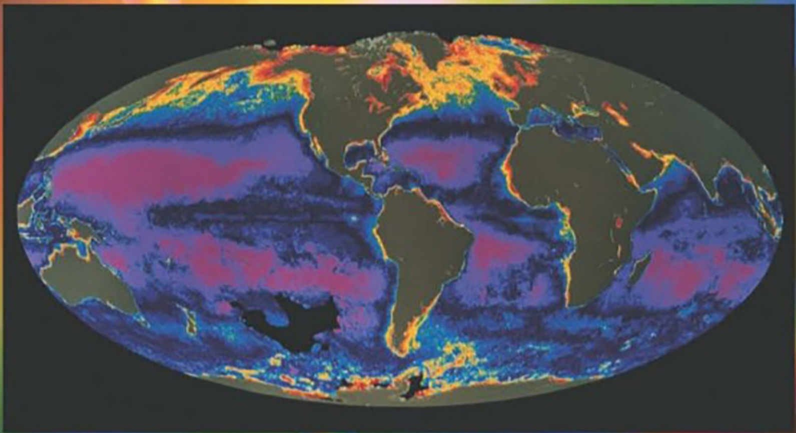
Photonics-Enabled Technologies

Infrared Systems for Homeland Security



OP-TEC

Optics and Photonics Series

Infrared Systems for Homeland Security

Photonics-Enabled Technologies

OPTICS AND PHOTONICS SERIES

OP-TEC: The National Center of Optics and Photonics Education

An NSF ATE Project

National Center for Optics and Photonics Education

This document was developed by OP-TEC: The National Center for Optics and Photonics Education, an initiative of the Advanced Technological Education (ATE) program of the National Science Foundation.

Published and distributed by
OP-TEC
University of Central Florida
http://www.op-tec.org

ISBN 1-57837-486-3

PREFACE

This module is one of three pertaining to the role of optics and lasers in homeland security. OP TEC treats the imagining component of homeland security as a *photonics-enabled* technology. The current OP-TEC series on photonics-enabled technologies comprises modules in the areas of manufacturing, biomedicine, forensic science and homeland security, environmental monitoring, and optoelectronics, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of OP-TEC modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module, *Infrared Systems in Homeland Security,* was prepared by Dr. Alan Ducharme.

CONTENTS

Infrared Systems for Homeland Security

INTRODUCTION

The National Strategy for Homeland Security and the Homeland Security Act of 2002 have mobilized a variety of agencies throughout our society. The primary function of the Department of Homeland Security is to utilize technology and information gathering capabilities to secure the United States against future terrorist attacks. An increasing effort has been made to monitor vital facilities and U.S. borders using video surveillance. Video reconnaissance utilizes a wide range of imaging systems operating in the visible and infrared spectrums to cover areas that would be difficult to cover using conventional armed forces. An example would be the perimeter of a water treatment facility.

Video reconnaissance allows a single operator to monitor hundreds of video cameras. These systems must be able operate under a variety of lighting conditions. Visible cameras are used during the day but are not operational at night unless artificial lighting is available. For surveillance applications, using artificial lighting is not always possible and can be a hindrance if unobtrusiveness is required. Infrared cameras operate by detecting temperature differences called *heat signatures.* Thus, they require no additional lighting and can be operated at night without detection from those under surveillance.

A video camera is the combination of a lens system and a focal plane detector array. The lens system is designed for a specific wavelength range over which the detector can operate. The focal plane detector array is a two-dimensional matrix of individual detector elements positioned at the focal plane of the system where the image is formed by the lens system. The individual detectors are constructed of semiconductor materials that can transform light to electrons. The electronic signal is then collected for viewing and storage. The collection of individual images at a set frame rate is called *video*. Modern systems have the ability to convert electronic signals to a digital format that can be stored on computers and viewed on a variety of display devices.

A semiconductor detector array can be constructed from specialized materials that allow the conversion of infrared light to electrons. All heated objects emit infrared light. The hotter the object, the more infrared light it emits. Infrared detectors have the ability to detect these heated objects. The imagery they produce is proportional to the temperature differences between the objects imaged by the lens system. The ability to see temperature difference gives infrared systems the unique ability to see in the dark. This makes them highly useful for security applications.

This module will begin by describing the theory of infrared light and how it is generated by heated objects. We will then discuss infrared detector technologies and how they are used in infrared cameras. Several specific infrared systems will be detailed, along with their application to homeland security. Finally, a description of how the performance of infrared systems is measured will be presented.

PREREQUISITES

The student should be familiar with the following before attempting to complete this module.

1. High school mathematics through intermediate algebra and basics of trigonometry
2. CORD's Optics and Photonics Series Course 1, *Fundamentals of Light and Lasers*
3. CORD's Optics and Photonics Series Course 2, *Elements of Photonics*

   Module 2-1: *Operational Characteristics of Lasers*
   Module 2-2: *Specific Laser Types*
   Module 2-3: *Optical Detectors and Human Vision*

4. CORD Optics and Photonics Series, photonics-enabled technology module *Lasers in Forensic Science and Homeland Security*

OBJECTIVES

Upon completion of this module, you should be able to do the following:

- Define what part of the electromagnetic spectrum constitutes the infrared light spectrum
- Define how infrared focal plane arrays operate
- Understand how heated bodies emit light radiation
- Define how light is transmitted through the atmosphere and why only certain regions of the infrared spectrum are utilized by infrared detection systems
- Calculate the flux transfer of light from a source to the detector in an infrared system
- Understand differences between various infrared detector technologies and over what part of the infrared spectrum they are used
- Understand different applications of infrared systems and how to determine the best infrared camera for particular applications
- Use infrared performance measurements to determine whether a system will meet an application requirement

SCENARIO

Teemus Clark is a technician for a high-technology company. In recent years the threat of industrial espionage and other breaches in homeland security has caused her company to add security measures for limiting access to its buildings and employees. Teemus's company develops technology used in high-speed X-ray scanning equipment that provides surveillance at the entrances of federal buildings and airports. The company is concerned that they could be a target for sabotage or property theft.

The company's board has recently approved a plan to purchase and install new infrared imaging systems. The purpose of the systems will be to provide nighttime surveillance of the perimeters of buildings that contain valuable equipment and critical design information. This will tighten the security of sensitive areas while reducing risk to security personnel. Teemus has been asked to assist the security department in evaluating available infrared technology. Because of the wide variety of infrared cameras now available, this is a sizable task. To be able to meet the company's performance and cost requirements, Teemus must understand infrared technology and optical systems.

INTRODUCTION TO INFRARED SYSTEMS

An infrared system is a specialized video camera that detects heat signatures at night and during the day. The basic infrared camera consists of a lens and a detector array positioned at the focal plane of the lens. The lens is made of a specialized material that is transparent to infrared light but has refractory properties. The detector array has the ability to absorb energy from infrared light and produce an electrical signal. A basic setup for the use of an infrared camera is shown in Figure 1.

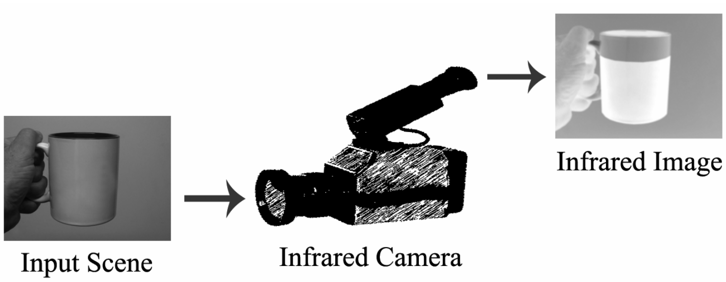


Figure 1 *Basic setup for the use of an infrared camera*

The "Input Scene" in Figure 1 is what we would see in visible light. The visible image shows a hand holding a mug. In the "Infrared Image" generated by the camera, it is easy to see that the mug is 3/4 filled with hot liquid. This is displayed using white pixels to represent high temperatures and black pixels to represent low temperatures. As you can see, the hand is not as bright or warm as the liquid in the mug. The handle of the mug is also at a lower temperature, allowing the person to hold it. This simple example demonstrates the usefulness and advantages of infrared imagery. The ability to sense temperature differences can provide information that cannot be seen with visible-light systems such as the human eye.

Electromagnetic Spectrum

The electromagnetic spectrum was covered in Course 1 of the CORD *Optics and Photonics Series.* For convenience, a brief review is included here.

The electromagnetic spectrum illustrates and categorizes the frequency distribution of electromagnetic radiation. The full range of wavelengths included in the electromagnetic spectrum spans from kilometers down to fractions of a single atom.

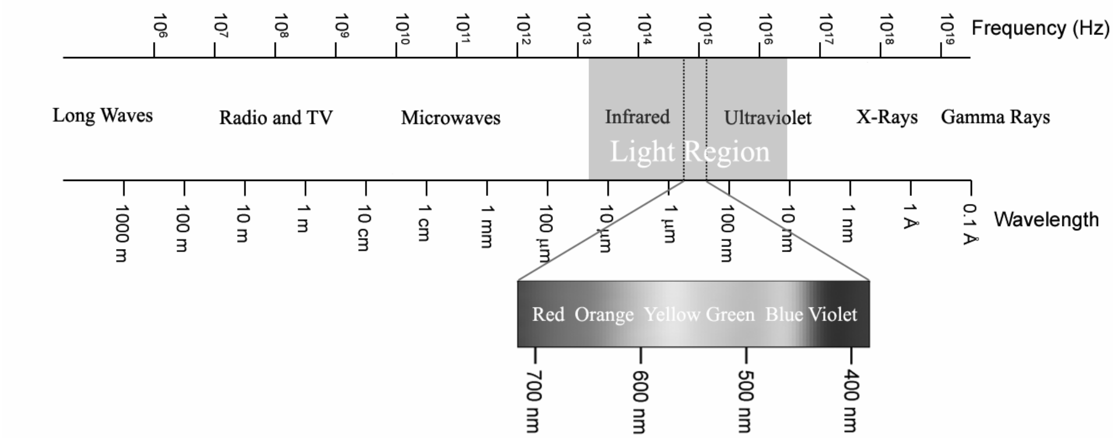


Figure 2 *The electromagnetic spectrum showing the light region in the grey area*

The light or visible portion of the electromagnetic spectrum is only a small piece of the full spectrum. This piece includes wavelengths from 10×10^{-9} m (or 10 nm) to 100×10^{-6} m (or 100 um). This span is further divided into the ultraviolet, visible, and infrared regions. The most relevant region for this module is the infrared light spectrum, which begins at 0.8 um and extends to 15 um.

