types of IR FPA sensors that can be controlled in order to generate high quality output image. On this criterion FPA controllers can be divided into two main distinct groups:

1. quasi universal FPA controllers,
2. specialized FPA controllers.

6.2.2 Specialized FPA controllers versus universal FPA controllers

FPA controllers from the first group are multi-board, reprogrammable, bulky laboratory electronic systems (Fig. 10). In detail, they are commercially available systems capable to control/image processing/enhancement of majority of IR FPA image sensors offered on the market [66-68]. Such universal controllers can be excellent tool for R/D projects to verify performance of different types of IR FPAs (or ROICs) but they cannot be used to build real thermal imagers due to too large dimensions, mass and cost. There are also some non-commercial FPA controllers belonging to the same group that have been developed in scientific projects (mainly astronomical projects) [69-71].



a)

b)

c)

Fig. 10. Photos of three commercially available quasi universal FPA controllers: a)CONIR controller [66], b)Gen IV ARC controller [67], c)PI-3105 Multi-Channel Data Acquisition System [68]

Virtually all FPA controllers used to design and manufacture thermal imagers are specialized controllers optimized for control of one specific type of IR FPA sensor (sometimes several similar sensors). Practically it means that design team knows precisely specifications of IR FPA sensor: bias voltages, clocking, amplification, output electronic format, etc. Limitation of group of sensors to be controlled enables simplification of design, miniaturization and cost reduction. Therefore commercially available camera cores are practically IR FPA sensor combined with such a miniaturized specialized FPA controller (Fig. 9). In most advanced form they are built as a specialized application specific integrated circuit (ASIC) designed to perform ROIC driving, amplifying and digitization functions for ROICs.

A significant drawback of specialized FPA controllers is their lack of flexibility. This limitation combined with long time needed to develop FPA controller explains why it is difficult for manufacturers of thermal imagers to change their supplier of IR FPA sensors or even to change types of image sensor from the same FPA manufacturer. Sometimes even a small change of manufacturing technology of the same type of FPA sensor (manufacturers often change bias voltages even when continue production of the same type of IR PFA) can generate necessity to introduce a significant change in electronics of the specialized IR FPA controller.

Finally, it should be noted that some manufacturers offer so called “proximity board” (see section 6.2.10) in order to help buyers of their IR FPA sensors to develop FPA controller.

6.2.3 Design diagram of FPA controllers

There are hundreds of types of IR FPA sensors used for manufacturing of thermal imagers. The same IR FPA sensor can be successfully controlled using a series of specialized controllers of different electronic design. In such a situation it can be expected that thousands of specialized FPA controllers are used worldwide. There are also much smaller number of universal/semi-universal FPA controllers.

As has been shown in previous section there are significant differences between specialized controllers and universal controllers. However, in spite of these apparent visual differences it can be said that all FPA controllers do follow the same task and design rules.

There are four main tasks of FPA controllers used to control image sensors of thermal imagers:

1. Control of IR FPA image sensor (delivery of proper bias voltages and clock signals to ROIC to make it work and generate output signals),
2. Analogue amplification and digital capturing of signals from IR FPA,

3. Image enhancement of electronic image generated by the IR FPA sensor (correction of spatial noise, contrast/brightness regulation, image resolution improvement, image sharpening etc).
4. Generation of output image in one of standards of electronic video image.

FPA controllers capable to fulfill these tasks can be built in myriads of ways but they are basically always an electronic system built using six main blocks (Fig. 11):

1. Bias generator
2. Pattern/clock generator
3. Analog amplifier/digital converter
4. System on chip
5. Video interface/transmitter
6. Proximity board.

The block diagram shown in Fig. 11 is generally valid for practically any FPA controller.

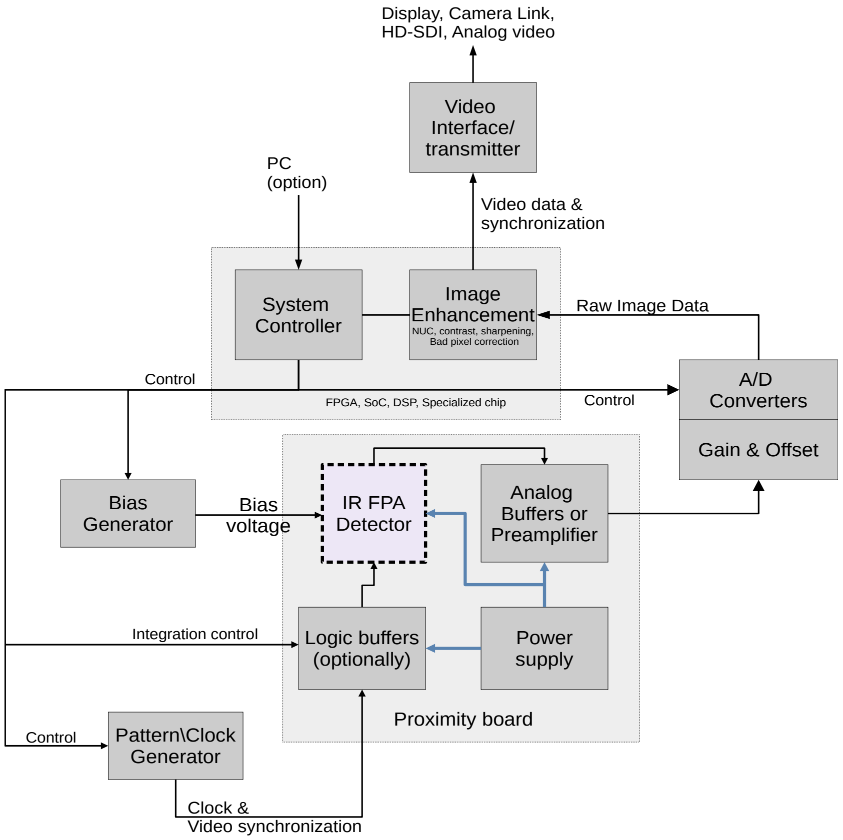


Fig. 11. Block diagram of typical FPA controller

6.2.4 Bias generator

Bias generator is a block that delivers a set of ultra precisely regulated voltage signals to inputs of IR FPA sensor. Supply of such analogue voltages is one basic conditions to make IR FPA sensor operational.

Number of bias voltages needed by IR FPA sensor vary from from 1-2 voltages in case of simple low resolution sensors up to 32 in case of sophisticated high resolution image sensors for space applications. Majority of IR FPA sensors need bias voltages of positive polarization in range from 0V to 5 V but some sensors needs voltages in expanded range from 0V to 15 V of both negative and positive polarization.

Commercially available electronic bias cards can serve as bias generators capable to generate up to four positive polarity voltages at range 0-5V (Table 5). By combining several cards it is possible to increase number of bias voltages. Therefore significant portion of FPA controllers is built using such commercially available bias cards. Another group are customized bias generators that are developed with aim to overcome limitations of commercial bias cards: wider voltage regulation range, both positive and negative polarity, lower noise spectral density, and better miniaturization.

Table 5. Specifications of a popular bias card for IR FPA sensors TIDA-01583 [72]

No	Parameter name	Parameter value
1	Number of output channels	4
2	Voltage range	0 V to 5 V
3	Polarity	Positive
4	Total noise at 0.1 Hz-1 MHz band	<4 μV_{RMS}
5	Voltage accuracy	<±10 mV
6	Digitization resolution of DAC	16 bit
7	Output current	from 10 mA – two channels up to 75 mA – two channels

6.2.5 Pattern/Clock generator

Pattern/clock generator is a block that delivers synchronous patterns (master clock, video synchronization signals) to digital inputs of IR FPA sensor (Fig. 12). Supply of such multi channel synchronous digital signals is the second basic condition to make IR FPA sensor operational. In detail, this block is needed to enable orderly read out (sampling) signals generated by pixels of IR FPA sensor.

If this block is to be quasi universal and serve for a group of sensors (high number of channels, set of different voltages, high memory per channel, both internal and external clock, both internal and external trigger) then it is a real separate block of FPA controllers. Specification of such a block are shown in table 6. However, if the control task is limited to a single specific IR FPA sensor then clocking task is carried out by System on Chip block that delivers directly basic synchronous clocking signals.

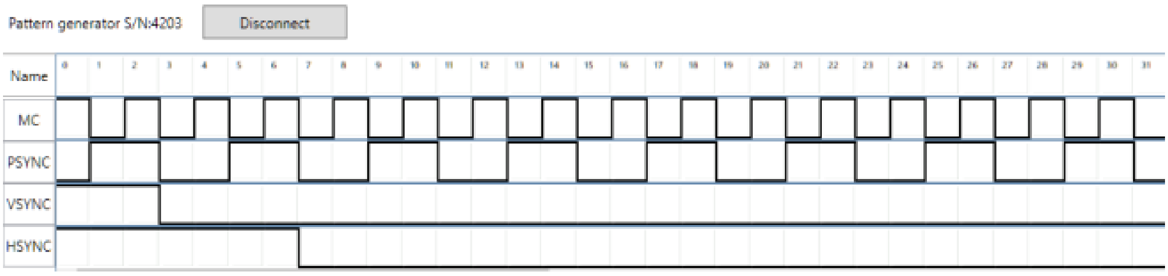


Fig. 12. Exemplary clocking signals generated by pattern/clock generator

Table 6. Specifications of pattern/clock generator of a quasi universal FPA controller

No	Parameter name	Parameter value
1	Number of channels	8 (two cards of 4 channels)
2	Memory per channel	16 Mbit
3	Clock rate	up to 250 MHz
4	Clock	both internal and external
5	Trigger	both internal and external
6	Voltages	1.8 V, 2.5 V, 3.3 V, 5.5 V (option 6 V)
7	Output impedance	50 Ω,

6.2.6 Analogue amplifier/digital converter

Raw output analogue signals generated at outputs of IR FPA sensors are weak and need to be amplified. It is also often necessary to regulate DC component of these analog signals to achieve optimal output analogue signal range for further digitization.

In addition, these output analogue signals transmit electronic image that is noisy, with dead pixels, and sometimes blurred. Therefore, extensive image enhancement of analogue electronic video image generated by IR FPA is needed. Such image enhancement is practically possible only by processing digital images. Due to earlier listed reasons analogue amplifier/digital converter block is a basic necessity in design of FPA controller. It looks like a paradox but A/D conversion is needed even in case of FPA controllers that finally generate analogue video imaget.

Analogue amplifier/digital converter block (shortly called A/D converter) is a block of FPA controller that carry out two main tasks:

1. gain/offset regulation of incoming raw analogue signals,
2. conversion of amplified/offset modified analogue signals into digital signals.

These tasks can be fulfilled by a long series of high performance A/D converters offered at the market of technical specs as shown in Table 7.

A/D dynamic range can be treated as the most important parameter of A/D converter that influences significantly design of FPA controller and use of image enhancement methods. High dynamic 14/16 bit A/D convertors enable high resolution capturing of radiometric signals emitted by targets in near total typical range of temperatures met at Earth conditions from about -50°C up to about 150°C. Such situation simplify and increase effectiveness of image enhancement to be carried out by FPA controller. However, high dynamic A/D converters are much more costly and slower comparing to low dynamic (8/12bit) A/D converters. Therefore, the latter ones are used in majority of thermal imagers.

Table 7. Specifications of an analogue amplification/digital conversion blocks used in FPA controllers

Parameter name	Value
number of A/D conversion channels	from 1 to 4 (option up to 16)
A/D converters input voltage range	0-5V (sometimes up to 10V)
A/D dynamic range	from 8bits to 16 bits
probe rate per channel	from 5MHz to 80MHz
analogue/digital noise	below 1 digital level
analogue gain per channel	from 1 to 8
gain/offset regulation	Yes

6.2.7 System on chip

System on chip (SoC) block can be treated as the brain of FPA controller responsible for two critical tasks:

1. Communication and control of all blocks of FPA controller,
2. Image enhancement of raw image generated by IR FPA sensor.

From electronic point of view, SoC is a general term for a wide group of integrated electronic circuits that compress a series of electronic components of different functionalities (digital drivers, high speed data processing, communication interfaces, memory interfaces or built-in RAM, and analogue peripherals) into one electronic chip. SoCs enables to simplify circuit board design, resulting in improved power and speed without compromising system functionality.

There are five main types of SoC used in design of FPA controllers:

1. FPGA,
2. FPGA with CPU,
3. DSP,
4. specialized ASIC,
5. microcontrollers.

Field-programmable gate array (FPGA) is a configurable integrated circuit that can be programmed by electronic design team. This structure allows the creation of almost any processing functions, as long as the system's memory allows it. Programming the FPGA system is mainly based on the hardware description languages VHDL, Verilog, but may also include an executable program written in C/C++, Assembler. In contrast to microcontrollers, FPGA systems allow easily implement of parallel data processing, which significantly increases data processing speeds. FPGAs are commonly used in applications where flexibility, speed, and parallel processing capabilities are required.

FPGA with a CPU core is a combination of a processor or microcontroller with FPGA programmable logic. The processor core can have its own independent peripheral pins and I/O ports and is connected to the FPGA programmable logic. To fully use the resources of such a system, the designer must design logical blocks in a hardware description language and write a management program in C/C++, Assembler. This solution is more flexible and allows to save a lot of time by use of ready-made CPU core and many peripherals.

DSP (digital signal processor) is a specialized microcontroller performing sequential calculations that contains special blocks supporting data processing. Basic communication peripherals such as USB, SPI, I2C can be included in this chip. Programming the DSP system involves writing a program in C/C++, Assembler and may be supported by additional tools. Only some DSP chips are suitable for thermal imagers as they are not as flexible as two solutions previously discussed that are based on programmable logic.

Microcontroller is an integrated circuit with a CPU and many additional peripherals. Microcontrollers can be used for imagers that do not require advanced data processing. In detail, they can be used in FPA controller to work with IR FPA sensors built using advanced DPROIC systems that reduce requirements to FPA controller. In practice such situation occurs only in case of some simple low resolution IR FPAs.

ASIC(application-specific integrated circuit) are specialized electronic chips components specially designed for precisely defined applications. Designing such a system is multi-stage and involves designing the entire internal logic (using an FPGA) and then designing structures in silicon based on the logic design. The process of manufacturing an ASIC for FPA controllers is expensive and only profitable in case of mass production. However, the dedicated architecture of such SoC allows to achieve advanced image enhancement when still keeping very high image frame rate.

To summarize, SoC block of microcontroller is suitable only for use in FPA controllers with very simple controls task (low resolution image, non need for image enhancement). Any of other form types of SoC (FPGA, FPGA+CPU, DSP, specialized ASIC) can be used to design FPA controllers capable to control advanced IR FPA sensors. However, nowadays SoC built in form of FPGA+CPU is the preferred solution due to flexibility and minimization of work load. Other details of types of SoC used in FPA controllers are shown in Table 8. Detail discussion on image enhancement tasks carried out by SoC is presented in Chapter 7.

Table 8. Comparison of types of SoC used in FPA controllers

	Type of chip	Flexibility	Peripheral availability	Speed	Workload	Implementation cost
1	FPGA	High	Programmed in logic	Medium/High, depending on the programmed logic and type of chip	Medium	Low
2	FPGA+ CPU	High	Programmed in logic+built-in	as in case of FPGA	Medium	Low
3	DSP	Medium	Built-in, limited	High data processing speed	Medium	Low
4	Microcontroller	Low	Built-in, limited	Low	Low	Low
5	ASIC	Limited	Dedicated	Very high speed	High	High

6.2.8 Image enhancement block

Image enhancement block is basically software of SoC block that carries our image enhancement of raw video image generated by IR FPA sensor. It can be treated as the brain of FPA controller. There are three main tasks to be done by this block:

1. Correction of spatial noise of IR FPA sensor,
2. Regulation of imager temperature span,
3. Improvement of sharpness of image generated by IR FPA sensor.

These tasks are carried out using myriads of methods that are to be discussed in detail in Chapter 7.

6.2.9 Video interface

Previously discussed image enhancement blocks of FPA controllers generate output thermal images in myriad non-standard forms of electronic video image that cannot be easily presented on typical commercially available electronic displays, recorded in mass memories used by computer sets or transmitted to different electronic systems. Video interface block of FPA controller is an electronic block that converts non standard video image generated by the image enhancement block into one of standardized forms that can be easily interpreted by typical video electronics.

Standard video image can be defined as an electronic signal that contain information of dynamic image sequence presented in standardized way (precisely defined electrical connector, transmission medium and electrical/software protocols) that is accepted internationally. Each standard proposes its own well defined interface and the terms video standard or video interface have basically the same meaning.

From design point of view video interface can be treated as a set of video transmitter and video connector. The transmitter is usually a specialized chip that prepares and sends data according to standard communication protocol to the transmission medium (such as a dedicated cable). The video connector is a type of electronic connector that that can be used for transmission of video image.

There are many standards that regulate design of video interfaces proposed by different organizations. Below is a list of most popular interfaces used in design of thermal imagers:

A. Analogue video interfaces:

1. standard analog video (PAL, NTSC)
2. enhanced analog video (AHD, HD-CVI, HD-TVI)

B. Digital video interfaces:

1. CameraLink (CL Base, CL Deca, CL HS)
2. USB (USB 1.0, USB 2.0, USB 3.0, USB3.1 Gen1, USB 3.2 Gen1)
3. SDI Serial digital interface (SDI), Variants include SD-SDI, HD-SDI, Dual Link HD-SDI, 3G-SDI, 6G-SDI, 12G-SDI
4. HDMI: 1.0–1.2a, 1.3–1.3a, 1.4–1.4b, 2.0–2.0b, 2.1–2.1b
5. UDP-IP over Ethernet: SMPTE 2022, Network Device Interface, SMPTE 2110
6. GigE (1GigE, 5GigE)
7. CoaXPress (CXP-1, CXP-1, CXP-2, CXP-3, CXP-4, CXP-5, CXP-6, CXP-10).
8. LVDS (Low Voltage Differential Signaling).

Analogue video standards (PAL, NTSC) are the oldest and still most popular video standards used in thermal imaging. These interfaces are used in applications where simplicity and reliability are critical, e.g. in military applications and monitoring. The drawbacks of PAL/NTSC video standard are

1. limitation on video resolution (only standard TV resolution),
2. one way transmission (another interface is needed to control imager settings),
3. sensitivity to EMC disturbances,
4. editing of video not possible,
5. difficult fusion of analogue with other video information (aiming mark, distance to target, imager azimuth etc),
6. huge memory needed for recording analog video, short distance of transmission of analog electronic signal via typical cable.

More advanced analogue standards like AHD, HD-CVI, HD-TVI remove limitation no 1. Digital video interfaces have been proposed to remove at least partially all limitations of analog interfaces.

The most common digital standards typically used for image transmission are HDMI (from 1.0 to the latest 2.1b), SDI (in many variants). The HDMI connection consists of differential pairs on which colour information and the clock are transmitted, the transmission medium, which is a multi-core cable, is strictly defined. The SDI connection is made via a single coaxial cable. Both interfaces only support defined resolutions and clocks, so they will not be suitable for cameras with non-standard resolutions. HDMI and SDI interfaces, like analogue ones, cannot be used for control imager settings.

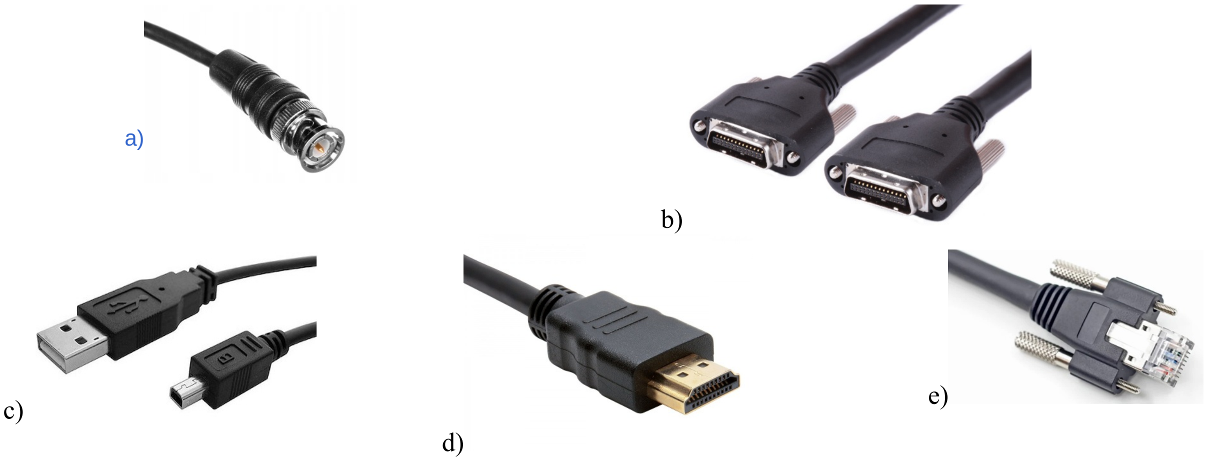
Some general-purpose digital interfaces can also enable video transmission: USB in various versions and Ethernet. As a result of the development of cameras, more standardized classes of these interfaces were created for use in imaging systems, such as USB3-Vision, GigE, and 5GigE. These interfaces also allow the implementation of control of imager settings.

Another type of interface often used in thermal imagers is CameraLink and LVDS. The first one can be treated as standardized version of the second one. LVDS are differential pairs that can be used to send a lot of information constituting an image in series: pixel values, synchronization signals. The CameraLink standard strictly defines all parameters regarding the number and arrangement of differential pairs, types of connectors, and frequency range, but at the same time it allows for sending images with non-standard resolutions. The CameraLink connection also has additional options such as the ability to power the camera and a control interface.

The newest and fastest interface created especially for industrial cameras is CoaXPress. It enables transmission from 1.25Gbit/s to 12.5Gbit/s. The main transmission medium of CoaXPress is a coaxial cable, over which transmission takes place from the camera to the receiver. CoaXPress also supports a Low speed uplink return channel, which allows to control imager and trigger parameters or update software.

The easiest noticeable feature of these video interfaces is electrical connector (see Fig. 13). However, this criterion to divide video interfaces is confusing as there are cases when several different video interfaces use the same video connector. For example BNC connector/cable can be used by both analogue video (PAL, NTSC, AHD, HD-CVI, HD-TVI), and digital interfaces like SDI and HD-SDI interfaces, CoaxPress interfaces and some of UDP-IP over Ethernet). Therefore, detail comparison of these video standards is possible only after studying lengthy documents prepared by organizations that issued these video image standards.

Basic rules to compare video interfaces are presented in Section9.4.2.



a)

b)

c)

d)

e)

Fig. 13. Photos of popular electrical connectors used in electronic output thermal imagers: a) BNC connector (used in analog video, SDI, CoaXPress, some Ethernet type interfaces), b)CameraLink connector, c)USB2.0 connector, d)HDMI connector, e)RJ45 connector (used in GigE/Ethernet imagers)

6.2.10 Proximity board

The proximity board is the name for a small electronic board located at very short distance to IR FPA sensor (sometimes the sensor is a part of this board) performing four different tasks:

1. delivery of power voltages,
2. analogue pre-amplification of sensor output signal,
3. protection of sensor inputs by use of various types of digital buffers,
4. ability to adjust voltage levels.

Properly developed proximity board is of high importance to design well working FPA controller. In order to facilitate design of FPA controller, IR FPA sensors are often sold with included proximity board. However, technically design of proximity board is typically much easier comparing to other blocks.

6.2.11 Testing FPA controllers

Testing FPA controllers is carried out using the same test system used for testing IR FPA sensors. The difference is only that now a reference IR FPA sensor of known parameters is used. If tested FPA controller is perfect then measured parameters of the set sensor-controller will be the same as parameters of the IR FPA sensor.

6.3 Optical objective

6.3.1 Basic work concept

The main task of optical objectives used in thermal imagers (called IR objective) is to create at IR FPA sensor located at objective focal plane an image of targets of interest (typically far away objects).

IR objectives are optical systems built typically using a set of refractive lenses of precisely manufactured surface curvature and separated by a precisely determined distance (Fig. 14). The objectives are sometimes built using also hybrid refractive-diffractive lenses or mirrors but it is a rare case.

In detail, IR objectives for thermal imagers have been traditionally designed as a set of lenses of spherical curvatures. Nowadays, objectives built in form of set of lenses with spherical surfaces represent market minority. More popular are objectives built using lenses with aspherical surfaces (non-spherical, rotational symmetric surfaces).

The main advantage of aspherical objectives is possibility to reduce number of lenses while keeping ability to generate high quality image. Practically it means that aspheric objectives can be much smaller and lighter comparing to traditional spherical objectives. However, aspherical objectives are more prone to image deterioration when working at extreme temperatures (athermality problems).

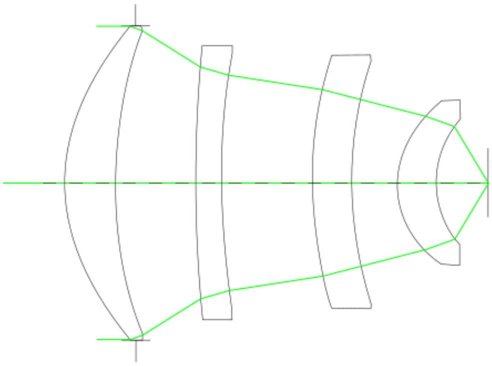


Fig. 14. Optical diagram of exemplary IR objective for thermal imagers

6.3.2 Characterization IR objectives

IR objectives offered at international market can be characterized using a series of seven criterion:

1. type of thermal imagers to cooperate (spectral band and cooling),
2. regulation ability of focal length,
3. focal length,
4. optics F-number,

5. minimal pixel size of IR FPA sensor,
6. maximal IR FPA sensor size,
7. level of athermality.

According to first criterion optical objectives for thermal imagers are divided into two main types:

1. LWIR objectives optimized for uncooled LWIR thermal imagers
2. MWIR objectives optimized for cooled MWIR thermal imagers

In detail, there are also objectives optimized for cooled LWIR thermal imagers but are rarely met. According to the second criterion the objectives for thermal imagers can be divided into three groups (Fig. 15):

1. 1-FOV objectives,
2. M-FOV objectitves,
3. Zoom objectives.

1-FOV objectives are objectives of fixed focal length that enable to design thermal imagers with a single field of view that cannot be changed.

M-FOV objectives are objectives of step regulated focal length that enable to design thermal imagers with field of view that can be changed in several steps (typically 2-5 steps).

Zoom objectives are objectives of continuously regulated focal length that enable to design thermal imagers with field of view that can be continuously regulated.

They are typically described by the ratio of their longest to shortest focal lengths. For example, a zoom lens with focal length ranging from 50 mm to 300 mm can be described as a "6×" zoom.

