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Review of infrared systems

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Review of infrared systems

The term "infrared" means a range of optical radiation. Therefore IR systems are the systems employing IR radiation. There are a great number of systems used in industry, military, science, medicine, environmental protection that can be called "infrared systems" on the basis of the criterion mentioned above. However there are some systems that use infrared radiation like industrial lasers, optical communication systems, optical security systems etc. but are not identified in literature as the infrared systems. Here in this chapter we will present the systems commonly called in literature "infrared systems".

1 Division of IR systems

The IR systems can be divided according the criterion of application into 6 basic groups: the imaging systems; the measuring systems; the detection, search and tracking systems; the communications systems; the infrared sources; and the countermeasures.

There is not always clear distinction between these group because some imaging systems can be also used for measuring applications. For example, some thermal cameras can be used as both imaging systems and as non-contact thermometers. Such a situation can create certain lack of precision in any definition and classification of IR systems. However, the classification presented in Fig. 1 based on system application can be justified in most situations.

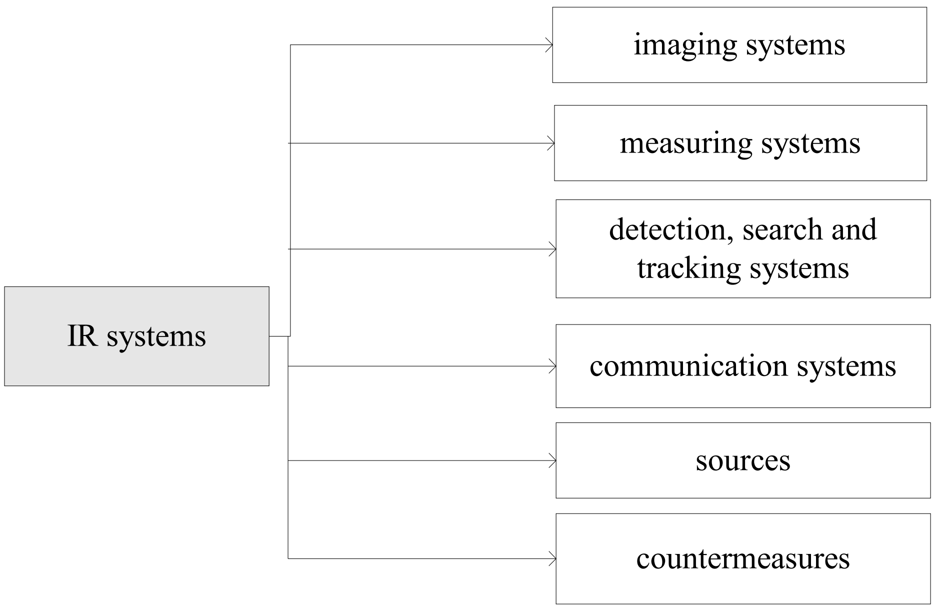


Fig. 1. Division of IR systems

Infrared imaging systems are systems that create image of the observed objects using infrared radiation emitted or reflected by these objects. Infrared imaging system of spectral sensitivity bands located in MWIR or LWIR regions (thermal imagers) use the emitted radiation; while imaging systems of spectral bands located in NIR range (image intensifier systems (IIS), low light level television cameras (LLLTV)). It must be emphasised that both the LLLTV cameras and the image intensifier systems use reflected radiation in both NIR and visible range to create image of the observed scenery. The first IISs and LLLTV cameras were active systems, co-operating with an IR illuminator, of spectral band located exclusively in near infrared range. Therefore mostly due to this historical reason most people still consider these systems as the infrared systems although it is not fully justified.

The systems from the second group – the infrared measuring systems – are systems measuring different physical quantities with use of infrared radiation. This group consists of non-contact thermometers, radiometers, spectroradiometers, monochromators, interferometers, power and energy meters, velocity meters, reflectivity meters, transmissivity meters, humidity meters.

The systems from the third group – the detection, ranging and tracking systems – are systems designed to detect and possibly also for ranging and/or tracking of military targets, intruders into security zones, chemical and biological compounds in gases, fluids and solids.

These systems can be further divided into the following groups: the missile seekers, the intruder detectors, the mine detecting systems, the sensors of chemical and biological compounds, the lidars, the range finders, and the ladars.

The systems from the fourth group – the communication systems – are systems using infrared radiation for communications. They can be divided into two basic groups: the cable (fiber) systems and wireless optical communication systems.

The fifth group – the infrared sources – are infrared sources used as independent systems for machining, illumination applications or as standards of IR radiation. Infrared lasers used for welding, cutting, and drilling in industrial applications; or for vaporization, coagulation, incision, excision and ablation in medical applications; or as destroying weapons in military applications belong to this group. Next, the infrared lasers used for illumination application or different types of blackbodies can also be classified here.

The countermeasures are different systems or techniques used in military applications to decrease effectiveness of the military infrared systems like the camouflage paints and nets, flares, decoys, the stealth techniques, the jamming or blinding systems, the warning systems.

The first two groups of infrared systems represent the majority of infrared systems and the further discussion in this chapter will be limited to these two groups: the infrared imaging systems and the infrared measuring systems.

2 Terminology

Before we start presentation of different infrared systems we must precise terminology used in this chapter in order to avoid possible misunderstandings and warn the reader about a certain chaos in literature.

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

The most surprising thing is that actually even the term "infrared radiation" or division of IR radiation is not standardised. There was presented in the International Lighting Vocabulary considered nowadays as the international primary authority on terminology in radiometry the range of optical radiation a proposal of division of optical radiation (see Table 1) but not as compulsory division but only as a recommended division [4.3]. Additionally, in case of visible radiation, due to human diversity, only approximate limits were given. Next, what is even more important, the these recommendations are not accepted in most communities working in the field of optical radiation due to many, mostly historical reasons.

Table 1. Division of optical radiation recommended by the CIE

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

Confusion in area of limits and further division of sub-ranges of optical radiation is particularly clear in case of infrared radiation range. There have been published in literature a dozen or more proposals of division of infrared range published in literature [4.3]. Precise division of the infrared radiation is particularly important for any book on subject of the infrared systems. Therefore for the purpose of this book a precise division of infrared radiation shown in Table 2.will be used.

The division shown in Table 2 is based on limits of spectral bands of commonly used infrared detectors. Wavelength 1 µm is a sensitivity limit of popular Si detectors. Similarly wavelength of 3 µm is a long-wave sensitivity limit of PbS and InGaAs detectors; wavelength 6 µm is a sensitivity limit of InSb, PbSe, PtSi detectors and HgCdTe detectors optimised for 3-5µm atmospheric window; and finally wavelength 15 µm is a long-wave sensitivity limit of HgCdTe detectors optimised for 8-12 µm atmospheric window.

Table 2. Division of infrared radiation used in this chapter

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

The situation in the field of names of different IR systems is very similar to the above described situation in division of the IR radiation. We will present this situation using only one example.

Let us define thermal camera as a infrared system enabling creation of two dimensional image of temperature distribution on the surface of the observed objects using thermal radiation emitted by these objects.

If we make a review of literature dealing with infrared technology then we find that there are at least eleven different terms used as synonyms of the term “thermal camera”: thermal imager [4.3], thermograph [4.3, 4.3], thermovision [4.3, 4.3,4.3], FLIR [4.3,4.3], thermal imaging systems [4.3, 4.3], infrared imaging radiometer [4.3], infrared imaging system IIS [4.3, 4.3], thermal viewer [4.3], thermal video system [4.3], infrared camera [4.3], thermal imaging device [4.3]. If we analyse internet resources we can easily find even more synonyms of the term “thermal camera”.

Next, an imaging system based on image intensifier tube technology is typically called night vision device (NVD) but in international military standards is called image intensifier system [4.3,4.3]. At the same time we must remember that logically thermal imagers or LLLTV cameras are also night vision devices.

It is possible to present many more examples of a certain chaos if infrared terminology. In this chapter we will try to present clear logical definitions of the IR systems presented. However, the reader must aware that due to lack of standardisation of IR terminology it will not always be possible.

3 Infrared imaging systems

Human sight can be considered as the most important of all human senses because it delivers to the brain over 90% of all information.

Human eye is as a small optical system very well adapted for work in Earth conditions characterised by very good visual acuity at day level conditions, relatively wide field of view, and remarkable dynamic far greater than any other artificial light sensing device [4.3]. Nevertheless the ability to see detail in a scene becomes worse as the luminance decreases until only large objects can be discerned, but not clearly recognised. Next, human brain can memorise images but these abilities are limited. Further on, human eye is sensitive only to visible radiation and humans sight cannot use information carried out by radiation in other ranges of optical radiation.

All imaging systems –infrared imaging systems among them- are designed in order to improve capabilities of human sight and remove the mentioned above limitations. Image intensifier systems IIS improve acuity of human eye at low level night vision conditions. ICCD cameras do the same but also enable recording and transmitting of images in electronic form. Both two types of imaging systems extend human sensitivity to radiation up to 0.9 μm or even 1.1 μm. Finally thermal imaging systems transfer sensitivity band of the human eye even further – typically to wavelengths over 3 μm (MWIR and LWIR ranges) where it becomes sensitive to thermal radiation emitted by targets at typical earth temperatures.

3.1 Image intensifier systems

Image intensifier system IIS are the imaging systems built using an image intensifier tube consisting of a photocathode, an anode in form of a phosphor screen, and other optional components. The tube intensifies a low-luminance image of the observed objects created on the photocatode into a brighter image created on the anode. In other words, the photocathode due to the radiation impinging onto its surface emits electrons that are focused onto a phosphor screen that emits brighter light. Spectral sensitivity of the IIS depends on design but generally IIS used for surveillance applications are sensitive to radiation from about 0.4 μm to 0.8 μm and sometimes up to 0.9 μm.