Light has a dual nature: It can be described either as a transverse wave or a stream of particles called *photons.* This dual nature becomes evident from the behavior of light. When light is passed through a narrow slit in a diffraction grating, it behaves like a wave. When light is allowed to interact with electrons in solar cells, it behaves like particles.

The photon is a tiny mass-less bundle of light energy that helps describe the particle behavior of light. The energy of a photon is related to the wavelength of the light. This relationship is expressed in the following equation:

$$E = \frac{hc}{\lambda}$$

The parameter h is Planck's constant (6.6×10^{-34} Js) and the parameter c is the speed of light (3×10^{-8} ms). The relationship between the wavelength and frequency of light is expressed by this equation:

$$\lambda = \frac{c}{f}$$

Example

Given: The wavelength of light is 8 um.

Find: The energy of a single photon

Solution

$$E = \frac{hc}{\lambda} = \frac{6.6\times10^{-34}\,\mathrm{J\cdot s}\cdot3\times10^{8}\,\mathrm{m}}{8\times10^{-6}\,\mathrm{m}} = 2.47\times10^{-20}\ \mathrm{J}$$

Atmospheric Transmission and Infrared Detector Ranges

Using infrared systems requires an understanding of what affects the transmission of infrared radiation through the atmosphere. As light passes through the atmosphere, it interacts with the molecules that make up air—oxygen (~21%), nitrogen (~78%), carbon-dioxide (~0.04%), argon (~1%), and water vapor (variable percentage). The interaction of light with these molecules is most evident in the infrared region, where absorption is the predominant effect.

Atmospheric transmission, which is related to absorption, can be plotted using programs such as HITRAN. The name HITRAN stands for *high-resolution transmission molecular absorption database*. The HITRAN database was started by the Air Force Cambridge Research Laboratory in the late 1960s. Figure 3 shows the atmospheric transmission plot for a 6000-foot path at sea level.

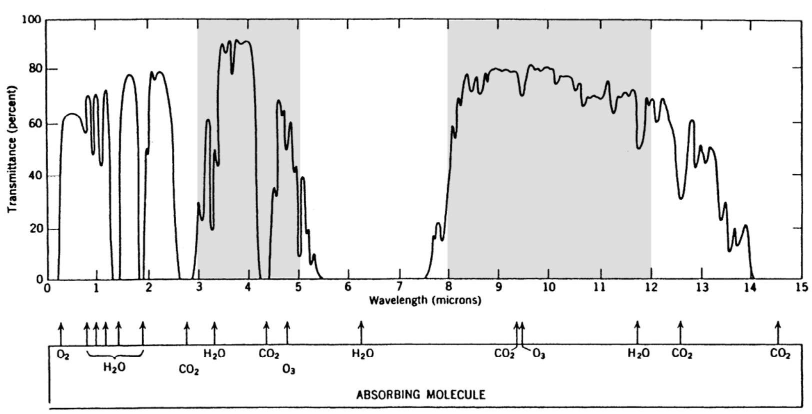


Figure 3 *Atmospheric transmission for a 6000-foot path* (adapted from Hudson, Infrared Systems Engineering)

The plot in Figure 3 shows that the transmission of light through the atmosphere varies for different wavelengths of light. Some wavelengths, such as 10 μm, pass through the atmosphere with less absorption than other wavelengths, such as 6 μm. Of particular interest are the two grey areas shown in Figure 3. These are considered infrared systems operational windows. Transmission over the wavelength ranges 3–5 μm and 8–12 μm is relatively high compared to transmission over other ranges (i.e., 5–8 μm). Conversely, the absorption in this range is low. This is where the majority of infrared systems are designed to operate. The designations for these two infrared operational windows are

3–5 μm range: MWIR (medium wavelength infrared), and
8–12 μm range: LWIR (long wavelength infrared).

The transmission plot in Figure 3 is for a range of more than a mile. However, even for short ranges, the absorption of infrared radiation due to H_2O is still significant. For this reason, almost all infrared systems operate within the transmission windows.

Blackbody Radiation

Any object that is heated emits thermal radiation. This radiation spans over a range of wavelengths called a *spectrum.* An object that is heated to a warm temperature will have a significant amount of radiation concentrated in the infrared portion of its spectrum.

A blackbody is an ideal object that absorbs all electromagnetic radiation that interacts with its surface. This means that none of the radiation is reflected or transmitted. The word "ideal" is used here because true blackbody radiation exists only in theory; it can only be *approximated* in nature. Blackbodies are excellent sources of thermal radiation because the emitted spectrum is directly proportional to their temperature. The higher the temperature, the greater the amount of radiation emitted. Blackbodies emit radiation in a smooth, continuous spectrum that includes visible and infrared light.

To understand how objects heated above 700 K appear to our eyes, consider a piece of steel heated in a fire or forge. As the heating process begins, soot forms on the steel and no light is seen to be emitted. The longer the steel is in the fire, the higher its average temperature becomes. At first the steel glows with a dull, deep red color that changes to red and then to orange. Finally, the steel begins to glow white or what we call white-hot. The progression of color is consistent with the behavior of heated bodies, which emit closer to the center of the visible spectrum as the temperature is increased.

Mathematically, the spectrum of blackbody radiation can be calculated using Planck's law of blackbody radiation:

$$M_\lambda(\lambda,T) = \frac{2\pi hc^2}{\lambda^5\left[e^{hc/\lambda kT}-1\right]}\left[\frac{W}{\text{cm}^2\ \mu\text{m}}\right]$$

The constants used in this equation are

Spectral exitance ≡ $M_\lambda(\lambda,T)$,
Planck's constant ≡ $h = 6.6\times10^{-34}$ J s,
Boltzmann's constant ≡ $k = 1.38\times10^{-23}$ J/K, and
Speed of light ≡ $c = 3\times10^8$ m/s.

This equation is used to determine the spectral output, also called the *spectral exitance,* for a given body heated to a temperature, T, in Kelvin. A plot for a family of blackbodies is given in Figure 4.

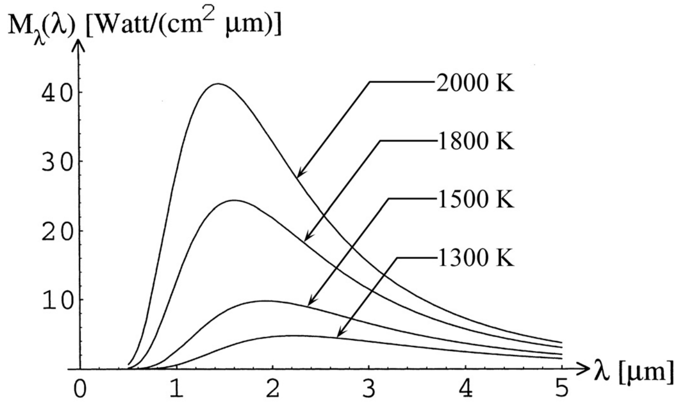


Figure 4 *Plots of spectral exitance for blackbodies at 1300 K, 1500 K, 1800 K, and 2000 K*

Example

Given: A blackbody heated to 1500 K

Find: The spectral exitance at 2 um

Solution

$$M_\lambda\left(2\text{um},1500\text{ K}\right)=\frac{2\pi hc^2}{\lambda^5\left[e^{hc/\lambda kT}-1\right]}=\frac{2\pi\cdot(6.6\times10^{-34}\,\text{Js})\cdot(3\times10^8\,\text{m/s})^2}{(2\times10^{-6}\,\text{m})^5\left[e^{\frac{(6.6\times10^{-34}\,\text{Js})\cdot(3\times10^8\,\text{m/s})}{(2\times10^{-6}\,\text{m})\cdot(1.38\times10^{-23}\,\text{J/K})\cdot1500K}}-1\right]}$$

$$M_\lambda(2\text{ um},1500\text{ K})=\frac{3.73\times10^{-16}\,\text{Js}\cdot\frac{\text{m}^2}{\text{s}^2}}{3.79\times10^{-27}\,\text{m}^5}=9.84\times10^{+10}\,\frac{\text{J/s}}{\text{m}^3}=9.84\times10^{+10}\,\frac{W}{\text{m}^3}$$

$$M_\lambda(2\text{ um},1500\text{ K})=9.84\times10^{+10}\,\frac{W}{\text{m}^3}\left(\frac{\text{m}}{100\text{ cm}}\right)^2\left(\frac{\text{m}}{10^6\,\text{um}}\right)=9.84\frac{W}{\text{cm}^2\text{um}}$$

Emissivity

As mentioned in the discussion of blackbodies, true blackbody radiation only exists theoretically and is not replicated precisely in nature. This is because no material can absorb *all* electromagnetic radiation without at least an infinitesimal amount being reflected or transmitted. In order to use the spectral exitance values calculated using Planck's law, a correction factor must be applied. This factor, called *emissivity,* ε, is a multiplicative constant that is a ratio formed by the energy radiated by a material and the energy radiated by a blackbody at the same temperature.

$$\varepsilon=\frac{\text{energy radiated by a material}}{\text{energy radiated by a black body}}$$

The emissivity values of many common materials have been measured. A selection of values is given in Table 1.

Table 1. Emissivity Values for Some Common Materials

Material	Emissivity
Aluminum (polished)	0.05
Aluminum (anodized)	0.55
Steel (polished)	0.03
Steel (oxidized)	0.79
Brick	0.93
Paper	0.93
Sand	0.90
Human skin	0.98
Wood	0.90
Candle soot	0.95

One of the most obvious facts about emissivity values is that the values for shiny materials are relatively low. This is because shiny materials reflect most of the light directed onto their surfaces.

Greybodies

Greybody spectral exitance is different from blackbody spectral exitance by a factor equal to the emissivity. Since emissivity is a constant value over all wavelengths, the effect to the blackbody spectral exitance curve is a reduction in the area under it. A blackbody curve adjusted for several emissivity values is shown in Figure 5.

