1

INTRODUCTION AND OVERVIEW

1.1. Electromagnetic Radiation 5
- 1.1.1. Visible and Infrared Wavelengths 5
- 1.1.2. Visible and IR Sources 6
- 1.1.3. Reflected and Emitted Energy 6

1.2. Heat Transfer 7
1.3. Thermal Detectors 7
1.4. Planck's Law 8
1.5. Waves and Photons 9
1.6. Quantum (Photon) Detectors Versus Thermal Detectors 10
1.7. Detectors as Transducers 11
1.8. Detector Parameters: Definitions 11
- 1.8.1. Responsivity 12
- 1.8.2. Noise 14
- 1.8.3. Frequency Spectrum of Noise 15
- 1.8.4. Signal-to-Noise Ratio 17
- 1.8.5. Noise-Equivalent Power 17
- 1.8.6. Specific Detectivity (D^*) 18
- 1.8.7. Linearity and Saturation 19
- 1.8.8. Frequency Response 20
- 1.8.9. Spatial Considerations 21
- 1.8.10. Crosstalk 22

1.9. Sources of Additional Information 23
References 24

Fundamentals of Infrared and Visible Detector Operation and Testing, Second Edition.
John David Vincent, Steven E. Hodges, John Vampola, Mark Stegall, and Greg Pierce.

Companion Website: www.wiley.com/go/vincent/fundamentals/2e

1

INTRODUCTION AND OVERVIEW

1.1 ELECTROMAGNETIC RADIATION

This book deals with the detection of radiation in "the visible and the infrared (IR)". We refer to that radiation in several ways:

- Visible and IR wavelengths, or spectral bands
- Radiation from visible and IR sources
- Reflected and thermally emitted energy.

There is some overlap and inconsistency between these terms. They are often used interchangeably, implying that the expressions are equivalent. In many cases, the fine distinctions do not matter, but it is instructive to discuss this a bit.

1.1.1 Visible and Infrared Wavelengths

IR radiation, visible light, radio waves, and X-rays are all forms of radiated electromagnetic energy, and all obey the same laws. The only fundamental difference between them is their wavelength (or frequency, which is equivalent) and how they interact with optical materials, including the atmosphere. This is shown in the chart of the electromagnetic spectrum in Figure 1.1.

The borderlines between the various "bands" (X-ray, visible, IR, far-IR, millimeter, radio waves, etc.) are not absolute, and we need not make any fine distinctions between them. These regions of the spectrum are segregated primarily for general discussions. *The primary criteria are the sources used, the available windows, and the detectors that respond to the radiation.* In general, *light* (visible radiation) is that region of the spectrum that includes wavelengths for which the *human eye* is responsive – about 0.4–0.7 μm – although even here there are "special spectral ranges" because the eye has more than one type of detector, each with its own spectral response curves. Many "IR detectors" can be used to detect visible radiation, but, in general, IR includes wavelengths longer than the visible but shorter than those that can be detected with the smallest microwave-like apparatus. Thus a statement