Typical image intensifier system IIS consists of an optical objective, an image intensifier tube, an ocular, a chassis, and an optional illuminator. The image intensifier tube is a heart of the image intensifier system. Therefore the term "image intensifier" is often used as synonym of the image intensifier system. Next, the image intensifier systems IIS are commonly called night vision devices (NVD) although also other infrared imaging systems like thermal imagers or LLLTV cameras enable imaging at night conditions.

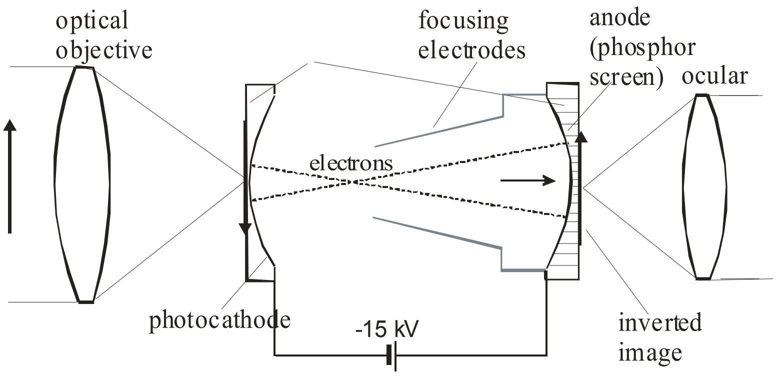
The technology of image intensifier tubes has progressed steadily over the years. There are so far five generations of image intensifier tubes: 0, 1, 2, 3 and possibly 4 [4.3].

Generation 0 refers to the technology of World War II, employing fragile, vacuum-enveloped image converters with poor sensitivity and little gain. These are single stage tubes that achieve image intensification due to acceleration by high voltage of electrons emitted by the photocathode and striking the phosphor screen. Typically S-1 photocathode (sensitivity up to 60μA/lm), electrostatic inversion and electron acceleration were used to achieve gain. Gen 0 tubes are characterised by significant distortion and necessity for active illumination (large searchlights with infrared (IR) filters). These tubes were in past used in active night vision systems cooperating with an illuminator. High power tungsten bulbs covered with an IR filter suppressing visible radiation were used as illuminators. Active character of use of first generation image intensifier systems was their significant disadvantage.

Generation 1 - First generation tubes are improved Gen 0 tubes. Typically S-10 or S-20 photocathode (photo sensitivity up to 200μA/lm), electrostatic inversion and electron acceleration are used to achieve gain. Because of higher sensitivity Gen 1 NVD were the first passive night vision systems.

Focusing is achieved usually achieved by using an electron lens to focus electrons originating from the photocathode onto the screen (Fig. 2).

In the inverter diode tube presented in Fig. 2 an electrostatic field directs the photoelectrons and focuses an inverted image on the phosphor screen. Electron lens can be achieved by combining an electrostatical field with an axial magnetic field provided by either a solenoid or permanent magnet. An uniform magnetic field enables to achieve good resolution over the entire screen and at the same time keeps distortion low. Fibre optics windows are used in Gen 1+ tubes to minimize degradation of the image resolution towards the edge of the tube. The fibre optics enables also efficient coupling to another image tube, to an imaging detector or to photographic film.



a) inverter diode b)

Fig. 2. a)Diagram of a NVD built using a Gen1 tube b)photo of Gen 1 tube

First generation image intensifier tubes are characterised by good image resolution (25-30 lp/mm), a wide dynamic range (the ability to reproduce the ratio between the bright and dark parts of an image), and low noise. However, they are also characterised only by a moderate gain. Luminance gains in the single stage tubes are usually in the order of 100 to 500 (up to 1500 in Gen 1+ tubes) in situation when luminance gain in the order of 10^5 is necessary to achieve ability to see at overcast starlight night conditions. Due to low production costs Gen 1 NVDs still dominate in commercial market but they are rarely used for military applications.

Generation 2 image intensifier tubes represent a significant breakthrough in night vision technology. Gen 2 tube are single stage imaging tubes built using an S-25(extended red) photocathode (with sensitivity of 240-450 μA/lm) and a microchannel plate (MCP) to increase significantly luminance gain up the level about 18 000-30 000 cd/m^2/lx. They are also typically equipped with automatic gain control and bright spot protection.

The microchannel plate is an array of miniature electron multipliers oriented parallel to one another; typical channel diameters are in the range 10-100 μm and have length to diameter ratios between 40 and 100. Channel axes are typically normal to, or biased at a small angle (≈ 8 °) to the MCP input surface. The channel matrix is usually fabricated from a lead glass, treated in such a way as to optimise the secondary emission characteristic of each microchannel and to render the channel walls semiconducting so as to allow charge replenishment from an external voltage source. Parallel electrical contact to each channel is provided by the deposition of a metallic coating on the front and rear surfaces of the MCP, which then serve as input and output electrodes, respectively. The total resistance between electrodes is in the order of 10^9 Ω. Such microchannel plates allow electron multiplication factors of 10^3 – 10^6. Spatial resolution is limited only by channel dimensions and spacing; 12 µm diameter channels with 15 µm center-to-center spacings are typical.

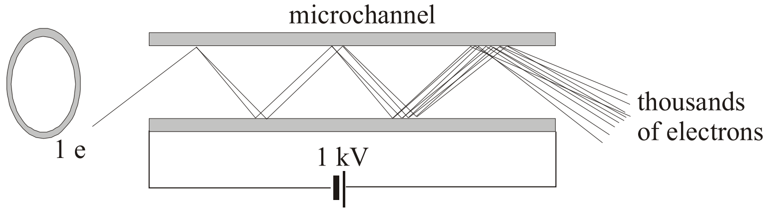


Fig. 3. Principle of work of a microchannel plate

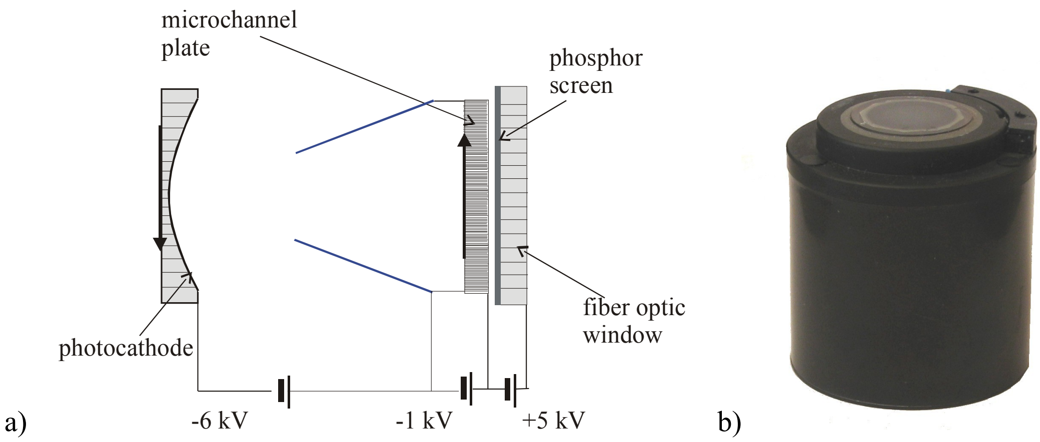


Fig. 4. Gen 2 image intensifier tube (inverter MCT tube) a)diagram b)photo

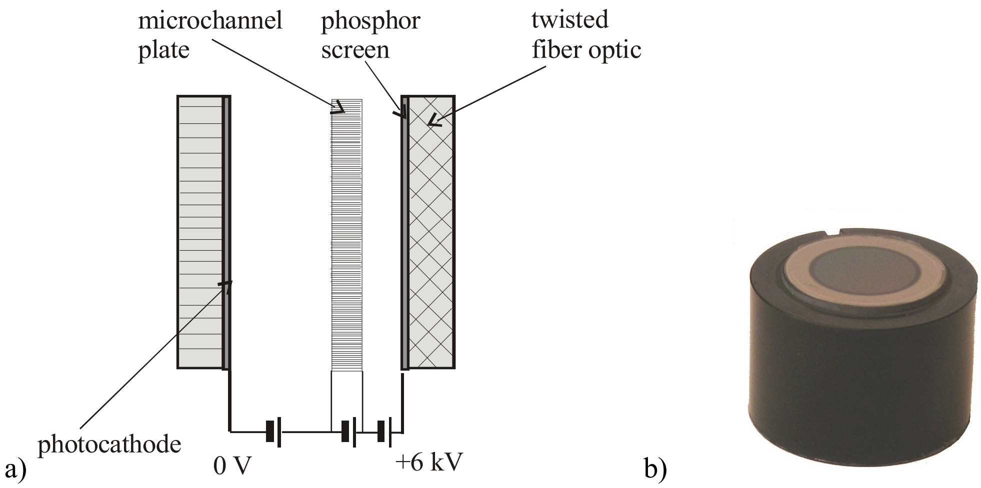


Fig. 5. Gen 2+ tubes (proximity focus MCT tube) a)tube diagram b)photo

First Gen 2 tubes were manufactured similarly to the Gen 1 tubes using the inverter diode tubes (Fig. 4). Newer Gen 2 tubes are usually proximity diode tubes shown in Fig. 5. They are characterised by lower size and higher gain in comparison to typical Gen 2 tubes.