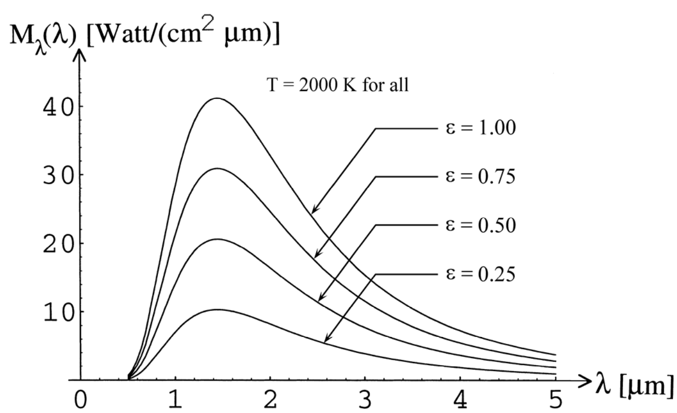


Figure 5 *Grey body curves for 2000 K for emissivity values: 0.25, 0.50, 0.75, and 1.00*

Example

Given: An oxidized plate of steel heated to 1500 K

Find: The spectral exitance at 2 um

Solution

$\varepsilon = 0.79$ from Table 1 for oxidized steel.

$$M_{\lambda,\text{graybody}} = \varepsilon \cdot M_\lambda(2\text{ um}, 1500\text{ K}) = 0.79 \cdot 9.84 \frac{W}{\text{cm}^2\text{um}} = 7.77 \frac{W}{\text{cm}^2\text{um}}$$

Radiometry Calculations

Radiometry is the study of how the power carried by radiation travels from one point to another. This is important because using infrared systems requires the ability to predict how much power emanating from a known infrared source will reach a detector.

Our discussion of radiometry begins with the quantities used to calculate flux transfer. The primary quantities are given in Table 2.

Table 2. Radiometric Quantities

Symbol	Quantity	Units
Q	Energy	Joule
ϕ	Flux or power	Watt=Joule/sec
I	Intensity	Watt/steradian or W/sr
E	Irradiance	Watt/cm^2
M	Exitance	Watt/cm^2
M_λ	Spectral exitance	Watt/cm^2·unit wavelength
L	Radiance	Watt/sr·cm^2

All of the quantities in Table 2 result from the energy carried by photons. Recall that the energy of a photon is given by

$$E = \frac{hc}{\lambda}$$

where $h = 6.6\times10^{-34}$ Js and c is the speed of light (3×10^8 m/s). To see how Table 2 depends on photons, consider the quantity called flux or power, ϕ. To define ϕ, consider a plane oriented perpendicular to the flow of a group of photons. The flux or power is the sum of all energies carried by photons that pass through this plane in one second. This plane typically represents the detector surface in an imaging system where light energy is converted into an electrical signal. Thus, the flux gives us an indication of the amount of power from the source that is incident on the detector surface. If this power is too low, the system may not be able to detect the light. If it is too high, it may damage the detector.

To determine how much power is incident on a detector surface, you must be able, in radiometry calculations, to define how much radiation is being emitted from a source in a certain set of directions. When radiation is emitted by a source, it goes out in all directions. However, a detector only intercepts radiation from a few of those directions, as shown in Figure 6. This figure shows that the directions that intercept the detector form a cone with the point source as its vertex. This cone defines a solid angle that can be described by a unit of measurement called a *steradian*.

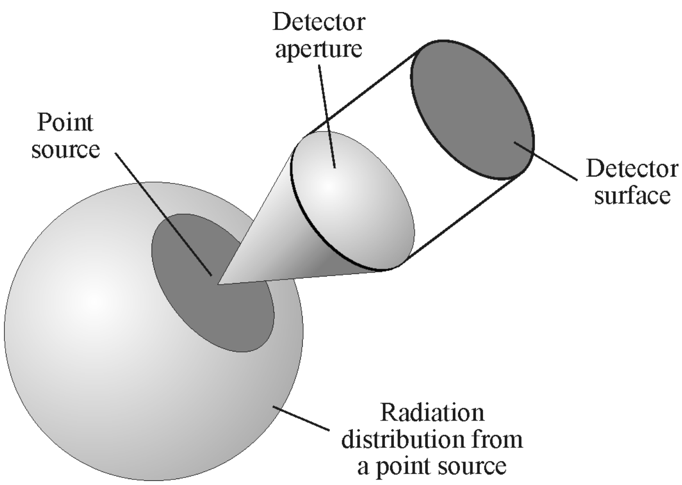


Figure 6 *Radiative distribution from a point source*

The steradian can be understood by observing the illustration in Figure 7.

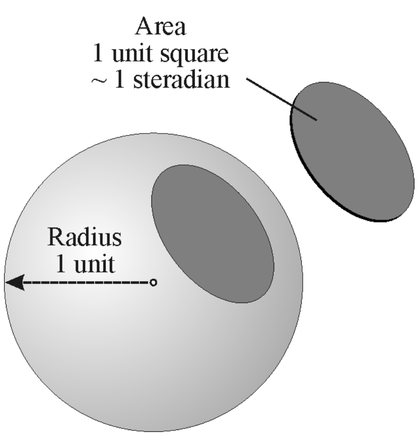


Figure 7 *Definition of steradians*

The solid-angle, Ω, with units of steradians is a three-dimensional angular quantity that can be thought of as a cone of angles or, as in our previous description, a cone of directions. Mathematically, the solid-angle is defined by the area of a cap on a unit sphere divided by the square of its radius. The total number of steradians in a sphere is equal to 4π steradians. For radiometric calculations, the solid-angle can be determined for a circular or square planer surface by:

$$\Omega = \frac{\text{Area}}{\text{Radius}^2} = \frac{A}{r^2}$$

Now let's use the concept of a solid-angle to define the quantities in Table 2. Intensity is the amount of light flux emitted per unit of steradian. This quantity is useful for characterizing the amount of radiation being emitted by point sources or single, very small emitters over the various directions that define a solid cone. The intensity of a point source is calculated using:

$$I = \frac{\phi}{\Omega}$$

Likewise, the flux emitted by a point source is given by:

$$\phi = I \cdot \Omega$$

Example

Given: A point source with an intensity of 3 *W*/sr

Find: (a) The total flux emitted into a sphere surrounding the point source and (b) the flux striking a 1 mm circular detector surface placed 3 cm from the point source

Solution

a) $\phi = I \times \Omega = 3W/\text{sr} \times 4\pi = 12\pi W = 37.7\text{W}$

b) $$\Omega = \frac{A}{r^2} = \frac{\pi(1\times10^{-3}\,m)^2}{(3\times10^{-2}\,\text{m})^2} = 3.5\times10^{-3}\,\text{sr}$$

$$\phi = I \cdot \Omega_{\text{aperture}} = 3W/\text{sr} \cdot 3.5\times10^{-3}\,\text{sr} = 10.5\text{ mW}$$

The quantities of irradiance and exitance have the same units, W/cm^2, but have different interpretations. The irradiance is the amount of power incident on a surface. The exitance is used for extended sources (larger than a point source) and is equivalent to the amount of power per cm^2 emitted from a surface.

The irradiance is considered to be uniform over the entire surface where the light is being measured. The quantity is sometimes given for specific conditions for special commercial sources. If the irradiance, E, on a surface is known, the amount of flux on a given area, A, of that surface can be calculated.

$$\phi = A \bullet E$$

The exitance is also considered to be uniform over the surface of an extended source. If the exitance, M, is given for a source, the amount of flux leaving the surface for a particular area, A, can be calculated.

$$\phi = A \bullet M$$

Example

Given: The irradiance on a surface is measured to be $4 W/cm^2$

Find: How much power falls on a $1\ mm^2$ portion of the surface?

Solution

$\phi = A \bullet E = 0.01\ cm^2 \bullet 4 W/cm^2 = 40\ mW$

The radiometric quantity radiance is used for extended sources where the amount of light emitted depends on the viewing angle of the imaging system. An example would be a laser where all of the light is directed in a small solid-angle. Radiance is different from exitance because of this angular dependence. The radiance, L, can be used to calculate flux, by using the solid-angle to a detector's surface, A_d and the area of the source, A_s.

$$\phi = L \cdot A_s \cdot \Omega_d = L \cdot A_s \cdot \frac{A_d}{r^2}$$

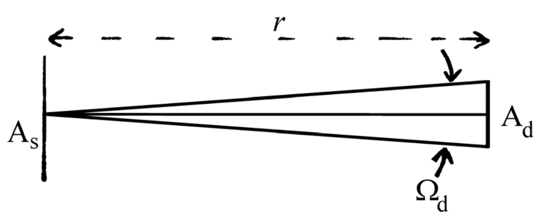


Figure 8 *Graphical description of parameters used to calculate flux using radiance*

Example

Given: A source with area of $1\ cm^2$ and radiance of $5 W/(cm^2\ st)$ at a distance of 10 m

Find: The flux that falls on a detector of $1\ mm^2$

Solution

$$\Omega_d = \frac{A_d}{r^2} = \frac{(1\times10^{-3}\,\mathrm{m})^2}{(10\,\mathrm{m})^2} = 1\times10^{-8}\,\mathrm{st}$$

$$\phi_d = L \cdot A_s \cdot \Omega_d = 5W/(\mathrm{cm}^2\mathrm{st})\cdot 1\,\mathrm{cm}^2 \cdot 1\times10^{-8}\,\mathrm{st} = 5\times10^{-8}\,W$$

INFRARED IMAGING SYSTEMS

We now understand what constitutes infrared radiation, what affects its transmission, and how the power it carries from one location to another is calculated. Let's turn our attention next to how this radiation is detected.

Optical detectors can be divided into two major classifications: photon detectors and thermal detectors.

Photon Detectors

A photon detector absorbs infrared radiation directly, causing a quantum change in the detector material. As a result of these changes, certain parameters of the detector—such as voltage, current, inductance, and resistance—also change. The output of a photon detector is governed by the rate at which it absorbs photons. Thermal detectors respond to the heating of the detector material that results from photon absorption. The output of a thermal detector is directly proportional to the energy carried by the photons.

Photon detectors can be divided further into three types: photoconductive, photovoltaic, and photoemissive (not covered here).

The operation of *photoconductive detectors* is based on the photogeneration of charge carriers in a semiconductor material. Photogeneration occurs when a photon is absorbed by a semiconductor, thereby generating an electron-hole pair, which is a charge carrier. The generation of charge carriers effectively increases the conductivity of the semiconductor. Photoconductive detectors include the following types:

- Quantum well infrared photodetector (QWIP)
- Mercury cadmium telluride (“MerCad” HgCdTe)
- Lead selenide (PbSe) and lead sulfide (PbS)

Photovoltaic detectors are fabricated using semiconductor materials in two forms. A positively doped (p-doped) semiconductor and a negatively doped (n-doped) semiconductor are joined to create a p-n junction. In electronics, this type of semiconductor device is referred to as a *diode*.