True zoom objectives are parafocal lens that keeps focus when its focal length changes. However, most of IR zoom objectives used in thermal imagers are varifocal lenses that do not maintain perfect focus when changing magnification (focal length) and need some refocusing. Further on, flexible FOV regulation is achieved at the cost of increased complexity, design compromises (decreased image quality, increased weight/dimensions, higher F-number) and increased cost.

Fig. 15. Photos of exemplary IR objectives representing three main groups: a)1-FOV objective (Opthir SupIR 24 mm f/1.0), b)M-FOV (Ophir SupIR 45/135 mm, f/1.1, f/1.6 Motorized Focus LWIR XGA), c)zoom objective (Ophir SupIR 40-300 mm f/1.5 LWIR Motorized Continuous Zoom SXGA Imaging Lenses)

Zoom objective are now the most popular type of IR objective of high end thermal imagers. M-FOV objectives are much less popular solution. However, it is often forgotten that there are some drawbacks of zoom objectives. comparing to M-FOV objectives. However, the M-FOV objectives are brighter (lower F-number→ better imager NETD) and offer lower boresigth errors when changing FOV. The latter means lower shift of image indicated by center aiming mark. The latter feature is extremely important for objectives used in thermal sights/targeting systems.

Focal length of IR objectives for thermal imagers can vary a lot from about 2 mm to about 1500 mm. There is no standard division of IR objectives depending on their focal length. However, it can be estimated that objectives of focal length below 3 mm can be called objectives of extremely short focal length and objectives of focal length over about 900 mm – objectives of extremely long focal length. Both extremes are rarely met.

The fourth criterion (F-number) describes relative brightness of image created by the objective. Mathematically, F-number is a ration of focal length to optics apparent aperture (diameter of input pupil).

F-number of optical objectives used in thermal imagers vary significantly from about 0.85 in case of ultra bright objectives for uncooled imagers to about 5.5 in case of objectives for cooled LWIR imagers (details in Table 9). Further on, there is a clear rule than F-number of 1-FOV objectives are lower than F-number of M-FOV objectives. F-number of M-FOV objectives are lower comparing to F-number of zoom objectives. Practically it means that it is easiest to develop thermal imagers of low NETD using 1- FOV objectives; most difficult when using zoom objectives.

Minimal pixel size of IR FPA sensor determines maximal acceptable aberration/diffraction blur of the objective. This condition is typically presented in form of requirements on MTF function of IR objectives (Table 10). It is typically required that MTF of optical objective at Nyquist frequency of IR FPA sensor is to be over a certain level.

Table 9. Approximate values of F-number of main types of IR objectives offered at the market

Objective type (type of imager)	1-FOV	M-FOV	Zoom
Uncooled LWIR imager	0.85-1.4	1.1-1.6	1.2-1.6
Cooled MWIR imager	1.2-2	3-5	3.4-5.5

Table 10. Requirements on MTF of IR objectives for thermal imagers [73]

MTF criteria for uncooled detectors:				MTF criteria for cooled detectors Please note that the criteria depend on the f//#:				
FPA Pitch	cy/mm	Min. Horizontal Edge MTF (S&T Average)		FPA Pitch	cy/mm	Min. Horizontal Edge MTF (S&T Average)		
						F/3.6	f/4	F5.5
25μ	20	35%		30μ	16.7		30%	25%
17μ	29.4	25%		20μ	25		25%	15%
12μ	41.7	17% or no less than half of the diffraction limit value		15μ	33.3		15%	7%
10μ	50	17% or no less than half of the diffraction limit value		10μ	50	8%	5%	

Several conclusions can be made on basis of Table 10:

1. requirements on minimal MTF of optical objectives at Nyquist frequency of IR FPA sensors systematically decrease: new generation of FPA of smaller pixels– lower requirements,
2. requirements on minimal MTF of MWIR optical objectives are significantly lower comparing to requirements on minimal MTF of LWIR optical objectives.

Practically it means that image blurring shall be more noticeable at thermal imagers built using IR FPA sensors with smaller pixels, especially for MWIR thermal imagers that use optical objectives of high F-number.

It is commonly known that best image is produced by optical objectives at optical axis of the objective. Practically it means that best image is generated at center of IR FPA sensor located of focal plane of the objective. It is natural that image quality (optics MTF) shall deteriorate with increasing distance to the center. The question is only how fast is this deterioration. Therefore there is always some maximal size of IR FPA sensor the objective can cooperate. The size depends mostly on acceptable tolerances of deterioration of off axis MTF comparing to on axis MTF of the objective measured at Nyquist frequency. Therefore maximal acceptable size of IR FPA sensor should be considered as one critical parameters of IR objectives.

Many of surveillance thermal imagers (military imagers) are expected to work at both laboratory and extreme conditions (ambient temperature vary from about -40ºC up to about +70ºC) without noticeable decrease of imaging performance. Use of athermal IR objectives (an optical system that is insensitive to an ambient temperature) is of crucial importance to achieve such an aim.

However, this aim is difficult to achieve because there are two main reasons for sensitivity of image quality of IR objectives working at variable ambient temperature:

1. High change of refraction index of most of materials used for IR objectives (at least one magnitude higher than for materials for visible band).
2. Thermal expansion of material used for housing optical elements.

Correction of these two effects is usually achieved by means of passive athermalization combined optionally with manual or automatic refocusing. The latter term can be defined as optimization of materials used for optical elements and parts of housing to achieve situation when thermal changes by one group of elements is corrected by changes introduced by another group of optical elements.

Manufacturers of almost all thermal imagers claim that their product are built using athermal optics and are capable to work at both laboratory and extreme conditions. However, in reality performance of thermal imagers under extreme temperatures vary a lot [74]. There are some imagers truly non sensitive to extreme temperatures but generally dominate thermal imagers that generate at extreme conditions images of significantly degraded quality. Poor athermality of IR objectives is typically the main reason for such a situation.

6.3.3 Comparison of IR objectives to VNIR objectives

The main task of IR objectives is the same as the task as of optical objectives used in popular VNIR cameras. The latter objectives are also built as systems composed from a set of lenses that can have spherical or aspherical surfaces. Therefore it is not surprising that optical objectives used in thermal imagers (called later as IR objectives) looks externally similar to objectives used in VNIR cameras (Fig. 16). However, there are significant differences between IR objectives needed for thermal imagers and popular VNIR objectives used in both VNIR cameras and classical optical systems like telescopes, or field glasses. These differences shall be presented when discussing development process of IR objectives.

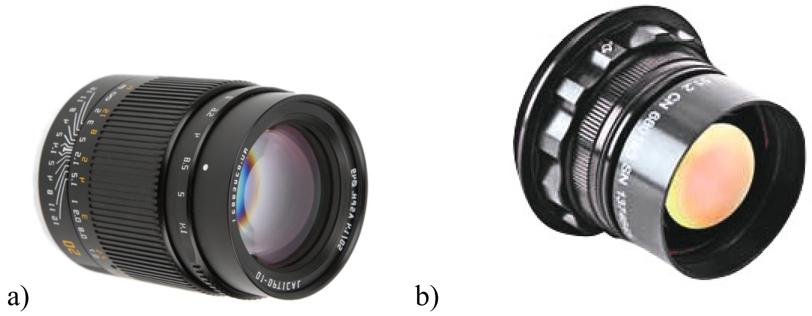

a) b)

Fig. 16. Photos of two optical objectives: 1)VNIR lens: Vbestlife Full Frame Camera Lens 50/1.4 ASPH [75], 2)LWIR lens: SupIR 50 mm f/1.2 Fixed Focus LWIR Lens [76]

IR objectives used in thermal imagers are developed in four main stages:

1. selecting optimal materials,
2. optical design,
3. manufacturing/testing of components,
4. assembling/testing of total objective.

These stages shall be discussed in detail in next sections.

6.3.4 Selecting IR optical materials

The list of potential materials that could be used to manufacture infrared objectives for thermal imagers is quite long: AMTIR-1 (Amorphous Material Transmitting Infrared Radiation), Barium Fluoride (BaF2), Cadmium Telluride (CdTe), Calcium Fluoride (CaF2), Cesium Bromide (CsBr), Cesium Iodide (CsI), Fused Silica-IR Grade, Gallium Arsenide (GaAs), Germanium (Ge), Lithium Fluoride (LiF), Magnesium Fluoride (MgF2), Potassium Bromide (Kbr), Potassium Chloride (Kcl), Silicon (Si), Sodium Chloride (NaCl), Thallium Bromoiodide (KRS-5), Zinc Selenide (ZnSe), Zinc Sulfide (ZnS). However, list of optical materials that are practically used to manufacture IR objectives is limited to five materials: Ge, Chalcogenide glasses, Si, ZnSe, and ZnS. The main reason is high refractive index of these materials that makes possible to design high quality objectives using small number of lenses.

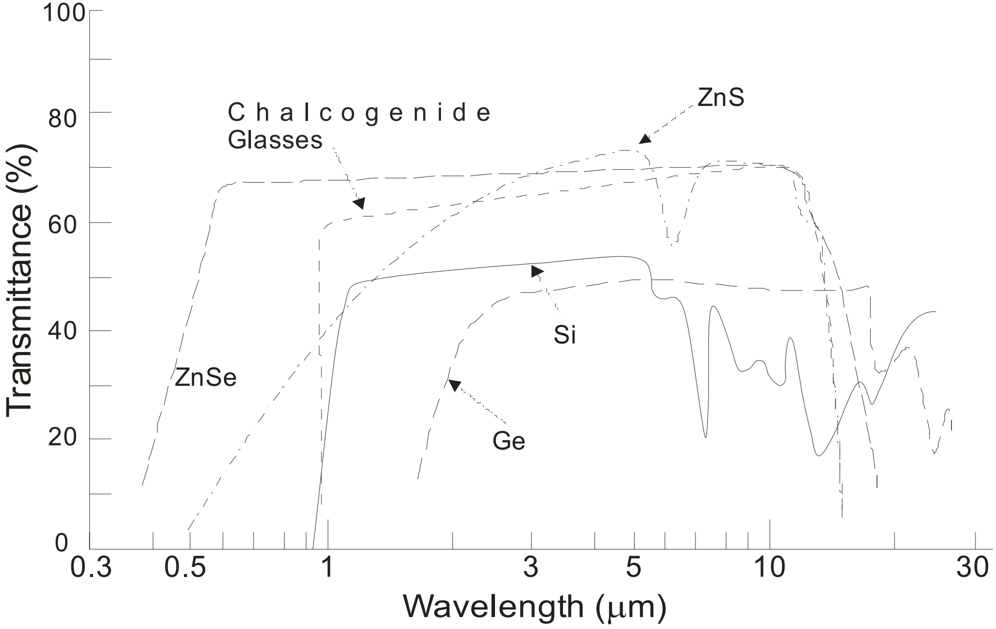


Fig. 17. Transmittance of a single flat window made from most popular IR materials

Germanium is a silvery metallic-appearing solid of very high refractive index (>4) that enables design of high-resolution optical systems using a minimal number of germanium lenses. Its useful transmission range is from 2 to about 15 μm. It is quite brittle and difficult to cut but accepts a very good polish. Germanium is non-higroscopic and non-toxic, has good thermal conductivity, excellent surface hardness, and good strength. Antireflection coatings are essential for any germanium transmitting optical system due to its very high refractive index and high reflectivity losses. Germanium has a low dispersion and is unlikely to need colour correcting except in the highest-resolution systems. A significant disadvantage of germanium is the serious dependence of its refractive index on temperature. It makes difficult athermalization of objectives made from Ge and problematic use of thermal imagers based on Ge optics at desert conditions for day surveillance. In spite of earlier mentioned technical drawbacks and high material price and cost of antireflection coatings germanium is a favourite choice of optical designers of high performance infrared objectives for thermal imagers.

Infrared Chalcogenide Glasses offer good transmission from about 1 μm to about 13 μm (from SWIR to LWIR range). Physical properties such as low dn/dT and low dispersion enable optical designers to engineer color-correcting optical systems without thermal defocusing. Next, these glasses moldable and this feature allows a cost-effective manufacture of complex lens geometries in medium to large volumes. Further on, these glasses can be also processed using conventional grinding and polishing techniques, single point diamond turning if higher performance is to be achieved.

Due to these features Infrared Chalcogenide Glasses made a revolution in manufacturing of optics for thermal imagers during last decades by enabling mass manufacturing of low cost, good optical performance optical objectives and now these glasses compete with germanium as the most popular IR optical material. Most popular brands of Infrared Chalcogenide Glasses are: AMTIR (amorphous material transmitting infrared) from Amorphous Materials Inc., GASIR® from Umicore Inc., and IRG glasses from Schott [78-80]. It should be however noted that chalcogenide glasses are more difficult for fabrication of high accuracy lenses comparing to germanium.

Physical and chemical properties of silicon are similar to properties of germanium. It has high refractive index (about 3.45), is brittle, does not cleave, takes an excellent polish and has large dn/dT. Similarly to germanium, silicon optics must have antireflection coatings. Silicon offers two transmission ranges: 1–7 and 25–300 µm Only the first one is used in typical IR systems. The material is significantly cheaper than germanium, ZnSe, ZnS. It is used mostly for IR systems operating in the 3–5 µm band. Due to its low density silicon is a good choice ideal for MWIR objectives with weight constraints.

ZnSe is is an optical material of optical properties mostly similar to germanium but of wider transmission range from about 0.55 µm to about 20 µm, and a refractive index about 2.4. It is partially translucent in the visible and reddish in colour. Due to the relatively high refractive index, antireflection coatings are necessary. The chemical resistance of the material is excellent. Popular material for lenses for both LWIR and MWIR objectives and for broadband infrared windows.

ZnS offers relatively good transmission in range from about 3 µm to 13 µm. It exhibits exceptional high fracture strength, and high hardness, and high chemical resistance. Due to high resistance to rain erosion and high-speed dust abrasion ZnS is popular for windows or external lenses in thermal imagers used in high speed airborne applications.

6.3.5 Design of IR objectives

Optical design is a process of selecting a series of precisely defined optical elements and putting them at precisely defined locations. This process includes estimation and optimization of system parameters with tolerances for their manufacturing, too.

Nowadays, process of designing optical objectives is computerized and supported by advanced computer programs. However, in spite of computerization design of new high performance optical objectives is a very difficult task. Designers of IR objectives face four challenges to design well working MWIR/LWIR optical objectives.

First, there is significantly fewer and much more expensive materials suitable for MWIR/LWIR optical objectives comparing to number of optical glasses used in VNIR range, or even for SWIR range. It make difficult to achieve objective achromatization.

The second challenge for designers of objectives for thermal imagers is veiling glare effect. High intensity targets outside FOV of thermal image can generate artefacts in image generated by thermal imager. The artefacts can mask real targets or be considered as targets of interest. The same effect can occur for VNIR optical objective but is typically much weaker. The main reason is higher reflectivity of theoretically black walls of lens housing. This phenomenon is especially strong in case of bright objectives for uncooled imagers due wide angle beam of passing rays. The designer should predict potential reflections and eliminate them by use of blackening or baffles.

Third challenge is Narcissus effect that generates fusion of image of real targets on imager FOV with blurred image of a cold IR FPA image sensor due to non intended internal reflections on surfaces of lenses of the objective. This effect is specific for cooled thermal imagers.

Fourth challenge is athermality problems. Optical properties (refraction index, thermal expansion coefficient) of IR optical materials are much more sensitive to ambient temperatures than properties of glasses used to manufacture VNIR cameras or SWIR imagers. Therefore, design of athermal IR objectives for thermal imagers capable to work at both laboratory and extreme conditions is much more difficult than in case of VNIR optics.

6.3.6 Manufacturing/testing optical components

There are two main tasks of the manufacturing stage. The first task is to make lenses to be shaped and polished to desired specifications. The second is to make lenses coated with an anti-reflective coating to reduce unwanted reflections.

High precision lenses used for applications in VIS-SWIR spectral band are typically manufactured using manufacturing process that uses a series of repeated grinding and polishing processes. Low precision lenses (like opthalmic lenses) are made by molding or casting. However, situation in case of optical components (lenses) for IR objectives is different.

Manufacturing of lenses for IR objectives is typically carried out using two methods:

1. Single Point Diamond Turning (SPDT),
2. Precision molding.

The first method is based on idea to use CNC lathes (or other precision machine) equipped with diamond-tipped tool bits to achieve specified shape of surfaces of optical elements.

Precision glass molding is a replicative process that involves heating optical material loaded at mold tool of desired shape up to working temperature between the transition temperature and the softening point of the material and later cooling this material.

Most of optical elements for IR objectives could be machined using classical method of grinding/polishing and higher accuracy can be achieved. However, classical grinding/polishing when applied to IR materials is more costly and time consuming comparing to SPDT method or precision molding. Therefore the latter methods totally dominate manufacturing of optical elements for IR objectives. However, it should be noted that accuracy of optical elements manufactured using SPDT method is significantly lower comparing to classical grinding/polishing (SPDT: not better L/4 at L=630nm when L/8 is easily achievable for grinding/polishing.

Anyway, this deteriorated manufacturing accuracy of lenses for IR objectives is perfectly acceptable due to longer wavelengths of spectral band of IR objectives.

All typical IR materials used for optical elements in IR objectives are characterized by high refractive index that leads to high reflections losses on uncoated surfaced of such elements. Practically it means that uncoated IR elements poorly transmit light due to low transmission (Fig. 17). Simplifying, it can be said that transmission of Ge objective made from three uncoated lenses is at level about 10%. Therefore, use of anti-reflection (AR) coating for optical elements of IR objective is mandatory.

Anti-reflection (AR) coating is a type of optical coating applied to the surface of lenses to reduce reflections from these surfaces. It is based on a concept of a transparent thin film of width and refractive index optimized to achieve relative phase shift between the beam reflected at the upper and lower boundaries at level of 180°. In this way is can be achieved near total destructive interference of reflected light beams from these two boundaries of the film that covers surface of optical element. Single thin film coating enables to reduce reflection to near zero level but only in narrow band near one specified wavelength. Optimal index of refraction of a thin film is to be calculated as square from product of refractive index of incident medium and refractive index of the coated optical element. Simple thin film made from MgF_2 of width at $1/4\lambda$ level optimized for 550nm wavelength is a prime example of such single film AR coating. Broadband anti-reflection (BBAR) coatings are designed to reduce reflections over a wider waveband by use of coatings in form of several thin films optimized for different wavelengths.

BBAR coatings optimized for optical elements used in MWIR objectives are built using methods very similar to methods used to develop coating for optical elements used in VNIR objectives: films from the same materials (mostly oxides) but only thicker. There are bigger differences in case of coating for LWIR objectives because typically used oxides do not transmit over about 7 μm. Therefore, coatings for LWIR optics are commonly made from three new materials like fluoride compound, ZnS, ZnSe.

It should be also noted that surface of external optical element in IR objective need to be not only of low reflectivity but must be also abrasion resistant. Therefore this external surface is typically coated using Diamond-Like Carbon Coating (DLC) that offers hardness, stress resistance, corrosion resistance, abrasion-resistance and scratch-resistance similar to properties of natural diamonds. Anti-reflection properties of DLC are near as good properties of typical BBAR coatings.

Testing manufactured optical components for IR objectives is of critical importance to assure they can be used to create high performance IR objective. Parameters of all optical components (typically lenses) must be measured. List of parameters includes: refraction index of optical materials, radius of spherical surfaces, aspheric coefficients of aspherical surfaces, lens width, lens edge angle, and non-centring errors.

Testing infrared optical components is typically carried out using computerized stations based on different interferometric methods that are similar to methods/stations for testing VNIR optics. However, there are some limitations. Typical interferometric test stations can be used to test MWIR/LWIR lenses only when working in reflective mode because typical MWIR/LWIR lenses are opaque for typical VNIR light sources used in typical test stations. Transmittive mode can be used only when using interferometric test stations uses lasers that operate in MWIR/LWIR range.

6.3.7 Assembling/testing IR objectives

High quality components is the necessary condition to enable manufacturing of high quality IR objectives for thermal imagers. However, it is not the sufficient condition because the components (typically lenses) must be also perfectly positioned. Practically it means that two conditions must be fulfilled:

1. optical axis of every lens is the same,
2. optical axis of the objective is coincident is the rotational axis of the objective barrel.

It is technically possible to manufacture both lenses and lens barrel with sub-micron accuracy. Therefore, it is theoretically possible to position lenses in the barrel with sub micron accuracy. However, practically such situation is not achievable because of potential mechanical stress of lenses due to thermal expansion at temperatures that differ from assembling temperature. There must be always some empty space for the lens to accommodate for thermal expansion of both lens and lens barrel and this tolerance shall generate some image quality deterioration.

Further on, distance between lenses must vary depending on ambient temperature. Therefore, it is typical to use some mechanical mechanisms (typically a spacer) that moves the lens to the correct focus position for different temperatures. Again, this movement cannot be achieved at sub-micron accuracy.

There are four main ways of assembling IR objectives:

1. Skilled optical technicians supported by simple optical tools,
2. Automatic assembling using robotic arms of modest accuracy (hundred of micrometers tolerances),
3. Advanced centring stations operated by humans,
4. Skilled optical technicians supported by MTF test stations.

The first way in form of skilled optical technicians (typically women) is still the dominant way of assembling IR optical objectives. Experienced optical staff supported by simple traditional optical tools can produce high performance objectives.

The second way is in form of automatic assembling using robotic arms offers high speed assembling but of modest accuracy (hundred of micrometers tolerances) that is suitable to low cost objectives.

The third way assumes to use advanced centring stations capable to measure centring errors of every lens and distances between all lenses in optical objective with sub-micron accuracy. However, centring of IR objectives using such machines is time consuming. If an objective has 4 lenses then it means that it is necessary to do measurement of centring for 8 surfaces, do measurement of 5 distances and later do analysis of the results and finally apply optimal corrections.

The fourth way is based on a concept to use MTF test stations that enable live MTF measurement of optical objective. Operator of such station can do live MTF measurement while changing positions of different lenses of the objective and can find optimal positions of all lenses (position of best MTF function). This way is much faster and can produce astonishing results when such test station is used by skilled optical technicians.

6.4 Imager housing

Imager housing is a wide term that describes mechanical block to which all other blocks (thermal camera core, IR objectives, optional blocks) are mechanically connected.

There are two main tasks of the imager housing:

1. protection of imager interior against outside environment: it must be heat resistant, dust resistant, waterproof, shock resistant, dry nitrogen filling.
2. keeping proper locations of optical/electrical parts thermal imager in order to achieve proper optical/mechanical aligning:
   - proper focus range of IR objective relative to IR FPA sensor,
   - proper mechanical axis of focusing/zooming of IR objective,
   - proper aligning of imager optical axis with mechanical reference axis (for example Picatinny rail),
   - parallel axis of output binocular optics,
   - zero deflection angle for thermal clip ons.

Level of difficulties to fulfil these tasks depends on type of thermal imager. There are very strict requirements on protection of interior of military thermal imagers against outside environment when in contrast the same requirements are much more relaxed for measurement thermal imagers to be used in civilian applications at laboratory conditions.

There are even bigger differences between different types of thermal imagers in case of the second task. In some simplifications it can be said that imager sensitivity to positioning errors are proportional to focal length of imager IR objective. Further on, the listed above aligning errors no. 2-5 are of critical importance for thermal sights/clip-ons, binoculars but totally acceptable for short range imagers used only for surveillance applications.

Due to these differences it is relatively easy to design housing for small short range thermal imagers to be used for only surveillance applications but it is really difficult to design housing for a long range thermal sight used for both surveillance and targeting applications.

Due to apparent simplicity it is a common mistake of design teams to underestimate importance of imager housing for total project. However, it is a risky approach as poor housing can severely limit overall performance of thermal imager.

6.5 Optional blocks

There is a series of optional blocks that can be used to in design of thermal imagers:

1. shutter,
2. display,
3. ocular lens,
4. angular stage,
5. stabilization platform.

Shutter is a mechanical block with electronically controlled movable part that is used to temporally fill imager field of view.

Display is an electronic module used in many portable imagers as internal block capable to present output image. If display is miniaturized then ocular lens is needed to project/magnify image of the display into direction of human eye. Both displays and oculars of thermal imagers are the same blocks as used in digital night vision devices.

Angular stage is a mechanical block to which thermal imager is connected and that enables to regulate angular position of the imager. Stabilization platform is a mechanical block that enables passive/active attenuation of vibrations of attached imager. Both latter blocks can be fused to create angular/stabilization platform commonly developed in form of different types of gimbals. In the latter case it is possible to achieve stable output image of scenery at regulated angular direction.

The optional blocks no 2-5 used to design some thermal imagers do not differ from similar blocks used in other types of EO imagers. Only the shutter is an important block specific to thermal imagers and only this block shall be discussed here in details.

The main task of shutter is to simulate a uniform thermal target filling total FOV of thermal imager in order to enable one-point non uniformity correction of raw noisy image generated by IR FPA sensor. Details on methods to enhance thermal image used by use of mechanical shutter are to be presented in Chapter7. Here we are only to note that majority of thermal imagers use shutters.

There are two main types of mass market shutters for thermal imagers:

1. one blade shutters,
2. multi blade shutters (Fig. 18).

The latter type is supposed to offer longer life time. Both types are typically designed using DC miniature solenoid motors.

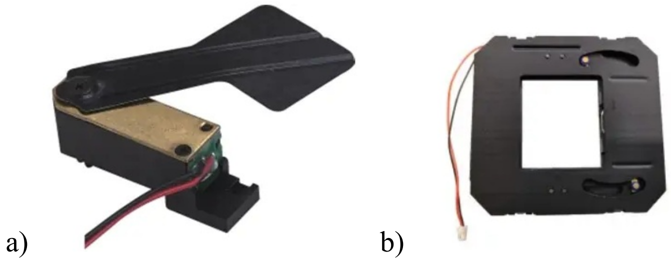


Fig. 18. Photos of two shutters: a)one blade shutter, b)multi blade shutter [77].

The shutter is typically located at short distance from the IR FPA sensor in order to keep low requirements on size of shutter active window (at level only slightly bigger than IR FPA sensor). Blades of the shutters are typically made in form of thin sheets from carbon fiber, aluminum or stainless steel coated with different types of finish: black anodized, electroless nickel, diffuse gold plate or paint. The switching time of such shutters can be as short as 50ms.

These mass market shutters offer small size/mass and high reliability at relatively low cost. However, there are also some limitations of mass market shutters:

1. modest thermal uniformity,
2. modest emissivity/reflectivity,
3. small size of active window,
4. too high minimal switching time.

In detail, ideal shutter should be characterized by following features:

1. perfect emitter/absorber (emissivity at level near one, reflectivity at level near zero, diffusive reflection, perfect temperature uniformity),
2. size of active window several times bigger sensor size in order to allow location of shutter at higher distance from the sensor between lenses of the objective (better simulation of uniform target seen through lenses),
3. switching time is not noticeable for a human observer (below about 20msec).