Gen 3 tubes are similar to the Gen 2 tubes in design. The primary difference is the material used for the photocathodes. Second generation image intensifiers use photocathodes with a multialkali coating whereas third generation image intensifiers use photocatodes with a GaAs/AlGaAs coating. This latter material is characterised by quantum efficiency in the near infrared over 10 times better in comparison to photocathodes with a multialkali coating. However, the advantage of higher sensitivity of photocathode is significantly reduced by necessity to use a protective ion barrier film to increase tube life that cause some signal losses. Therefore luminance gain of Gen 3 tubes (range 20000-90 000 cd/m^2/lxis) is usually no more than about 1.2-3 times higher that luminance gain of typical Gen 2 tubes (range 18000-30 000 cd/m^2/lxis).

Gen 4 tubes are modified Gen 3 tubes. The main difference is the protective ion barrier that was removed in Gen 4 tubes. Gated power supplies are also used to pulse on and off the Gen 4 tubes. Using these quick, controlled voltage pulses, Generation 4 tubes are able to adjust automatically to lighting conditions -- less power is consumed when ample light is available, and more in darker situations. However, it must be emphasised that the existence of Gen 4 tubes is not officially confirmed by the US authorities.

All these types of intensifier tubes are also differentiated by the nominal useful diameter of the photocathode. Typical diameter values are 18, 25, and 40 mm.

There is a common view that higher generation number means better tube. It is usually true if we compare Gen 0, Gen 1 or Gen 2 tubes but do not have to be true if we compare Gen 2, Gen 3 or Gen 4. Gen 3 and Gen 4 tubes are manufactured exclusively by USA manufactures. European and Asian manufactures instead of changing technology concentrated on improving Gen 2 technology and offer different equivalents to Gen 3 tubes (Supergen, SHD-3, XD-4, XR5). These equivalents can be sometimes better than Gen 3 tubes. Gen 2 tubes are also generally more tolerant to urban night conditions.

Image intensifier systems (night vision devices) are nowadays mostly used military applications in form of binoculars, goggles, and scopes to enable observation at night conditions (Fig. 6). They prove to be useful also in industrial and scientific applications where light amplifications is required.

Fig. 6. Exemplary image intensifier system: Lucie (courtesy by Thales Angenieux)

More detail information on image intensifier technology imaging tubes can be found in Ref.[4.3, 4.3], in numerous papers published by SPIE [4.3-4.3] or in internet sites of manufacturers [4.3,4.3,4.3,4.3,4.3,4.3].

3.2 LLLTV cameras

Low light level TV cameras similarly to the NVD enable observation at night conditions. However the NVD are direct viewing devices that generate the output image by optical amplification of the input image. In case of the LLLTV cameras the input image is converted into electrical signal that after electrical amplification generate the output image. Therefore the LLLTV technologies offer inherent capabilities to record, processing and transmit image of the observed scenery.

There are a few distinct groups of LLLTV cameras: silicon intensified target (SIT) tube cameras, intensified silicon intensified target (ISIT) tube cameras, intensified charge couple device (ICCD) cameras, cooled CCD cameras and electron-bombarded charge couple device (EB CCD) cameras.

In case of the SIT cameras the phosphor screen is replaced with a silicon anode containing p-n junction diodes [4.3]. When accelerated electrons strikes , they create electron hole pairs that are read at the camera output as an amplified signal.

Taking the SIT concept a step further, it is possible to add an intensifier tube to a SIT camera and make an intensified silicon intensified target (ISIT) tube cameras. Both SIT cameras and ISIT cameras are characterised by lag – the time it takes to remove one set of electron hole pairs from the anode in preparation for the next – that can severely reduce dynamic resolution.

Classical intensified charge coupled devices (ICCDs) are built by combing using different types of couplers two separate modules: image intensifier tube and a typical CCD detector. When proper type of phosphor is used and screen persistence of the tube is short then the ICCD cameras are almost lag free like typical CCD cameras and posses also sensitivity of typical image intensifier systems.

Coupling of the image intensifier tube with a CCD detector can be done using fibre optic couplers or relay optics. The fibre optics couplers (faceplates or tapers) are more light efficient than relay optics couplers. ICCD cameras with fibre optics coupling can use image intensifier tube of lower luminance gain than ICCD cameras with relay optics coupling. Therefore ICCD cameras with fibre optics coupling are usually characterized by better S/N ratio in comparison to ICCD cameras with relay optics coupling at similar scene illumination level. However, an advantage of LLLTV cameras built using relay optics is slightly superior image quality.

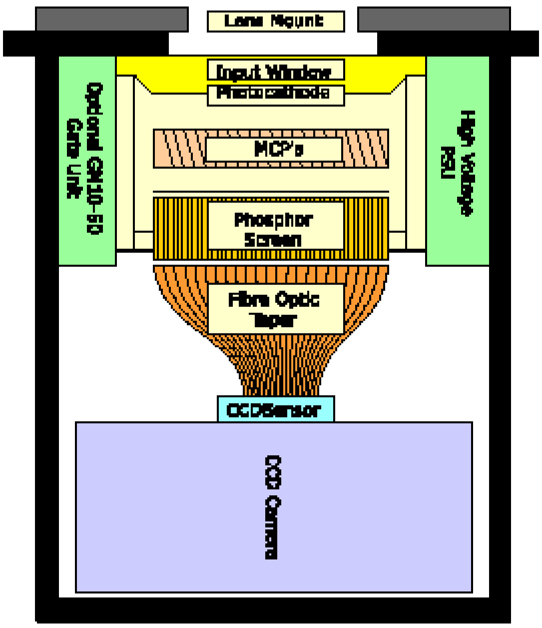


Fig. 7. Block diagram of typical ICCD camera built using fibre optic coupler

Electron-bombarded CCD cameras are cameras built using modified CCD/CMOS arrays and image intensifier tubes integrated into a single sensor. In contrast to classical ICCD cameras the

CCD/CMOS detector is not illuminated by photons but is bombarded directly by electrons. Next, only photocathode of classical II tubes is used in electron-bombarded CCD cameras.

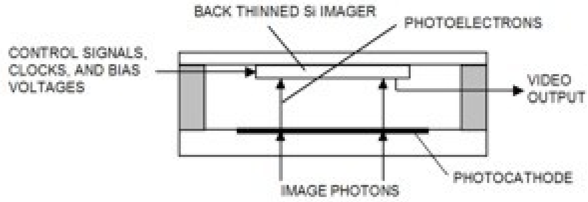


Fig. 8. Block diagram of typical EB CCD sensor

In general, the EB CCD sensor has a transparent glass window through which photons are focused onto different type photocathodes. When photons strike the photocathode, electrons are emitted into a vacuum cavity. These electrons are then electrically accelerated into a CCD (CMOS) array that outputs a high resolution, low noise video signal. Gain is achieved through the electron bombarded semiconductor gain process in silicon.

Model 3000-XL Image Intensifier mounted on Canon XL-1 with 16x lens

Fig. 9. ICCD camera of OpTech Inc. (designed by combing Canon XL camera with an image intensifier tube)

It is possible by cooling detector and using long integration times to reduce noise and improve detectivity of CCD detectors to the level that enable design CCD cameras of sensitivity equal to sensitivity of ICCD cameras. Such cooled CCD cameras are characterized excellent S/N ratio but long integration times (a dozen of seconds or more) required to achieve sensitivity of ICCD cameras are acceptable only in limited number of applications like astronomy. Having short integration times like a few frames is not possible to design cooled CCD cameras comparable to ICCD cameras but such cameras can be a useful tool at higher scene illumination range over about 5-10 mlx.

More detail presentation of different types of LLLTV cameras can be found in Ref.[33,32,33,32] or in internet sites of manufacturers [4.3,4.3,4.3,4.3,4.3,4.3, 4.3].

3.3 Thermal imaging systems

Objects of typical earth temperatures emits mostly in the spectral region from about 3 μm to about 15 μm. Thermal radiation emitted these objects dominate over the radiation reflected by them at this spectral range because the radiation emitted by sun, moon, stars and typical artificial sources is weak for wavelengths over 3 μm. There are two „atmospheric windows” in the above mentioned range: the

3-5 µm window and the 8-12 µm window. Therefore there are two main types of thermal imaging systems: the middle-wave MW systems using the 3-5 µm windows and the long-wave LW systems using the 8-12 µm window and rarely available commercially SW systems of spectral band located within 1-3 µm range.

Thermal imaging systems can be divided into two distinct groups: thermal cameras and airborne thermal scanners.

Thermal camera (see Section 2 for terminology discussion) is a thermal imaging systems that enable creation of a two dimensional thermal image of the observed scenery independently whether the system or objects are movable or stationary.

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

Thermal cameras represent probably over 99% of all existing thermal imaging systems. Imaging thermal scanners are almost exclusively airborne systems used for reconnaissance applications because the offer very wide field of view (standard 120°) in contrast to the thermal cameras offering field of view not wider than about 30°.

Because of distinct differences in design of these two types of thermal imaging systems and narrow specialised market, the imaging thermal scanners are high cost systems. Due to mass application of thermal cameras their prices are significantly lower. Detail presentation of imaging thermal scanners design was presented in Ref. [4.3], detail discussion of design of thermal cameras – in Ref. [4.3,4.3].