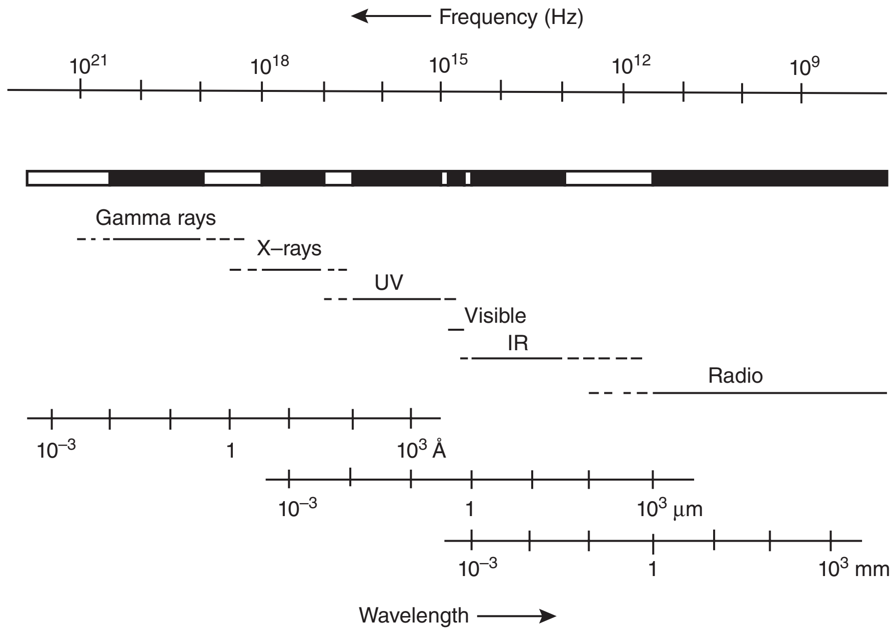

Figure 1.1 The electromagnetic spectrum.

like "IR extends from 0.7 μm to 1000 μm" is someone's definition or *convention*, *not* a statement of a physical law.

1.1.2 Visible and IR Sources

Visible sources refer to those that are readily seen with the human eye, and IR *sources* are those that provide energy at longer wavelengths – but the two are not mutually exclusive: many sources provide radiation that has significant amounts of both visible and IR wavelengths.

1.1.3 Reflected and Emitted Energy

The eye and conventional cameras respond to visible radiation (from sunlight or lamps) that is generally *reflected* by the target or scene of interest, so it is common to hear the term "reflected energy" used interchangeably with "visible source". Although strongly related, the two phrases are not synonymous.

Similarly, most IR detector applications depend on *emission* directly from the source of interest, so you may hear the term "thermal emitter" used interchangeably with "IR source". Again, the two phrases are strongly related, but not synonymous.

These "strongly related" expressions are not synonymous because visible detectors can respond to the direct thermal emission from a glowing object (a cigarette or hot filament), and IR detectors can respond to reflected energy.

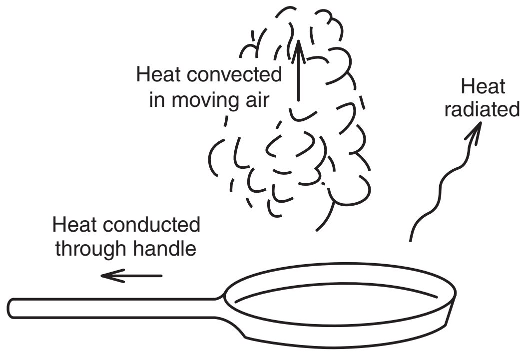

Figure 1.2 Three methods of heat transfer.

1.2 HEAT TRANSFER

Heat is transferred in three ways:

- Radiated – electromagnetic radiation
- Conducted – as through a hot piece of metal
- Convected – for example, through warm air circulating in a room.

These three methods of heat transfer are illustrated in Figure 1.2. Radiant transfer is important because our IR detectors will measure the radiant transfer of heat (or photons). We devote one chapter to the prediction of radiant transfer effects.

Warm objects radiate more IR power than cooler ones, but all objects give off *some* power in the IR. Room-temperature objects and even ice cubes emit some IR. In Chapter 2, we discuss methods to predict the power and photon flux from objects of different temperatures.

Since our eyes are not sensitive to IR, our everyday awareness of IR is limited: it is generally sensed only by the heat carried by the IR radiation. If we can set up a situation in which conduction and convection are limited, it is possible to sense the IR radiation directly: the warmth from the sun on a cold day or the heat from a hot fire is carried through electromagnetic radiation, most of which is in the IR.

Most detectors will be operated well below room temperature, and all three methods of heat transfer will be important to us when we consider the detector cooling problem. To minimize the heat transferred from the room-temperature laboratory to the cold detectors we will need to minimize the radiated, conducted, and convected heat leaks.