Some advanced manufacturers of thermal imagers use customized shutters that almost fulfil these requirements. The latter improvement is particularly important as such shutters enable to develop new generation of shutter thermal imagers having advantages of shutter (near perfect correction of spatial noise) without typical drawbacks of old shutter technology (human noticeable non-work periods of thermal imagers).

7. Methods of image enhancement

Image enhancement is wide term that refer to image improvement method that covers all EO imaging technology. Therefore, it is not surprising that there is very numerous scientific literature on image enhancement methods. There have been published probably ten of thousand of scientific papers on this subject during last five decades. Only SPIE digital library generates over 10000 results for search using key word "image enhancement". However, even rough analysis of such literature can quickly show that there is no one standardized definition of image enhancement term. In author opinion the most universal solution could be to define image enhancement as any process of improvement any image (any spectral band, static or dynamic video, digital or analogue, any image resolution, any image dynamic) to achieve a series of different aims: making image visually more appealing, reduction of noise, reduction of blurring, improving contrast, improving scene uniformity, highlighting interesting details, etc. Further on, the same term image enhancement refers both to time unlimited process of image enhancement of static images (editing recorded bitmaps/video using PC software) or to on-fly image enhancement of raw video image by fast image processors (microcontrollers, DSP, FPGA) used in different video imagers including thermal imagers.

Image enhancement methods have been generally developed for improving of images generated by VNIR cameras. These cameras are built using CMOS sensors that generate relatively good raw video image comparing to images from IR FPA sensors. The latter sensors generate raw image with many drawbacks:

1. high number of dead pixels,
2. high spatial noise,
3. low number of image pixels,
4. moderate sharpness,
5. low contrast.

Therefore some image enhancement is a must-have solution in design of thermal imagers. Use of advanced and effective method of image enhancement is probably the best indicator of a professional design team. Even beginner team can buy good IR FPA sensor, IR optics, and develop working FPA controller. However, there is low probability that such a team can develop advanced software capable to convert noisy, low resolution, low contrast image to near noise free, high resolution, high contrast/optimal brightness of overall image quality comparable to VNIR cameras.

There are three main tasks for image enhancement carried our by thermal imagers:

1. Reduction of spatial noise in video image generated by thermal imagers,
2. Correction of blind pixels,
3. Regulation of imager temperature span,
4. Improvement of resolution/sharpness of video image generated thermal imagers.

The first two tasks are obligatory activity. Typical raw video image generated by IR FPA sensors (especially uncooled sensors) is so noisy that thermal imagers without the noise correction are non suitable to be used in both surveillance and measurement applications.

Further on, contrast of raw images generated by IR FPA sensors is very low and such images cannot be directly presented on standard 8-bit electronic displays. Therefore, it is necessary to do some regulation of contrast and brightness of such imagers by regulation of imager temperature span.

The third task is an optional activity used only at most advanced thermal imagers.

7.1 Reduction of spatial noise

There are two types of noise present in video image generated by thermal images:

1. temporal noise,
2. spatial noise.

Temporal noise is generated by temporally random process of optical signal incoming to IR FPA sensor, and random conversion to electrical signal and further processing of this signal. Spatial noise is mainly generated by non uniform pixel offset/gain of IR FPA sensor. Electronic blocks add some spatial noise, too. The spatial noise is particularly strong in case of uncooled thermal imagers when it is much stronger over temporal noise. Temporal noise is typically characterized by NETD parameter; and spatial noise by FPN (high frequency spatial noise) and NU (low frequency spatial noise).

Temporal noise cannot be reduced if image frame rate cannot be decreased (or at least it is very difficult to correct temporal noise). However, spatial noise does not change in time (at least in short time intervals). It cannot be reduced by frame averaging but can be be corrected using a series of other methods.

The most popular method of correction spatial noise is based on a concept of two stage calibration of thermal imagers:

1. Rarely repeated two point NUC (non uniformity correction) operation to correct gain (and partially offset) of thermal camera core,
2. Frequently repeated one point NUC to correct temporal fluctuations of offset of IR FPA sensor.

During the first stage thermal imager captures at short time intervals a video image of two blackbodies at two significantly different temperatures (for example ambient temperature and temperature higher by 30°C). Comparison analysis of these two video images enables calculation of mathematical model that enables correction of both non uniform gain and non uniform offset of IR FPA sensor (Fig. 19). This calibration is carried out during final manufacturing stage of thermal imagers and is rarely repeated during imager life time.

Two point NUC calibration is typically done by moving tested imager between two area blackbodies that simulate uniform targets of different temperature (Fig. 20). Such solution is typically used in order to shorten time intervals between two moments when imagers “sees” two blackbodies of different temperature. This two point NUC calibration set can be replaced by a single blackbody but the risk is that in time needed for blackbody to change its temperature noise of tested imager shall change and results of two point NUC operation shall change for wrong ones.

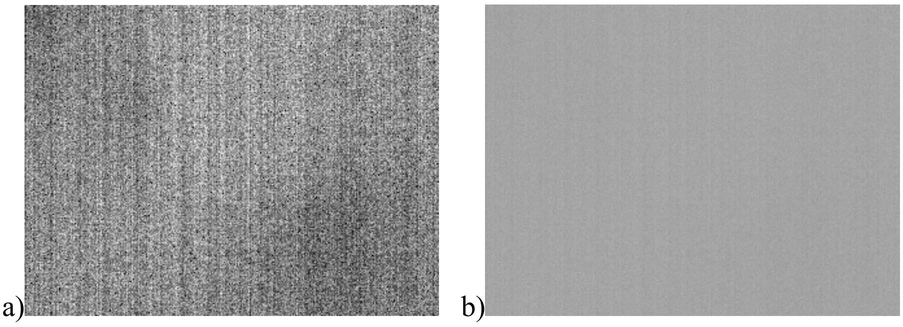


Fig. 19. Exemplary images: a)raw image from IR FPA sensor, b) image from thermal imager after two point NUC (removal of blind pixels and reduction of spatial noise)

Fig. 20. Photo of a specialized set for two point NUC calibration of thermal imagers

Two point NUC operation enables calculation of both gain and offset correction tables that enable reduction of both effects. However, the offset non uniformity is temporally non stable and therefore thermal imagers must cyclically capture image of its shutter that simulates a uniform target (not valid for shutterless imagers). The shutter can rotate and temporally block FOV of the thermal imager. In this way, the shutter simulates a large target of uniform, near ambient temperature. Image of such a target is used to develop correction of temporal variations of non-uniform offset of IR FPA image sensor.

Combination of external two point NUC calibration with cyclically repeated one point NUC calibration using imager shutter creates a low cost, very efficient way to reduce spatial noise of thermal imagers. If two point NUC is carried out at several ambient temperatures that vary from -40°C to over +60°C (tests at temperature chamber) then it is possible to design thermal imager that can generate thermal image of low spatial noise at any work conditions (ambient temperature). Situation when FPN parameters is below NETD parameter is a good indicator that of low level of spatial noise.

The drawback of shutter based thermal imagers is that the shutter makes the imager blind for a period of time (time up to 1 sec in old thermal imagers). Such situation is not acceptable in some applications of thermal imagers (for example military thermal imagers used in anti-aircraft systems). Therefore, technology of shutterless thermal imagers have been developed.

Shutterless thermal imagers are imagers that do not have mechanical shutter but use advanced image processing/enhancement software to correct imager spatial noise.

A series of different algorithms of shutterless offset noise correction have been developed [81-84]. Significant portion of thermal imagers offered on the market are shutterless imagers. However, personal experience of the author shows that shutterless thermal imagers up to now cannot deliver correction of spatial noise at level as shutter thermal imagers. Fixed pattern noise FPN parameter is typically noticeable higher in case of shutterless imagers especially when imagers work at extreme temperatures. Further on, shutterless imagers have a tendency to generate some image artefacts around point sources. Therefore, the author personally prefers improved shutter method in form of a high speed shutter. The shutter in this method blocks FOV only for a very short time (typically below 30ms). Such short time of temporal blindness is usually acceptable even in applications that require surveillance of dynamic targets.

To summarize, spatial noise correction can be carried out using a long series of methods based on imager calibration, scene analysis or deep learning algorithms [13]. However so far most popular and effective method is imager calibration concept based on combination of two point NUC operation and cyclically repeated one point NUC operation using a mechanical shutter.

7.2 Correction of blind pixels

Blind pixels (bad pixels) is a commonly used term to describe defective pixels of IR FPA sensor. Most of blind pixels are seen in raw image generated by IR FPA sensor as pixel size high contrast spots but blind pixels can also form clusters (group of neighbour blind pixels). Blind pixels typically appear in output image as black spots, but bright spots can occur, too.

Pixels of IR FPA sensor are classified as blind pixels typically on basis of improper responsivity into two groups [85]:

1. dead pixels (under-responding pixels) – pixels with responsivity much lower comparing to responsivity of average pixel (example precision criterion: below a certain level comparing to average responsivity),
2. overheating pixels (over-responding pixels) – pixels with responsivity much higher comparing to responsivity of average pixel (example 30% comparing to average responsivity).

Pixel can also be classified as blind on criterion of too high noise or too high/too low offset but improper responsivity is typically the main criterion.

Location and properties of great majority of blind pixels do not change with time (fixed blind pixels). However, there are also some pixels (termed as transient or variable blind pixels) that can change location and properties (responsivity, offset, noise) with time. In addition, in time new blind pixels can occur.

Number of blind pixels vary depending on IR FPA sensor operability declared by sensor manufacturer. Operability is defined as percentage of effective (non-blind) pixels from all pixels and can vary from about 99% to about 99.9%. Even in case of the latter high operability IR FPA sensors blind pixels of IR FPA sensor are noticeable, annoying and must be corrected. The blind pixels are typically corrected using two stage process:

1. Determination of location blind pixels,
2. Replacing blind pixels signal by substitutes that imitate well working pixels.

The methods to determine location of blind spots differ depending on type of thermal imagers:

1. shutter thermal imagers
2. shutterless thermal imagers

Blind pixels of shutter thermal imagers are determined in two stages. First, rarely performed accurate detection of of group of blind pixels (mostly fixed pixels) during typical two point NUC operations by accurate measurement of responsivity/offset/noise of all pixels of calibrated imager [85-86].

Second, frequently performed rough detection of blind pixels (including new transient pixels) during one point NUC by the shutter using uniform target method (pixels that generate signals that significantly differ from average signal are considered as blind).

Blind pixels of shutterless imagers are detected using the scene-based method that is based on assumption that even in case of not uniform scene the neighbour pixels should behave similarly. As such, comparison of their response can be used to detect abnormal behaviour. Typically neighbour median is used as a criterion for detection of blind pixel [87], but there are many different detail approaches [88,89].

Sometimes instead of neighbour pixels, the movement of the detector or tracking object in field of view is used. When frames are captured in quick succession, it is reasonable to assume that observed scenery or object is unchanged. The algorithm compares response of the pixels to the prediction based on direction of movement [90].

Some scene non uniformity is acceptable for scene based method but anyway the method can work better in case of quasi uniform background. Therefore optical defocus to blur images generated by calibrated thermal imager is commonly used. In addition, in order to simulate different background temperatures (ability to check signal transfer), exposure time of cooled thermal imagers can be varied [91].

Finally, replacing detected blind pixels signal by substitutes that imitate well working pixels can be carried out using a series of methods. Example such methods are: pixel replication method, spatial filter method, median filter method, temporal estimation method and combinations of these methods [92]. The same substitution methods can be used to replace blind pixels in both shutter thermal imagers and shutterless imagers.

Blind pixels phenomenon can be treated as an extreme form of spatial noise (fixed pattern noise) of thermal imagers that generate extremely strong fixed pattern noise (very low or very high output signal). Therefore, the task of correcting blind pixels is often combined with the earlier discussed task of reduction of typical spatial noise. In detail, from mathematical point of view correction of blind pixels is often carried out first and later is carried out image processing for reduction of spatial noise.

7.3 Regulation of imager temperature span

In case of measurement thermal imagers used for non contact temperature measurement the imager temperature span is a range of target temperatures that can be measured and visually presented using colour palette. Information on temperatures outside this span is lost, such temperatures are marked as black or white. In case of typical surveillance thermal imagers that dominate market precision values of imager temperature span are not known as they are not needed but anyway imager temperature span is still regulated and this concept is useful to explain regulation of contrast/brightness of output thermal video image.

Typical thermal imagers used in surveillance applications are expected to generate image of targets of differential temperature from about -10°C degrees centigrade to about +80°C located at backgrounds of ambient temperature from about -40°C to about +70°C. It means that temperature of targets to be visualized can vary from about -50ºC to over +150ºC (target temperature span at level of 200ºC).

At the same time it should be noted that that temperature resolution of modern thermal imagers is at level about 40mK for uncooled imagers and about 20mK for cooled imagers. It means that thermal imagers are expected to capture and process input radiometric images of huge dynamic, approximately equal to ratio of earlier mentioned work temperature range to imager temperature resolution (dynamic at level about 10000 for non cooled imagers and 20000 for cooled imagers). The imager dynamic must be actually much higher for two reasons:

1. digital level of A/D converter must be at least two times smaller comparing to analogue noise (temperature resolution),
2. the relationship between temperature and radiometric intensity is actually non-linear (especially for MWIR spectral band).

At the same time it should be remembered that thermal imagers are to generate output electronic images at analogue/digital displays of of 8-bit dynamic (dynamic of typical analogue output images is approximately the same).

The problem of displaying high dynamic input radiometric image to be presented at low dynamic displays is solved by regulation of imager temperature span that is to be visualized. In detail it is achieved by two main ways of regulation:

1. contrast regulation (regulation of width of imager temperature span),
2. brightness regulation (regulation of mean temperature of imager work span).

The aim is typically to use imager temperature span that covers temperatures of all targets located in imager FOV. If this requirement is not fulfilled then some information on these targets can be lost (Fig. 21).

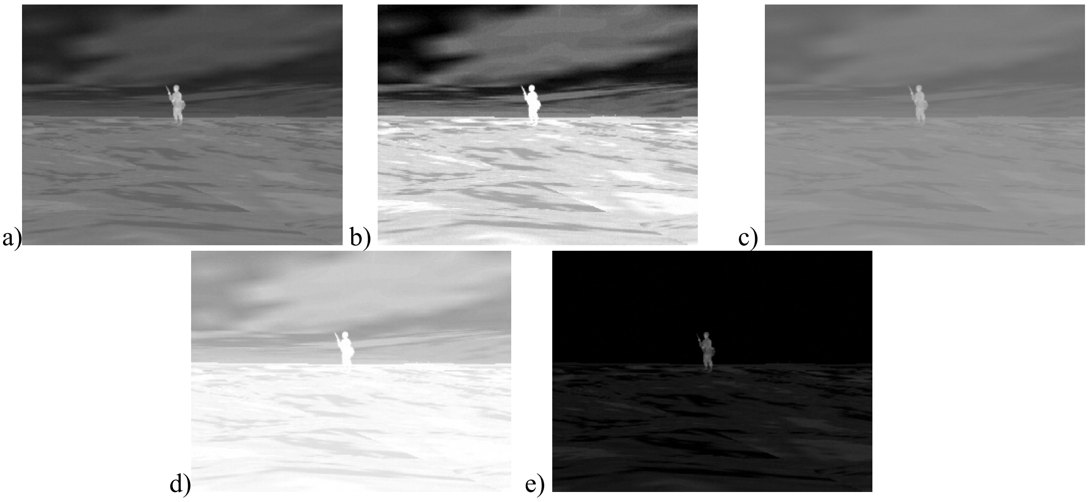


Fig. 21. Image of a single soldier obtained using the same thermal imager but at different output image setting: a)optimal contrast/brightness, b)too high contrast, c)too low contrast, d) too high brightness, e)too low brightness

It is a typical situation that software of thermal imagers offers both manual, semi-automatic and automatic regulation of contrast/brightness settings. In detail, thermal imager can work in four modes of regulation of contrast/brightness:

1. manual regulation of contrast/brightness: imager temperature span of any width and any location can be set,
2. automatic contrast but manual brightness: width of imager temperature span is optimized to cover all targets temperatures but mean span temperature can be non optimal (differ from mean targets temperature),
3. manual contrast but automatic brightness: mean span temperature is optimal (equal to mean targets temperature) but width of imager temperature span can be non optimal (differ from width of temperature span of targets)

4. automatic contrast and automatic brightness: both width and mean temperature of imager span are optimal.

Technically contrast/brightness regulation is achieved by gain/offset regulations at four stages of image processing chain of thermal camera core:

1. radiometric gain: regulation of integration time of IR FPA -valid only for photon IR FPA sensors,
2. electrical gain/offset: regulation of gain/offset of preamplifiers of ADC converter,
3. input ADC offset/range selection: regulation of range (width/mean level) of analog signals to be digitized,
4. output ADC offset/range selection: regulation of range (width/mean level) of digital signals to be presented as final output image.

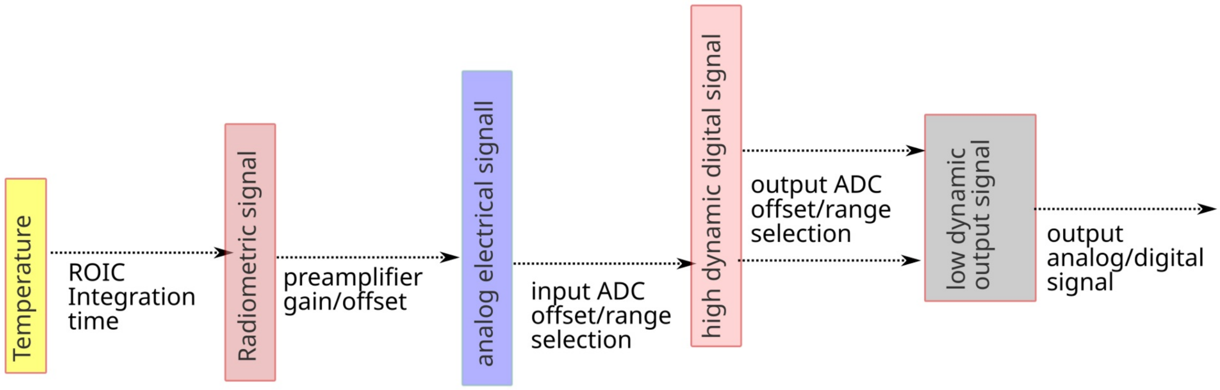


Fig. 22. Stages of gain/offset regulation

It should be noted that the same effect (contrast/brightness change) can be achieved using different regulations. Therefore, it is common that software of thermal imagers offers contrast/brightness regulations using several buttons and actual methods vary from imager to imager. However, the basic rules for stages of gain/offset regulation remain as show in Fig. 22.

7.4 Image quality improvements methods

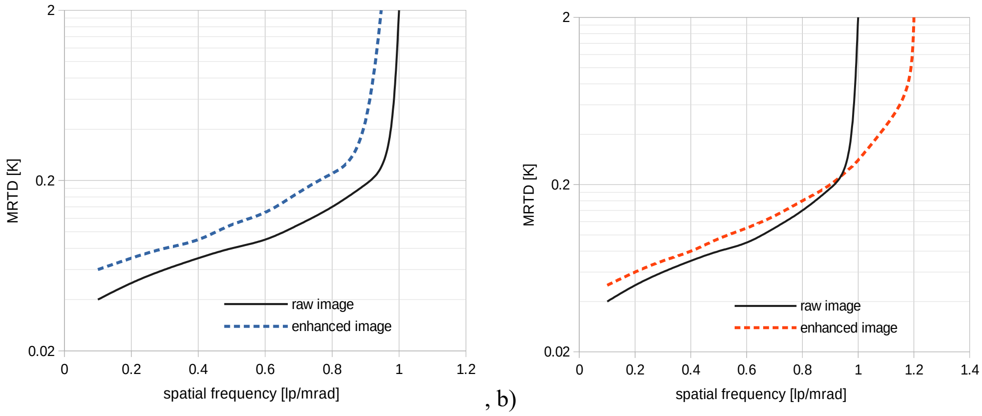
There has been some interest in image quality improvement (enhancement) of images generated by thermal imagers almost since beginning of thermal imaging technology at end of 1970s [93]. There has been published many dozens of scientific papers that present a long series of methods for improving quality of images generated by such imagers [94-101]. A long series of image enhancement methods has been proposed: variable threshold zonal filtering, statistical differencing operator, unsharp masking, histogram equalization, high-pass filter, image convolution with dedicated Laplace operator, improved Canny algorithm, discrete cosine transform (DCT), fast unitary transforms, Wiener filter, Lucy–Richardson algorithm, and regularized filter, fuzzy logic, adaptive algorithms, and so on.

Each of these published papers claims that the proposed enhancement method works well. Effectiveness of proposed methods is typically verified by presenting enhanced images of large targets that truly look more appealing for human observer. However, such subjective photo comparison is not a precise criterion for evaluation of image quality improvement methods for thermal imaging where the most important task is detection of long range targets of small angular size. What is even more important, it is actually not known which of earlier listed image enhanced methods are practically implemented by manufacturers of thermal imagers because they treat such information as company secrets. Therefore in next part of this discussion the author shall omits literature but presents information based mostly on his experience in practical testing thermal imagers.

From user point of view it is actually not important what enhancement method is used by a thermal imager but is important what effect the method generates. In author opinion, effectiveness of methods for enhancement of thermal images can be well characterized by measured MRTD characteristic of thermal imagers. In detail, the difference between MRTD of imager with turn off enhancement and MRTD of imager with turn on enhancement enables precision determination of real value of enhancement method.

MRTD is the most important characteristic of thermal imagers that is commonly used to calculate DRI ranges of thermal imagers used for evaluation of such imagers. Therefore, better MRTD means longer DRI distances. This statement is valid especially for high frequency part of MRTD curve.

As can we see in Fig. 23 results of methods for image enhancement used by different thermal imagers vary a lot. The are thermal imagers turning on image enhancement generates image that looks sharper but it is also more noisy and effective resolution of such image slightly deteriorate. Activating image enhancement in such imager only deteriorate image MRTD (Fig. 23a). However, there are on market imager with implemented advanced image enhancement methods capable to deliver significant improvement of imager MRTD curve (Fig. 23b). As can be see in this figure MRTD deteriorates slightly at low frequency range but there is significantly improvement at high frequency range (MRTD asymptote limit is moved by about 20%). Improvement at this frequency range is of critical importance because operational range of thermal imagers depends directly on position of MRTD asymptote limit.



a) , b)

Fig. 23. MRTD curves of two thermal imagers: a) imager with poor performance image improvement method, b) imager with high performance image improvement method

The explanation is that the first imager uses classical edge enhancement algorithm that significantly increases image contrast perceived by humans. It can be said in spatial domain that this method improves MTF at low/medium frequency range but decreases it at high frequency range close to Nyquist frequency.

The second imager employ a well working super resolution reconstruction algorithm. It means that the method increases image resolution and reduces image blurring. Some of advanced thermal imagers built using 640×480 pixel IR FPA sensors can generate image of effective resolution at level about 800×600 pixels. This case can be treated as successful example of image quality improvement using one of super resolution reconstruction methods.

To summarize, it is not clear what image quality improvement methods are actually used in thermal imagers offered on the market. However, it is clear that effectiveness of these methods vary a lot and it is recommended to determine it by measurement of MRTD at two work mode (image improvement turn on/turn off).

8. Commercial division of thermal imagers

All thermal imagers are basically built using the same main blocks (IR FPA sensor, FPA controller, IR objective, mechanical case) and some optional blocks. However, depending on details of these block the final results can differ a lot and there are myriads of types of thermal imagers offered at international market. Manufacturers of thermal imagers use different forms of division in order to help potential customers to understand their offer. Here let us analyse logic of division used by Teledyne-FLIR – probably the biggest and most advanced manufacturer of thermal imagers and multi-sensor EO systems based on thermal imagers in the world.

As can be seen in the company website of one of main manufacturers [102] thermal imagers are divided into ten main markets that are further divided into 29 sub-groups with names that indicate intended application. In this way a huge number (over 250) of types of thermal imagers is classified.

The division of thermal imagers on criterion of intended market/application shown in Table 11 works fairly well for potential customers. They need first to identify what market/application they represent and later they can find what the manufacturer can offer for them. However, this typical commercial division gives little precision technical information on design differences, or even on actual technical capabilities/performance differences between different groups of thermal imagers. Therefore, a new division based on technical capabilities/design of thermal imagers shall be proposed in next sections.

Table 11. Commercial division of thermal imagers based on market criterion

A. Government and defense 1. airborne systems 2. UAS (unmanned aerial systems) 3. land systems (1-fixed surveillance, 2-vehicle/mobile systems) 4. tactical solutions (1-handheld, 2-weapon sights) 5. maritime systems	**B. Industrial** 1. handheld thermal cameras 2. fixed thermal cameras 3. gas detection cameras 4. UAS cameras 5. FLIR one
C. Public Safety 1. firefighting cameras 2. tactical and law enforcement 3. UAS cameras and kits	**D. Security** 1. Thermal security cameras 2. Counter UAS
E. Intelligent transportation systems 1. Urban 2. Inter-Urban	**F. Test and measurement** 1. thermography cameras 2. FLIR One
G. Research and development 1. Bench Top Test Kits 2. high performance cameras	**H. Marine** 1. fixed mount cameras 2. handheld thermal cameras 3. monitoring systems
I. Home and outdoor 1. FLIR ONE 2. Handheld Optics 3. UAS cameras	**J. OEM cameras** 1. infrared camera cores and lenses 2. automotive 3. spherical imaging systems

9. Technical division of thermal imagers

Thermal imagers offered on the market vary a lot depending on imager capabilities and imager design that are interrelated. Commercial criterion used to divide market of thermal imagers are confusing. Therefore it is proposed to carry out technical review of market of thermal imagers by dividing thermal imagers using seven precision technical criterion (Table 12). Thermal imagers divided in such a way shall be discussed in detail in next sections.

Table 12. Criterion for technical division of thermal imagers according to imager capabilities

No	Criterion	Division
1	Image sensor cooling	1)Cooled, 2)Uncooled
2	Imager spectral band	1)MWIR, 2)LWIR
3	Radiometric calibration	1)Non-radiometric thermal imagers (surveillance/military imagers), 2)Radiometric thermal imagers (industrial/measurement imagers)
4	Form of output image	1)optical output image 2)electronic output image and additional subdivision
5	Operational range	1)Ultra short, 2)Very short, 3)Short, 4)Medium, 5)Long, 6)Very long, 7)Ultra long imagers.
6	Radiometric measurement capabilities	1) Thermography cameras 2) Gas imaging cameras 3) Firefighting cameras
7	Integration with imaging/laser sensors	1)Independent thermal imagers, 2)Thermal imagers with simple laser tools, 3)Multi imaging/laser systems

9.1 Sensor cooling

Cooling of image sensor is probably most popular criterion to divide thermal imagers that is frequently used in scientific literature, manufacturer websites, educational websites and so on. In detail, there are some manufacturers who do not use commercial market division presented in Section 8 but divide their products using this simple technical criterion into two groups:

1. cooled imagers/modules
2. uncooled imagers/modules.