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

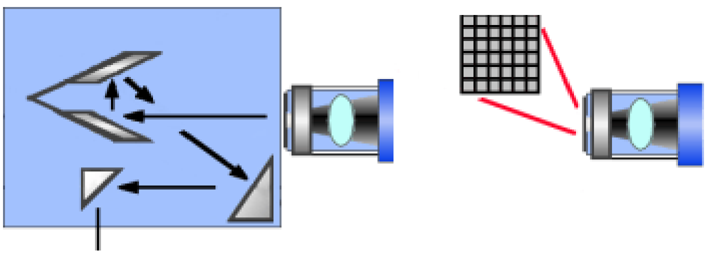


Fig. 10. Principle of work of the scanning thermal cameras and the matrix thermal cameras

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

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

Fig. 11. Exemplary Gen 2 thermal camera: Sophie (courtesy of Thales Optronique)

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

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

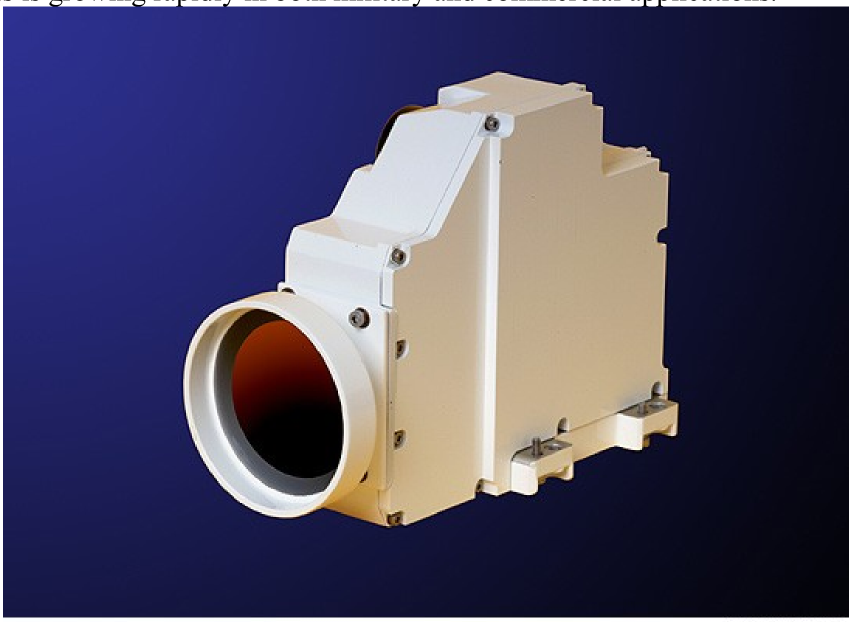


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Fig. 12. Exemplary cooled Gen 3 thermal camera: Catherine XP (courtesy of Thales Optronics)

Fig. 13. Exemplary non-cooled Gen 3 thermal camera: ELVIR (courtesy of Thales Angenieux)

Parameters of thermal cameras from the same generation can vary significantly. Therefore it is not possible to form a single table enabling accurate comparison of parameters of thermal cameras from different generation. The Tab.1 was created on the basis of a review of parameters of different observation thermal cameras offered during last 30 years but should be treated as an estimation of the sophisticated situation in the market.

Tab. 1. Typical parameters of thermal cameras

No	Examples	temperature resolution NETD [K]	image resolution	cooler type	mass [kg]	price [EUR}
Gen 1	60,120 pixels CMT (US common modules) 8,14 pixels CMT SPRITE (US, UK common modules)	0.2	250×190	-liquid nitrogen -Joule Thomson - Stirling	> 20	>400000
Gen 2	94×4 pixels CMT (Ophelios) 288×4 CMT (Synergy, Catherine, Sophie, Iris)	0.1	640×288	-Stirling Joule-Thomson	>4	>90000
Gen 3	320×240 HgCdTe MWIR (Opal, Spike Matiz) 320×240 QWIP LWIR (Thermovision 2000, Catherine QWIP) --------------------------------- 640×512 HgCdTe MWIR (High Definition POD) ---------------------- 320×240 ferroelectric (Lion 320×240 bolometric (Elvir)	0.05 ---------- 0.15-0.3	320×240 640×480 (microscanning) ----------------- 640×512 -------------- 320×240	Stirling --------- Stirling ------------ uncooled	>2	>70 000 >90 000 -------- >30 000

As we see in Tab. 1 the Gen 2 thermal cameras are characterised by significantly better thermal and spatial resolution that the Gen 1 thermal cameras. This mean the quality of the image and sensitivity offered by the latter cameras is significantly inferior. However, situation is not so clear if we compare Gen 2 and Gen 3 cooled thermal cameras. Thermal sensitivity of Gen 3 cooled thermal cameras is usually at least slightly better that thermal resolution of Gen 2 cameras. However, image resolution of modern Gen 2 thermal cameras is superior to image resolution of typical Gen 3 cameras based on 320×240 FPA, particularly in horizontal direction. This inferiority of Gen 3 cameras can be eliminated by use of microscanning technique, that can improve up to two times image resolution in both horizontal and vertical direction. However, the disadvantage of microscanning technique is higher production cost and reduced reliability. The inferiority of image quality offered by typical Gen 3 thermal cameras in comparison to Gen 2 cameras can be fully eliminated if 640×512 or bigger FPAs are used. However, due to high production post such FPAs are nowadays used only for space or aircraft surveillance imaging systems.

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

Fig. 14. Sophie MF – thermal camera integrated with laser range finder, goniometer, day light TV camera and laser pointer (courtesy of Thales Optronique)

Detectors used in Gen 1, Gen 2 and partially Gen 3 of thermal cameras require cooling, typically to temperature equal to 77K. First thermal cameras used were cooled using dewar coolers. The dewar cooler is essentially a " thermos bottle" filled with a coolant. Different liquid gases can be used as coolants. However, liquid nitrogen is used as a coolant in almost all dewars used in practice.
The criogenic cooling is characterised by a few significant disadvantages like necessity to have a source of liquid nitrogen supply readily available, limited working time of the dewar after filling, and

necessity to keep quasi-horizontal position of the thermal camera. Therefore later cooled thermal cameras employ Stirling coolers, or rather rarely Joule-Thomson coolers.

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

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

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

Both Stirling coolers and Joule-Thomson coolers are relatively expensive components that represent a dozen of so percents of cost of a whole thermal camera. Therefore it was highly desirable to eliminate these components as it has been done recently by introduction of non-cooled FPA based on microbolometer and pyroelectric/ferroelectric technologies. However, please not the so called non-cooled FPAs usually require temperature stabilisation and thermoelectric coolers are usually used in the non-cooled thermal cameras.

The thermoelectric coolers employ the Peltier effect who found that when current flows in a circuit consisting of two dissimilar conductors. In constrast to the criogenic coolers, Stirling coolers and Joule-Thomson coolers the thermoelectric coolers cannot be used to cool detectors up to very low temperatures; temperature difference of not more than about 50°C – 70°C to ambient temperature can be achieved. Next significant difference is low cost of these coolers in sharp contrast to the Stirling coolers and the Joule-Thomson coolers.

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

The SWIR cameras are only a marginal group of thermal cameras. The SWIR cameras are commercially available on the market for no more than a decade. This situation originated the fact that that the SWIR range has not been an interesting range for both military and civilian applications. Due to dominance of the emitted thermal radiation and the atmospheric windows military agencies were interested mostly in the MWIR and LWIR ranges. Because of sensitivity range of human sight and well developed silicon technology civilians were interested in the visible and NIR ranges.
This lack of significant interest create situation when up to middle of the 90s no well matured technology of detector arrays for SWIR range was available [4.3]. Currently this vacuum is occupied by InGaAS arrays and the SWIR cameras found a few applications; mostly in telecommunication sector enabling accurate coupling of optical fibre s working at 1.53 μm and in museums for painting reflectography.

There are a few significant advantages of thermal cameras as imaging systems. First, thermal imaging systems do not need even minimal illuminance of the observed scenery to create clear image in contrast to the image intensifiers and the LLLTV cameras. Second, they offer higher observation ranges at difficult atmospheric conditions. Third, it is much more difficult to conceal against observation with thermal cameras than against observation with the image intensifiers and the LLLTV cameras. Because of these features thermal imaging systems has no rival in many military applications but they will also find more applications in civilian sector. Automotive industry is a prime place where thermal cameras can be used in high numbers in very near future.

4 Measuring systems

As it was stated earlier the infrared measuring systems can be in general divided into two basic groups: the non-contact thermometers and the radiometers. The first ones are used for non contact temperature measurement; the latter ones – for measurement of different quantities of infrared radiation.

4.1 Non-contact thermometers

Non-contact thermometers employ different physical phenomena to determine temperature of the tested object: radiation phenomenon, refraction or phase Doppler phenomenon, luminescence phenomenon, Schlieren phenomenon etc. However, almost all systems used in practice for non-contact temperature measurement employ the phenomenon of thermal radiation that carries information about object temperature and are termed the radiation thermometers. Because objects of typical temperatures met in industry emit almost exclusively in the infrared region almost all radiation thermometers have spectral band located in this range and are often called the infrared thermometers.

Infrared thermometers always measure temperature indirectly in two stages. Power of optical radiation that comes to the system detector (or detectors) in one or more spectral bands is measured in the first stage. Object temperature is determined on the basis of the measured radiometric signals in the second stage by carrying out a certain calculation algorithm.

Even simple infrared thermometers usually consists of five or more blocks. An optical objective is usually used before the detection system to increase the amount of radiation emitted by the tested object that comes to the detector and to limit thermometer field of view. The signal at the output of the detector is typically amplified, converted into more convenient electronic form and finally digitised. A separate visualisation block is typically used for presentation of the measurement results.