1.3 THERMAL DETECTORS

In 1800, while he was using a prism to spread sunlight into its component colors (wavelengths), the English astronomer Sir William Herschel (1738–1822) first

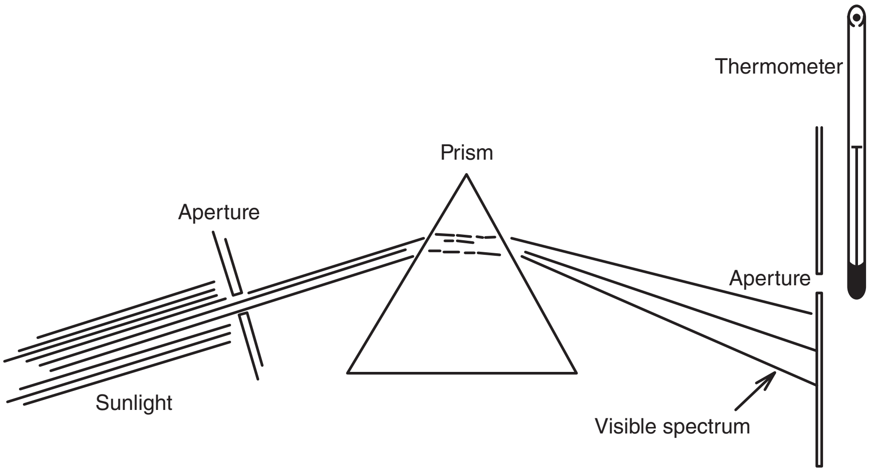

Figure 1.3 Herschell's IR detector.

discovered radiant energy beyond the visible spectrum. His experiment is described by Hudson (1969) and illustrated in Figure 1.3. Herschel used a thermometer to measure the temperature at places at which different portions of the spectrum fell and was surprised to find that even where he could not see any color, the thermometer registered a significant heating effect. The detectors that were employed thereafter were simply more and more sensitive thermometers. Detectors that operate by sensing temperature changes are called *thermal detectors*; we will discuss them and their performance in Chapter 3.

1.4 PLANCK'S LAW

For any given source, some wavelengths carry more of the power than others. Lummer and Pringsheim are credited with the first accurate measurements of the distribution of energy within the electromagnetic spectrum (Eisberg, 1961). Their work was done in 1899, and the measurements disagreed with predictions based on the accepted physical laws. Resolution of the disagreement became the subject of intense research; Hudson (1969) gives a concise account of the flurry of work this discrepancy caused.

In 1900, Max Planck derived an equation (plotted in Figure 1.4) that fitted the observed data. His derivation assumed that the oscillators responsible for the radiation were limited to discrete energy levels related to the frequency f of the radiation: they could have energy hf, $2hf$, $3hf$, and so on, but not $1.2hf$, or $3.7hf$, where h is a constant – now known as *Planck's constant*. His revolutionary hypothesis and the resulting equation led to modem quantum theory and earned him a Nobel Prize in 1918 (Wehr and Richards, 1960). We will use Planck's radiation law and Planck's constant to calculate the power emitted by many of our IR sources.

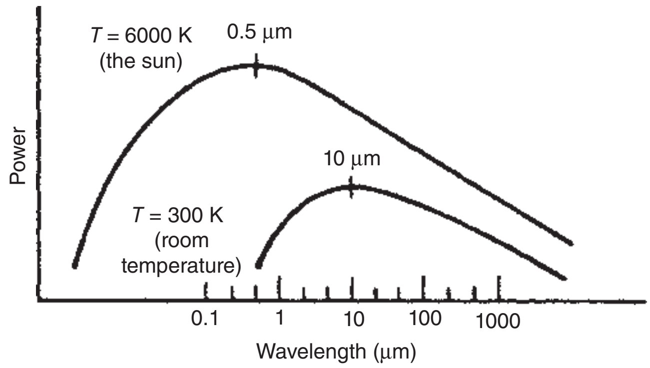

Figure 1.4 Planck's radiation law.

We look at Planck's law in Chapter 2, but some characteristics are shown in Figure 1.4 and described here.

The warmer the source, the more energy it radiates. This is a very strong dependence: a small increase in temperature causes a large increase in the emitted power.