The main reason for popularity of this division criterion if a fact that the terms “cooled’ or uncooled” determine not only image sensor temperature but also type of image sensor, type of FPA controller and type of imager optics. In fact the terms cooled/uncooled often even indicate imager spectral band.

Cooled imagers are built using cooled photon image sensors when uncooled thermal imagers are built using thermal microbolometric image sensors that work at temperature approximately equal to ambient temperature. Further on, cooled imagers require different FPA controller due to differences in input signals (variable current for photon IR FPAs and variable resistance for uncooled IR FPAs), sensor control, and image processing/enhancement. Finally, there is typically a big difference in F-number (ratio of focal length to diameter) of optics used by both types of thermal imagers. These technical differences generate also significant differences in range of effective surveillance.

Therefore, due to these fundamental differences the cooled imagers and the uncooled imagers can be treated as totally different groups of thermal imagers.

On the basis of analysis of data sheets of TI offered on the market four main conclusions can be presented. First, there are two main groups of TIs:

1. Uncooled LWIR imagers built using thermal LWIR FPAs and bright optics of F-number in range from about 0.9 to 1.5;
2. Cooled MWIR imagers built using photon MWIR FPAs and dark optics of F-number in range from about 3 to 5.5.

Cooled LWIR imagers built using photon LWIR FPAs and optics of F-number in range from about 2 to 3 are manufactured in much lower quantities comparing to cooled MWIR imagers. Uncooled MWIR imagers so far are not used on market of surveillance thermal imagers due to poor thermal resolution due to too small amount of IR radiation emitted at MWIR band by targets of typical Earth temperature.

Second, there is some difference of temperature resolution of these two types of imagers but the difference is not very big:

1. uncooled TIs: NETD in range from 30 mK to 70 mK
2. cooled MWIR imagers: NETD in range from about 10 mK to about 30 mK

Third, uncooled LWIR thermal imagers built using objectives of focal length up to about 200 mm dominate market for short/medium range thermal imagers when cooled MWIR TI built using objectives of focal length up to 1000 mm (or more) dominate market of long range TIs.

Let us now find reasons, logic and design rules that have created this market situation. In detail, let us find answers to following questions.

1. How is it possible that temperature resolution NETD of uncooled LWIR imagers differs so little in situation when it is know that detectivity of cooled MWIR FPAs is several magnitudes better comparing to detectivity of uncooled LWIR FPAs?
2. Why uncooled LWIR imagers dominated market of short range imagers but are not used for long range surveillance?
3. Why cooled LWIR imagers are rarely used comparing to cooled MWIR imagers?
4. Why non cooled MWIR imagers are not used in market of surveillance applications in situation when they are used for some industrial applications.
5. Why uncooled LWIR imagers are designed using bright optics (F-number in range 0.9 to 1.5) when cooled MWIR imagers use dark optics (F-number in range 3-5.5)?

Detectivity of uncooled thermal FPAs at level about $2x10^8$ cm $Hz^{0.5}$ W – is 500 times lower comparing to detectivity of cooled photon MWIR FPAs at level about $1x10^{11}$ cm $Hz^{0.5}$. However, as stated earlier temperature resolution NETD of uncooled LWIR thermal imagers is only about two times worse comparing to NETD of cooled MWIR thermal imagers.

This apparently non logical situation occurs due to three main reasons. First, differential radiance of objects of typical Earth temperature (300 K) at typical band of modern MWIR imagers (3.7 μm to 4.8 μm) is much lower comparing to differential radiance at LWIR band (8 μm to 12 μm). In detail, the ratio is over about 13.5 times.

Second, uncooled thermal imagers are built using ultra bright optics (F-number close to 1) when cooled imagers are built using much darker optics (F number about 4). This difference in optics brightness improves NETD of uncooled thermal imager approximately 13 times (temperature resolution NETD of non cooled imagers is proportional to square of optics F-number).

Third, integration time of signals from uncooled IR FPA sensors is typically much longer comparing to integration time of signals from cooled MWIR FPAs. In detail, NETD is inversely proportional to square root from integration time and 4 times longer integration time can decrease NETD about 2 times.

These arguments give answer why NETD of best uncooled LWIR imagers is almost as good as NETD of cooled MWIR imagers. Now let us find reasons why uncooled LWIR imagers are not offered at market of long range imagers that is dominated by MWIR imagers even when NETD of both types are quite similar.

Long range surveillance against human targets can be achieved only by using imagers of long focal length optics that are capable to generate image of pixels of low angular size. It can be estimated using Johnson detection criteria (angular size of an equivalent square target is two time bigger than image pixel size) that uncooled LWIR imager built using 17 μm pixel FPA (typical pixel size of majority of uncooled FPAs) can detect human target (size of equivalent square 0.95m) at distance 10km only if optics focal length is about 350mm. Practically longer focal length is needed if atmospheric attenuation is to be included in calculation model. Further on, it should be noticed that zoom objectives (or step variable FOV objectives) are needed for most of surveillance tasks.

Technically there is no problem to develop LWIR zoom objectives of maximal focal length over 350mm. However, in order to keep imager temperature resolution NETD at reasonably low level it is necessary to use bright optics of F-number below about 1.5 (preferable below 1.2). It means that optics of huge aperture over 233mm (practically lenses of aperture over about 250mm) is needed to develop long range uncooled long range imagers. The problem is that there is no such huge LWIR objectives in typical offer of main manufacturers [73]. There are two main reasons for such situation. First, very high manufacturing costs of large LWIR optics due high material prices (typically germanium) and price of costs of polishing of large lenses. Second, competition from MWIR imagers that can use dark optics of high F-number (from about 3.5 to about 5.5). It means that MWIR optics for cooled MWIR imagers can be much cheaper than LWIR optics of the same focal length for uncooled LWIR imagers because optics aperture is several times smaller in the first case. Therefore, due to high cost of optics manufacturing long range LWIR imagers is not economically sound (Fig. 24).

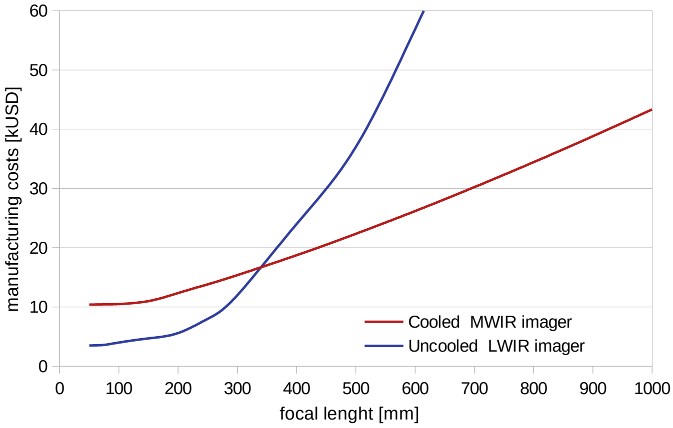


Fig. 24. Rough estimation of costs of MWIR cooled thermal imager built using 640x480 FPA sensor and dark F4 zoom 15x optics and LWIR uncooled thermal imager built using 640x480 FPA sensor and bright F1.2 zoom 5x optics

Long range uncooled LWIR imagers would be systems of huge size and mass. Therefore, there is practically almost no uncooled long range imagers with optics of focal length over 250 mm in spite of great demand for such imagers due to better reliability (longer life time) of the uncooled imagers. However, there some exceptions from this rule (Fig. 25). Sadad 102 thermal imager built by Iran Electronics Industry (IEI) a decade ago at time when Iran had limited access to cooled IR FPA technology, can be treated as a rare case of long range uncooled thermal imager. It is a bulky and costly system but it was supposed to be an effective imaging system in Syria war. It is a very good visual example to show what could occur if cooled thermal imaging have not been available.

Fig. 25. Photo of two long range thermal imagers of similar operational range a)uncooled Sadad 102 thermal imager from Iran Electronics Industry [103] , b)cooled Ranger HDC from Teledyne-FLIR

9.2 Imager spectral band

It is the second popular criterion to divide thermal imagers. However, in spite of huge popularity this criterion gives actually little information on imagers capabilities.

It is logical that spectral band of thermal imagers (practically spectral band of image sensor and imager optics) must be the same as so called atmospheric window (spectral bands of high transmission of atmosphere). It is known for decades that there are two atmospheric windows in so called "thermal infrared range" where dominates thermal radiation emitted by targets of typical Earth temperature: MWIR window from about 3 μm to about 5 μm and LWIR window from about 8 μm to about 12 μm. Therefore, it is natural that on criterion of spectral band thermal imagers are divided into two types: the middle-wave MWIR systems and the long-wave LWIR systems. However, precision borders of spectral band of these two types of thermal imagers vary: MWIR imagers (3-5 μm, 3.7-4.8 μm, 2.7-5.3 μm, 3.4-4.2 μm) and LWIR imagers (7.7-9.5 μm, 8-10.4 μm, 8-12 μm, 8-14 μm). Anyway the division on MWIR imagers and LWIR imagers is valid.

Discussions on optimal spectral band for thermal imagers (superiority of LWIR imagers over MWIR imagers or vice versa) has been carried out for decades [104-108].There are hundreds or may be thousands of publications related to this subject but the conclusions from this numerous literature are often conflicting. Therefore, here only short summary of practical views of the author on this never ending scientific conflict shall be presented.

In author opinion there is no binary Yes/No answer on a question of optimal spectral band for thermal imagers. The answer depends not only on atmosphere physics (laws of radiation propagation) but also on radiation physics (laws of emission of thermal radiation), available technology of IR FPA sensors/IR optics, and manufacturing costs.

In general, physics of emission of thermal radiation and propagation of such radiation through atmosphere favours LWIR thermal imagers for a series of reasons.

First, differential radiant power emitted by targets of typical Earth temperatures in LWIR band is many times higher than the same power emitted in MWIR band. A target of differential temperature 1ºC located at background of 20ºC shall emit about 15 times more in LWIR band (8-14 μm) than in MWIR (3-5 μm) band. This ration increases to about 38 times for the same target located at cold background of

-20ºC temperature. It means that well working LWIR imagers can be built using IR FPA sensors of much lower detectivity comparing to IR FPAs needed for MWIR imagers.

Second, due to longer wavelength transmission at LWIR band is generally better comparing to transmission at MWIR band. The difference increases significantly at poor visibility conditions (smoke, fog, rain). The exception is clear humid atmosphere at tropical regions.

Third, there are additional advantages of LWIR imagers in military applications:

1. LWIR imagers are much less sensitive to reflections of Sun light on water or to artificial targets (solar glints) that can mask targets of interest.
2. LWIR imagers are less sensitive to high temperature flares that can saturate parts of output image.
3. it is more difficult to blind LWIR imagers, especially if spectral band is limited to 8-10 μm (elimination of dangers from bulky CO2 lasers emitting at 10.6 μm) due to lack of portable LWIR lasers.

These are very important advantages that favours LWIR imagers and have made uncooled thermal LWIR imagers to dominate market. It should be noticed that technically it is easy to make uncooled thermal MWIR imagers but such imagers are not manufactured due to reported earlier much lower level of thermal radiation in MWIR band. However, superiority of LWIR band is not so clear in case of thermal imagers built using photon IR FPAs due to limitations of technology of cooled LWIR imagers.

There are three main advantages of cooled photon MWIR imagers over the same type of imagers working at LWIR band.

First, detectivity of cooled photon MWIR FPAs is typically many times higher over detectivity of cooled photon LWIR FPAs (typical ratio is about 4-5 times in favor of MWIR FPAs).

Second, it is technically easier and cheaper to manufacture cooled MWIR FPAs comparing to difficulties and costs of manufacturing cooled LWIR FPAs.

Third, due to shorter wavelength (lower diffraction effect) it is possible to design much smaller MWIR lenses of the same resolution (MTF) as bigger LWIR lenses (the same focal length but aperture about 2.5 times smaller).

This feature enables dominance of cooled photon MWIR imagers on market of medium/long range thermal imagers (already discussed in section section 9.1).

9.3 Radiometric calibration

All thermal imagers generate thermal image of brightness that depends directly on radiometric intensity (radiance, exitance), and indirectly on temperature of objects in imager field of view. If positive image polarization is used then higher radiometric intensity/temperature means brighter image. This relationship means that there is a potential to determine target temperature/radiometric intensity on basis of brightness of target image.

According to the criterion of imager calibration thermal imagers are divided into two main groups:

1. non-radiometric imagers,
2. radiometric imagers.

The imagers from the first group create thermal image that gives some information on distribution of radiometric intensity of surface of targets in imager FOV but precision relationship between output brightness and target temperature/radiometric intensity is not known. Therefore, radiometric intensity of targets cannot be measured on basis of image of these targets generated by non-radiometric imagers (typical surveillance thermal imagers).

The imagers from the second group create thermal image that is radiometrically calibrated. It means that they produce output image of brightness (or colour) that depends on temperature/radiometric intensity of targets according to a known relationship. Therefore, the radiometric intensity (typically temperature) of targets can be determined on basic of images of these targets generated by radiometric imagers.

The non-radiometric thermal imagers do typically produce monochromatic gray scale image. The radiometric imagers do typically produce colour image (different colour palettes are used). Image generated by radiometric imagers includes typically some additional data (numbers, scale) that enables to estimate radiometric intensity of targets in such image (Fig. 26). Therefore type of thermal imagers (non-radiometric/radiometric) can be predicted by looking on output image.

The non-radiometric imagers are mostly used in military/security applications to enable observation of battlefield in darkness and/or difficult atmospheric conditions by creating the relative temperature distribution of the terrestrial scenery being observed and are are often called surveillance imagers. The radiometric imagers are used mostly for civilian applications in industry, science, and medical business (mainly for non-contact temperature measurement). Due to this market difference the non radiometric imagers look often like military style, hardened product when radiometric imagers looks like civilian photo equipment (Fig. 27).

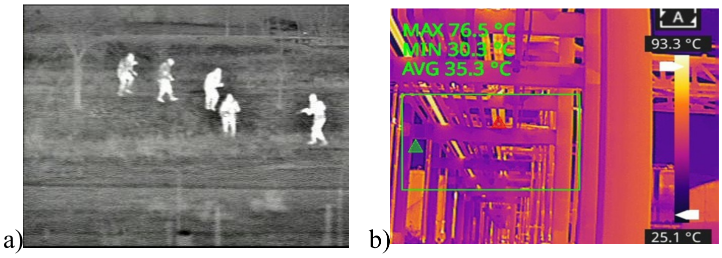

a) b)

Fig. 26. Exemplary images generated by two types of thermal imagers: a) image generated by non-radiometric imager [109], b)image generated by radiometric imager [110]

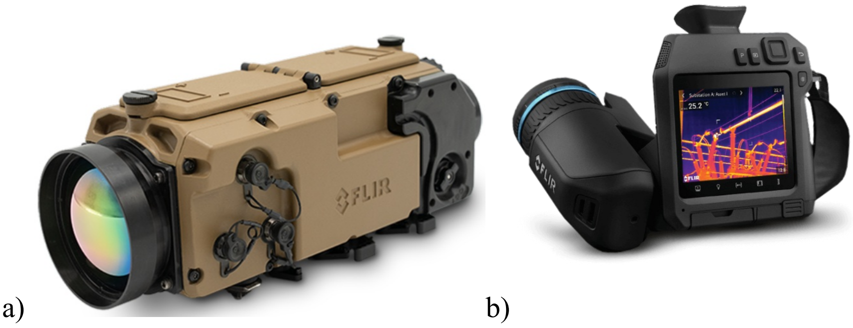

a) b)

Fig. 27. Photos of two thermal imagers that differ on criterion of radiometric calibration:a)non-radiometric Thermosight HIS-HD long range cooled thermal sniper sight, b)radiometric FLIR T865 (both from Teledyne-FLIR)

From design point of view the radiometric thermal imagers can be treated as a special modified group of non-radiometric thermal imagers. Four main modifications are needed to convert typical non radiometric imager into a radiometric one:

1. image processing/enhancement electronics capable to process absolute electronic signals (output signal proportional to absolute input signal),
2. radiometric calibration (measurement of relationship between electronics signal and temperature of an external blackbody,
3. additional VNIR camera to capture visual image of targets of interest,
4. special radiometric video format to record images with information on radiometric intensity distribution (typically temperature distribution).
5. ability to record static/video image of observed targets.

These modifications look non significant because both groups use the same image sensors and IR objectives. However, these modifications create totally different products. Non radiometric thermal imagers are almost useless for many industrial applications that require absolute temperature measurement and typical radiometric imagers are of limited use for long range surveillance, especially at extreme field conditions. Therefore, division non-radiometric/radiometric is of crucial importance.

9.4 Imagers of different type of output image

Thermal imagers generate output image in two main forms:

1. optical output image,
2. electronic output image.

Therefore thermal imagers can be divided into two groups:

1. optical output imagers,
2. electronic output imagers.

The optical output imagers are thermal imagers that generate output optical image at its internal display. This image can be immediately seen by a human observer. In most cases the image is seen by human observer through an optical ocular.

The electronic output imagers (can be called also video thermal imagers) are thermal imagers that generate output image in form of electronic video image. This output image needs later to converted to optical image to be seen by humans.

The border between direct view imagers and video imagers is sometimes blurred as there are optical output imagers that are capable to generate also electronic video signal. However, this second output is treated as a spare one and proposed division on optical output/electronic output imagers is generally valid.

Both groups of thermal imagers can be further divided as shown in Fig. 28. It should be noted that terminology used this figure is a proposal of the author. It is a non perfect solution but it is an attempt to make some terminology order for this group of thermal imagers in situation when different manufacturers use different names to describe basically the same thermal imagers.

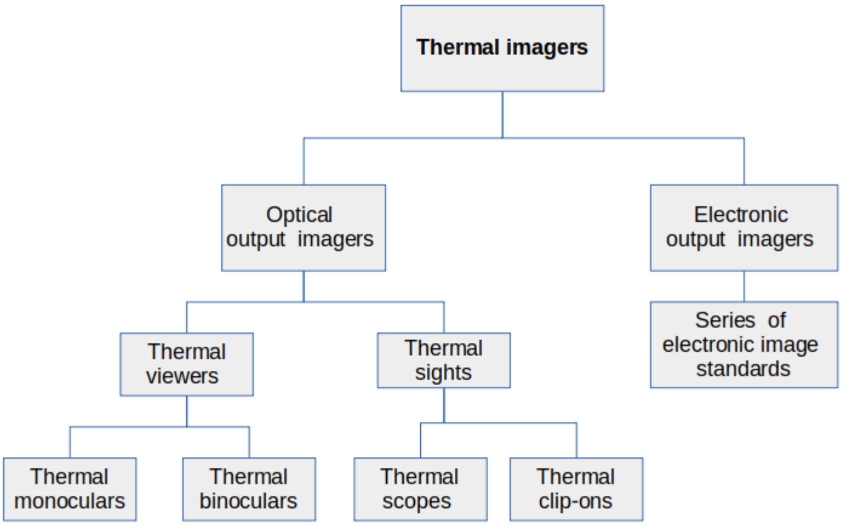


Fig. 28. Division of thermal imagers on criterion of type of output image

9.4.1 Optical output imagers

The optical output imagers can be further divided into two groups (photos as in Fig. 29):

1. thermal viewers,
2. thermal sights.

Thermal viewers are optical output thermal imagers that generate thermal images for use in general surveillance.

Thermal sights are output thermal imagers that generate thermal images with some aiming marks and are intended to be used in aiming applications (typically to support shooting). These imagers typically have also special mechanical design (mechanical rail that works as mechanical reference axis).

Thermal viewers are further divided according to number of output optical channels onto two groups

1. thermal monoculars (single output channel),
2. thermal binoculars (two output channels).

Thermal monoculars are thermal viewers that produce a single image to be seen by a single eye. They can be treated as equivalent to night vision monoculars due to similar design: thermal camera core combined with display replaces image intensifier tube.

Thermal binoculars are thermal viewers that produce two output images to be seen via two human eyes of the observer. They are typically built as imagers with two output optical channels (two displays and two ocular lenses) but only one input optical channel (one optical objective and one IR FPA sensor). Please note that typical thermal binoculars do not offer true stereoscopic vision for human observer like binocular night vision goggles.

Finally, thermal sights are to be divided into two groups:

1. thermal scopes,
2. thermal clip ons.

Thermal scopes are thermal sights of design optimized for situation when output image is seen via ocular directly by human observer.

Thermal clip ons are thermal sights of design optimized for situation when output image is seen indirectly by human observer looking through a telescopic sight.

Both types of thermal sights (thermal scopes, thermal clip ons) have design that support aiming small arms: aiming mark in the output image, and special mechanical reference mechanical axis. However, there are some design differences due to different style of use them.

From design point of view thermal clip ons can be treated as special thermal scope with large ocular. Further on, output image from thermal scope located on a riffle is supposed to be seen directly by shooter. Output image from thermal clip on located on a rifle is supposed to be seen indirectly by shooter looking through a telescopic sight. This indirect concept o vision using thermal clip ons combined with a typical telescopic sight looks as non practical but in reality thermal clip ons are favoured by sharp shooters.

Fig. 29. Photos of four different types of optical output imagers: a) thermal monocular: Ocean Scout 320 from Teldyne-FLIR, b) thermal binoculars: NPL-1T from PCO SA, c) thermal scope: THOR 5 XD 4-40X from ATN, d) thermal clip ons: ThermoSight® T75 from Teledyne-FLIR.

It should be also noted that some of types of optical output thermal imagers combined with night vision channel offer fusion capabilities (ability to present a single fused image combined from thermal imager and night vision imager).

Finally it should be emphasized that some of radiometric thermal imagers are optical output imagers as they have internal display. However, in general division presented in this section is limited only to surveillance thermal imagers.

9.4.2 Electronic output imagers

Electronic output imagers are thermal imagers that generate output image in form of electronic signal prepared in a standardized way to include detail information on moving visual images (electronic video image) (Fig. 30). In contrast to optical output imagers discussed in previous section they are supposed to use external display connected in many different ways.

As clarified in Section 6.2.9 these imagers can generate output image in form of a series of over myriads of versions of standards of electronic video image (video interfaces).

There is no fixed rules to evaluate video interfaces. However, a set of twelve criterion can be recommended to evaluate different video interfaces used in thermal imagers.

1. Compatibility of the interface for specific resolution of image sensor (some interfaces like HDMI can cooperate only with image sensors of a set of resolution; others are flexible (like CameraLink) and can enable capture video image from sensors of any resolution,
2. Compatibility of interface with specific infrastructure that cannot be changed (sometimes new thermal imager must cooperate with display of specific standard or video image must be transferred using old specified cable/connector)
3. Maximal acceptable bandwidth to characterize ability of fast transfer of video images in Mbit/sec units (calculated as product of a number of sensor pixels, frame rate and image bit depth),
4. Max acceptable cable length (max length of cable to connect imager to a receiving device)
5. Optional support for compressed video images (all interfaces do support transfer of uncompressed video images but only some can support transfer of compressed video images),
6. Connector reliability (some connectors are more reliable over other connectors; for example BNC connector used in SDI interface is more reliable over HDMI connector)
7. Fibre optic compatibility (some interfaces can cooperate with fibre optics lines)
8. Frame grabber requirements (some interfaces like CameraLink require a frame grabber to capture video image when other like GigE, Ethernet over IP do not),
9. Market availability of receiving devices (displays, computer cards) compatible to specific interface (some interfaces can be directly connected to displays),
10. Camera power options/communication (some interfaces enables not only to transmit video image but also communication to control/power imager),
11. Ability for field termination of the cables (some interfaces use cables that can be easily terminated in the field)
12. Market price of interface and compatible devices.

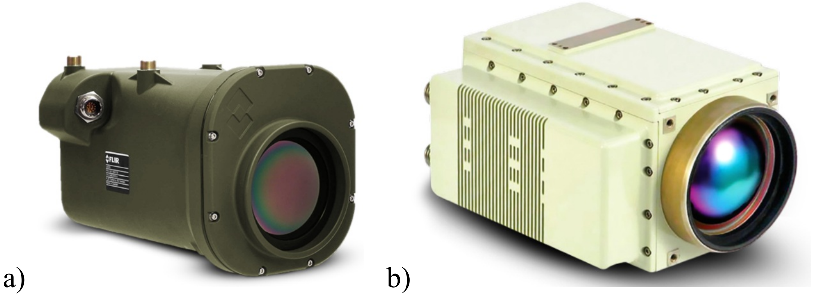

a) b)

Fig. 30. Exemplary electronic output imagers: a) remote weapon sight ThermoSight V4000, b)MilSight® LIRC vehicle sight (both from Teledyne-FLIR)

As we can see evaluation of video interfaces used thermal imagers is difficult due to a series of discussed earlier criterion and high number of versions of video standards. To complicate situation even more it should be remembered that there is also a long list of video compression formats (video coding formats) used for transfer of video images (examples formats: H.120, H.261, Motion JPEG, MPEG-1, MPEG-2, DV, H.263, MPEG-4, and many others).

Finally, there is a long series of video file formats used for storing digital video data on a computer system. Example popular formats are: MP4, MOV, WMV, AVI, AVCHD, FLV, F4V, SWF, MKV, WEBM, HTML5, and MPEG-2. Video images are typically stored using compression to reduce the file size. Therefore video file formats are related partially to earlier discussed video compression formats.

To summarize, electronic output thermal imagers offered on the market vary a lot due to different video interfaces, video compression formats, and video file formats. The situation is basically the same as in case of typical video cameras used for home use or for CCTV applications. This high number of standards that regulate interfaces, video compression and file recording is a challenge for both designers and users of thermal imagers but it is also an advantage to enable to find optimal solution for any application.

9.5 Maximal surveillance range

Military all over the world love to evaluate performance of thermal imagers on bases of operational range of effective surveillance against military-style targets. This criterion is also often used in purchase tenders to describe requirements on thermal imagers [111]. The operational ranges are sometimes presented directly in data sheet of surveillance thermal imagers. In detail, operational range is defined as set of distances that describe imager ability to detect, recognize, identify some targets of interest (DRI ranges).

It is technically possible to determine the operational ranges at field conditions during tests against real targets. However, this solution is time consuming and costly. Therefore the DRI ranges of thermal imagers are typically calculated using theoretical models based on some parameters of thermal imager.

There have been proposed in literature dozen of models/methods to calculate DRI ranges. Further on, it is natural that DRI ranges depend also on type of target of interest (man, tank, truck, ect). Therefore, making division of thermal imagers on criterion of DRI ranges is difficult due to not clear criterion. However, some rough characterization of performance of surveillance imagers is needed.

In such a situation, the author has decided to divide thermal imagers according to detection range of a human target calculated using classical Johnson model (discrimination level 1 cycle/target) [112]. The main advantage of this criterion to divide thermal imagers is simplicity and clarity.