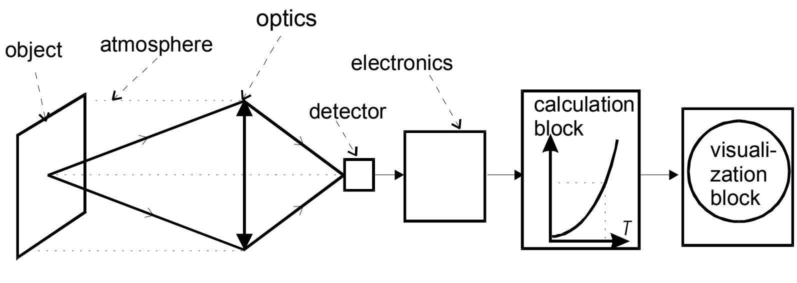

Fig. 15. A general diagram of a simple non-contact thermometer (Ref. [4.3] permission from SPIE PL)

The infrared thermometers can be divided into a few groups according to different criteria: presence of an additional co-operating source, number of system spectral bands, number of measurement points, width of system spectral bands and transmission media (Fig. 16)

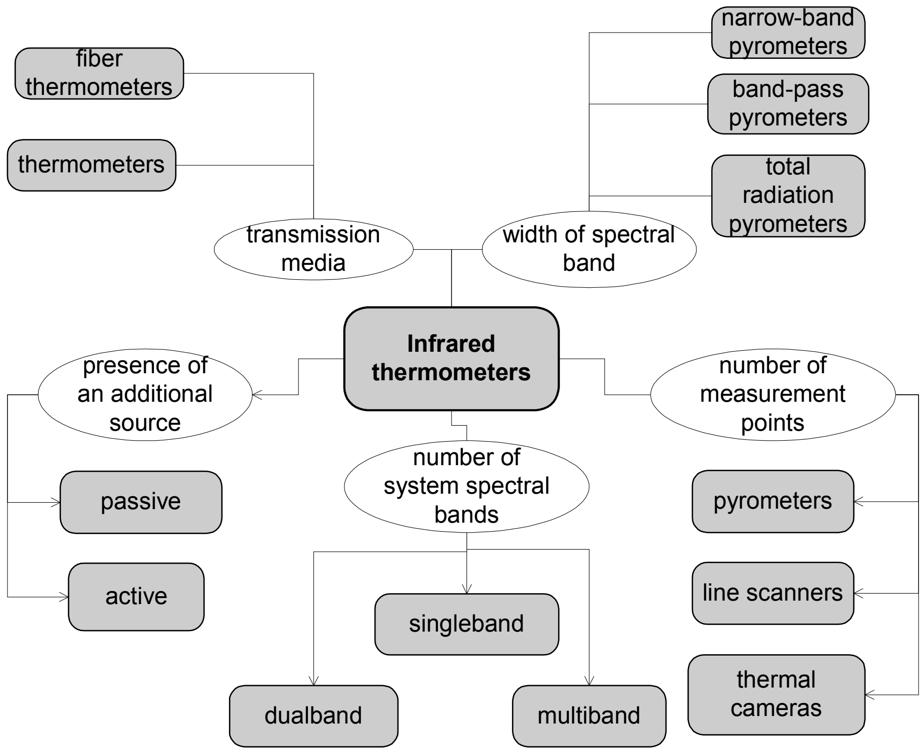

Fig. 16. Classifications of non-contact thermometers

It is possible to measure passively object temperature only on the basis of power of radiation emitted by the object in one or more spectral bands. The systems using this measurement methods will be termed "the passive systems".

By using an additional co-operating source that emits radiation directed to the tested object and measuring the reflected radiation we can get some information about emissive properties of the tested object. Such information can at least theoretically improve accuracy of non-contact temperature measurements. The systems that consist of a co-operating source emitting radiation directed to the tested object and a classical passive thermometer measuring both the radiation emitted by the source and reflected by the object and the radiation emitted by the object will be called the active systems.

Active thermometers are more sophisticated, more expensive and so far only in few applications they can really offer better accuracy than passive systems. Therefore, nowadays, almost all practical non-contact thermometers are passive ones.

To prevent any possible misunderstanding we must add that many modern systems use an artificial source of radiation -a laser- but only for indication of the measurement point, not as the additional radiation source really needed in measurement process and they are typical passive thermometers.

Both passive and active non-contact thermometers, according to criterion of number of system spectral bands, can be divided into three basic groups: single-, dual- and multiband systems. Singleband systems determine object temperature on the basis of the power of optical radiation measured in one spectral band; dualband systems - in two spectral bands, and multiband systems - in at least three spectral bands.

Passive singleband systems measure directly the power from the tested object within a single spectral band of the measuring instrument. Radiation emitted by the object that comes to detector produces an electrical signal at the detector output. The value of this signal carries information about the object temperature, which is determined using system calibration chart derived from radiometric calculation of the output signal as a function of blackbody temperature. The temperature measured in this way can be corrected for case of real objects (non-blackbodies) if only their emissivity over the spectral band is known. Incomplete knowledge of the object emissivity is the most common source of bias errors in temperature measurement using passive singleband systems. These systems are additionally vulnerable to such error sources as reflected radiation, limited atmospherics transmittance, variations of radiation emitted by optical components, detector noise and other system internal electronic sources [4.3]. However, their overriding advantage is simplicity, as they require only one spectral band and these systems dominate in industrial applications (Fig. 17, Fig. 18, Fig. 20, Fig. 21, Fig. 22).

The ratio of the power emitted by a graybody at two different wavelengths does not depend on the object emissivity but only on the object temperature. Passive dualband systems use this property of Planck function, measuring received power in two separate spectral bands. The object temperature is usually determined using a calibration chart that represents a ratio of the emitted power in these two bands as a function of the object temperature. However, a dual-band temperature measurement is unbiased only in the case of grey-body objects, or when the ratio of the emissivities in the two bands is known. Additionally, dual-band systems are still vulnerable to the error sources previously mentioned. These systems are used in limited number of applications where these conditions are fulfilled because simultaneous measurement in two bands results in more complex instruments.

Passive multiband systems apparently differ from single- or dualband systems only because of higher number of system spectral bands. However, there exist more subtle differences.
Single- or dualband systems usually use their calibration chart or a single analytical formula for determination of object temperature. Multiband systems determine an object temperature by solving a set of n equations with m unknowns as presented below:

$$
\begin{aligned}
&S_1 = f\,(T_{ob}, \varepsilon(\lambda_1), T_{back}, \ldots) \\
&S_2 = f\,(T_{ob}, \varepsilon(\lambda_2), T_{back}, \ldots) \\
&\quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
&S_n = f\,(T_{ob}, \varepsilon(\lambda_n), T_{back}, \ldots)
\end{aligned}
\qquad (1.0)
$$

where n is the number of detection bands, S_n is the signal measured as at n-th band, T_{ob} is the true object temperature, $\varepsilon(\lambda)$ is the object emissivity at wavelength λ, T_{back} is background temperature.
When the number of system spectral bands n is higher than the number of unknowns m of theoretical model it is possible to solve the set of equations (1.1) and to determine the true object temperature T_{ob}. Spectral variation of object emissivity is the main obstacle to have the number of system spectral bands equal to number of unknowns. Closure in the calculation can be achieved by setting equal emissivities in some pairs of spectral bands [4.3]. Other methods include the so called balancing of intermediation observation [4.3] and curve fitting of spectral emissivity [4.3].

At present, at least 95% of systems available commercially on market are passive singleband systems; passive dualband systems are rather rarely used; passive multiband systems are still at a laboratory stage of development.

Infrared thermometers according, to number and location of measurement points, can be divided into pyrometers, line scanners and thermal cameras. Pyrometers enable temperature measurement of only a single point or rather of a single sector (usually a circle or a square) of the surface of the tested object. Line scanners enable temperature measurement of many points located along a line. Thermal cameras enable temperature measurement of thousands of points located within a rectangle, square or circle and create a two-dimensional image of temperature distribution on this area.

Most commercially available non-contact thermometers are pyrometers (Fig. 18,Fig. 19,Fig. 20,Fig. 21). They are small, light and low-cost systems that found numerous applications in industry, science etc. enabling easy point temperature measurement.
Line scanners (Fig. 22) are specially suitable for temperature measurement of moving objects and found applications in automotive industry, welding, robotics etc.
Thermal cameras (Fig. 21) offer the greatest capabilities of all discussed types of non-contact thermometers. Modern cameras enable creation of two-dimensional image of resolution close to resolution of typical television image. As they enable presentation of measurement results in form of

electronic image they are very convenient for users. Therefore, in spite of their high price, thermal cameras found numerous applications such as control of electrical supply lines, heat supply lines, civil engineering, environmental protection, non-destructive testing and so on, and their number is rising quickly. To avoid possible misunderstanding we must emphasise that there are significant differences between typical thermal cameras used for observation applications and thermal cameras manufactured for measuring applications. Generally the observation thermal cameras do not have measuring capabilities and cannot be used for absolute temperature measurement.

Almost all pyrometers, line scanners and thermal cameras are passive singleband systems that use the passive singleband method of temperature measurement. This means, they measure the signal generated at the detector output by the radiation emitted by the tested object within the system spectral band and the object temperature is determined on the basis of the value of this signal. However, in spite of the same method of temperature measurement there are great differences in construction of pyrometers, line scanners and thermal cameras; particularly when we compare pyrometers and thermal cameras.

Basically, all these groups of systems are built using the same blocks: optics, detector, electronics, calculation block, visualisation block. However, the mentioned above blocks are simple in case of pyrometers but can be very sophisticated in case of measuring thermal cameras because of a few reasons. First, the pyrometers use usually a single or two lens (or mirrors) optical objective while thermal cameras typically employ multi-lens systems. Additionally, sophisticated scanning systems are used in thermal cameras with single or linear detectors to create two- dimensional thermal image. Second, the pyrometers usually use low cost thermal detectors or non-cooled photoelectric detectors in situation when much more expensive cooled photoelectric detectors are employed in thermal cameras. Next, typical singleband pyrometers are always built using single detector when many thermal cameras are built using linear or two-dimensional matrix of detectors. Third, the electronic block of pyrometers is needed to amplify and convert into more convenient form low-speed signal at the output of the detector, when in case of thermal cameras it is a high-speed signal that must be determined with much greater accuracy. Fourth, the visualization block of pyrometers is needed only to present measurement results in form of a row of digits in situation when the visualization block of thermal cameras is needed to present high quality thermal image.