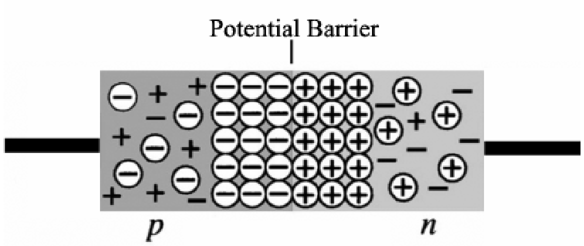


Figure 9 *Semiconductor diode formed by joining p-doped and n-doped semiconductor materials*

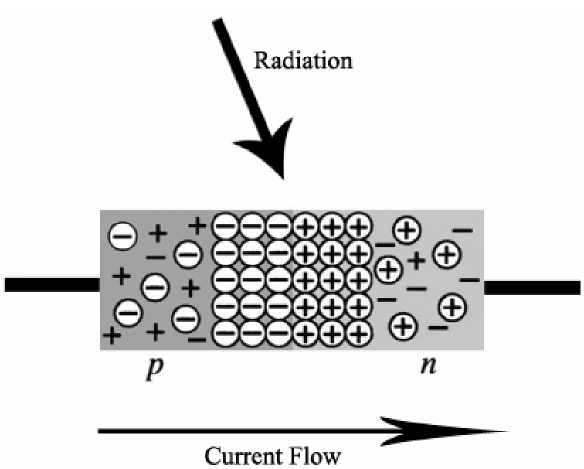


Figure 10 *Illustration of photovoltaic effect when radiation is incident upon diode*

When infrared radiation is incident upon the diode shown in Figure 10, it is absorbed by the semiconductor material. Electrons are freed from the atoms in the n-doped material, allowing them to flow to the p-doped material. Simultaneously, positive charges called *holes* flow in the opposite direction. The "flow" of these electrons and holes constitutes a current. Photovoltaic detectors used in the infrared include the following types:

- Platinum silicide (PtSi)
- Mercury cadmium telluride ("MerCad" HgCdTe)
- Indium antimonide (InSb)

All photon detectors, including those used for detecting infrared radiation, suffer from large *dark currents* that can hide useful signals. The magnitude of the dark current is proportional to the temperature of the detector. Lowering the temperature reduces the dark current. This reduction is crucial for the useful operation of some photon detector technologies.

Dark current is a type of noise that degrades the quality of the signal produced by a detector. The relationship between noise and signal in a system is expressed as *signal-to-noise ratio* (SNR).

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}$$

or

$$\mathrm{SNR(dB)} = 10\log_{10}\left(\frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}\right)$$

where P is the average power of the signal and noise.

This ratio is used by engineers to determine how much useful signal will be available from a system that contains noise sources.

Figure 11 shows an example of a signal that has noise on it. The signal has a sinusoidal shape. The noise causes the shape to appear fuzzy. Since the SNR is 10, the signal is still discernible and its information could be detected. But if the SNR significantly decreased, the noise could completely mask the signal and no information could be detected.

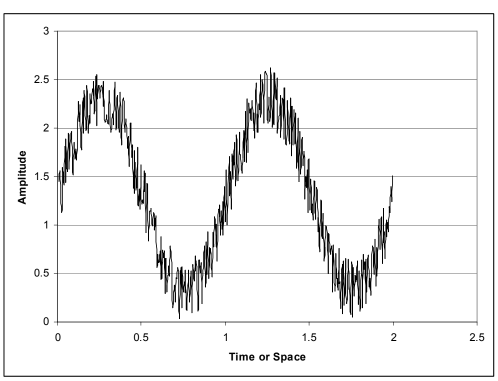


Figure 11 *Example signal with noise for SNR=10*

As previously mentioned, cooling a detector reduces the dark current and increases the SNR, allowing for more effective detector operation. Cooling is typically achieved using liquid nitrogen (77 K) or liquid helium (4 K). Some detectors, such as HgCdTe, have been engineered to operate at temperatures of 200 K. However, the use of this type of cooling makes these detectors difficult to implement in field instruments. Liquid gas cooling requires a dewar (vessel for holding cold liquids) that must be refilled before each measurement. Miniature Stirling-cycle coolers can achieve 70–75 K cooling and are used in place of dewars in some systems. A major goal of infrared detector research in the last 50 years has been towards "room temperature" detector technology.

One of the most common types of photon detector is the HgCdTe devices. This detector technology can be operated at 200 K in both the MWIR and LWIR ranges. Detectors made from InSb and PtSi are restricted to operate in the MWIR region. Platinum silicide, PtSi, can be fabricated into large arrays of detectors with reasonable uniformity. (Uniform illumination yields consistent values from pixel to pixel.)

Another recent advance in infrared detector technology is the quantum well infrared photoconductors (QWIP) based on AlGaAs/GaAs quantum well structures. The main advantage of QWIP technology is that its operational wavelength range is in the LWIR. These types of detectors are still maturing and research is continuing.

Thermal Detectors

Vastly different from photon detectors, thermal detectors do not generate a signal directly but rather in two stages. In the first stage, the detector element absorbs energy from photons in the incident radiation, causing the temperature to rise. The change in temperature alters a physical property of the detector element such as electrical conductivity. In the second stage, the detector measures this change and correlates it to the amount of incident radiation that interacted with the detector element.

One advantage of thermal detectors is that they respond equally to all wavelengths, since 1 watt of green light is equal in power to 1 watt of infrared light. The disadvantage of these detectors is that they must fight the thermal inertia of the element and therefore have reaction times that are proportional to their areas. Examples of thermal detectors are given in Table 3.

Table 3. Example Thermal Detectors

Technology	Temperature Dependant Parameter
Bolometer	Resistance
Thermocouple	Voltage
Pyroelectric	Capacitance
Superconductor	Resistance

A *bolometer* is a device whose conductivity changes with temperature. To achieve high sensitivity, the bolometer area must be large. The effective area of the bolometer can be enhanced using micro-lenses called *immersion lenses* or by collecting radiation and concentrating it in the detector area of the bolometer. At the same time, the inherent noise in the bolometer increases with area. These competing effects require a careful design trade-off to ensure signal detection and processing. Common bolometers use platinum and semiconductor materials that include polycrystalline silicon and vanadium oxide.

Thermoelectric devices, also referred to as *thermocouples* or *thermopiles,* are based on a junction of dissimilar metals. The absorbed optical radiation increases the temperature differences across the junction, thereby generating a voltage change. The voltage is sensed by an external pre-amplifier. Typical designs utilize a series connection of several junctions to raise the voltage level, thus reducing the pre-amplification required.

The operation of a *pyroelectric* detector is much different from the operation of bolometer or thermocouple-type detectors. The underlying principle of operation is that a change in the temperature of a dielectric material creates a change in electrical polarization. A typical material used in the fabrication of pyroelectric detectors is lithium tantalite. This material changes electrical polarization in response to temperature changes caused by incident photons. The material is housed between two thin electrodes similar to a capacitor. An external circuit is used to measure the surface charge density on the plates or electrodes. However, these devices can only measure change in temperature over time. Therefore, they must employ a chopper device to artificially vary the incident radiation and subsequent potential on the capacitor configuration. Pyroelectric detectors are one of the most common types of infrared detectors. They can be operated at room temperature and are inexpensive to manufacture.

Now that we have seen some different infrared detectors and better appreciate their positive and negative features, let’s look at the constraints of the lens systems that will work with them. Infrared imaging systems are designed in the same way that imaging optics are designed for visible systems. One difference is that visible and infrared systems require different materials for fabricating optics. Common glasses used for visible optics have limited transmission in the MWIR and LWIR bands. For example, visible glass such as BK7 is one of the most common visible optics materials (Figure 12).

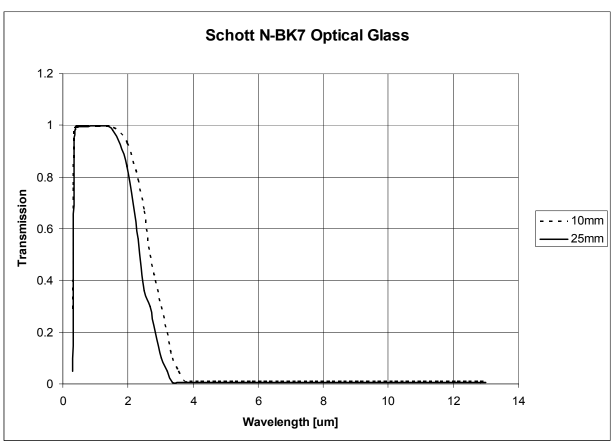


Figure 12 *Transmission spectrum for BK7 visible optical glass*

As Figure 12 demonstrates, the transmission of radiation through BK7 is highly dependent on wavelength. There is no transmission through BK7 in the MWIR or LWIR wavelength bands.

It would not be possible to use glass with a transmission like that of BK7 for the fabrication of an imaging lens system in the infrared. Special materials have been developed specifically for use in the infrared. The primary infrared materials are given in Table 4.

Table 4. Infrared Optical Materials

Name	Wavelength Band	Index of Refraction
Silicon	MWIR and LWIR	3.38–3.46
Germanium	MWIR and LWIR	3.90–4.10
Zinc sulphide	MWIR and LWIR	1.90–2.27
Zinc selenide	MWIR and LWIR	2.15–2.55
AMTIR (Ge/As/Se)	MWIR and LWIR	2.48–2.6
Gallium arsenide	MWIR and LWIR	2.12–3.34
Sapphire	MWIR	1.74–1.83

The complication with infrared lens materials is that they are crystalline and therefore must be grown using specialized vacuum chambers. In contrast, visible glass is an amorphous (lacking crystalline structure) material that can be melted and poured into blanks. The growth process of infrared lens material can be expensive, depending on the base material. In addition, these materials are much more delicate than visible materials. This complicates the shaping, grinding, and polishing stages of manufacture.