Typical human target (1.8×0.5m) can be converted to equivalent square target of size 0.95m that is approximately equal to 1m. In such a situation the detection range of human target calculated using simplified Johnson model is approximately equal to imager Nyquist frequency:

$$R_{(D-human)} \sim \frac{f'}{2 \cdot pix} = NF , \qquad (2)$$

where f' is focal length of imager optics, *pix* is pixel pitch of IR FPA sensor, and *NF* is imager Nyquist frequency in lp/mrad.

In detail, the author proposes to divide thermal imagers onto seven groups depending on detection range to a human target (Table 13):

1. extremely short,
2. very short,
3. short,
4. medium,
5. long,
6. very long,
7. extremely long.

Table 13. Division of thermal imagers on criterion of operational range (detection range to human target)

Parameter name	Extremely short	Very short	Short	Medium	Long	Very long	Ultra long
Range value [km]	<0.1	<0.3	0.3-1	1-3	3-10	10-30	>30
Nyquist frequency [lp/mrad]	<0.1	<0.3	0.3-1	1-3	3-10	10-30	>30
Focal length [mm] for 15um FPA	<3	<9	9-30	30-90	90-300	300-900	>900
Horizontal FOV [°] for 15 µm/640×512 FPA	>116	56.1-116	56.1-18.2	18.2-6.11	6.1-1.83	1.8-0.61	<0.61

It is known that Johnson model generates over optimistic results, especially for case of long distances (atmospheric transmission is not included). Further on, Johnson model applied to thermal imaging is based on assumption that bar width of resolution target is approximately equal to size of pixels of thermal imagers. This assumption is perfectly fine for old generation of FPAs of big pixel sensors but there is noticeable difference between these two parameters for modern thermal imagers built using small pixel

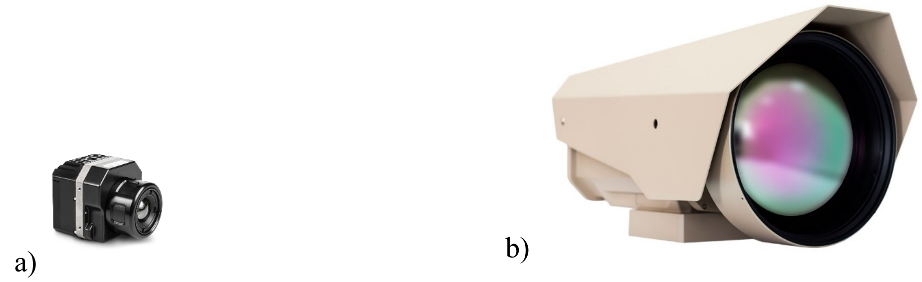
FPAs (example 12 µm pixels of modern uncooled thermal imagers). Therefore, real detection range can be much shorter, especially for case of very long/ultra long range imagers due to influence of atmosphere that is not included in Johnson model. Anyway, division presented in Table 13 can still be useful for preliminary classification of thermal imagers according to their range.

The formula (2) shows that DRI ranges are proportional to focal length of imager optics and inversely proportional to size of pixels of IR FPA sensor. It practically means that in order to achieve long DRI ranges it is necessary to use optics of long focal length. However, it should be noted that interpretation of the term “long focal length” gradually decrease with time with arrival of new generation of FPA sensors with smaller pixels. At present 15 µm cooled FPA sensors and 17 µm uncooled sensors can be considered as typical solution but new generation in form of 10 µm cooled FPA sensors and 12 µm uncooled sensors can dominate market in near future.

Further on, FOV of thermal imager is inversely proportional to focal length of imager optics and proportional to sensor size. Therefore, long range imager built using optics of long focal length means also imager of narrow FOV (see Table 13).

Finally, (2) shows that DRI ranges are indirectly proportional to aperture of optical objective because ration of focal length to aperture must be kept at low value (below 1.5 for uncooled imagers and below say 5.5 for cooled imagers). It means that in order to achieve longer operational range it is necessary to use optics of bigger size, and finally imagers of bigger dimensions and mass.

Optical output thermal imagers discussed in Section 9.4.1 are typically portable imagers optimized for short/medium distance range applications (human detection at distance from about 300 m to about 3 km). As can be seen in Fig.29 they do not differ much in size. There are much bigger differences in case of electronic output thermal imagers (video thermal imagers) discussed in Section 9.4.2 due to much wider field of applications that require imagers of operational range to human targets that vary from several dozens of meters to over 10 km. Therefore, electronic output imagers offered on market vary a lot from microscopic cameras of weight below 0.1 kg to huge ultra long range imagers of mass over 30 kg (Fig. 31). There is also a valid another general rule that price of thermal imager is approximately proportional to square of its operational range.



a) b)

Fig. 31. Photos of two thermal imagers of different operational range: a)very short range imager: Vue Pro 336, (focal length 9 mm, FOV 35°) from Teledyne-FLIR; b) very long range imager: HeatSeekIR (variable focal length 57-825mm) from Optix JSC

9.6 Radiometric measurement capabilities

The are three main types of radiometric thermal imagers according to criterion of measurement capabilities:

1. Thermography cameras,
2. Optical gas imaging thermal imagers,
3. Firefighting thermal camera

9.6.1 Thermography cameras

Thermography cameras are radiometric imagers optimized for non-contact temperature measurement capable to generate output images of colour that is directly related to target temperature (several colour palettes can be used) using a mathematical model (calibration chart) understood as a relationship between temperature/emissivity of gray body target and measured output signal generated by such a target.

Thermography cameras can be divided into two groups [102]:

1. Handheld thermography cameras,
2. Fixed thermography cameras.

The first group are portable, optical output cameras that generate output image on an internal) display. These cameras are typically built in form a thermal camera module connected to large handheld frame (Fig. 32a). However, they are also manufactured in forms that externally looks like photo cameras (Fig. 32b), or smartphone with attachments (Fig. 32c). In all cases the crucial external feature is ability to be held and operate using two human hands and. The latter feature generates name of this type of thermography cameras.

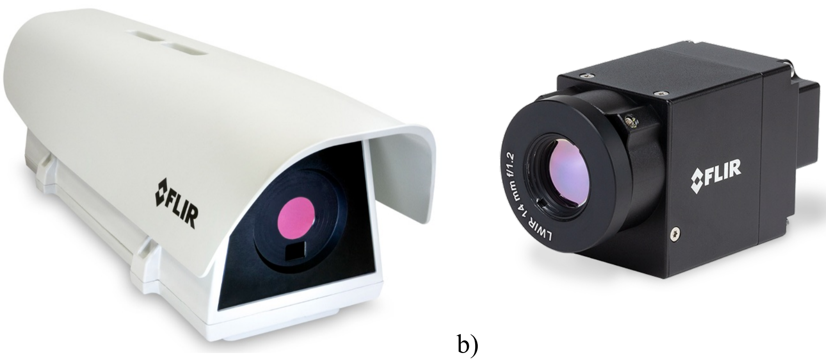
Fig. 32. Three forms of handheld cameras: a) handheld frame camera (FLIR E86 24°) b)photo like camera (FLIR T560 24°), c) smartphone attachment camera (FLIR ONE® Edge Pro),

The second group of thermography cameras (fixed thermography cameras) are electrical output cameras that generate radiometric image of scenery of interest in form of electrical video image. They are supposed to be fixed (origin of the name) to an external platform to enable proper work (imaging proper targets of interest).

The fixed thermography cameras can be further divided into two groups:

1. outdoor cameras optimized for outdoor monitoring and early fire detection,
2. indoor cameras for industrial automation and machine vision.

Both types represent similar design. The main difference is external housing needed for outdoor cameras. It should be noted that outdoor thermography cameras (Fig. 33a) look externally similar to surveillance thermal imagers used in security applications (Fig. 27a). However, outdoor thermography cameras generate radiometric image when the security thermal imagers generate non radiometric thermal image. The effect is that in first case absolute temperature of surface of targets can be precisely determined when in the second case only rough estimation of differential temperature is possible.



a) b)

Fig. 33. Two types of fixed thermography cameras: a) outdoor cameras (FLIR A500f/A700f for outdoor monitoring and early fire detection), b) indoor camera (FLIR A38/A68 for industrial automation and machine vision)

9.6.2 Optical gas imaging thermal imagers

Optical gas imaging (OGI) thermal imagers are radiometric imagers optimized for detection, visualization and optionally analysis of leaks of different gases used in industry. OGI imagers can be used for detection, visualization and analysis of a long series of gases: Hydrocarbons, VOC, Carbon dioxide, Carbon monoxide, Methane, HFCs, Refrigerant gases, Ammonia, Sulfurhexafluoride, Ethylene. These imagers generate image that shows gas leaks as blurred streaks that differ from background (Fig. 34).

There are some similarities of OGI imagers to thermography cameras because both thermography cameras and OGI imagers are radiometric thermal imagers. However, in principle the work concept of OGI differ totally from work concept of thermography cameras. Thermography cameras are based on a concept to determine temperature of targets on basis of measured radiometric signal emitted by surface of such targets. Typical spectral bands of thermography cameras are relatively wide (about 3-5 μm for MWIR cameras or about 8-12 μm for LWIR cameras) and such bands are located in so called atmospheric windows where average transmission is high for typical short work distances of thermography cameras.

Concept of work of OGI imagers is based on two different physical phenomenons:

1. Gas leaks have typically different temperature comparing to surrounding targets,
2. Majority of gases of interest for industry have narrow absorption bands (high emissivity bands) in spectral range from about 3 μm to about 15 μm.

It means that specially modified thermography camera with narrow spectral band that fit exactly to absorption band of gas of interest can see leaks of such gas. OGI are in principle thermography cameras modified in this way. List of spectral bands used by OGI imagers to detect and visualize different gases is shown in Table 14. However, design of OGI imagers is not as easy as suggested by its working principle.

Table 14. Absorption bands of different gases used by OGI thermal imagers for gas imaging

No	Spectral band [μm]	Name of gas
1	3.2-3.4	Hydrocarbons, VOC, methane
2	4.2-4.4	Carbon dioxide
3	4.52-4.87	Carbon monoxide
4	7.0 -8.5	Methane, HFCs
5	8.0-8.6	Refrigerant gases, HFCs
6	10.3-10.7	Ammonia, Sulfurhexafluoride, Ethylene

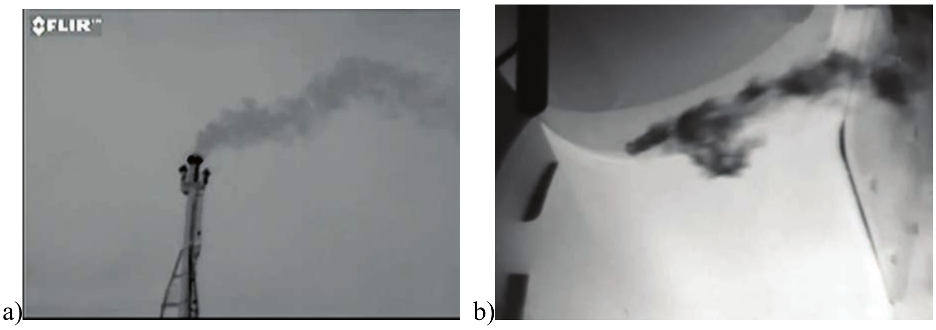


Fig. 34. Photos of two exemplary gas leaks: a)Hydrocarbons leaks, b)R124 compression leaks [113]

Easy low cost solution in form of adding typical narrow band IR filter to a typical uncooled LWIR thermography camera is not possible due to two main reasons.

First, approximately half of gas absorption bands is located in MWIR band. Second, cooled filters (integrated with cooled IR FPA sensor) are needed in order to eliminate harmful radiometric signal emitted by the filter.

Therefore, cooled MWIR/LWIR FPA sensors of ultra high detectivity are needed in order to detect low differential radiometric signals emitted by gases (low temperature difference of gas comparing to targets in neighbourhood in narrow spectral band). Due to these reasons market of OGI imagers is dominated by expensive cooled thermal imagers based on photoelectric sensors (InSb, HgCdTe, QWIP) (Fig. 35a). Uncooled lower cost OGI are only used for less demanding applications (Fig. 35b).

Test capabilities of OGI cameras offered on the market vary a lot. All of OGI cameras offer detection and visualization of gas leaks (cameras sensitivity can differ). However, most advanced OGI cameras can offer also so called quantification understood as the numerical characterization of detected gas leak. Practically it means that such advanced OGI cameras offer numerical survey of gas leak: determination of mass leak rates, volumetric leak rates, concentration (ppm-m), and size of the gas leak. Such cameras potentially eliminate the need for secondary sampling using a contact gas analyser (EPA Method 21). However, OGI technology is still not mature and accuracy of such numerical surveys vary a lot on experience of OGI operator [114].

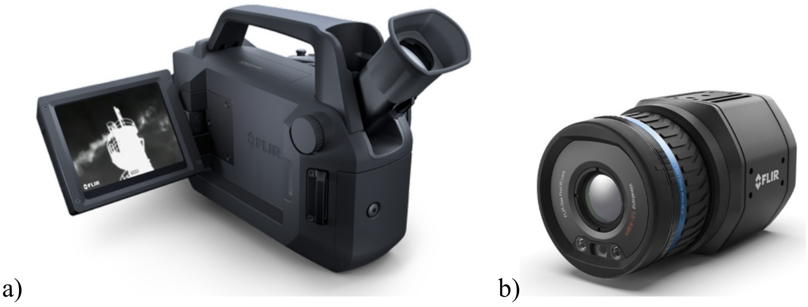


Fig. 35. Two types of OGI cameras: a) cooled OGI camera for hydrofluorocarbons (FLIR G304), b)uncooled OGI camera for methane (FLIR GF77a)

9.6.3 FireFighting cameras

Firefighting thermal cameras can be treated as handheld thermography cameras (discussed in Section 9.6.1) optimized for firefighting applications. In detail, they are expected to see through smoke and to enable visualization and rough measurement of temperature of targets met during firefighting conditions.

There are two main features of firefighting thermal cameras comparing to typical thermography cameras:

1. ruggedness,
2. ultra wide temperature range.

The first feature means that firefighting thermal cameras are manufactured in a way that makes them heat- and water-resistant and rugged to withstand the hazards of fire ground operations.

The second feature, means ability to generate useful image of human body even when ultra heated target of temperature up to 1100°C is located in camera FOV.

Great majority of firefighting thermal cameras are handheld cameras like units presented in Fig. 36. However, sometimes helmet fixed cameras are used, too. Detail requirements on design and performance of firefighting thermal cameras can be found standard: NFPA 1801 Standard on Thermal Imagers for the Fire Service,2013.


a) b)

Fig. 36. Two exemplary Firefighting thermal cameras: a)FLIR K65 NFPA Compliant TIC 320×240, b)ARGUS4 HR320 Thermal Fire Fighting Camera

9.7 Integration with other imaging/laser systems

Majority of thermal imagers on the market are fully independent (stand alone) thermal imagers. However, there are also thermal imagers integrated with another imaging/laser systems to increase total system capabilities. Therefore according to criterion of integration with other imaging/laser system thermal imagers can be divided into four groups (Fig. 37):

a) Independent TI,
b) TI with additional simple laser tools,
c) Multi imaging systems.
d) Multi imaging/laser systems.

Thermal imagers that belong to the first group independent imagers that produce only one thermal image of scenery of interest.

Thermal imagers that belong to the second group are thermal imagers equipped with some simple laser tools (laser pointer/illuminator, simple laser range finder) and can offer additional capabilities like pinpointing, illumination, or short range distance measurement. Thermal imagers from the second group looks externally similar to independent imagers from the first group because the laser tool is typically small.

Thermal imagers that belong to the third group can generate image in at least two spectral bands due to use use of additional imaging system (VNIR camera or SWIR imager).

Thermal imagers that belong to the fourth group can generate image in at least two spectral bands and are additionally equipped with advanced laser systems (long range LRFs/ designators) that enables them to be used for targeting applications.

Integration of thermal imagers with laser/imaging systems can increase significantly system imaging/targeting capabilities in surveillance/targeting applications. Therefore, there is a clear market trend for such integration. Multi sensor imaging/laser systems are becoming increasingly popular, especially at military market. Independent thermal imagers are nowadays offered mostly for market of short range portable imagers. Market of long range applications (both airborne, marine or land) is dominated by multi sensor imaging/laser systems.

a) Thermal Sniper Sight ThermoSight® HISS-XLR

b) Thermion 2 LRF XQ50 Pro thermal sight with LRF[115] (Group II)

c)Dual Channel Day/Night Thermal Biocular Recon® B2-FO

d) STAR SAFIRE®380-HLD multi imaging/targeting system

Fig. 37. Photos of four thermal imagers divided according to criterion of integration with other imaging/laser systems: a)independent thermal imager, b)thermal sight with simple LRF, c)multi imaging systems, d)multi imaging/laser systems.

10. Basics of characterization thermal imagers

Thermal imagers are sophisticated systems that cannot be precisely described using common language words. For accurate description, they require using a series of technical parameters. Parameters are quantitative physical measures of thermal imagers. Parameters describing thermal imagers can be divided into two groups: general parameters suitable for any technical device and specific parameters unique to thermal imagers.

Parameters from the first group can be further divided into mechanical parameters (mass, dimensions), electrical parameters (power/voltage supply) and environmental parameters. The latter parameters describe properties of environment in which the imager can work properly or can be safely stored: work temperature range, storage temperature range, humidity temperature range, vibration/shock resistance and many others.

Parameters of mechanical, electrical and environmental properties of thermal imagers do not differ from the same parameters of any electrical/mechanical systems used in mass applications. Further on, the measurement methods of these parameters can be found in numerous literature and will not be discussed here. We are to concentrate on measurement of the parameters that describe design and performance of thermal imagers.

10.1 Concept of characterization of thermal imagers

Measurement of parameters of thermal imagers delivers some knowledge about these imagers. This knowledge can be useful at any stage of life of thermal imagers enabling different tasks:

1. optimization of design of thermal imager during R/D project,
2. quality control of modules purchased from subcontractors,
3. quality control of thermal imager during manufacturing process,
4. evaluation of thermal imager to be purchased
5. quality checking during maintenance tests,
6. metrological support during repair process.

It seems that it is easy to determine performance of thermal imagers because images generated by these imagers can be evaluated by humans used as image analyzers. Therefore, it is theoretically possible to use the thermal imager in real work conditions (typically field conditions), look at an image of real targets of interest generated by the tested imager and based on the image, evaluate the properties of the imager. However, practically the concept of the characterization/testing of thermal imagers by a visual, subjective evaluation of images of real targets in real work conditions works rather poorly for two main reasons.

First, required field tests are costly, time consuming and generate low repeatability results due to variable atmospheric conditions. Second, humans cannot precisely judge an imaging system like a thermal imager by looking at an image of real targets of sophisticated shape, located at a non uniform background, like scenarios shown in Fig. 38. In detail, humans can precisely compare quality of two images seen at Fig. 38, but only when those images are seen at the same time. However, humans are poor meters of quality of an image of sophisticated targets, if there is a major time interval between the tests.

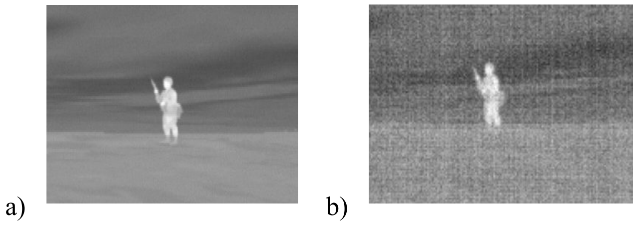


Fig. 38. Two images of different quality of the same target:a)sharp noise-free image, b)blurred noisy image

To summarize, properties (parameters) of thermal imager cannot be properly evaluated on the basis of generated image of several targets of interest in real field scenery due to limitations of human sight and variability of field conditions.

However, humans can quite precisely evaluate quality of an image of simple shape targets (4-bar, edge, circle, slit, cross, square, uniform). Further on, images of such simple shape targets generated at laboratory conditions can deliver at lot of valuable objective information on a thermal imager when the images are analyzed by software. Therefore, characterization of thermal imagers is typically carried out by analysis (subjective by humans or objective by software) of images of simple shape targets at laboratory conditions [18-20].

In detail, special infrared image projectors are used to project images of such targets into direction of tested thermal imager. Later, based on a knowledge about radiometric and photometric parameters of the radiation emitted by simulated target of interest, it is possible to determine parameters that precisely describe properties of a video image generated by the tested thermal imager.

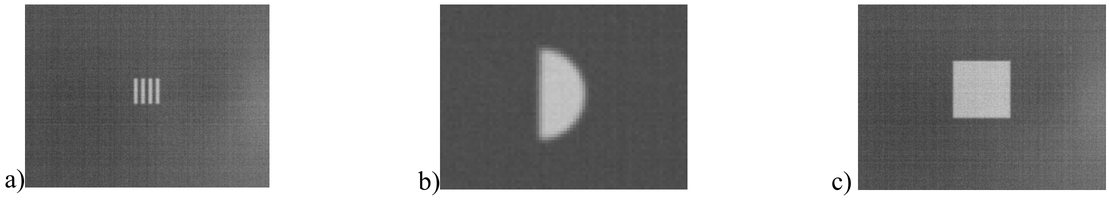


Fig. 39. Images of exemplary simple shape targets used at tests of thermal imagers: a)4-bar target, b)edge target (magnified), c)square target

The task of a test system for testing thermal imagers is to generate images of some standard static targets of a 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 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.

Image projectors used for testing thermal imagers at laboratory conditions are typically systems in a form of an off axis reflective collimator that projects images of test target of different patterns inserted to a rotary wheel that is located at focal plane of the collimator. The target to be projected is irradiated by an area blackbody. By rotating the wheel, it is possible to quickly exchange the target to be projected.

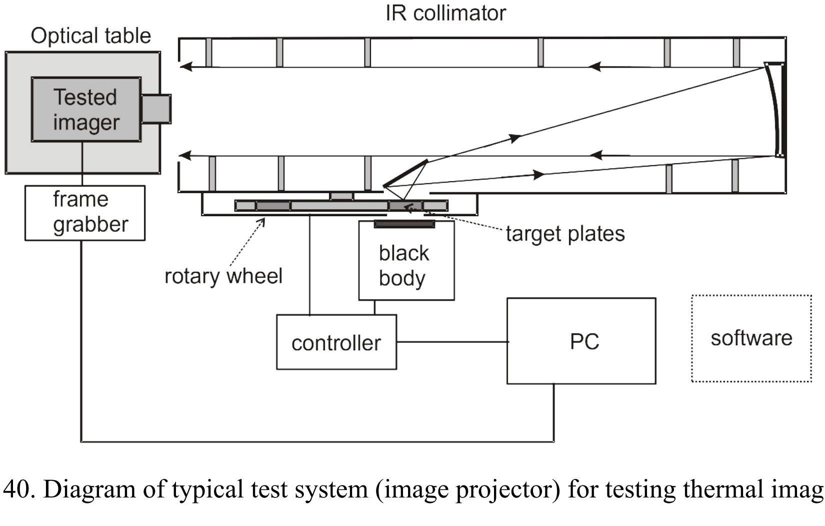


Fig. 40. Diagram of typical test system (image projector) for testing thermal imagers.

Fig. 41. Exemplary system (DT150 from INFRAMET[116]) for testing thermal imagers composed from six main blocks: off axis reflective collimator, area blackbody, set of targets, PC, frame grabber, software

The tested thermal imager is located at the output of IR collimator and sees images projected by the collimator. The optical distance between the test target and the tested imager is very short (approximately double focal length of the collimator). Such distance is usually below focusing range of typical surveillance thermal imagers. However, due to the use of the collimator as an image projector the imager "sees" the target as if it is located at a very long distance, optical infinity, and tests are carried simulating such ultra long distance focusing.

It can be estimated that 99.9% of tests of thermal imagers is carried out at laboratory conditions using earlier described concept. 0.1% is for tests at the real field conditions. It is also technically possible to test thermal imagers using IR scene projectors capable of projecting images of targets of complex thermal shape at a realistic background [117]. However, the barrier is huge cost of the IR scene simulators, and lack of clear test rules what complex targets should be used to characterize responses of thermal imagers.

10.2 Performance parameters of thermal imagers

Division of performance parameters of thermal imagers vary in literature. Most popular is division on six groups [18-20]:

1. focus and system resolution,
2. system responsivity,
3. system noise,
4. Contrast/Modulation/Phase functions,
5. Geometric Transfer Function,
6. Observer Interpretation of image quality

However, in author opinion more parameters is needed to describe performance of thermal imagers and such parameters can be divided into twelve groups (Fig. 42):

1. Electronic image parameters
2. Subjective image quality parameters,
3. Response parameters,
4. Noise parameters (including blind pixels),
5. Modulation Transfer Function,
6. Geometric parameters,
7. Focus parameters (minimal focus, infinity focus, diopter power range, output pupil distance, output pupil diameter)
8. Radiometric parameters .

9. Boresight parameters, (including binoculars)
10. Athermality parameters,
11. Temporal parameters,
12. Spectral parameters.

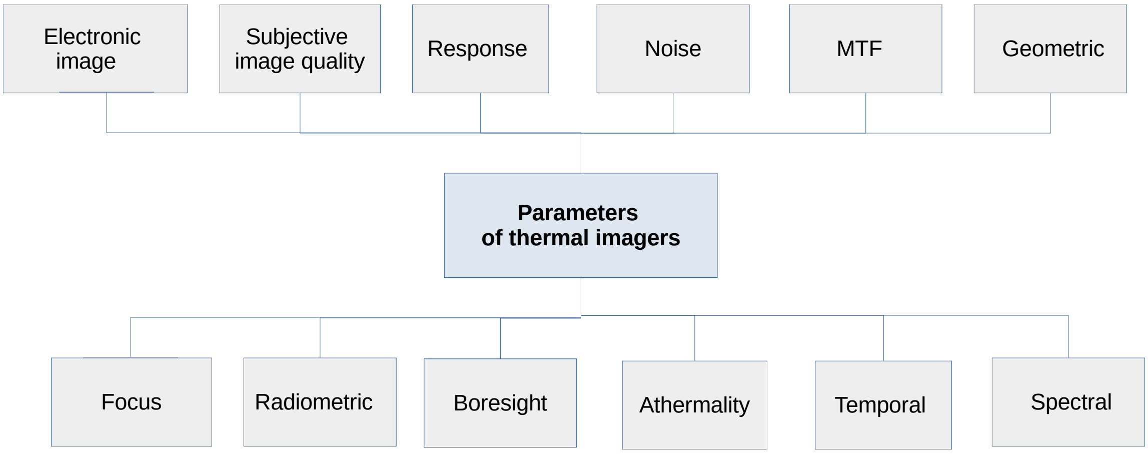


Fig. 42. Division of performance parameters of thermal imagers

Short description of proposed groups of parameters that characterize thermal imagers treated as black box is presented in Table 15.