Non-contact thermometers can be divided on the basis of width of system spectral band onto three basic groups.

The first group are total radiation (broadband) thermometers that measure radiation in theoretically unlimited, practically broadband, spectral band. These systems typically use thermal detectors. The width of their spectral band is limited by spectral region of transmission of the optics or windows. Their spectral band usually varies from about 0.3-1 μm to about 12-20μm. They have been termed "total radiation thermometers" because they measure almost all of the radiation emitted by the tested objects. They are usually simple, low cost systems of wide temperature spans susceptible to measurement errors caused by limited transmittance of the atmosphere.

The second group are band-pass thermometers. They were initially derived from total radiation (broadband) thermometers. Lenses, windows and filters were selected to transmit only a selected portion of spectrum. The 8-14μm band is a typical choice for general-purpose band-pass thermometers because of very good atmospheric transmission in this band.

The third group are narrow-band thermometers that operate over a narrow range of wavelengths. The spectral range of most narrow band thermometers is typically determined by the optical filter. Filters are used to restrict response to selected wavelengths to meet the need of a particular application. For example, the 5±0.2μm band is used to measure glass surface temperature because glass surface emits strongly in this region, but poorly below or immediately above this band. Next, the 3.43±0.2μm band is often used for temperature measurement of thin films or polyethylene-type plastics etc.

For a typical non-contact thermometer the radiation emitted by the tested object comes through atmosphere, next through optics (lenses, windows, filters) before it reaches the detector. The distance between the object and the optics is usually over 0.5 m, and the distance between the optics and the detector is typically below 0.1m. The optics, the detector and other blocks of the thermometer are mechanically mounted in the same housing. This fixed, inflexible configuration is not a good solution in situations when direct sighting due to obstructions is impossible, significant RF and EMI interference is present and electronics must be placed in safe distance, or very high temperatures exist. It is better in such situations to use flexible fibre thermometers.

Fibre non-contact thermometers (Fig. 20) can be generally defined as systems in which an optical fibre is used for transmission of radiation emitted by the object to the detector. There are a few different designs of such systems.

It is possible to design a fibre thermometer without the optics block. One end of optical fibre is located close to the surface of the tested object and the other end is adjacent to the surface of detector. However, in order to have small measurement area, the fibre end must be located very close to the surface of the object. As it is not always possible or convenient, fibre thermometers with a small optical objective at the end close to the tested object are more popular.

There are nowadays carried out many projects on development of new types of non-contact thermometers. It is possible to find in literature reports about new types of systems that are not included to the discussed above classification scheme. One of these new systems is for example laser absorption pyrometer that uses laser to modulate temperature of the tested object [4.3]. However, it seems that probably over 99% of commercially available systems can be classified using the scheme used in this book.

Fig. 17. Singleband broadband pyrometer: Mikron IR Man®

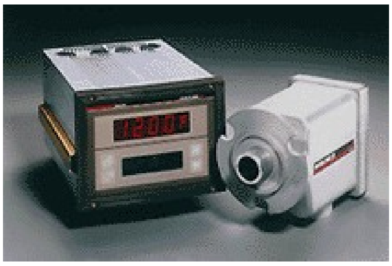

Fig. 18. Singleband narrowband pyrometer: Modline 3 manufactured by IRCON[1]®

[1] Modline 3 is also available as fibre optics pyrometers.

Fig. 19. Dualband narrow-band pyrometer: DICHROMA manufactured by E^{2}T®

Fig. 20. Singleband broadband fibre pyrometer: Infrared Fibre Transmitter M50 manufactured by MIKRON Instruments®

Fig. 21. Singleband broadband thermal camera: ThermaCAM manufactured by FLIR Inc.® (former Inframetrics Inc ®)

Fig. 22. Singleband broadband thermal scanner Thermo Profile TM Infrared Line Scanner manufactured by FLIR Systems®

4.2 Radiometers

Radiometer is a term given to an instrument designed to measure radiant flux [4.3]. On the basis of this definition a wide range of instruments can be called radiometers.
In general the infrared thermometers discussed in the previous section can be treated as a class of radiometers because the infrared thermometers determine temperature on the basis of the signal generated by the radiant flux coming to the detector. However the infrared thermometers were designed to measure only temperature and it is usually not possible to use them to measure radiant flux. Therefore we will treat infrared thermometers as instruments completely separate from radiometers although they are sometimes termed radiometers [4.3].

On the basis of the measured radiant power other quantities of infrared radiation; radiant properties of materials or detector parameters can be determined. Therefore let us define the infrared radiometer as an instrument designed to measure quantities of infrared radiation, radiant properties of materials, or infrared detector parameters.

The infrared radiometers can be divided into a few groups according to different criteria: measured quantity, number of spectral bands, number of measurement points (Fig. 23).

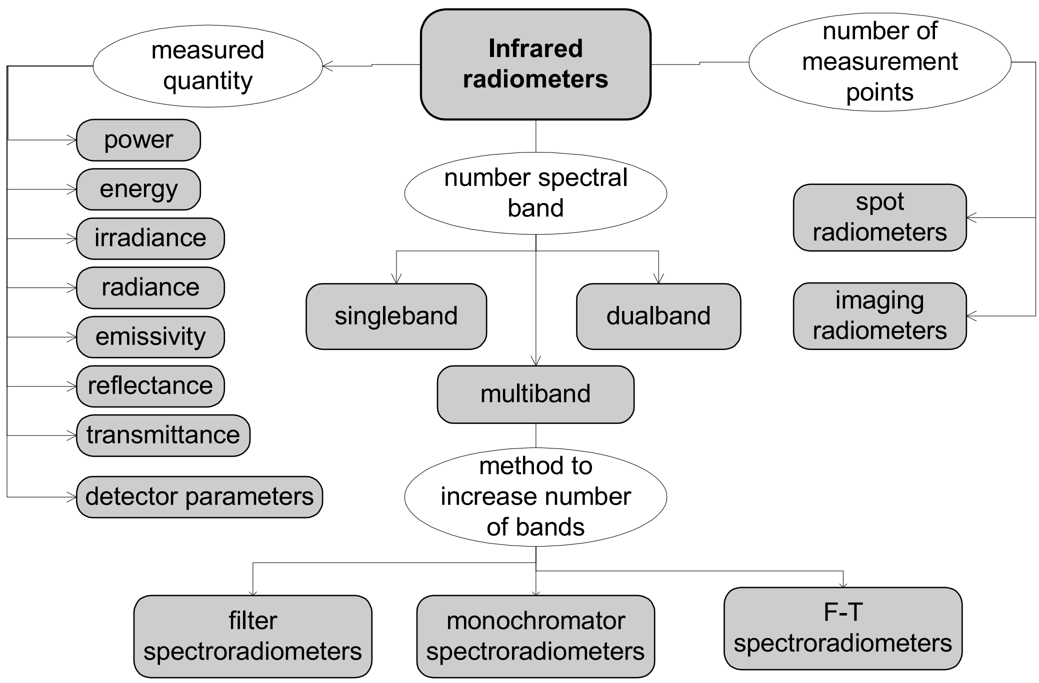

Fig. 23. Classifications of infrared radiometers

In general radiometers enable measurement of such quantities of infrared radiation like radiant power, radiant energy, radiant intensity, radiance, irradiance, radiant exposure; radiant properties of materials like emissivity, reflectance and transmittance; parameters of infrared detectors like responsivity, and detectivity, However all these features posses only a small group of radiometers that are generally bulky, laboratory type systems (Fig. 24). Their extremely versatility is usually achieved by modular approach coupled with an extensive selection of accessories and powerful application software packages what enables the user to tailor a turn-key system to their exact requirements as well as insure expandability in the future.
On the opposite side there are radiometers of design optimised for measurements of only a single quantity. Optical power meters are the prime example of radiometers from the latter group (Fig. 25)

a) b)

c) **d)**

Fig. 24. OL 750 spectroradiometric measurement system from Optronics Laboratories (see www.olinet.com) a)configuration for measurement of specular reflectance b) configuration for measurement of diffusive reflectance c) configuration for measurement of spectral transmittance d) configuration for detector testing

Fig. 25. Optical power meter Model 1830 (see www.newport.com) (courtesy of Newport Inc.)

According to the criterion of number of spectral bands the infrared radiometers can be divided into these groups: single-band radiometers, dual-band radiometers and multiband radiometers.

Singleband radiometers are radiometers designed to enable measurements of one of the above mentioned radiometric quantities within a single spectral band. Location of the spectral band is determined by the choice of the detector and optics (optionally also filters). When the spectral band is wide then the radiometer is termed the broadband radiometer, when its spectral band is narrow then it is termed narrow-band radiometer.

Dualband radiometers are the radiometers designed to enable measurements of one of the above mentioned radiometric quantity in two separate spectral bands. Radiometers enabling measurements simultaneously in the two atmospheric windows 3-5μm and 8-12 μm can be treated as the prime example of this group.

Multiband radiometers are the radiometers designed to enable measurements of one of the above mentioned radiometric quantities in at least three separate spectral bands. When the spectral bands are narrow and their numbers is high enough then the multiband radiometers enable measurement of spectral distribution of the measured quantity and such systems are termed spectroradiometers. In

contrast to situation in non-contact thermometry where the singleband infrared thermometers dominate on the market, the spectroradiometers have found wide area of applications and the most popular group of the radiometers.
The key component of any spectroradiometer is a module that can be termed spectral band selector. Its task is to select the desired spectral band from the incoming radiation. This task is achieved by use of three methods: variable filters, monochromators, F-T interferometers.