One advantage of infrared optics is that the diffraction-limit, which is proportional to wavelength, is easier to achieve in the infrared than in the visible. Remember that the diffraction-limit is found by calculating the diameter of the disc at the center of an Airy pattern, as here,

$$d_{\text{diff}} = 2.44\lambda F/\#$$

where F/# (the "*f*-number" of the lens) is a ratio of the focal length divided by the diameter of the optical aperture of the lens. Since the diffraction-limit is also related to the resolution of the lens system, d_{diff} provides a measure of the resolving power of the system.

Example

Given: An infrared lens system with an F/# of 2.4

Find: The diffraction-limit and effective resolution for a wavelength of 10 um

Solution

$d_{\text{diff}} = 2.44\lambda F/\# = 2.44 \cdot (10\times10^{-6}) \cdot 2.4 = 58.6$ um

EXAMPLES OF INFRARED SYSTEMS

Introduction

In this section, examples of several infrared systems operating in the MWIR and LWIR ranges will be presented. The advantages and disadvantages of each technology will be provided. Many infrared systems are commercially available. The ones described in this module were chosen for their applicability to homeland security.

Infrared systems have been developed over the last 30 years. They are classified by "generation."

- The first generation was based on a single detector or a small number of detectors. An image was formed using two-dimensional mechanical scanning systems to raster scan the image plane. Raster scanning is the process of building an image by scanning a detector across the image plane for each row in an image. The result is a two-dimensional image.
- The second generation contained an entire row of detectors that once again was scanned across the image plane. This is sometimes called "push broom" scanning. An image was generated for each sweep of the linear detector array.
- The third generation utilizes two-dimensional arrays to capture an image. Called *staring arrays,* these were sometimes mechanically scanned in order to improve the signal-to-noise ratio.
- The fourth generation, what we use today, contains two-dimensional staring arrays that do not require scanning. Images are formed by capturing the entire image plane in a single snapshot.

As you can see, the advancement from one generation to the next primarily centered on achieving more sophisticated means of capturing the image from individual detectors located on the focal plane array. For fourth-generation technology, the primary workhorse in the MWIR spectral range is the InSb focal plane arrays. This technology requires cooling to reduce noise but performs well and is considered a mature technology.

These InSb systems are available in 320×240 and 640×480 detector element arrays. An advantage of MWIR operation is that the resolution is higher as a result of the below-LWIR wavelength range. This enables shorter focal length infrared optics, reducing the overall size of the camera. Infrared InSb detectors have very good sensitivity, which means that the diameter of the infrared optics can be smaller.

Systems based on InSb detectors have several disadvantages. The cooling system decreases portability, since electrical power consumption is higher than in uncooled systems. The "turn-on" time of cooled systems is longer, since the cooler requires time to reach operational temperature. In general, InSb systems are more expensive than uncooled detector technologies.

The InSb detector has been incorporated in both long- and short-range camera systems. The long-range capability of these systems is enhanced by the high sensitivity of InSb detector technology.

Example

Given: An infrared system based on an InSb focal plane array used in the MWIR band; the F/# of the infrared optics is 4.

Find: If the width of the detector elements in the 320×240 element InSb array is 30 um, will the system be limited in resolution by the lens or size of the detector elements in the focal plane array?

Solution

Use the longest wavelength in the 3–5 um MWIR range of 5 um in the diffraction-limit equation.

$d_{\text{diff}} = 2.44\lambda F/\# = 2.44 \cdot (5\times10^{-6}) \cdot 4.0 = 48.8$ um

This means that the lens can only resolve features in the image that are 48.8 um apart. However, the detector is capable of resolving features on the image that are 30 um apart. Therefore the lens is limiting the resolution of the system. At the 3 um end of the MWIR range, the diffraction-limit is matched to the pixel size and both have the same resolution.

$d_{\text{diff}} = 2.44\lambda F/\# = 2.44 \cdot (3\times10^{-6}) \cdot 4.0 = 29.3$ um

The advantage of the LWIR band over the MWIR band is that the LWIR band permits greater visibility through smoke, smog, dust, and water vapor. The longer wavelength allows penetration through airborne particulate matter. Shorter wavelengths are easily absorbed by high concentrations of particulate matter such as carbon in smoke. For this reason, LWIR systems are used in fire fighting and marine applications.

The main technology used today in the LWIR band is the uncooled microbolometer detector. A significant advantage of microbolometer technology is that it operates at room temperature. This reduces electrical consumption, weight, and cost.

Microbolometer technology was originally developed by Honeywell in the 1980s under contract with the U.S. Department of Defense. The technology was declassified in 1992 and licensed to several manufactures. The licensing of this technology was met with a large increase in the applications of infrared cameras. The use of microbolometer detectors made infrared cameras relatively inexpensive and thus finally obtainable by civilians. Their applications include law enforcement, fire fighting, and security.

The operation of a microbolometer detector element can be understood as a two-stage process. First, infrared light is absorbed by a tiny element made from vanadium oxide or amorphous silicon. The energy from the absorbed light raises the temperature of the element and changes its resistance. Second, the change in resistance is sensed by a pre-amplifier that uses bipolar transistor technology. The important requirement for obtaining high sensitivity is proper thermal insulation between the detector element and the substrate containing the transistor. Typically, the detector is vacuum encapsulated.

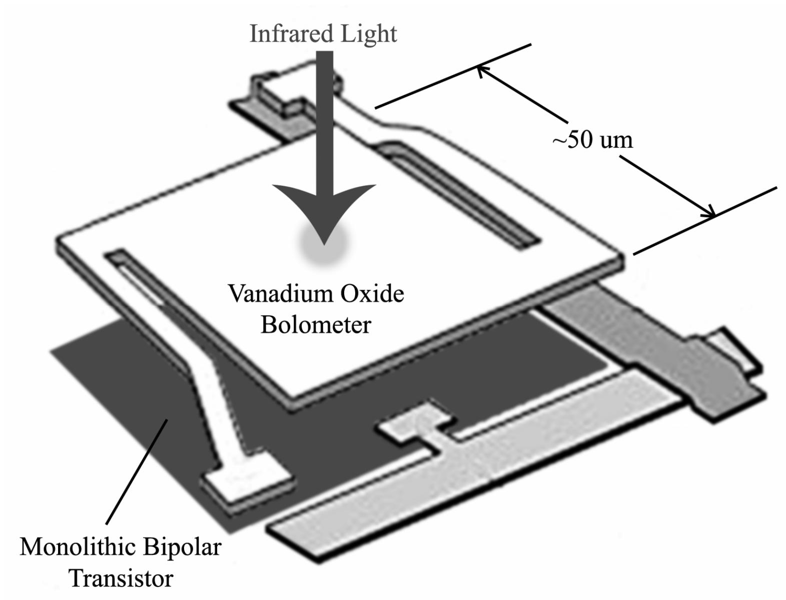


Figure 13 *Schematic diagram of single microbolometer detector element*

Advantages of uncooled microbolometer technology include the following:

- Less expensive
- No moving parts for cooling, thus yielding long mean-time-between-failure (MTBF)
- Low power consumption compared to cooled detector technologies
- Do not require cryogenic cooling systems; signal is produced immediately after the system is turned on. (Cooled systems can take as long as 10 minutes to cool down to operational temperatures.)
- Small and lightweight. This equates to entire infrared cameras that you can hold in the palm of your hand.

Applications of Infrared Systems in Homeland Security

The usefulness of being able to detect thermal images at night or through dust and smoke has been evident since infrared imaging systems were first developed. The potential applications of infrared imaging systems are endless. Lower-cost systems, as a result of microbolometer technology, have allowed a broad range of customers to benefit from the use of infrared technology. In this section, some of the most important applications of infrared technology in homeland security will be presented.

Port and harbor security

Infrared camera systems in the MWIR and LWIR are used to monitor ship and small craft movement. The use of advanced infrared systems allows monitoring during adverse conditions and night observation. The advanced systems are integrated with automated software to mark virtual perimeters around ships. An example of a virtual perimeter around one side of a liquid natural gas (LNG) tanker is shown in Figure 14.

Figure 14 *Example of infrared system used for harbor security. White lines mark the virtual perimeter.*

Airport security

Airport security has been significantly heightened in the past few years. Advanced technology is now being employed both inside and outside airport terminals. Two areas of interest outside airport terminals are runway areas and perimeter fencing. Infrared cameras can be used to monitor these perimeters at night, giving security personnel the ability to detect intruders.

Figure 15 *Example of infrared image of airport perimeter fence*

Law enforcement

One of the most difficult problems facing law enforcement is pursuit of perpetrators at night. Infrared systems are now used by helicopters and patrol vehicles to find fugitives. These temperature detecting systems are used in many ways. Two of the most common are (1) detection of stationary but recently running automobiles and (2) detection of fugitives, whether hiding or moving on foot. One way fugitives attempt to hide from law enforcement is to park their vehicles in crowded lots or drive them into hidden, off-road areas. Infrared cameras are used to quickly scan parking lots to look for warm vehicles. This helps to narrow the number of vehicles to be searched. Vehicles hiding just off roadways or deep in protected areas can be seen easily from the air with infrared cameras.

Figure 16 *Law enforcement application for vehicle location in parking lot*

Many fire departments have at least one infrared camera and have even moved to helmet-mounted systems. In firefighting, infrared cameras can pinpoint the "hot points" where water flow should be concentrated. Infrared cameras can locate persons trapped in burning buildings and help firefighters navigate smoke-filled environments. Once the fire is has been extinguished, the cameras are used to locate potential areas of "flare-up," which may be hidden behind or within walls.

Figure 17 *Example of how infrared cameras are used in fire fighting*

Petrochemical plant security

Chemical products made from petroleum are called petrochemicals. Examples include ethylene, propylene, isopropyl alcohol, and benzene. Because they are highly flammable, these products are potential targets of terrorism. Once again, infrared cameras can be used for perimeter security. They can also be used to detect leaks, hot areas, and potential sabotage damage. An example of a visible image of a petrochemical plant is shown in Figure 18.

Figure 18 *Example of modern petrochemical plant*

Power plant security

A vital resource during any conflict is the power plants that supply electricity to the power grid. Nuclear power plants require even tighter security than fossil fuel and hydroelectric plants, since their destruction could release radiation. Infrared cameras are used to monitor perimeter intrusion.

PERFORMANCE MEASUREMENTS

Selecting and purchasing infrared systems requires an understanding of how they are rated for performance. Performance is measured using standardized criteria that include two critical operating parameters: thermal sensitivity and spatial resolution.