Table 15. Short definitions of groups of parameters that characterize thermal imagers

No	Name of group of parameters	Definition (information delivered by the group)
1	Electronic image parameters	Basic information on electronic image generated by thermal imager
2	Subjective image quality	Ability of the system: thermal imager– human observer to detect/resolve targets of variable contrast
3	Response parameters	Response of the thermal imager to variable size or variable temperature targets.
4	Noise parameters	Noise phenomenon that limits imager ability detecting low contrast targets including blind pixels
5	MTF	Deterioration of contrast of image of sine target with spatial frequency
6	Geometric parameters	Geometrical properties of output image
7	Focus parameters	Optimal conditions to operate thermal imagers to achieve best perceived image sharpness.
8	Radiometric accuracy parameters	Accuracy of non-contact temperature measurement using radiometric thermal imagers
9	Boresight parameters	Relative positions between different optical/mechanical axis of thermal imager
10	Athermality parameters	Information on stability of performance of thermal imager versus variable ambient work temperature
11	Temporal parameters	Temporal inertia of thermal imager
12	Spectral parameters	Imager relative responsivity versus wavelength

Detailed lists of parameters of thermal imagers from different groups is presented in Table 16.

Table 16. List of performance parameters of thermal imagers

Electronic image parameters 1. Output image resolution (pixel number) 2. Frame rate (in FPS) 3. Bit depth 4. Type of video interface	Focus parameters 1. Optimal focus 2. Infinity focus 3. Minimal distance focus 4. Infinity diopter setting 5. Diopter power range 6. Exit pupil diameter 7. Exit pupil distance
Subjective image quality parameters: 1. MRTD (minimum resolvable temperature difference) 2. MDTD(minimum detectable temperature difference) 3. Auto MRTD 4. Dynamic MRTD 5. TOD (triangle orientation discrimination) 6. MTDP (minimum temperature difference perceived) 7. Virtual MRTD	Radiometric accuracy parameters 1. “Accuracy” (Minimal Error) 2. NETD – Noise Equivalent Temperature Difference (Noise Generated Error) 3. Temperature stability 4. Temperature measurement range 5. Slit Response Function 6. Measurement angular resolution
Response parameters 1. Response function (including signal transfer function SiTF, linearity and dynamic range) 2. ATF (aperiodic transfer function) 3. SRF (slit response function) 4. PVF (point visibility function)	Boresight parameters 1. Zoom through 2. Focus-through 3. Ocular focus through 4. TI to reference mechanical plane/axis 5. Deflection angle of clip-ons 6. TI to VIS-NIR 7. TI to LRF (or laser designator)
Noise parameters 1. NETD (noise equivalent temperature difference) 2. FPN (fix pattern noise) 3. Non-uniformity 4. 1/f 5. gain/offset non-uniformities 6. 3D noise model (seven components) 7. NPSD (noise power spectral density) 8. Blind pixels	Athermality parameters: 1. Normalized spatial resolution 2. Normalized temperature resolution
Modulation Transfer Function 1. MTF	Temporal parameters 1. Time constant 2. Effective frame rate
Geometric parameters 1. Field of view 2. Distortion 3. Magnification	Spectral parameters 1. Relative spectral sensitivity

10.3 Most popular parameters

Table 16 lists over 50 parameters used for characterization of thermal imagers. Each of them can deliver some valuable knowledge on performance of thermal imagers. However, presentation of detailed definitions and measurement methods of all the parameters listed in Table 16 is outside main scope of this book, due to very wide subject[*]. Study of specialized books/papers devoted to characterization and testing of thermal imagers is recommended [18-20]. Further on, all these parameters are measured rarely,

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[*] The author plans to write a new book on subject of characterization/testing thermal imagers.

typically only during expanded R/D projects. Tests of thermal imagers are typically limited to measurement of a set of three parameters: MRTD, NETD, and FOV. Here only performance of these most popular parameters are to be shortly discussed.

10.3.1 MRTD

The MRTD (minimal resolvable temperature difference) is a subjective parameter (function) that describes ability of the imager-human system for resolving details of a reference target of a variable contrast and variable size. In detail, it is a function of a minimum temperature difference between the bars of the standard 4-bar target (length to width of the bar equal to 7) and the background required to resolve the thermal image of the bars by an observer versus spatial frequency of the target. The spatial frequency is understood as inverse angular size of a pair of bar of 4-bar target.

MRTD is typically measured by human analysis of an image of a 4-bar target of a variable differential temperature (Figs.43-44). The task of the observer is typically to find a minimal differential temperature for a target of given spatial frequency when he can still resolve the bars. He should be able for see all four bars, although it is not needed to see the bars all the time. Optimal differential temperature (MRTD value) is determined by making experiments with a series of differential temperature values. The procedure is carried out for both positive contrast and negative contrast of the 4-bar target and mean value is calculated. Later, the procedure is repeated for other 4-bar targets (spatial frequencies). Measurement of MRTD at 5-6 spatial frequencies is recommended to determine accurately MRTD function. If thermal imager works at several FOVs, then the tests should be repeated for each of FOV.

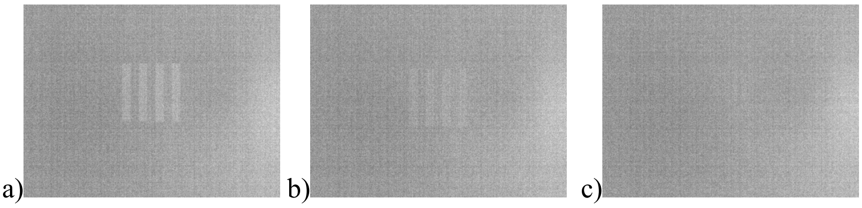


Fig. 43. Image of the same large 4-bar target at three differential temperatures (a)80mK,b) 40mK, c)20mK – non resolvable) generated by an uncooled thermal imager of NETD at 52mK

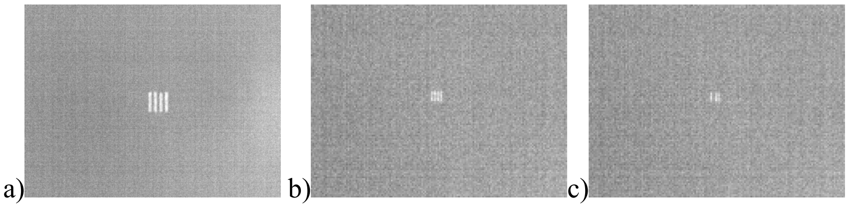
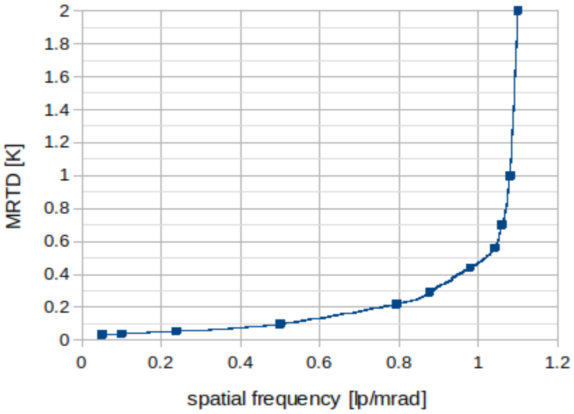
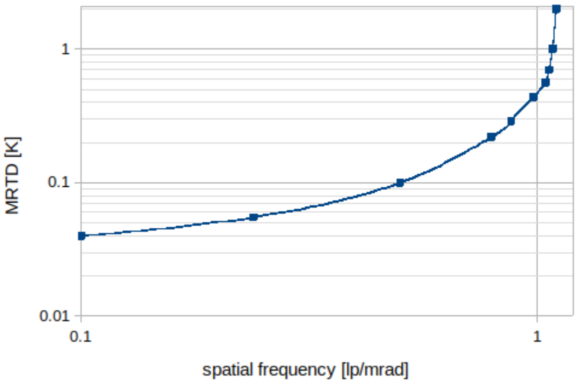


Fig. 44. Image of three small 4-bar targets of different spatial frequency (a)0.6lp/mrad, b)1.1 lp/mrad, c)1.2 lp/mrad – non resolvable) at differential temperature (500mK) generated by thermal imager of Nyquist frequency at 1 lp/mrad

After repeating measurement of MRTD using a set of 4-bar targets of a different spatial frequency two dimensional function like one shown at Fig. 45 is created. The X-axis is a spatial frequency of 4-bar targets used in measurements. Y-axis – values of minimal differential temperature needed to resolve bars of 4-bar targets. The main commonly met challenge is to measure accurately MRTD at spatial frequencies close to Nyquist frequency (close to vertical asymptote at Fig. 45) where small changes of target spatial frequency generate significantly different values of measured MRTD. Such situation generates necessity to have a very long series of 4-bar targets of different spatial frequencies to be able to accurately measure MRTD of myriads of thermal imagers offered on market.



a)



b)

Fig. 45. MRTD of exemplary short range thermal imager: a) linear scale, b)logarithmic scale.

MRTD is considered as the most important (popular) parameter of thermal imagers. This is due to three main reasons:

1. It is easy to understand measurement concept and do direct interpretation of test results,
2. MRTD delivers information on performance of total system: imager and human observer.
3. MRTD delivers information on imager performance against targets from three main groups met at real work conditions: large targets of low differential temperature, medium size targets of medium differential temperature, small targets of high differential temperature.

Therefore, MRTD is the most popular and most commonly measured parameter of thermal imagers.

10.3.2 NETD

The original concept of direct measurement of NETD was based on idea to regulate target differential temperature to achieve situation when rms noise voltage equals to a relative signal difference caused by a target of that differential temperature. However, this direct method is not convenient as it is difficult and time consuming to regulate differential temperature to achieve such situation. It is more convenient to use higher differential temperature in order to obtain a higher signal to noise ratio (ratio of voltage differential signal ΔV to rms noise Vn) and calculate NETD using following formula:

$$NETD=\frac{V_n}{\frac{\Delta V}{\Delta T}}=\frac{V_n[mV]}{SiTF[mV/K]} \tag{3}$$

where SiTF (signal transfer function) is a linear part of an imager response function called also imager responsivity (Fig. 46).

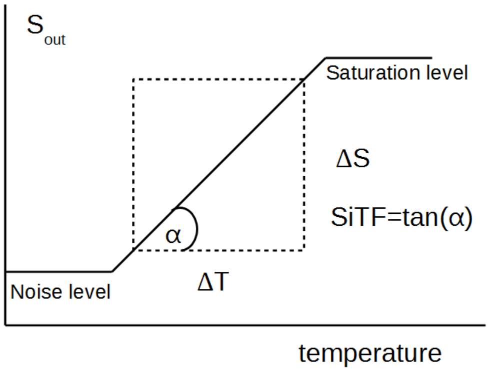


Fig. 46. Graphical concept of SiTF

It should be also emphasized that NETD defined in this way:

1. is a measure of only high frequency temporal noise of a single video line of old scanning thermal imagers,
2. the definition gives no information about the spatial noise between different video lines of scanning imagers.

Nowadays, old scanning thermal imagers have been totally replaced by modern staring thermal imagers. There is a general consensus that NETD of modern staring thermal imagers is a measure of temporal variations of brightness of all pixels within a certain 2D area (potentially total output image). Output brightness is typically measured in digital levels.

Therefore after changing analog voltage V (in Volt units) to more general term signal S (in digital level units) the formula (3) is converted to a new form:

$$NETD = \frac{N_{\mathrm{im}}[digL]}{SiTF[digL/mK]} \quad . \tag{4}$$

There is also an agreement that SiTF is to be measured by capturing an image of a blackbody at two different temperatures. One of these temperatures is typically equal to ambient temperature.

Further on, it looks that there is an agreement that reference test conditions are as follow [118,119]:

1. NETD to be measured for temperature of the blackbody equal to 300K,
2. measurement data is corrected to simulate case of ideal blackbody and collimator (emissivity of the blackbody is one, transmission of the collimator is one).

However, there is no agreement noise N_{im} is to be defined and measured. Different manufacturers of thermal imagers or manufacturers of test systems use slightly different definitions and measurement methods.

10.3.3 FOV

Field Of View (FOV) is an angular size of a scenery which image is created by thermal imager. FOV is typically of a rectangular shape and is expressed in a form of two angles: horizontal and vertical. FOV of a thermal imagers can vary a lot: from a fraction of degree (about 0.5°) to over 100°.

FOV is one of the most important parameters of thermal imagers. Wider FOV means wider area can be analyzed. It is easy to improve DRI ranges of thermal imagers by reducing FOV but it is state of art to improve DRI range while keeping wider FOV. Therefore, DRI comparison between imagers of different FOV should be avoided.

Thermal imagers are mostly used for long distance surveillance when distance imager-targets is thousand of focal lengths of objective of the imager. In other words, it can be assumed that approximately they are used for surveillance of targets located at so called optical infinity (Fig. 47). For such a situation FOV can be estimated as

$$\text{a)}\, HFOV = acrtg\left(\frac{H}{2f'}\right) \qquad \text{b)}\; VFOV = acrtg\left(\frac{V}{2f'}\right) \tag{5}$$

where HFOV is horizontal FOV, VFOV is vertical FOV, H is horizontal size of IR FPA sensor, V is vertical size of IR FPA sensor, f' is focal length of imager objective.

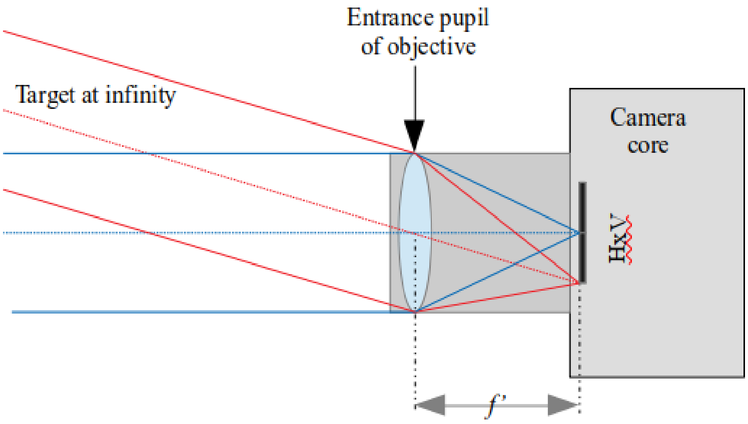


Fig. 47. Graphical relationship between imager FOV, objective focal length and size of IR FPA sensor-

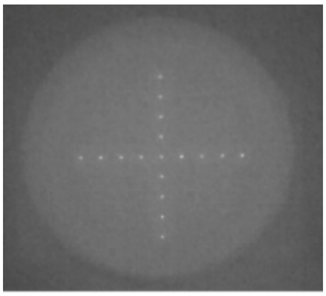


Fig. 48. Image of a cross target projected by collimator test system

FOV of thermal imagers is typically determined by software analysis of image of a cross target of know angular dimension projected by collimator test system (Fig. 48).

10.4 Parameters of critical importance

The trio parameters (MRTD, NETD, FOV) presented in previous section can called most popular because in author opinion at least 80% of tests of thermal imagers is made in form of measurement of these three parameters. However, there are two limitations of this crucial trio parameters:

1. The trio can well characterize image quality of thermal imagers working at laboratory conditions but say nothing about performance of imager working at extreme ambient temperatures.
2. The trio say nothing about image shifts/rotation relative to aiming mark that are extremely important for thermal sights used for shooting or targeting applications.

Therefore, there are two additional groups of parameters of critical importance:

1. athermality parameters
2. boresight parameters

10.4.1 Athermality parameters

Thermal imagers are typically tested at laboratory conditions, when both imager ambient temperature and temperature of background of the target of interest are equal to about 20ºC, in situation when in real life these two temperatures can vary in range from about -40ºC up to about +70ºC. This shockingly high difference between laboratory test conditions and real work conditions make difficult, or even impossible to precisely evaluate effectiveness of thermal imagers working at extreme temperatures on a basis of tests made at laboratory conditions.

In order to partially solve this problem, manufacturers of surveillance thermal imagers often carry out environmental tests of these imagers according to requirements of the popular MIL-810-STD military standard [120]. The tests are typically done by subjecting the imager located in a temperature chamber to a set of extreme ambient temperatures for a prescribed time period and later checking if there is negligible performance deterioration due to the environmental tests comparing to performance tests before the environmental tests. The notice about such tests can be often met in data sheets of surveillance thermal imagers [121-124]. However, results of such environmental tests according to MIL-810-STD standard give precise information only about the imager ability to survive a certain period of time at extreme ambient temperatures without substantial performance loss after the test is finished. These tests do not give information on real performance of tested imager when working at extreme work conditions.

It is a tempting solutions to characterize athermality of thermal imagers (stability of performance at variable work temperatures) using a set of MRTD functions measured at a series of different work temperatures in range from -40ºC to about +70ºC. However, there are important drawbacks of this solution. First, measurement of MRTD is time consuming even at typical lab conditions due to significant number of measurement points. Second, analysis of MRTD graphs measured at dozens of work temperatures would be difficult and time consuming.

In such a situation the author in a recent paper [74] has proposed to replace typical MRTD in form of one dimensional function for simplified MRTD in form of two number parameters. The latter number parameters describe extreme limits of MRTD function: imaging resolution and thermal resolution (Fig. 49). This solution shortens measurement time. Further on, in order to make analysis of measurement results easier, it has been proposed to normalize results of measurement of both imaging resolution and thermal resolution to values of these parameters measured at laboratory temperature (Fig. 50).

When measuring imaging resolution the aim is to find a target of highest spatial frequency for which bars can still be resolved. In contrast, when measuring thermal resolution the aim is to find what is minimal differential temperature of a large four bar target for which bars can still be resolved.

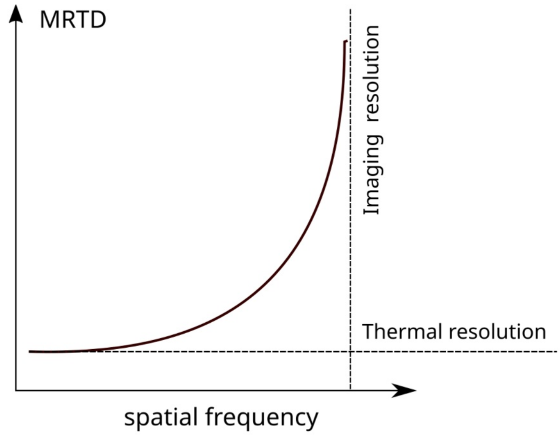


Fig. 49. Concept to determine two limits of MRTD function

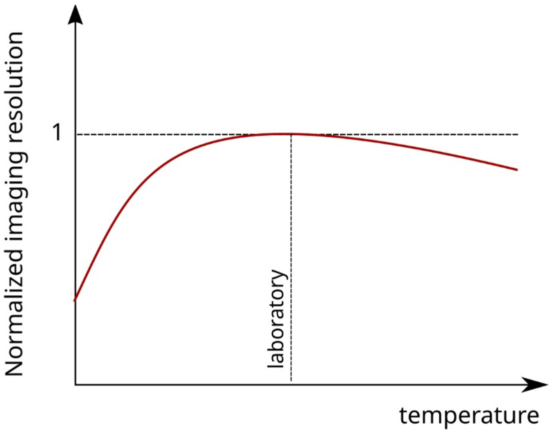


Fig. 50. Concept of normalization of measured resolution

The set of these two parameters give precise information needed to analyze stability of performance of thermal imagers in full range of work temperatures. As shown in Figs. 51-52 athermality of thermal imagers offered at international market vary a lot. There are thermal imagers of stable performance (imagers no 3-5) across entire analyzed range of work temperatures. However, there are also imagers (imagers no 1-2) of performance that deteriorate very significantly at extreme temperatures (below 0ºC or over 40ºC). In fact, there are many thermal imagers that cannot survive athermality tests and simply stop working at extreme work temperatures. Therefore, athermality tests in form of simplified MRTD measurement at variable ambient work temperatures are of critical importance. Only athermality test can determine real value of tested thermal imager to be used at extreme temperatures.

The conclusion is that tests using typical test systems (Figs. 40-41) carried out laboratory conditions cannot determine real value of tested thermal imagers. Athermality tests as presented in this section should be carried out using special versions of test systems (Figs. 40-41) capable to work at temperature chamber.

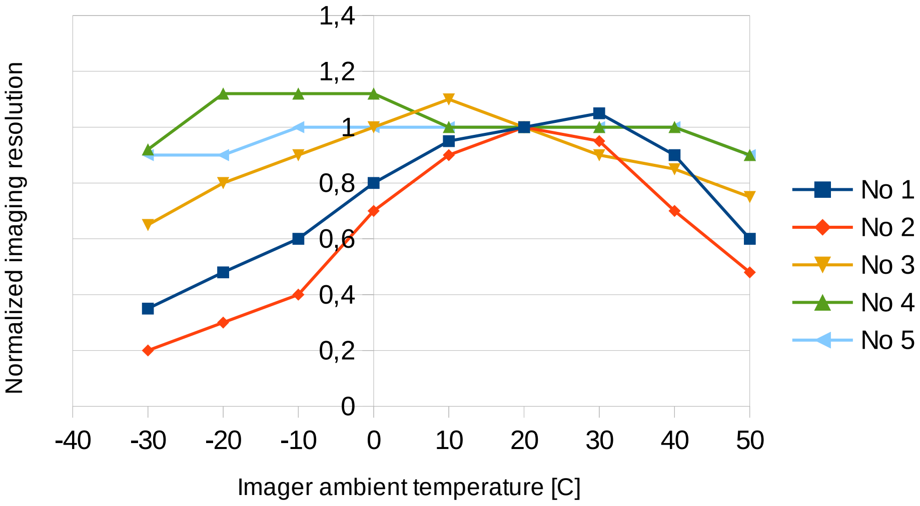


Fig. 51. Normalized imaging resolution versus imager work temperature for five exemplary thermal imagers [74]

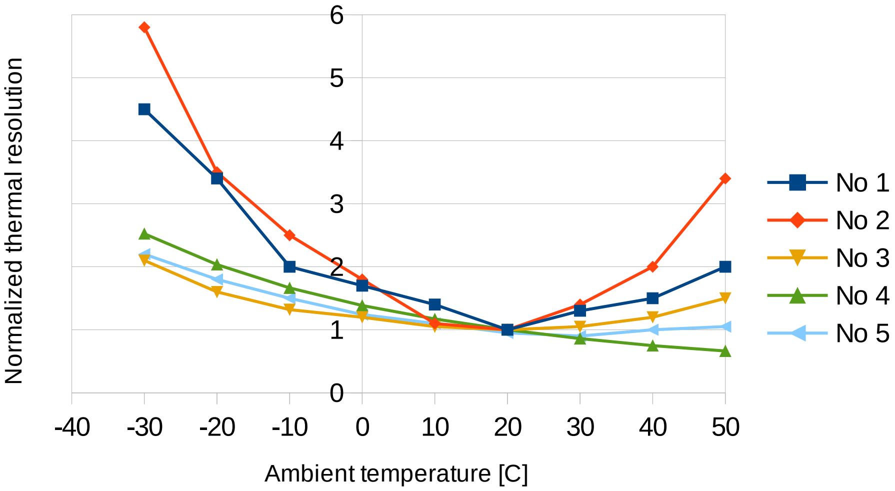


Fig. 52. Normalized thermal resolution versus imager work temperature for five exemplary thermal imagers[74]

10.4.2 Boresight parameters

A. List of boresight parameters

Boresight parameters are parameters that describe defects due to non perfect aligning of blocks of thermal imager or thermal imager relative to external imager/laser that reduce shooting/targeting accuracy of thermal sights or multi sensor targeting systems built using thermal imagers.

There are at six boresight parameter (errors):

1. zoom/step FOV through (valid only for variable FOV thermal imagers)
2. focus through (valid for all focusable thermal imagers),
3. deflection angle (valid for optical output imagers)
4. thermal imager to reference mechanical axis/plane (valid for thermal sights having reference axis/plane)
5. thermal imager to VNIR/SWIR imager (valid for thermal imagers used in multi imaging systems)
6. thermal imager to laser(valid for thermal imagers used in multi-sensor imaging/laser systems)

B.Zoom/step FOV through

Zoom/step FOV through describes angular shift of output image when zooming/step changing FOV. Zoom through error is typically measured as maximal angle between targets (pixel positions) indicated by aiming mark at two settings of zoom objective/step FOV. Measurement result can be presented in pixels or in angular units normalized for optical objective working at NFOV mode.

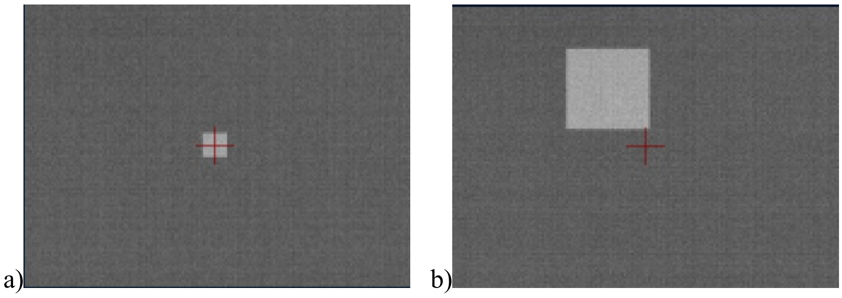

a) b)

Fig. 53. Image of the same square target generated by a thermal imager at two different magnifications of zoom objective a)image at WFOV mode, b)image at NFOV mode

C. Focus through error

Focus through describes angular shift of output image when changing focus due to variable distance to target of interest. Focus through error is typically measured as angle between targets (pixel positions) indicated by aiming mark at two settings of focus mechanism of optical objective. Measurement result are presented in pixels or in angular units normalized for optical objective focused at infinity.

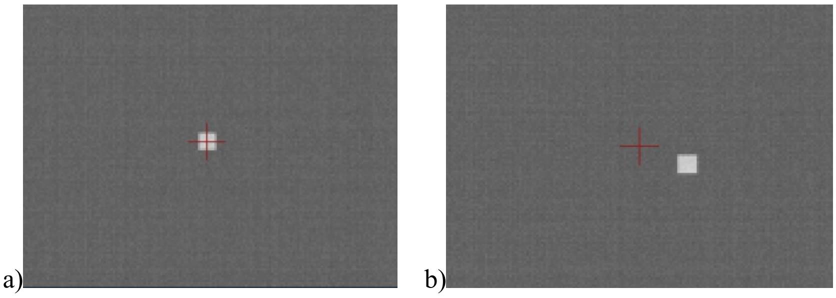

a) b)

Fig. 54. Image of the same square target simulated by a collimator for two distances and generated by a thermal imager at two positions of focusing mechanism: a)image of a target at infinity distance, b)image of a target at simulated 100m distance (extreme case of objective having faulty focusing mechanism)

D. Deflection angle

Deflection angle is an angle between axis of light beam incoming to optical objective of thermal imager and axis of light beam emitter via ocular of thermal imager. In case of thermal clip ons the deflection angle can be also defined as angular shift of image seen by human observer when clip ons is inserted on its position before/after telescopic sight. This parameter plays crucial importance to evaluate real performance of thermal clip ons.