Circular (linear) variable filters are the filters whose transmission wavelength changes continuously (discretely) with position of the fraction of the filter (Fig. 26).
This means that basically using optical objective, VF and a detector it is possible to build a spectroradiometer. Simplicity of design is a great advantage of the spectroradiometers based on VF technology as it enable design of small size, reliable, high speed and mobile systems (Fig. 26). However using the variable filters it is not possible to achieve very good spectral resolution (typically about 2% of the wavelength). Next because the system must measure output radiation selected by variable filter of narrow spectral band and low transmission coefficient it is necessary to use cooled infrared detectors. Cooled sandwich InSb/HgCdTe enabling measurement in the spectral range 2.5 μm to 15 μm is a typical option in this type of spectroradiometers.

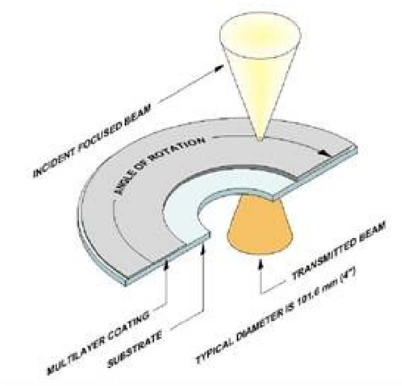

Fig. 26. RAD 314 spectroradiometer (courtesy of HGH Systemes Infrarouges www.hgh.fr) and diagram of typical circular variable filter (courtesy of OCLI www.ocli.com)

Monochromator is an optical instrument that uses a dispersing component (a grating or a prism) and transmits to the exit slit (optionally directly to detector) only a selected fraction of the radiation incoming to the entrance slit (see figure – optical scheme). The centre wavelength of the transmitted spectral band can be changed within the instrument spectral region by rotation of the dispersing element. Dispersing prisms, or more often gratings are used as the dispersing elements in monochromators.

Dispersive spectroradiometers build using monochromators are characterised by good spectral resolution (up to about one hundredth of per cent of the wavelength), and very good stray light rejection. They are well suited for absolute radiometric measurements as their sensitivity can be determined on the basis of known parameters of the detector, monochromator, and the input optic; or they can be easily calibrated using an external source. However they are also characterised by a few disadvantages, too. First, these spectroradiometers are generally large size, bulky laboratory type systems (Fig. 24). Second, because of high F-number (focal length to aperture ratio) of the monochromator optics and transmission losses of the radiant flux reaching the detector in the desired spectral band is very low. Therefore sensitivity of these spectroradiometers is lower than sensitivity of previously described variable filter spectroradiometers. Cooled IR detectors are needed to enable detection of this weak signal at rates higher than about 1Hz. Non-cooled detectors can also be used but for long time scans in minutes.

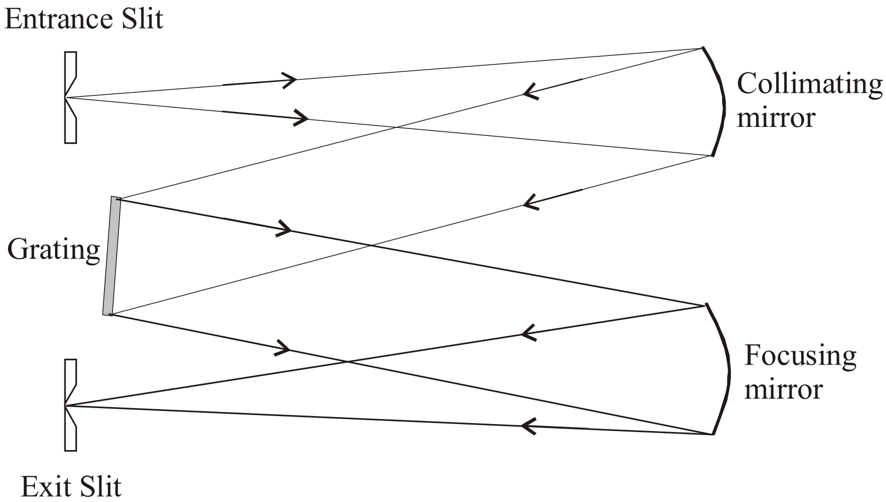

Fig. 27. The Czerny-Turner configuration of a grating monochromator

Michelson interferometer is the spectral band selector in Fourier Transform spectroradiometers. The interferometer is usually built as an optical instrument consisting of a beam splitter and two flat mirrors arranged such as to recombine the two separated beams back on the same spot at the beamsplitter. One of the mirrors moves linearly in order to produce variable optical interference.

The Michelson interferometer can also be seen as a modulator. From a constant spectral radiation input, a temporal modulation occurs at the detector having a unique modulation frequency for each wavelength of radiation. The modulation frequency can be scaled via the velocity of the mirror movement. This modulated signal registered by the detector is called the interferogram. It is digitised at the rate of at least two times the maximum modulation frequency and a mathematical operation, the Fourier Transform, is applied to retrieve the spectral distribution of the input radiation. A calibration with a known source, is required in order to obtain quantitative radiometric results.

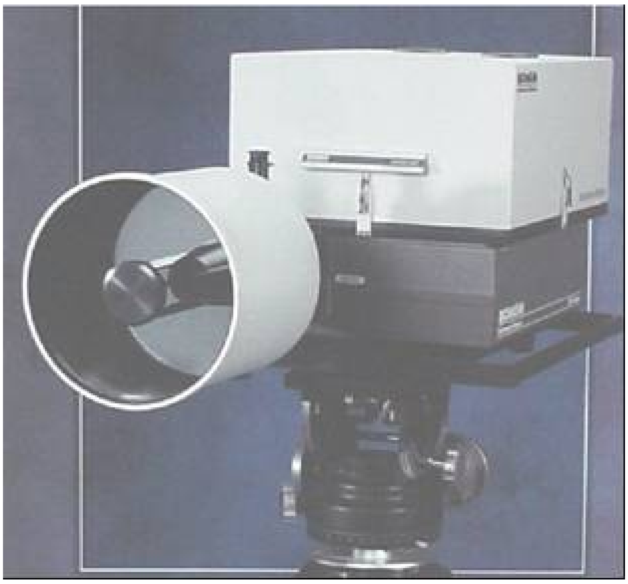

Fig. 28. FT spectroradiometer (permission from Bomem Inc.)

FT spectroradiometers differ from the VF and monochromator based spectroradiometers not only due to different spectral band selector. There are also significant differences in role of the optics (Fig. 29). In case of the variable filter spectroradiometers and dispersive spectroradiometers selection of the desired spectral band is done using convergent beams; the while the interferometer used in FT spectroradiometer works with parallel beams. Next, the variable filter and the monochromator are self-contained blocks in the sense that major spectral characteristics do not depend very much how you irradiate the input slit of the monochromator (the variable filter) and how you collect the radiation from the exit slit of the monochromator (the filter output). Changing the external optics gains or losses you sensitivity, adds or reduces stray radiation and aberrations. However, in case of the FT spectroradiometers the spectral characteristics depends also on the external optics and that creates a greater role of the external optics in FT spectroradiometers.

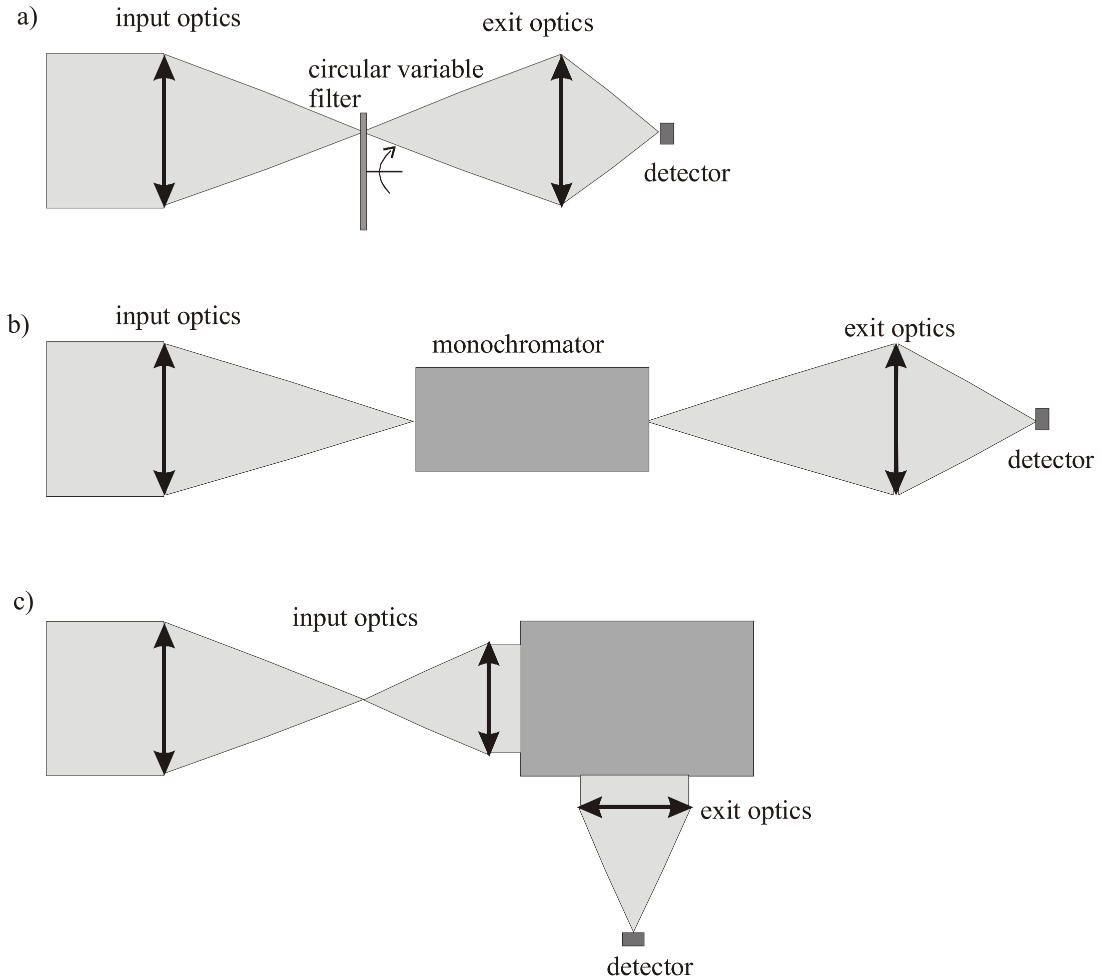

Fig. 29. Typical optical layout of the external optics of the three types of spectroradiometers a) VF spectroradiometers, dispersive (monochromator based) spectroradiometer, c) FT spectroradiometer