Thermal Sensitivity

The thermal sensitivity of an infrared system is the minimum temperature difference above the noise level that can be detected. The standard method of measuring thermal sensitivity is by measuring *noise-equivalent temperature difference* (NETD). The value of NETD is the amount of temperature difference between the target and background that produces a target signal equivalent in power to the signal being produced by noise in the system. If the temperature difference is less than this amount, the detector will not be able to discern the target signal from the noise signal. Thus, no thermal information about the target will be obtained. Another way of defining NETD is the temperature difference that produces a peak signal-to-noise ratio of one.

NETD is used as a rating of how sensitive an infrared system is to temperature differences in a given scene. Comparing two infrared systems can be done quantitatively using NETD. The system with the lower NETD value will be more sensitive and, in some cases, will perform better.

An experimental setup for measuring NETD is shown in Figure 19. In this diagram, the *instantaneous field-of-view* (IFOV) is the area at the target plane covered by a single detector element on the infrared focal plane array. For an infrared detection system to be effective, the target area should be much larger than the IFOV but well within the overall FOV of the camera.

If the target area is smaller than the IFOV, the infrared system cannot resolve the target and provide information on its details. Likewise, if the target area is larger than the FOV, the full target cannot be imaged by the system.

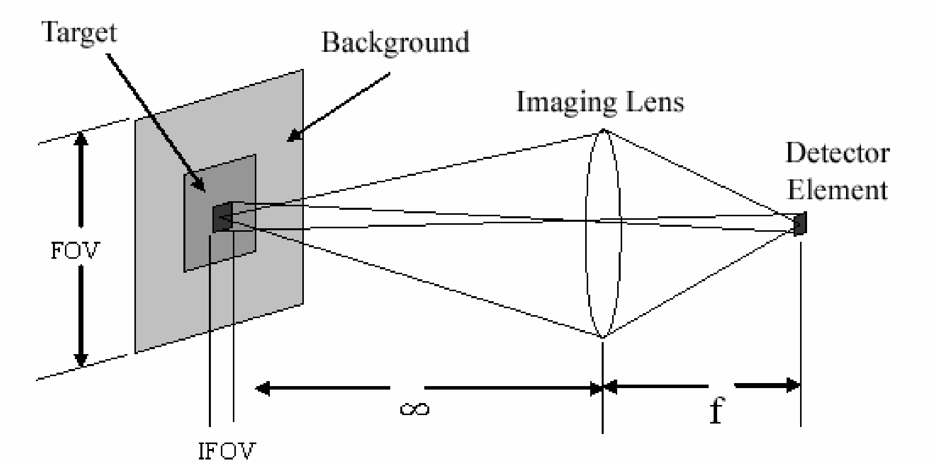


Figure 19 *Experimental setup for measuring NETD*

To measure the NETD, the target is heated such that it has nearly a constant temperature over its surface. The heating of the target will cause the emission of infrared radiation. This radiation will interact with the focal plane array, producing a distinct voltage across each detector element. The voltage will be measured by the imaging system for each detector element and stored in memory.

To find NETD, these stored voltages are plotted as shown in Figure 20. The ordinate is the measured voltages. The abscissa is locations on the background and target areas. This plot clearly shows the boundaries of the background and target areas. The wavy lines on the two sides of the plot represent the naturally occurring thermal noise present in the background area. The hump represents the thermal activity in the target area.

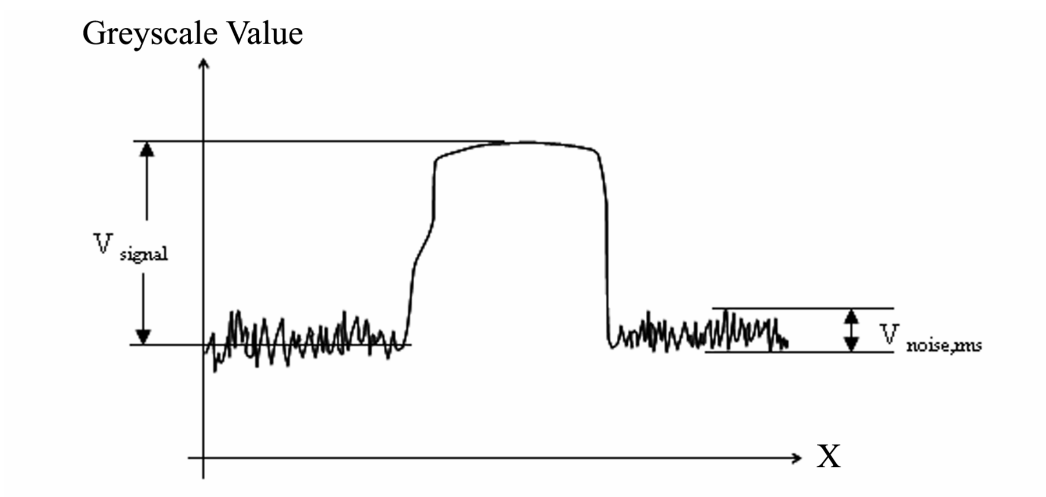


Figure 20 *Cross-section of image from NETD measurement system*

We can measure the background area noise by finding the root-mean-squared (RMS) value of the voltages in the wavy segments of the plot. This RMS can be calculated using

$$V_{\text{noise,rms}} = \sqrt{\frac{\left(X_1^2 + X_2^2 + X_3^2 + \ldots + X_N^2\right)}{N}}$$

where the values of X_n are values of the voltage in the noise portion of Figure 20.

Example

Given: A set of noise values: –2, –1, –3, 1, 5 (all in mV)

Find: The RMS value of these voltages

Solution

Step 1: Count the total number of values.

$N = 5$

Step 2: Square each value.

4,1,9,1,25

Step 3: Take the average of the square values.

$$\frac{(4+1+9+1+25)}{5} = 8$$

Step 4: Take the square root of the average values.

$$RMS = \sqrt{8} = 2.83$$

$$V_{\text{rms,noise}} = \sqrt{8} = 2.83 \text{ mV}$$

The thermal activity in the target area can be determined from the voltage peak (or grayscale value) labeled V_{signal} in the plot. This is measured from the middle of the noise to the peak value seen in the plot. The temperature difference between the background and target area is then measured. These values are used in the following equation to determine the NETD for the infrared system.

$$\text{NETD} = \frac{(T_{\text{target}} - T_{\text{background}})}{\dfrac{V_{\text{signal}}}{V_{\text{rms,noise}}}}$$

NETD will be measured for an infrared system in the laboratory at the end of this module.

This equation gives us insight into what generates a good NETD performance measure. Since we want to measure the smallest possible temperature differences between the target and background, the lower the value of the numerator, the more sensitive the detector. Likewise, the lower the noise voltage, the easier it is to discern more about target thermal features from the signal voltage, i.e., the “cleaner the signal.” Thus, the larger the denominator of the equation, the greater is the capability of the system. Putting these two together, a small numerator and large denominator, we can clearly see that system performance increases as the NETD decreases.

Spatial Resolution

Spatial resolution is a measure of a system's ability to resolve targets of different sizes and spacings. This is accomplished by imaging periodic targets with known sizes or spatial frequencies. The most common target for measuring spatial resolution is a 3- or 4-bar target.

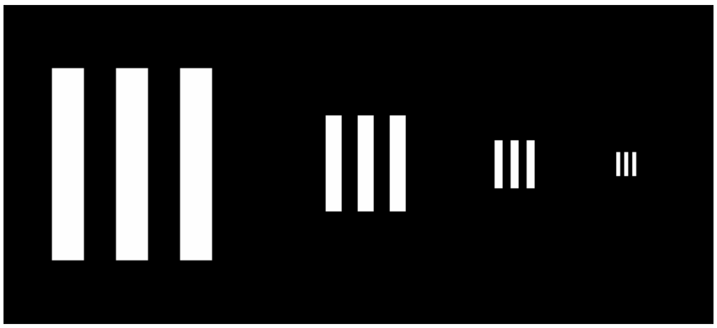


Figure 21 *Sample bar targets for measuring spatial resolution*

Accessing the spatial resolution of an imaging system involves the use of bar targets with spacings like those shown in Figure 21. The spatial resolution of a system is determined when a given spatial frequency of the targets cannot be resolved. This is known as the *limiting resolution* of the system.

To find the limiting resolution, we place targets of varying spatial frequencies and sizes in front of an extended blackbody source. This is a specialized source used in laboratories to simulate targets at specified temperatures. An image of each target is recorded by the infrared system. The image will show maximum and minimum voltage values, as depicted in Figure 22.

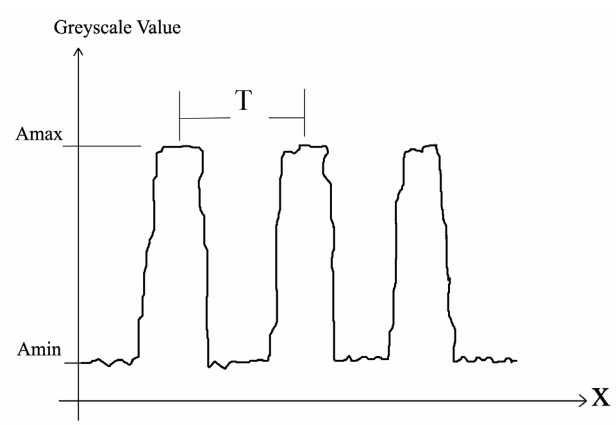


Figure 22 *Cross-section of image from modulation depth measurement system*

The modulation depth of each target is calculated from $A_{\min}$ and $A_{\max}$ values determined from the image. The ordinate of Figure 22 is usually a relative scale (no units) that is set by the imaging system processing software. The modulation depth, M, is calculated in the following manner:

$$M = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}}$$

The spatial frequency of each target is calculated based on the period, T, of the pattern. T is the total number of pixels in the interval shown in Figure 22. The pixel width is then used to express the spatial frequency, ξ, in terms of cycles/mm.

$$\xi = \frac{1}{T \cdot \text{pixelwidth (mm)}}$$

Example

Given: A measurement of a bar target as shown in Figure 23. The pixel width is 10 um.