E. Imager to reference mechanical axis error

imager to reference mechanical axis error is to be defined in different ways depending what type of reference mechanical plane/axis is used by the imager:

1. Angle between imager line of sight and a mechanical axis perpendicular to reference front wall of thermal sight (case of thermal sights having reference mechanical front wall)
2. Angle between imager line of sight and a mechanical axis of bottom mechanical mount for riffle rail (case of small thermal scopes to be used at small arms,

F. Thermal imager to VNIR/SWIR imager error

Imager to imager error can be defined in two ways. First, angular shift between centers of images generated by two imaging systems (for example thermal imager and VNIR camera). Second, angle between targets indicated by aiming marks of two imaging systems. This boresight error is expressed typically in angular units like mrad.

G. Imager to laser error

Imager to laser error can be defined angle between target indicated by aiming mark of thermal imager and a target indicated by center of laser beam emitted by laser system (transmitter of LRF/laser designator, laser pointer). This boresight error is expressed typically in angular units like mrad.

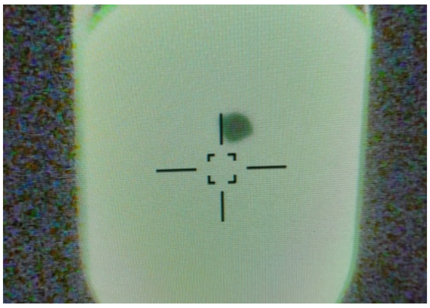


Fig. 55. Image of laser sensing card irradiated by LRF relative to aiming mark of thermal imager

H. Importance of boresight parameters

The author has added boresight parameters to a narrow group of critical performance parameters of thermal imagers. However, these parameters are truly important only for some of thermal imagers

1. Zoom/step FOV through error is a negligible cosmetic defect for typical surveillance imagers (thermal viewers). It becomes critically important only for high end thermal sights used to support shooting or in targeting applications.
2. Typical targets of interest for thermal sights are typically medium/long distance targets. There is no need to focus on and shoot to short distance targets. Due to small focus change at shooting conditions focus through error is typically negligible for such small focus change even if it becomes noticeable for wider focus change from minimal focus distance to optical infinity.
3. Deflection angle is a boresight error of critical importance only for narrow groups of thermal imagers: thermal clip ons. For other types of thermal imagers like thermal scopes, thermal monoculars it is a minor defect.
4. Thermal imager to VNIR/SWIR imager error is important only for thermal imagers used in multi imaging systems used in targeting applications. If such multi imaging system is to be used only for imaging applications then boresight errors even up to 1 degree is commonly acceptable.
5. Thermal imager to laser error is important only for thermal imagers used in multi imaging/laser systems used for targeting applications.
6. Thermal imager to reference mechanical axis error is important only for case of thermal sights having such reference mechanical axis/plane.

To summarize, boresight parameters are not related to quality of output image like image quality parameters (MRTD, MTF, focusing parameters). Therefore boresight parameters (errors) are important only for specific type of thermal imagers: mostly for thermal sights used to support shooting or in any other targeting applications.

10.5 DRI ranges of thermal imagers

The long series of parameters listed in Table16 present detailed information about performance of thermal imagers. However, evaluation of thermal imagers on the basis of measured long list of parameters is potentially acceptable for manufacturers, but not for final users, especially for military customers. The latter group prefers simple, easy to interpret parameters. Due to this reason, performance of surveillance thermal imagers is commonly characterized by three ranges of effective surveillance. The ranges are defined as the maximal distance at which a selected object can be seen and perceived following three surveillance task perception criteria: detection, recognition, identification. The rules is simple: longer DRI ranges – better thermal imagers.

There is very numerous literature on subject of calculation of DRI ranges of thermal imagers. Hundreds of papers related to this subject can be found only at SPIE Digital Library. Therefore here only simplified summary about five most popular models are to be presented:

1. Johnson method,
2. STANAG 4347 method,
3. TRM4 model,
4. TOD model,
5. NV-IPM model.

According to Johnson model, the task perception criteria are related to ratio of angular size of target of interest and angular size of pair bar of minimal bar target that can be resolved using tested imager [112]. In detail, DRI ranges can be calculated using following equation

$$\text{DRI range= R when } R=\frac{X_T(R)}{k\cdot\alpha_{min}}, \tag{6}$$

where R is imager range in kilometers, X_T is angular size of a target of interest (typically assumed to be square equivalent to the target area) in mrad unit, αmim is angular size of pair of bars of smallest resolution target that can be resolved using the imager (in mrad unit), and k is coefficient that depends on type of range (k=1 for detection range, k=4 for recognition range, k=6.4 for identification range – attention recommendations vary depending to literature).

The bar width of the resolution target is typically approximately equal to angular size of pixel of IR FPA sensor used in thermal imager. Therefore, the angular size of a pair of bars α_{mim} in (6) is typically replaced by an angular size of pair of pixels of IR FPA sensor.

STANAG 4347 method can be treated as improved Johnson criteria method [125]:

1. Measured two dimensional characteristic MRTD (minimum resolvable temperature difference) replaces a single value parameter (angular size of pair of bars of smallest resolution target α_{mim}) to characterize thermal imager,
2. Atmospheric transmission and target thermal contrast are taken into account in contrast to previous method.

TRM4 range model can be also treated as significantly improved Johnson method due to two main changes:

1. Measured two dimensional characteristic MTDP (minimum temperature difference perceived) replaces angular size of pair of bars of minimal resolution target to characterize thermal imager,
2. Atmospheric transmission and target thermal contrast are taken into account in similar manner like STANAG 4347 method, but the atmospheric model is more advanced.

TRM4 model, including MTDP concept, has been developed and is still promoted by Fraunhofer Institute of Optronics, System Technologies and Image Exploitation IOSB, Germany [126]:].

TOD model differs significantly comparing to Johnson method, and related STANAG 4347 method and TRM4 model. All previously discussed DRI models are based on a use of 4-bar resolution target. Use of such targets generate phase problems (results depending on position of test targets) when testing undersampled imagers. To overcomes this problem, Netherlands TNO Human Factors Research Institute has proposed to characterize performance of thermal imagers by measurement of a characteristic called Triangle Orientation Discrimination (TOD) based on use of triangle targets [127]. TOD gives the temperature difference that allows an observer to identify the orientation of an equilateral triangle with a probability of 75 %. DRI ranges are later calculated on basis of measured TOD function using rules similar to Johnson method.

The Night Vision Integrated Performance Model (NV-IPM) has been developed by U.S. Army Combat Capabilities Development Command (DEVCOM) [128,129]. The primary application of this model is the calculation of human performance metrics (DRI ranges) like previously discussed models. However, there are two main differences of NV-IPM model comparing to other DRI models. First, all previously discussed DRI models use single input parameters (angular size of pair bars of resolution target, MRTD, MDTP, TOD) to characterize thermal imager as a whole. NV-IPM uses a series of input parameters that characterize blocks of thermal imager. Second, all previously discussed DRI models use some form of Johnson criteria to characterize task perception criteria. NV-IPM uses concept of Targeting Task Performance (TTP) metric. An empirically derived Target Transfer Probability Function (TTPF) is used to relate probability of task performance to the ratio of $N_{resolved}$ to V_{50}, where V_{50} is the metric value needed to accomplish the task with a 0.5 probability. Again, V_{50} is established experimentally for specified type of targets of interest.

To summarize, there is no universally accepted method to determine DRI ranges of thermal imagers. There are five main methods to determine these ranges but these methods can be used in many variants. In addition there are also less popular methods not listed in this section. The result is that DRI ranges presented commonly in data sheets of thermal imagers can be calculated using dozens details methods that generate significantly different results. Therefore, DRI ranges can deliver precision information about imager performance only if the calculation method is specified in detail.

The author personally prefers STANAG 4347 method that is the only method for calculation of DRI ranges of thermal imagers supported by official standard of international organization. Presenting in a tender precise rules for DRI calculation of a target of interest according to this standard avoids chaos and to allows comparison of DRI ranges between all offered thermal imagers [111].

11. Future trends of thermal imaging

In commercial terms future of thermal imaging technology looks bright, or even very bright. All market analysis predict annual growth at level between 7% and 9% in period of next present decade [130-132]. In author opinion, the real growth shall be actually higher due to four main factors.

First, bigger orders can be expected from defense/security sector due lessons from recent wars that have proved extremely high value of thermal imagers for modern military.

Second, there is a growing trend for mass use radiometric thermal imagers in machine vision applications to enable non contract temperature measurement at production lines.

Third, low cost thermal imagers for automotive industry are becoming increasingly accepted by main automotive manufacturers as necessary tool of modern cars to increase security of drivers at night conditions.

Fourth, it can be predicted that future artificial intelligence/humanoid robots shall use thermal imagers to enhance their vision.

After this brief outlook of commercial situation let us analyse what major technical trends of thermal imaging technology can be expected in near future.

It can be logically expected that general aim of technology trends of thermal imaging technology will be the same as aims of improvements of any product offered at international market: to increase ratio of product capabilities or to decrease manufacturing costs.

In author opinion, ten main directions of development of thermal imaging technology can be expected in future:

11. Automotive thermal imagers,
12. Long life, small weight, low power cooled thermal imagers based on HOT photoelectric IR FPAs,
13. High sampling thermal imagers based on ultra small pixel IR FPAs,
14. Ultra high image resolution thermal imagers based on large IR FPA sensors,
15. Fusion thermal imagers,
16. Renaissance of cooled LWIR thermal imagers for military applications,
17. Super-range thermal imagers,
18. Folded thermal imagers,
19. Space thermal imagers for Earth observation,
20. Moderate performance, mass production, low cost thermal imagers.

It should be noted that the directions no 2-5 agree with predictions of IR FPA community for future of these image sensors [133].

11.1 Automotive thermal images

Automotive thermal imagers are thermal imagers optimized to deliver driving assistance at night and/or at low-visibility environment; or to work as imaging sensors of autonomous driving systems. In both types of application the main aim is to improve driving safety by recognizing pedestrians and vehicles and generating early warnings signals for human/robot drivers.

Driving assistance can be delivered in two main forms. First, by providing thermal images of in-road scenario that are to be analysed by the driver. Second, thermal imager works as part of ADAS (advanced driver assistance system) and driving is partially controlled by software of this driving assistance system.

In case of automotive thermal imagers used in autonomous driving systems the real driving is carried out by a robot optimized to function as a driver (optionally at AI level).

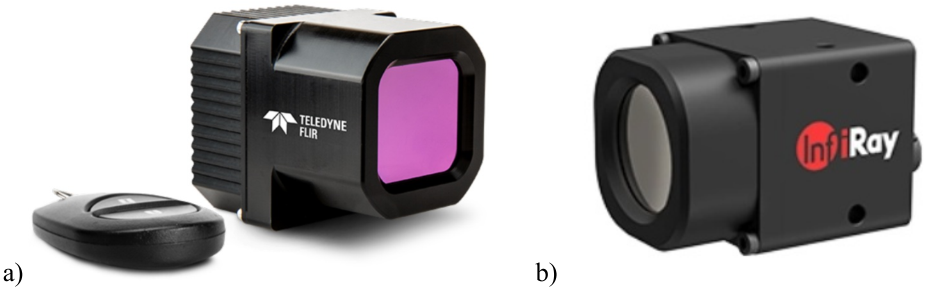
Automotive thermal imagers are known for at least two decades. However, in past due to relative high cost and limited performance (only low resolution thermal images available) they had been used only in high-end cars/trucks as exotic technical novelty. Nowadays, due to lower manufacturing cost and technology improvements (higher resolution images, advanced software) number of automotive thermal imagers installed in newly sold vehicles is rising quickly. Therefore it can be expected in near future that automotive thermal imagers can become a huge market comparable to market of military/security thermal imagers.

The main technical reason for this predicted fast growth of automotive thermal imagers is technical superiority of thermal imaging over competing technologies (passive/active VNIR cameras/SWIR imagers, LIDARs). Thermal imaging is practically the only technology enabling reliable detection/classification of humans in cluttered environments at required safety distance due to two main advantages. First, natural positive high contrast of humans/vehicles due to their higher temperature. Second, ability to see at night and low visibility conditions. Third, thermal imagers are non sensitive to glare from Sun or artificial sources (other vehicles).

From technical point of view automotive thermal imagers can be described using a set of twelve features (Fig. 56):

1. non radiometric (surveillance type) imagers that deliver image of brightness that depends on differential temperatures of targets in imager FOV,
2. electronic output imagers – output image is delivered in form of electronic video signal,
3. short range imagers– typical maximal range of detection human target is not more than 300 m (typically lower),
4. wide FOV imagers – typical FOV of automotive imagers is over 20º,
5. uncooled LWIR imagers – cooled imagers are too expensive and not needed for this short range application,
6. non-focusing – in order to reduce costs non-focusing optics is used,
7. athermal imagers– automotive thermal imagers must work at wide ambient temperature range from about -40ºC (extremely cold winter) to about +70ºC (direct Sun irradiation at summer conditions),
8. miniaturized imagers – miniaturization is needed due to mechanical constraints of front part of mechanical vehicles,
9. advanced tools for spatial noise corrections – simple slow shutter method cannot be used as it generates noticeable period when there is no image. Fast shutter method or scenario-based non-uniformity correction method are needed,
10. cooperating with advanced software for driving assistance/ autonomous driving – old generation automotive imagers capable only to generate output image are not acceptable nowadays as tools for driving assistance. Software capable to convert thermal imager into advanced driver assistance system (ADAS) or autonomous vehicle (AV) system is needed.
11. imagers with heated window – this tool can enable all-weather driving by eliminating water vapour/frost condensation,
12. low cost – price of automotive thermal imagers cannot increase significantly cost of mechanical vehicles if such imagers are to be used in mass manufactured vehicles.

Design of automotive thermal imagers is extremely difficult. Technically they are similar to military imagers due to the same ultra wide ambient work temperature range but commercial price of these imagers is to be several times lower. However, automotive thermal imagers represent a potentially huge market. Therefore, it can be expected that vehicles equipped with thermal imagers will become common solution in near future and number of such imagers shall continue to be rising quickly.



a) b)

Fig. 56. Two exemplary automotive thermal imagers: a) FLIR ADK™ thermal imager from Teledyne-FLIR Inc., 2) IR-Pilot640X/M thermal imager from Infiray Inc.

11.2 Long life, low size/weight/power cooled thermal imagers

Market of high performance medium/long range thermal imagers is dominated by thermal imagers built using cooled photoelectric IR FPAs. Thermal imagers built using photoelectric FPAs offer can offer frame rate at level up to 1000 FPS or more when maximal frame rate of uncooled thermal FPA is about 60 FPS. However, the latter speed is totally acceptable in great majority of applications of cooled thermal imagers. Therefore, in spite of popular opinion the real advantage of cooled photoelectric thermal imagers is not speed but it is good sensitivity (low NETD at level below 30 mK) even when working with dark optics of F-number in range 3.5-5.5. Such optics (especially zoom optics) is simply much cheaper comparing to bright optics of F-number in range 0.9-1.5 needed for uncooled thermal imagers. However, there are also some important drawbacks of cooled thermal imagers.

All typical photoelectric IR FPAs that dominate market for at least three decades (HgCdTe/ InSb/QWIP sensors) need cryogenic cooling to temperature about 80 K. Cooling to this temperature improves detectivity by at least two magnitudes comparing to work at laboratory temperature.

Cooling large IR FPA sensors to so low temperature as 80 K requires use of costly, relatively big (dimensions about 125×70×30 mm, mass about 450 g), high power consumption (steady state power consumption over 5 W) Stirling coolers.

Significant power consumption (peak consumption can be over 15 W) is another big drawback of cooled imagers. Such power consumption level is negligible for imagers powered from mains but is a challenge for battery powered systems.

Finally, most of cryogenic coolers are also characterized by modest life time (MTBF up to 10000 hours) and what is sometimes even more important the cooler cannot be exchanged by the user after imager breakdown. This MTBF value looks apparently high but such life time is not sufficient in case of imagers working 24 hours per day as in many defence/security applications. It means that user can expect problems at time intervals only slightly higher than one year; sometimes earlier. Potential manufacturer service in form of replacing the cooler means not only considerable costs (as high as 10% of imager price) but means also time periods when thermal imager does not work and additional logistical problems to carry out cooler service at different geographical locations.

In such a situation it is not surprising that during last three decades due to pressure from military customers a lot of efforts have been done by scientists worldwide to develop photoelectric FPAs sensors that do not require cooling (work at ambient temperature) or to be capable to accept non-cryogenic cooling (sensor temperature at level about 150K). A long series of different techniques have been analysed: photoconductor detectors, photoelectromagnetic detectors, excluded photoconductors extracted photodiodes magnetoconcentration effect detectors, detectors with optical immersion, photon trapping detectors, cascade infrared devices, InAs/GaSb type-II superlattice (T2SL), type II strained-layer superlattices (T2SLSs), and bulk barrier detectors such as nBn devices [134,135]. For many years only rather poor results have been obtained: scientific publications but no real products. However, recently (period of last three years) the latter three technologies have improved significantly, and IR FPA sensor built these methods have started to be offered commercially [136,137]. Such FPA sensors (called HOT cooled FPAs) also used in serially manufactured thermal imagers [137,138].

InAs/GaSb type-II superlattice (T2SL) are sensors where superlattice is formed by alternating the InAs and GaSb layers over several periods [139].

The Gallium-free InAs/InAsSb type-II strained-layer superlattice (T2SLS) is an adjustable band gap, broadband III-V infrared detector material [140].

nBn is an IR photodetector of structure type nBn in which the barrier layer (BL) is sandwiched between an n-type semiconductor, which is a contact layer (CL), and an n-type absorber [141].

All three technologies differ a lot but the common feature is non-cryogenic work temperature that has enabled use of miniaturized Stirling coolers, lowering their power consumption, some increase in cooler life time (Table 17, Fig. 57). Additional bonuses of use non-cryogenic coolers are reduced cooler price and potential maintenance of such coolers by well trained team at customer workshops.

Table 17. Parameters of two commercially available microcoolers: a) K508 for traditional cryogenic IR FPA sensors; b)K580 for HOT IR FPA sensors [142]

Parameter	K508	K580
Total cooling power	550mW@80K	600mW @110K
MTBF	15000 hour	17000 hour
steady state power consumption	5.5W at 80K	1.5 W at 150K
Cooldown time @23°C	5 min @ 80K	3 min @ 150K
Cold tip temperature	65-110K	130-150K
Cooler/controller weight	450g	215g

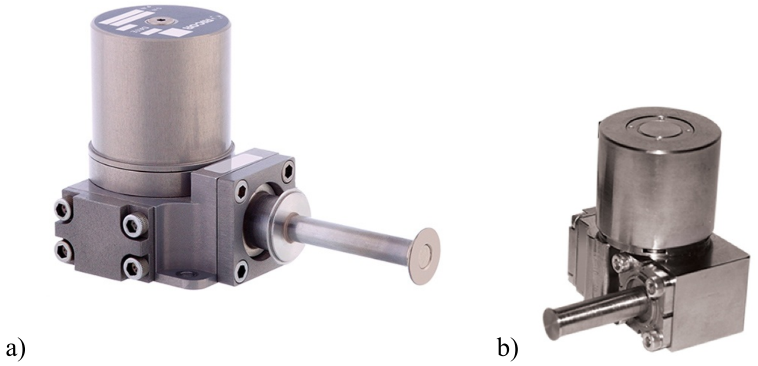

a) b)

Fig. 57. Two Stirling microcoolers: a)for cryogenic HgCdTe FPA sensor (Scorpio from Lynred), b)for HOT T2SL FPA sensor

To summarize, after decades slow progress technology of HOT photoelectric IR FPAs has crossed recently commercialization level and market share of cooled thermal imagers based on HOT FPAs is expected to increase quickly. High tech portable thermal imagers are expected especially to profit from this new technology.

11.3 High sampling thermal imagers

IR FPA image sensor is a system that does spatial sampling of image generated by IR objective. The sampling is carried out at so called Nyquist frequency that is equal to inverse from pair of pixel pitch. When the highest spatial frequency of optical image is lower or equal to the Nyquist frequency of the sampling systems (IR FPA sensor) then the optical image can be recorded perfectly without any distortion known as aliasing.

It is also commonly known that maximal spatial frequency of optical signals that describe image generated by IR objective is determined by optics diffraction effect and can be calculated as an inverse of product of mean wavelength and optics F-number (ration of focal length to diameter of exit pupil). This max frequency can be also interpreted as spatial frequency when diffraction MTF of optics drops to zero.

Therefore, pixel pitch of IR FPA sensor should be optimized for a task to sample image generated by imager optics. Sampling frequency (pixel pitch of IR FPA) cannot be too low (case of under-sampling imager) because IR FPA sensor cannot read all details of image generated by imager optics. Sampling frequency should not be too high (case of oversampling imager) because then IR FPA sensor is capable to read details so small that cannot be generated by imager optics. The minimal pixel pitch of IR FPA sensor optimized for effective spatial sampling of images generated by imager optics can be calculated using equation (7):

$$NF=\frac{1}{2d}=\frac{1}{\lambda F} \quad \rightarrow \quad d=\frac{\lambda F}{2}, \tag{7}$$

where NF is Nyquist frequency of IR FPA sensor, λ is mean wavelength and F is optics F-number, and d is pixel pitch.

It should be noted here that formula (7) derived here using simple logic based on signal sampling theory and optics diffraction theory is the same as formula derived by IR PFA community for minimal pixel pitch that generates increase in range of effective surveillance using sophisticated mathematical model to simulate thermal imagers [143].

If we assume typical mean wavelength for thermal imagers (4 μm for MWIR imagers or 10 μm for LWIR imagers), and bright optics of F-number equal to one then we can calculate minimal effective pixel pitch of IR FPAs as equal to 2 μm for MWIR band and 5 μm for LWIR band. Practically, it is technically very difficult to design ultra bright (F number equal to 1) diffraction limited objectives. Therefore, to set more realistic aims it is reasonable to assume F1.2 optics and then the minimal pixel pitch equals to 2.4 μm for MWIR FPAs and 6 μm for LWIR FPA.

At present majority of manufactured IR FPAs has pixel pitch at level 15/17 μm. Image sensors of smaller pixels at level 10/12 μm are still market novelty. It means that thermal imagers used nowadays are still undersampling imagers that are not capable to capture all details of images created by perfect, diffraction limited bright IR optics. The low values of minimal effective pixel pitch (almost two times below mean wavelength) indicated by (7) even for case F1.2 optics shows huge potential (especially for MWIR imagers) to increase range of effective surveillance of thermal imagers by traditional way of decreasing of pixel pitch of FPA sensors. Therefore, the original paper that presented theory on limit on minimization of pixel of IR FPAs has generated considerable enthusiasm of IR FPA community about bright future of so called small pixel FPAs with pixels close to the limits determined by (7) [144-146]. In detail, FPAs with pixels below wavelength are considered by some FPA scientists as oversampling image sensors but it is not precisely true according to original sampling signal theory.

Use of such ultra small pixel FPAs (pixel pitch in range of 2.4-4 μm for MWIR band and 6-10 μm for LWIR band) and building high sampling imagers is supposed to bring a series of benefits:

1. smaller manufacturing costs (more sensors from the same wafer or the same number of sensors but with higher number of pixels),
2. higher range of surveillance,
3. smaller size and power consumption comparing to present day imagers. 12/10 μm FPAs.

All these predictions are apparently based on very sound logic. First, there are mathematical models that clearly show that it is possible to get increase of surveillance range by decreasing pixel pitch of FPA sensors up to limit when effective diffraction blur is two times higher than pixel pitch [143].

Second, ultra small pixel IR FPAs have already been manufactured as test devices by a number of manufacturers [144-145]. The projects on development of ultra small pixel FPAs have been supported by DARPA [145].

However, the author still have serious doubts about ratio of performance gains to manufacturing costs of thermal imagers built using on ultra small pixel FPAs and bright optics.

First, the formula (7) of this paper and findings in Figs. 6-7 from Ref. 143 are based on two non realistic assumptions:

1. aberration free optics,
2. target of high thermal contrast (or noise free imager).

However, practically aberration MTF of the optics is comparable to optics diffraction MTF even for so called diffraction limited objectives offered at the market. Further on, thermal imagers are often used for surveillance against long distance targets that appear as low contrast targets (differential temperature below about 2ºC).

Second, there are also some commercial limitations for manufacturing optics needed by high sampling thermal imagers. Present day high tech MWIR imagers are built using dark zoom optics (F-number in range from 3.5 to 5.5) in situation when ultra bright zoom optics of F-number not higher than 1.2 is needed for new high sampling imagers. It is very difficult and costly to design ultra bright diffraction limited zoom optics. Therefore, the author estimates that ultra bright optics of F-number below 1.2 shall be manufactured only for short/medium range imagers that use relatively small 1-FOV optics. Optics of F-number about two (including zoom objectives) can be expected for medium/long range imagers.

The economic prospects look much better in case of non cooled LWIR imagers. They have already been built using ultra bright optics of F number as low as 1. Therefore only some quality improvements (near total reduction of aberrations) is needed to enable use in optimal sampling thermal imagers. However, it should be noticed that in case of LWIR imagers the theoretical gains of use of optimal sampling imagers are not as big as in case of MWIR imagers.

To summarize, high sampling thermal imager built using ultra small pixel IR FPAs offer potential design of thermal imagers of significantly increased surveillance range without increase of imager mass/size. However, these potential capabilities must be verified by design and tests of real high sampling imagers to evaluate true performance/cost ration of such imagers.

11.4 Ultra high image resolution thermal imagers

Increase of image resolution means continuation of an old trend to increase number of pixels of IR FPA sensors. It enables to increase of FOV of thermal imagers in situation when this parameter is of utmost importance for military thermal imagers, especially imagers used for automatic targets recognition in air defense systems.

There have already been reports on fabrication cooled photoelectric IR FPAs of resolution as high as 2048×2048 [133] and microbolometer FPAs of image resolution 2048×1536[146]. However, it is uncertain when such ultra high resolution FPAs shall pass to serial production phase and be offered on the market. As a warning should be noted that there is a big discrepancy between image resolution of IR FPAs presented in scientific papers and image resolution of IR FPAs offered on the market.

There has been published also a paper that suggests even that development of new ultra high resolution IR FPAs (a large chip with very high number of detectors) shall eliminate use of optical zoom optics to regulate FOV of thermal imagers [143]. Costly, bulky, and slow optical zoom objectives are to be replaced by electronic zoom in form of software.