FT spectroradiometers are characterized by very good spectral resolution and very good sensitivity, better than offered other types of spectroradiometer. Very good spectral resolution is the effect of use of the interferometer as a spectral selector. Very good sensitivity originates from the fact that the detector is irradiated not only by the radiation from a desired narrow spectral band (the case of the variable filter spectroradiometer and the dispersive spectroradiometers) but by a full spectrum of radiation coming to the interferometer input. This feature enables design of high-speed, high spectral resolution FT spectroradiometers using non-cooled or thermoelectrically cooled detectors (typically HgCdTe detectors) instead of bulky liquid nitrogen cooled detectors needed in the variable filter or dispersive spectroradiometers. However performance of the FT spectroradiometers can be severely reduced even by a very small non-alignment of the optical system what makes this type of spectroradiometers inherently sensitive to shocks and vibrations. Therefore FT spectroradiometers were for the last few decades considered as rather laboratory type equipment that cannot be used in field applications. However, at present this opinion is outdated as there are on the market fully mobile FT spectroradiometers (Fig. 28).

Great majority of the commercially available spectroradiometers are systems enabling measurement of the spectral distribution of radiation emitted or reflected by a single spot and these systems can be termed the spot radiometers. There exists also another group termed the imaging spectroradiometers because these systems offer some imaging capabilities.

The term "imaging spectroradiometer" has a few different meanings and can be a source of a confusion as there are significant differences in real imaging capabilities of different "imaging spectroradiometers".

The first class of the imaging spectroradiometers are actually typical spot spectroradiometers with a modified optical system and detection system in form of a linear detector instead of a single detector (Fig. 29).

Optical system of any monochromator creates at the output plane a series of adjacent images of the input slit corresponding to wavelength. At one time only one of these images fits to the exit slit and this radiation is measured by the detector located behind the stationary exit slit. Rotation of the dispersing element cause movement of these series images and the radiation from each of them can be measured.

If we put an array detector at the output plane of the monochromator optical system instead of traditional configuration (an exit slit and a single detector behind) then this series adjacent images of the input slit corresponding to wavelength will be focused on different parts of the array detector. Therefore by use of an array detector we could expect possibility of simultaneous measurement of radiation spectrum of different spots within the input slit. However, due to significant aberrations (curved output field, astigmatism) of the optical systems this cannot be achieved in standard non-imaging spectroradiometers. The aberrations create situation when only one image from the series – the image that fits the exit slit – is horizontally sharp. By use of modified optical system with corrected curved output field and astigmatism we can get sharp images of the input slit corresponding to wavelength focused on different parts of the array detector what enables simultaneous measurement of spectrum.

The second class of the imaging spectroradiometers are multiband (in literature multispectral or hyperspectral) imaging systems generating simultaneously two dimensional images of the observed scenery in a number of spectral bands, where this number can vary from a few bands to over a hundred (Fig. 30).

Fig. 30. Airborne Imaging Spectroradiometer GER EPS-H series

Tab. 2. Basic parameters of the GER EPS-H imaging spectroradiometers (see www.ger.com/epsh.html) (permission from the GER Inc.)

Scanner:	Kennedy large-size scan head
Spectrometers	1 Si (VIS / NIR) - 76 channels; 4.3 - 1.05 µm 1 InGaAs (SWIR 1) - 32 channels; 1.5 - 1.8 µm, 1 InSb (SWIR 2) - 32 channels; 2.0 - 2.5 µm 1 HgCdTe (LWIR) - 12 channels; 8 - 12.5 µm 1 InSb (MWIR) - 3 - 5 µm (option)
IR Detector Cooling	Liquid nitrogen (closed cycle – option)
IFOV	Choice of 1.25 mrad, 2.5 mrad, 3.3 mrad, or 5.0 mrad
Swath angle	up to 90°
Scan Speed	up to 25 Hz with all bands, continuously selectable
Pixels Per Line	512

High number of spectral bands being simultaneously recorded is typically achieved by use of a number of dichroic beam splitters, gratings, and linear detectors of different spectral sensitivity regions (Fig. 31). The beam splitters separate the incoming parallel polichromatic beam onto a few beams of separate spectral bands: for example the visible and near infrared range, the SWIR range, the MWIR range and LWIR range. The grating separate the beams further and finally all these separated spectrally beams are focused by output optical objectives at different elements of the linear detectors.

The above described system enables measurement of flux from a single spot in a number of spectral bands. However, because these systems employ a scanning system (typically the Kennedy-type reflective scanner) and are used in airborne applications the imaging spectroradiometers generate two dimensional image of the land below the aircraft in different spectral bands. (Fig. 32).

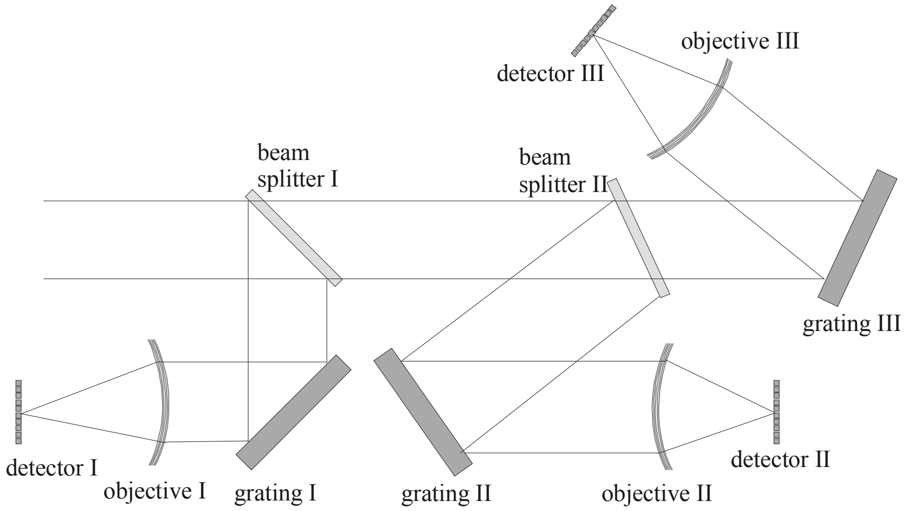

Fig. 31. Optical diagram of a typical imaging spectroradiometer

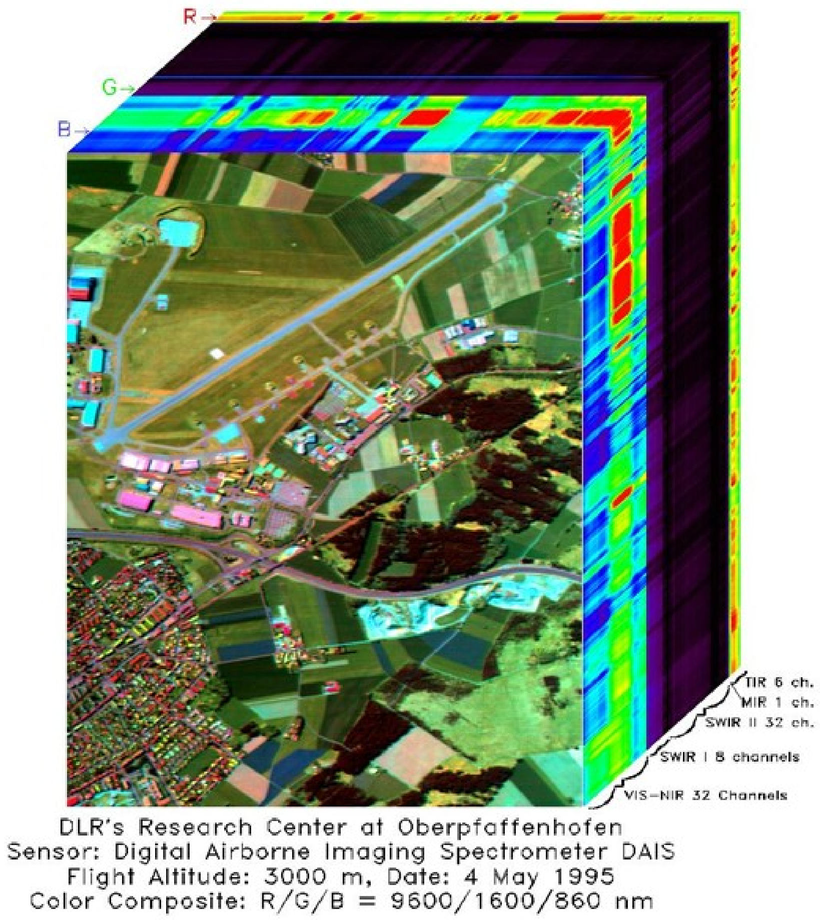

Fig. 32. Colour composite image recorded using the Digital Airborne Imaging Spectroradiometer DAIS (permission from German Aerospace Center DLR) (see http://www.op.dlr.de/dais/dais-gal.htm)

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