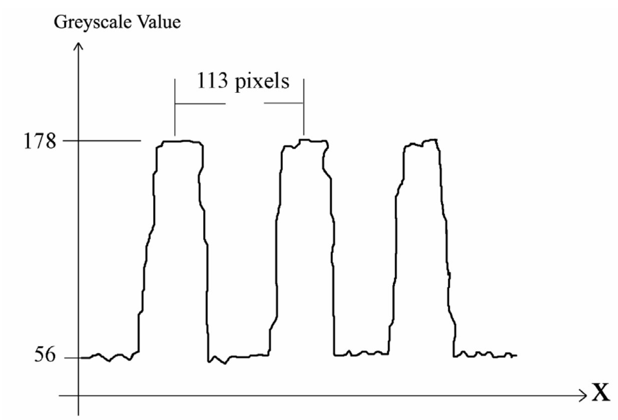


Figure 23 *An infrared imaging system response to a specific bar target pattern*

Find: The modulation depth and the spatial frequency of the bar target measurement

Solution

$$M = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}} = \frac{178 - 56}{178 + 56} = 0.52$$

Modulation depth is another way of assessing how noise is affecting thermal measurements. If you mathematically evaluate modulation depth, you will find that the greater the difference between $A_{\max}$ and $A_{\min}$, the larger the value of M. Since $A_{\max}$ represents signal strength and $A_{\min}$ represents the noise level in the imagining system, the greater their difference, the better the system can discern details in the thermal signature. Another way of saying this is that we want the “humps” that represent the thermal signal in Figure 23 to be well above the wavy lines that represent the noise. Therefore, the larger the modulation depth, the better is the performance of an imaging system.

$$\xi = \frac{1}{T \cdot \text{pixelwidth (mm)}} = \frac{1}{113 \cdot 0.010 \text{ mm}} = 0.89 \text{ cycles/mm}$$

This means that the target maximums repeat every 113 pixels or 1.12 mm in the image of the infrared system. If one cycle represents one “hump” in Figure 23, then over a distance of 1 mm in the image only 0.89 of the cycle is repeated. This repetition rate is referred to as the *spatial* *frequency* of the target. The smaller the spatial frequency, the closer is the spacing of the bars in the target.

When the modulation depth and spatial frequency are determined for each bar target, they form an ordered pair with spatial frequency representing the abscissa value and modulation depth the ordinate value—(spatial frequency, modulation depth). When the ordered pairs from each bar target are plotted, they generate a curve called the *modulation transfer function* (MTF). The MTF describes how well the infrared system performs over all spatial frequencies.

Figure 24 shows MTF curves for two infrared imaging systems with equivalent resolutions. Comparing these two curves, you can see that system B has a higher *M* value at mid-range spatial frequencies. The image quality overall will be much better for system B than for system A. This is because over the mid-range spatial frequencies, system B will provide a much greater contrast between the target signal and background signal. This is illustrated in Figure 24, in which M_B is greater than M_A at a selected mid-range spatial frequency, ξ_{mr} .

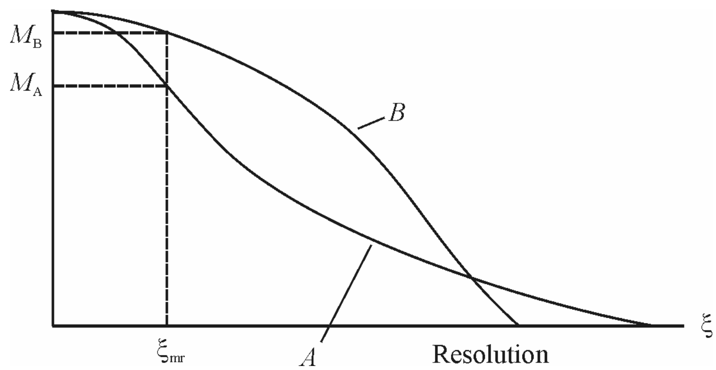


Figure 24 *MTF measurements for two systems: A and B*

Before going on to the next section, we should define one more term—MTF(ξ). The MTF curve is continuous, which means that it is defined for all spatial frequencies. However, only discrete points defined by the modulation depth are used in the generation of this curve. To represent the whole curve, not just these discrete points, we must define a function. This function must be dependent on the spatial frequency and provide information on the performance of the imaging system. We define this function as MTF(ξ). Thus, on all the MTF curves we have discussed up to now, the curve itself is defined by this function. Using function notation, we see that the spatial frequency, ξ, is the independent variable and represents values on the abscissa (*x*-axis) of the MTF curve and that MTF is the dependent variable and represents values on the ordinate (*y*-axis). Like the modulation depth, *M*, the value of MTF at a given spatial frequency provides a prediction of an imaging system's performance. Also, like the modulation depth, the larger the value of MTF(ξ), the better is the performance of the system. In summary, MTF(ξ) gives us a means of representing the whole MTF curve, not just discrete points on it. We will use this function in the next section.

Relating Spatial Resolution and Thermal Sensitivity

The NETD measurement and MTF measurements can be combined into a single measurement called *minimum resolvable temperature difference* (MRTD). This combined measurement is calculated and plotted using this formula:

$$\mathrm{MRTD}(\xi) = \frac{\mathrm{NETD}}{\mathrm{MTF}(\xi)}$$

To use this formula, we need the NETD of the imaging system, which must be found experimentally or obtained from the manufacturer. Likewise, M values for the imaging system at several spatial frequencies must be found either experimentally, so that an MTF curve can be generated, or this curve must be provided by the system's manufacturer. Once the NETD value is determined and the MTF curve has been generated, the MRTD formula can be used to calculate the imagining system's MRTD value at any given spatial frequency. These values and their associated spatial frequencies form a set of ordered pair (spatial frequency, MRTD). These ordered pairs can be plotted with MRTD values along the y-axis and spatial frequencies along the x-axis. An example of this plot is shown in Figure 25.

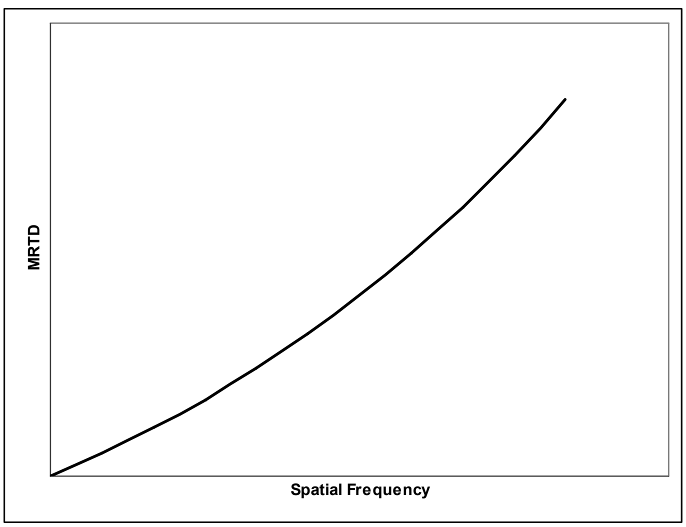


Figure 25 *MRTD plot showing characteristic increase in value as spatial frequency increases*

MRTD plots typically show a gradual increase in value for increasing spatial frequencies. This is because the higher spatial frequency bar targets will require larger temperature differences, increasing the effective NETD.

The MRTD can be used to compare different infrared imaging systems. As seen earlier, the smaller the NETD and the greater the MTF value, the better the performance of a system. Since the equation for MRTD has the NETD in the numerator and the MTF value in the denominator, smaller values of MRTD indicate better system performance. When MRTD plots, such as that in Figure 25, are generated from for two systems, the better-performing system is the one that has the lowest MRTD values and the smallest slope.

Why is slope an important factor? The slope of an MRTD curve indicates how fast MRTD is changing with respect to changes in the spatial frequency. If the slope of this curve is positive, the MRTD value is getting larger as spatial frequency increases. Larger MRTD values indicate less performance. So, when two systems are compared, the one with the best performance is the one with the lowest values of MRTD and the least MRTD rate of increase (smallest slope) as spatial frequency increases. For example, if system A has a lower MRTD than system B at one spatial frequency, but system A's MRTD rate of increase (slope) is greater, eventually at some larger value of the spatial frequency system A's MRTD values will become larger than system B's. If system A's slope is less than system B's, system A's MRTD will never exceed system B's. Thus, when comparing the performance of two systems, you must compare the values of their MRTDs over the spatial frequencies of interest and also their slopes. The following example illustrates this comparison.

Example

Given: Teemus Clark, whom we met in the scenario at the beginning of this module, has been given the task of evaluating several commercially available infrared cameras. She has selected two cameras because their specifications are similar and they both meet the criteria for her company's security application. She must now make a final determination of which camera to purchase.

Find: Determine which camera Teemus should purchase based on the MRTD measurements she has made on the two cameras (see Figure 26).

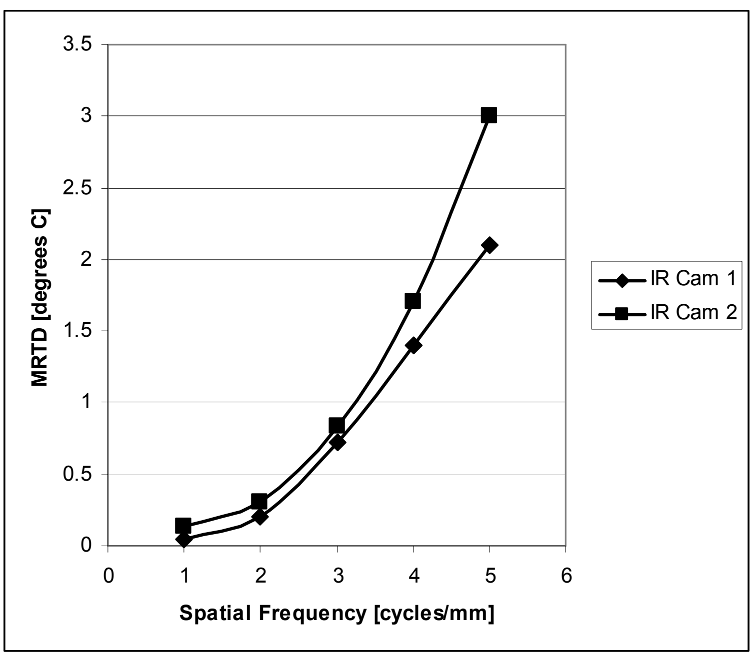


Figure 26 *MRTD measurement comparison*

Solution

Teemus compared the MRTD measurements for the two cameras. Since the MRTD values for IR Cam1 were less than those for IR Cam2, and the slope of IR Cam 1 is less than that of IR Cam2, she made a solid determination that IR Cam 1 is better suited for her application.