This scenario has already materialized in case of typical digital photo cameras (including phone cameras) where old cameras based on low resolution CMOS sensors (pixel number below 1 Mpx) combined with a zoom objective of variable focal length has been replaced by cameras based on based on ultra high resolution CMOS sensors (pixel number over 10 Mpx), simple 1-FOV optical objective and low resolution display. The latter cameras enable regulation of magnification of image seen at camera display by use of electronic zoom software. Here it must be emphasized that we talk not about old type quasi electronic zoom when software increase artificially number of pixels in order to magnify image. Modern electronic zoom is a method to regulate image magnification (imager FOV) by presenting variable size centre part of high resolution image generated by image sensor on a lower resolution display. Minimal magnification (max FOV) occurs when full image from the sensor is presented; maximal when only small centre part is presented.

In author opinion, this prediction is unlikely to materialize in near future because situation in VNIR cameras differs much from situation in thermal imaging.

Maximal true magnification of electronic (software) zoom Mmax can be calculated using simple formula (8)

$$M_{(max)}=\frac{SHR}{DHR} \tag{8}$$

where SHR is sensor horizontal resolution (in pixels), and DHR is display horizontal resolution (in pixels).

IR zoom objectives offer typically regulation of magnification (FOV) from 1 to 10 or even 20 in case of cooled MWIR imagers or 4-7 times in case of objectives of uncooled LWIR imagers.

As can be seen in Table 18 design of thermal imagers that offer regulation of image magnification (FOV) at range similar to optical zoom is totally impossible in near future due to necessity to use very high image resolution IR FPA sensors. In detail, present day IR PFA technology enables to develop electronic zoom of magnification not more than two times. It is very low level comparing to magnification of zoom objectives (10-20 times). However, in long terms (several decades) it is probably that high resolution thermal imagers with high magnification electronic zoom shall be developed.

Table 18. Maximal magnification of digital zooming of potential thermal imagers based on ultra high resolution FPAs and lower resolution displays

	Display resolution [px]		
Sensor resolution	640×480	1024×760	1280×1024
640×480	1.0	N/A	N/A
1024×760	1.6	1.0	N/A
1280×1024	2.0	1.3	1.0
2560×2048	4.0	2.5	2.0
5080×4096	7.9	5.0	4.0
10160×8188	15.9	9.9	7.9

To summarize, it should be expected in near future that image resolution of thermal imagers shall increase at least 2 times over typical so called TV resolution level (640×480 pixels). However, it is too low resolution to eliminate the need to use optical zoom objectives.

11.5 Fusion thermal imagers

As discussed in Section 9.7 multi-imaging systems (thermal imagers integrated typically VNIR cameras or more rarely with SWIR imagers) are a fast growing group of EO imaging systems. These multi imaging systems can deliver image of scenery of interest in two (or more) spectral bands. User can choose preferred spectral band: thermal image, VNIR image or SWIR image.

In such multi imaging systems user can see at one moment only image from one channel presented on system display, more rarely user can see output images at several displays or on one divided display.

These multi imaging systems have proved to be extremely useful for surveillance applications but have also some limitations. The main drawback is necessity for human observer to do cyclic jump of visual concentration from one display to another or at least from one part of display to another part. This drawback limits significantly effectiveness of typical multi imaging systems but can be eliminated by use of fused imaging systems.

From hardware point of view fusion imaging system are basically typical multi imaging systems with software capable of analyzing video images generated by two (or more) sub-imagers, and do fast fusion of these images into one fused video image that combines most valuable information delivered by images generated by different sub-imagers. Thermal imager is typically the most important and expensive part of such fusion imaging systems and such imaging systems are often called fusion thermal imagers.

Human eye can be treated as a good example of fusion imaging systems. Electro-optical systems of human eye generate three images in different spectral bands (blue, green, red) but human brain combines these images into one output colour image.

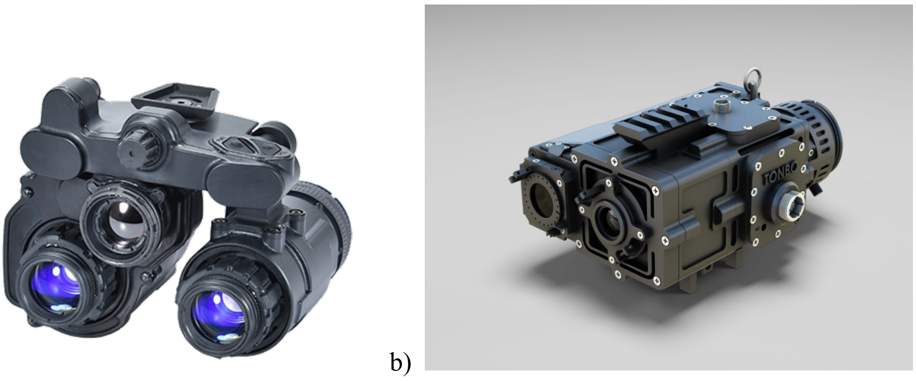
Fusion imaging systems imagers are theoretically much better comparing to typical multi imaging systems operated by humans. It is simply much easier to detect target of interest indicated by high contrast/colour in fused image comparing to typical low contrast original images. These advantages are not as high in case of automatic target recognition systems that are capable to do live analysis of several video images but still some image fusion is useful.

Fused thermal imagers in different forms (fused night vision googles, fused sights, fused monoculars, fused thermal binoculars) are known for at least two decades. Promotional images generated by fusion imaging systems in form of high contrast/bright colour image that clearly indicate detected thermal target located at visible band background can be found in many internet websites. Fused thermal imagers are offered by a long series of companies [147-149]. Further on, there is a very numerous literature on thermal image fusion [150-153]. Therefore, it can be surprising to readers of this book to find fused thermal imagers as future trend of thermal imaging technology. The main reason is that in author opinion present day fusion technology is at beginner stage.

There are two main techniques to fuse images (Fig. 58):

1. optical fusion
2. electronic (digital fusion).

The first fusion imagers do fusion by combining two optical images using a special merge optical system (a kind of inverse beam splitter). The second type fusion imagers do fusion by capturing electronic video image from two channels, do image analysis, and generate a new fused video image.



a) b)

Fig. 58. Examples of present day fusion technology: a)Binocular night vision device BNVD-Fused from L3Harris (optical fusion), b) Fusion Thermal Weapon Sight Cobra from Tonbo Imaging (electronic fusion)

Apparent design simplicity of optical fusion imagers is an advantage of the first group. However, such fusion imagers suffer typically from non accurate alignment of two optical images that generates noticeable blurring or image shifts and future is rather bleak for this group of fusion thermal imagers.

Situation in case of electronic fusion imagers is much better due to possibility to do advanced image processing to achieve better image aligning and pinpointing targets of interest. However, the electronic fusion imagers still suffer from non accurate alignment of two images. The author tested a series of fused imagers (both optical fusion and electronic fusion) and has found that imager MTF is typically significantly worse when test is done on for fused image. It explain that some users of thermal fusion imagers are not satisfied with performance of fusion channel and switch to use thermal channel or visual channel. However, methods of electronic fusion have improved recently from level of product of scientific projects to level of reliable commercial products. Some of big manufacturers of thermal imagers offer now image signal processing software development kit (SDK) for embedded systems that can do advanced image fusion (thermal and visual) and other functions like noise reduction, super-resolution, electronic image stabilization, turbulence mitigation [154]. Therefore the author expects that ultra advanced electronic output fusion thermal imagers shall become a popular tool in both automotive industry (advanced driver assistance systems, autonomous vehicle systems), and military/security applications (scene surveillance, target recognition and object tracking) in near future. However, the real revolution in technology of fusion thermal imager is to come in longer future.

Present day fusion thermal imagers are basically two separate imagers: thermal imager and VNIR camera. Practically it means two imaging systems that differ a lot (FPA of different pixels, optics of different axis and magnification). Advanced software can align these two images to some degree but there will always be some limit at pixel level. Aligning two images at sub-pixel accuracy for full area of two images is rather not possible. Therefore real big progress can bring use of dual band FPA sensors in form of two overlapped image sensors capable to generate at the same time two images of different spectrum (thermal and visible image). Perfect aligning of these two images can be achieved because both images are created by the same image sensor. There is noticeable progress in FPA technology for multi band FPAs and such advanced fusion systems built in form of multi-band overlapped FPA and a single broadband optical system can become reality in future.

Fusion imaging can be also treated as important part of augmented reality technology. The Integrated Visual Augmentation System (IVAS) developed by Microsoft for the United States Army can be treated as example of augmented reality headset that improves situation awareness by overlaying sensor imagery (fusion of thermal imaging and VNIR imaging) and other information (including display maps of terrain and interiors of buildings, positions of friendly and enemy forces) (Fig. 59). This system shows important direction for future application of fusion technology.

Fig. 59. The Integrated Visual Augmentation System (IVAS) from Microsoft Inc.

11.6 Renaissance of cooled LWIR thermal imagers

Cooled LWIR thermal imagers built using linear LWIR FPAs had dominated market of military imagers in 1970s and 1980s. In was only in 1990s when they started gradually to loose this market for cooled MWIR imagers built using quickly improving staring MWIR image sensors and later for uncooled staring LWIR imagers. At present market of short/medium range imagers is dominated by uncooled LWIR imagers and market of medium/long range imagers is dominated by cooled MWIR imagers for detail reasons explained in Section 9.1. Main manufacturers of optics for thermal imagers rarely offer LWIR optics due to limited demand. However, situation can change significantly in near future for reasons related to both conditions on modern battlefield and to improvements of technology of cooled LWIR FPAs.

First, recent military conflicts have shown use of increasing number of MWIR lasers applied to blind or damage seekers guided at MWIR range or even typical MWIR imagers. Technology of MWIR laser have improved to level when they are portable, moderate cost and can be used at field conditions.

Second, it is known for decades that performance of MWIR imagers degrade to smoke or even dust generated by military vehicles.

These features increase attractiveness of LWIR imagers that are less sensitive to smoke/dust and there are practically no lasers that operate in LWIR band with one exception: old cumbersome but still effective CO_2 lasers. It is commonly known that CO_2 lasers that operate at 10.6 µm can be used to blind typical LWIR thermal imagers sensitive in band from 8 µm to about 12 µm. However, the latter drawback can be eliminated. Cooled LWIR imagers of spectral band limited to 7.7-9.4 µm can be treated as best solution to threat of CO_2 lasers because such imagers are totally non sensitive to CO_2 lasers and can offer better NETD comparing to uncooled imagers. In addition, due to shift of mean wavelength from typical 10 µm to about 8.5 µm diffraction effect is weaker comparing to typical uncooled LWIR imagers.

It should be also noted that recent technology improvements in HOT photoelectric LWIR FPA have created techniques to develop moderate cost cooled LWIR thermal imagers of such optimal spectral band [155]. Therefore, it can be expected that due to reasons listed above market share of cooled LWIR imagers shall rise in near future.

11.7 Super range thermal imagers

The race to develop thermal imagers of longer operational range have been fueled for decades by increasing requirements of military/security organizations. Three decades ago detection of humans at distance up to 5km were considered as super achievement. Nowadays, it is quite common to find tender requirements on thermal imagers for border surveillance towers capable to detect humans at distances up to 20 km. Thermal imagers have already proved to be valuable passive tools of long range air defence systems or aircraft surveillance systems enabling effective surveillance against targets at distances up to 40 km or more. Therefore, it is natural to expect that this race shall continue and imagers of increased range (human detection at 30 km) can be expected in near future.

It is commonly known that maximal operational range of effective surveillance of thermal imagers is approximately proportional Nyquist frequency of thermal imagers. In other words in order to increase range it is needed to increase inverse angular size of pixel of thermal imager under tests. Therefore the range can be increased in two ways:

1. by decreasing pixels of IR FPA sensor,
2. by increasing focal length of the optics.

During last three decades the resolution (Nyquist frequency) of thermal imagers and indirectly operational range have been improved several times mainly by decreasing pixels of IR FPA sensors. Maximal focal length/aperture of optics has been kept at near constant level (focal length up to about 1250 mm; aperture up to about 250 mm).

However, this model of improving resolution/range of thermal imagers by decreasing pixel of IR FPA sensor while keeping intact optics aperture cannot be kept in future.

At present market of ultra long range thermal imagers is dominated by cooled thermal imagers built using dark (F-number in range 3.5-5.5) objectives of focal length up to about 1250 mm. As discussed in Section 11.3 new generation of IR FPA sensors of smaller pixel pitch (as low as 2.4 μm) is expected but such sensors shall need to cooperate with bright optics (F-number as low as 1). It means that Nyquist frequency of MWIR thermal imagers can be improved but at the costs of increasing aperture of optics for MWIR super range thermal imagers. Therefore, it can be predicted that new super range MWIR imagers built using large optics up to 400 mm or more can be expected in near future.

Further on, if cooled LWIR imagers are to compete with MWIR imagers in this super range surveillance race then they need to use optics of similar focal length but of bigger aperture due to longer wavelength. Therefore, super range LWIR imagers of large optics up to 600 mm or more can be expected in future, too.

To summarize, in future super range thermal imagers of huge optics that make them similar to small radars can be expected. The main challenge for such imagers is huge material cost and technical difficulties of design of required ultra large IR objectives.

11.8 Folded thermal imagers

IR objectives used in thermal imagers are built in form of mechanical cylinders where lenses are installed. Optical axis of all lenses is approximately the same and such case can be called straight optical axis objective. It is classical solution to design optical objectives used for centuries that enables easy alignment/centring of optical elements. However, this classical design method becomes problematic in case of design of large aperture/long focal length objectives optimized for use in long range thermal imagers. The problem is that imager length must be approximately longer over optics focal length. This rule means practically huge length (over 1 m) of long range imagers built using optics of long focal length at similar level is situation when in many applications (for example thermal imager for military vehicles) such long imager are not acceptable due to lack of empty space.

One of potential solutions to decrease length of IR objectives (and later length of thermal imagers) is so called folded (another name: U-turn) design of objectives of long focal length (Fig. 60). The method is based on idea to fold optical axis of the objectives by use of several flat mirrors. In this way it is possible to design compact thermal imagers when both optics and electronics can be inserted into empty cube.

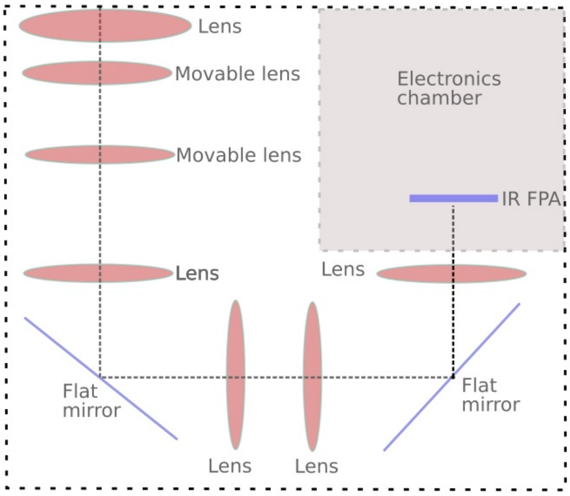


Fig. 60. Block diagram of U-turn optical objective

Compact design is a huge advantage of folded IR objectives and such imagers are becoming popular. However, there are also big drawbacks due to increased difficulties in aligning/centring of optical elements, or even in final performance tests (MTF measurement) of such objectives. In detail, manufacturing of such objectives requires special customized alignment/centring/performance tests stations because typical stations are optimize only for straight optical axis objectives.

11.9 Space thermal imagers for Earth observation

Nowadays, there is a huge interest in space satellite technology. Even small countries start space programs. New satellites are being developed by hundreds of scientific institutes/companies world wide. Increasing numbers of satellites are launched every month. Due to quickly changing numbers it is difficult to deliver statistics but at beginning of 2024 year there have been in space 8377 active satellites [156]. It can be estimated that about 22% are satellites for Earth observation [157]. Another important point is that small satellites (mass up to about 300kg) dominate space (over 72% of total number).

Great majority of Earth observation satellites are reconnaissance (surveillance) satellites designed for military or dual use applications. Therefore, it is not surprising that satellite images of areas of recent conflicts are frequently published in media. Images from high resolution/ultra high resolution satellites are especially impressive as they are capable to produce images where resolution targets of small bar width can be resolved can be about or below 1 m for case of ultra high resolution satellites. Such satellites can deliver sharp images of small ground targets like different military targets (tanks, trucks, aircraft, helicopter, boats, ships) or civilian targets (cars, lorries, cranes, city infrastructure). However, it should be noted that virtually all high-res image that are publicly available are images obtained in VIS, NIR or VNIR spectral bands. There is no publicly available space images in MWIR/LWIR spectral bands of resolution similar to earlier mentioned images at VNIR band.

Precision information on majority of Earth satellites is not public. Therefore it is highly probably that some of surveillance medium/large satellites do enable thermal imaging. However, it is predictable that this number is low or very low for techno-commercial reasons to be presented below.

Thermal imagers have dominated market of military/dual use EO imaging systems working at Earth conditions due to a series so advantages: high thermal contrast of typical targets of interest, vision at total darkness, good vision at difficult atmospheric conditions, and better anti-camouflage abilities comparing to other EO systems like VNIR cameras. However, there are also two main drawbacks of thermal imagers comparing to VNIR cameras:

1. higher price,
2. bigger size/mass.

The first drawback could be probably accepted in most of space programs as minor cost. The second drawback is typically of minor importance when thermal imager is used at Earth conditions but is of critical importance for space satellites due to very high launch costs that depends on mass of satellites. There are also strict constraints on size of thermal imager to be inserted into satellite housing.

There are two main reasons for this high mass/large size problem of MWIR/LWIR thermal imagers:

1. pixel size of IR FPAs used in thermal imagers (over 10 µm) is typically much bigger comparing to pixel size of CMOS sensor (5 µm or smaller),
2. due to diffraction effect bigger IR objectives comparing to VNIR objective are needed to generate image of the same angular resolution.

For example F4 MWIR optics (or F2 optics for LWIR range) is needed for thermal imagers when space VNIR cameras commonly use F8 optics (Table 19). In addition IR optical objectives of at least two times longer focal length comparing to VNIR objectives are needed to compensate differences in pixel pitch of FPA image sensors (10 µm for IR FPA when 5 µm for CMOS sensor). There is secondary problem for thermal imagers in form of mass/dimension of IR FPA cooler that is not needed by VNIR cameras. All these factors create situation when ratio of volume/mass of long focal length MWIR thermal imagers for space satellites can be as high as 16 times over volume of comparable performance VNIR cameras. In case of LWIR imagers this ration can again increase by 4 times.

Table 19. Parameters of three space imagers of the same spatial resolution located at typical Earth low orbit at 320km height designed using available technology according to typical design rules

Imager spectral band	Pixel pitch [µm]	Optics F-number [-]	Focal length [mm]	Optics aperture [mm]	Nyquist frequency [lp/mrad]	Ground resolution at 320km height [m]
VNIR	5	8	1600	200	160	1
MWIR	10	4	3200	800	160	1
LWIR	10	2	3200	1600	160	1

To summarize, there are fundamental drawbacks of space thermal imagers comparing to VNIR cameras in form of huge size/mass. This drawback makes not possible for thermal imaging to dominate space in the same manner as surveillance in Earth conditions. However, due to high importance thermal imaging to military it can be expected that number of space thermal imagers shall rise.

11.10 Mass manufacturing of thermal imagers

The previous sections of this chapter have been devoted to thermal imagers with special features that make them technically better comparing to present day thermal imagers. However, as recent military conflicts have proved forces equipped with high number of moderate performance weapons can overcome forces equipped with small number of ultra high performance weapons. Situation in automotive industry is similar. If thermal imagers are to make driving safer then they must be used in high numbers; use of thermal imagers only by elite cars is not enough.

Further on, another experience from recent military conflicts is that thermal imagers are needed almost everywhere: single soldier, mechanical vehicles, drones, helicopters, aircraft, anti-air defence systems. It means that huge numbers of thermal imagers are needed for military/security all over the world. The same can be said about civilian applications as automotive industry is only an example of civilian market. Therefore the most difficult challenge for thermal imaging is not technical improvements but mass manufacturing of moderate performance thermal imagers at lower cost.

An ideal could be situation when thermal imagers are sold at price comparable to price of VNIR cameras. Probability of this scenario to materialize is almost zero. However, the price ration between thermal imagers and VNIR cameras of similar FOV can drop significantly. At present this ratio can be estimated at level about 10; in near future it can drop to 5 or may be 3.

This very significant price drop is expected to occur due to two main factors. First, mass manufacturing in natural way decreases unit costs. Second, number of manufacturers of critical modules for thermal imagers (IR FPAs sensors) is rising. Increasing competitions will lead to reduction of market price of these critical modules and finally to reduction of price of thermal imagers.

12. Conclusions

Thermal imaging is a matured technology that has found mass applications in both military and civilian sectors. In detail, thermal imagers are the most important electro-optical imaging systems used in defense/security applications. These imagers are also extremely important for a series of civilian applications to enable non-contact temperature measurement.

Thermal imaging has received a lot of attention from scientific community world wide. There has been published hundreds of thousands of scientific papers related to this technology.

In spite of this huge number of scientific papers devoted to this technology this book is unique because it makes an attempt to present a review of total thermal imaging technology and to present answers for fundamental questions related to this technology:

1. how thermal imagers are manufactured,
2. how blocks of thermal imagers are built,
3. how thermal imagers available at world market can be technically divided,
4. what are basic rules of characterization of thermal imagers,
5. what are future technical trends for thermal imaging.

Therefore, this review of modern thermal imaging technology can help readers to understand sophisticated situation on international thermal imaging market and potential future technical trends. The author hopes that it shall become a reference book for students and engineers working in field of thermal imaging worldwide. However, it should be noted that this book presents some simplifications that have been made in order to cover fully this very wide technology. Further on, characterization and testing thermal imagers has not been included in this book. Therefore, further reading of literature on design, manufacturing, division, applications, characterization and testing of thermal imagers is recommended as a supplement to this book.

Acknowledgments

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13. List of abbreviations

a-Si – amorphous silicon
a-SiGe – silicon-germanium
ASIC – application specific integrated circuit
A/D – analog to digital conversion
AMTIR-1 – Amorphous Material Transmitting Infrared Radiation
AR – Anti-reflection coatings
ADAS - advanced driver assistance system
AV – autonomous vehicle
ATF - aperiodic transfer function
AHD – analog high definition, video interface
BaF2 – Barium Fluoride
BBAR – Broadband anti-reflection coatings
BNC – Bayonet Neill-Concelman, connector type
CaF2 – Calcium Fluoride
CdTe – Cadmium Telluride
CsBr – Cesium Bromide
CsI – Cesium Iodide
CCD – charge couple device (a technology for constructing integrated circuits that use movement of electrical charge by "shifting" the signals between stages within the device one at a time
CCTV- close circuit television (type of VNIR cameras used for short range surveillance)
CMOS -complementary metal–oxide–semiconductor (a technology that uses pairs of p-type and n-type metal oxide semiconductor field effect transistors for constructing image sensors
CPU – central processing unit
CO2 – carbon dioxide
CL – contact layer or CL – camera link, video interface
CXP – CoaXPress, video interface
DRI – detection, recognition, identification ranges
DROIC – digital read-out integrated circuit
DPROIC – digital pixels read-out integrated circuit
DSP – digital signal processor
DLC – Diamond-Like Carbon Coating
DCT – discrete cosine transform
DARPA – Defense Advanced Research Projects Agency
DHR – display horizontal resolution
EO – electro-optical
EMC – electro-magnetic
FPA – focal plane array
FOV – field of view
FLIR – forward-looking infrared camera (one of the names for thermal imager)
FIR - far infrared (spectral range from about 15 µm to about 1000 µm)
FPS – frames per second
FPGA – field-programmable gate array
FPN – fixed pattern noise
Gen – generation
GaAs – Gallium Arsenide
Ge – Germanium
GigE – Gigabit Ethernet, video interface
HgCdTe – Mercury (Hg) cadmium (Cd) telluride (Te) is a material for infrared sensor applications
HD – high definition
HD-CVI – High Definition Composite Video Interface, video interface
HD-TVI – High Definition Transport Video Interface, video interface
HDMI – High Definition Multimedia Interface, video interface
InSb – Indium antimonide (InSb) is a crystalline compound made from the elements indium (In) and antimony (SB)
IR – infrared band (spectral range from about 0.78 µm to about 1mm)

FLIR (forward looking infrared) – old term used to describe thermal imagers
Ge - germanium
IIT – image intensifier tube
IRT – infrared thermography
IEI – Iran Electronics Industry
IVAS – integrated visual augmentation system
KBr – Potassium Bromide
KCl – Potassium Chloride
KRS-5 – Thallium Bromoiodide
lp/mm – line pairs per millimeter
lp/mrad – line pairs per miliradian
LWIR – long wave infrared band (spectral range from about 6 µm to about 15 µm)
LiF – Lithium Fluoride
LRF -laser range finder
LVDS - Low Voltage Differential Signaling, video interface
MgF2 – Magnesium Fluoride
MWIR – medium wave infrared band (spectral range from about 3µm to about 6 µm)
MIL – United States defense standard, often called a *military standard*
MTF – modulation transfer function
MRTD – minimum resolvable temperature difference
MTDP - minimum temperature difference perceived
MDTD - minimum detectable temperature difference
MTBF – mean time before failure
NIR – near infrared band (spectral range from about 0.8 µm to about 1 µm)
NVD – night vision device
NETD – noise equivalent temperature difference
NaCl – Sodium Chloride
NU – non-uniformity
NUC – non-uniformity correction
NTSC – national television system committee, video interface
OGI – Optical gas imaging
PbSe – polycrystalline lead (Pb) selenide (Se) is a material for infrared sensor applications
PAL – phase alternating line, video interface
PVF - point visibility function
QWIP – quantum well infrared photodetector
RMS – root mean square
ROIC – read out integrated circuit
R/D – research and development
SiTF – signal transfer function
SNR – signal to noise ratio
SWIR – short wave infrared (spectral range from about 1 µm to about 3 µm)
SoC – System on chip
Si – Silicon
SPDT – Single Point Diamond Turning
SHR – sensor horizontal resolution
SDK – software development kit
SDI – serial digital interface, video interface
SRF – slit response function
T – temperature
TIC – thermal imaging camera
TI – thermal imager
TOD – triangle orientation discrimination
T2SL – type-II superlattice
T2SLSs – type II strained-layer superlattices
USB – universal serial bus, video interface
UDP – User Datagram Protocol, video interface
V – voltage

VNIR – spectral band that covers both visible and near infrared (from about 400nm to about 1000nm)
VIS – visible band (spectral range from about 0.4 µm to about 0.8 µm)
VOx – vanadium oxide
ZnSe – Zinc Selenide
ZnS – Zinc Sulfide

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