Student Exercises

1. Define the region of the electromagnetic spectrum that is considered the infrared region.
2. Calculate the wavelength of a photon having energy of 2×10^{-20} Joules.
3. Define *MWIR* and *LWIR*.
4. Describe what is meant by a blackbody source.
5. Approximately determine the peak spectral exitance of a 2000 K blackbody.
6. What is the spectral exitance at 3 um of a 1750 K blackbody.
7. Describe what is meant by a greybody and explain how this relates value of emissivity.
8. Define signal-to-noise measurement of a space varying signal.
9. Describe the purpose of radiometry calculations.
10. What are the advantages of uncooled infrared technology, compared to cooled?

Laboratory

The laboratory procedures presented here require the use of an infrared camera. There are several options for obtaining an infrared camera. One option is to buy or lease a low-cost microbolometer infrared camera from FLIR systems at http://www.flirdirect.com, which currently offers the highest-quality cameras at reasonable prices (~$5000). A better option might be to borrow a camera from a local fire or police department. The experimental setup can be assembled ahead of time, requiring only about a one-hour demonstration to capture several images.

Materials

Microbolometer based infrared camera system

Candle

Ice

Coffee and mug

Plastic cup

Computer

ImageJ Software (freeware) (http://rsb.info.nih.gov/ij/)

Kapton Heating Element (www.minco.com Model: HK5318R15.7L12A)

Wire

12 V power supply with adjustable current up to 1 amp

Aluminum block – 2″ × 2″ × 1/4″

Aluminum sheet – 12″ × 12″ × 1/32″

Flat black high-temp spray paint (Krylon #1618)
5-minute epoxy resin
Wooden sticks (Popsicle sticks)
Digital thermometer

Procedures

The procedures consist of two measurements of a low-cost infrared camera. The first is a simple demonstration of the capture of infrared imagery using objects with different temperatures. The second procedure measures the NETD of the infrared camera.

Procedure 1—Demonstration of Infrared Imagery

Initial Setup

Position the lit candle, coffee mug (half filled), and plastic cup filled with ice as shown in Figure 27.

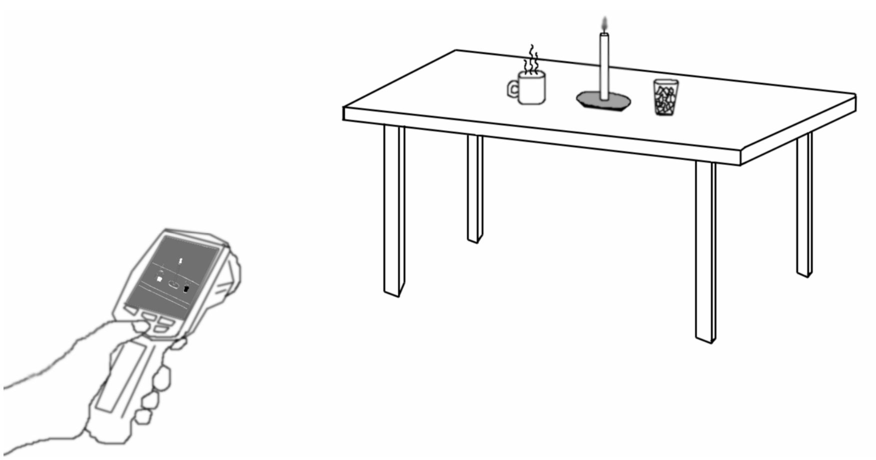


Figure 27 *Laboratory setup for Procedure 1*

Procedure

1. Position the infrared camera so that the three objects are seen clearly in the field-of-view (FOV) and are focused.
2. Record an image of the scene using the camera's on-board storage.
3. Transfer the image to a host computer.
4. View the image using the ImageJ software.
5. Take several additional images of other objects such as people, soldering irons, running water, and steam.
6. Discuss how the images appear different, depending on the objects' temperatures.

Procedure 2—Measurement of NETD

Initial Setup

For this procedure we will need to construct the NETD target.

1. Begin by cutting a hole in the center of the sheet of aluminum approximately 2.25″×2.25″. The objective is to be able to position the 2″×2″ block of aluminum behind the hole without touching the aluminum sheet.
2. Mix approximately 2 tablespoons of 5-minute Epoxy resin. Be sure to follow the manufacturer's instructions.
3. Use a liberal amount of Epoxy to glue the Kapton heater onto the aluminum block.
4. Attach the leads of the Kapton heater to the variable-current 12V power supply using extension wire if necessary.
5. Mix approximately 2 tablespoons of 5-minute Epoxy resin.
6. Use the Epoxy and wooden sticks to fasten the aluminum block in the center of the hole cut in the aluminum sheet.
7. Spray the entire target side (opposite Kapton heater side) of your assembly with the flat black spray paint.

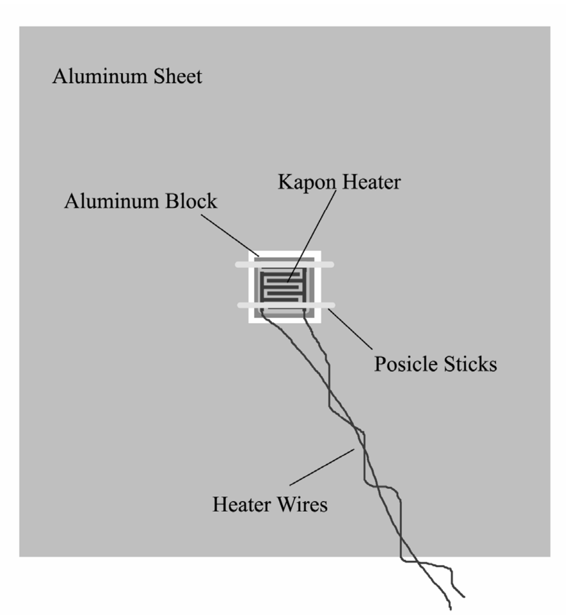


Figure 28 *NETD measurement target assembly diagram*

Procedure

1. Position the infrared camera so that the aluminum sheet is seen clearly in its field-of-view (FOV) and is focused.

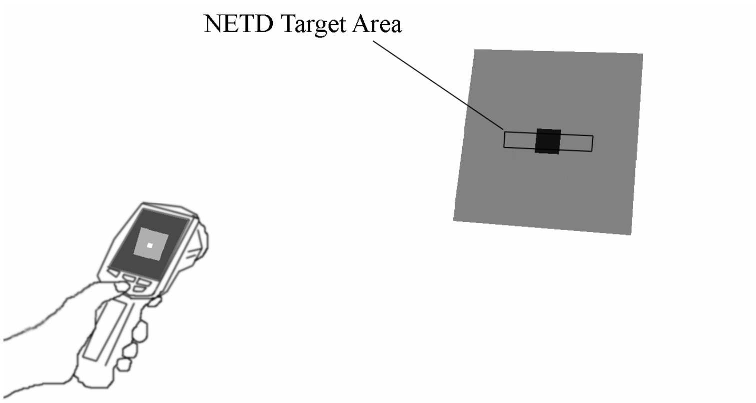


Figure 29 *Laboratory setup for Procedure 2*

2. Record an image of the scene using the camera's on-board storage.
3. Using the digital thermometer, measure the temperatures of the aluminum block and the aluminum sheet. Write those values in your laboratory notebook.
4. Transfer the image to a host computer.
5. View the image using the ImageJ software.
6. Use the mouse to select the NETD target area in the image as shown in Figure 30. Choose Analyze→Plot Profile from the menu in the ImageJ software. This is a cross-sectional average of the NETD target area that you have selected.

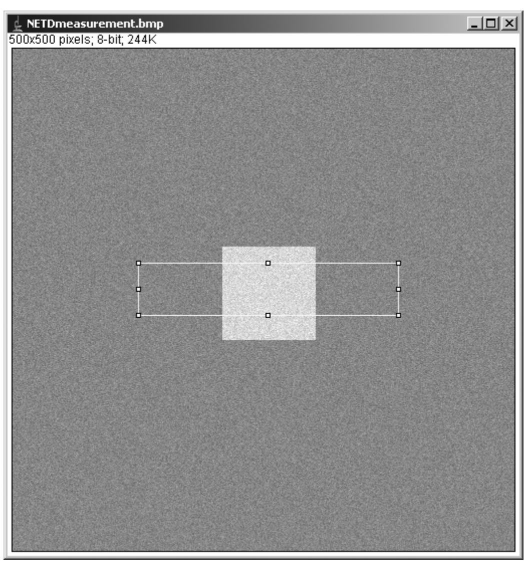


Figure 30 *Example of NETD target area selection in ImageJ software*

7. Calculate the RMS value of the portion of the image that corresponds to the aluminum sheet. Use the mouse to determine the grayscale value of several pixels. You should use at least 10 values. (The more values you use, the higher the accuracy will be.)

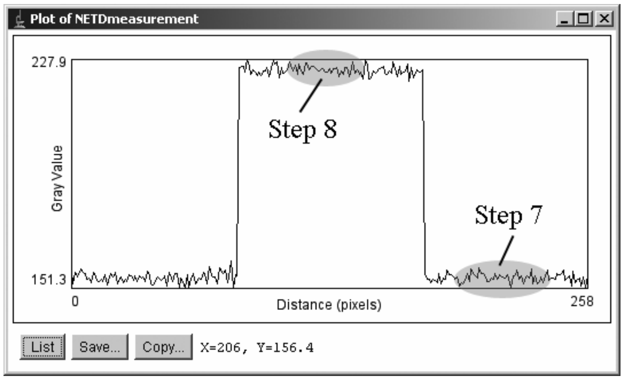


Figure 31 *Profile plot from NETD target area selection shown in Figure 30*

8. Use the mouse to determine the average grayscale values for the portion of the image that corresponds to the aluminum block, the center of the NETD target area.
9. Calculate NETD using:

$$\mathrm{NETD} = \frac{(T_{\mathrm{target}} - T_{\mathrm{background}})}{\dfrac{V_{\mathrm{signal}}}{V_{\mathrm{rms,noise}}}}$$

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E.L. Dereniak and G.D. Boreman, *Infrared Detectors and Systems*, Wiley-Interscience (1996).

Daniels, *Field Guide to Infrared Systems,* SPIE Press (2007).