As the temperature of the source increases, the wavelength at which most of the energy is given off decreases. The relationship is fairly direct: increasing the temperature by a given factor decreases the peak wavelength by the same factor.

At short wavelengths, the shape of the curve can be described very accurately by a relatively simple equation. Another simple equation works well at long wavelengths, but the equation to describe the whole curve – Planck's law – is complex. We will discuss it in detail in Section 2.2.2.

The distribution of wavelengths and the physiology of the human eye work together to allow us to very roughly gauge temperature by its appearance, as shown in Table 1.1.

1.5 WAVES AND PHOTONS

Many experiments with visible and other electromagnetic radiation can be explained by treating the radiation as a wave. For those situations, we need to know the wavelength and the power transmitted by the wave. Unfortunately, other experiments do not agree with the results of calculations based on wavelike behavior, and for much of our work we will need to visualize electromagnetic radiation in a different way.

In 1887, Heinrich Hertz discovered that electromagnetic radiation striking one plate in a vacuum tube could generate a current that depended on the intensity of the "light." Subsequent experiments at first raised questions, but then led to answers that helped understand the effect. In 1905, Einstein showed that the photoelectric cell was responding to light as though it were individual "packets" or "bullets" of energy instead of a continuum. This theory is now completely accepted, and we speak

TABLE 1.1 Thermal Emitter Temperature and Color Correlation

T (°C)	*T* (°F)	Apparent Color
400	752	Red heat visible in the dark
474	885	Red heat visible in twilight
525	977	Red heat visible in daylight
581	1078	Red heat visible in sunlight
700	1292	Dark red
800	1472	Dull cherry red
900	1652	Cherry red
1000	1832	Bright cherry red
1100	2012	Orange red
1200	2192	Orange yellow
1300	2372	Yellow white
1400	2552	White welding heat
1500	2732	Bright white
1600	2912	Dazzling white (bluish white)

Source: A compendium of vendors spec sheets compiled by Boston Electronics Corporation, Brookline MA. Accessed February 2014 at http://www.boselec.com/products/documents/IRSourcesBROCHURE12-12-13WWW.pdf

of *photons* or *quanta* of electromagnetic energy. Einstein was awarded the Nobel Prize in 1921 "for his contributions to mathematical physics, and especially for his discovery of the law of the photoelectrical effect" (Eisberg, 1961; Wehr and Richards, 1960).

Although the duality of light is discussed by most books on modern physics, it is a distressing situation for some students. We cannot say that light is a wave or that it is a bunch of particles. Neither the *photon* or *wave* model is perfectly "correct." Electromagnetic phenomena are complicated, and both models are simple means to help us understand and make predictions. In some situations, a particular analogy will work, but in others it will not.

1.6 QUANTUM (PHOTON) DETECTORS VERSUS THERMAL DETECTORS

We mentioned that Herschel's detector was a thermometer – the first thermal detector. Thermal detectors respond to the power falling on the detector and they are still used – though they are more sensitive than Hershel's thermometer. However, another detector type is now very important. Called *photon detectors*, these respond not to the *power* falling on the detector but on the rate of arrival of *photons* – discrete packets of energy. We will discuss photons in Chapter 2, and the two detector types in Chapters 3 and 4.

1.7 DETECTORS AS TRANSDUCERS

A *transducer* is a device that converts one type of signal to another. We can think of the detector as a transducer that converts IR or visible light to electrical signals (Figure 1.5). The incoming radiation and the electrical signal generated are both described in terms of wavelengths, frequencies, power, and spectral distribution.

As you begin to think about IR detection, be careful to make a distinction in your mind between the input (IR) signal, with its wavelengths, frequencies, and power, and the output (electrical) signal, with *its* wavelengths, frequencies, and power. The IR wavelengths have values of a few micrometers, with frequencies of about 1×10^{14} Hz (cycles per second). The electrical signals generated by our detectors (transducers) are interesting only at relatively low frequencies, from DC up to 1 MHz or less.

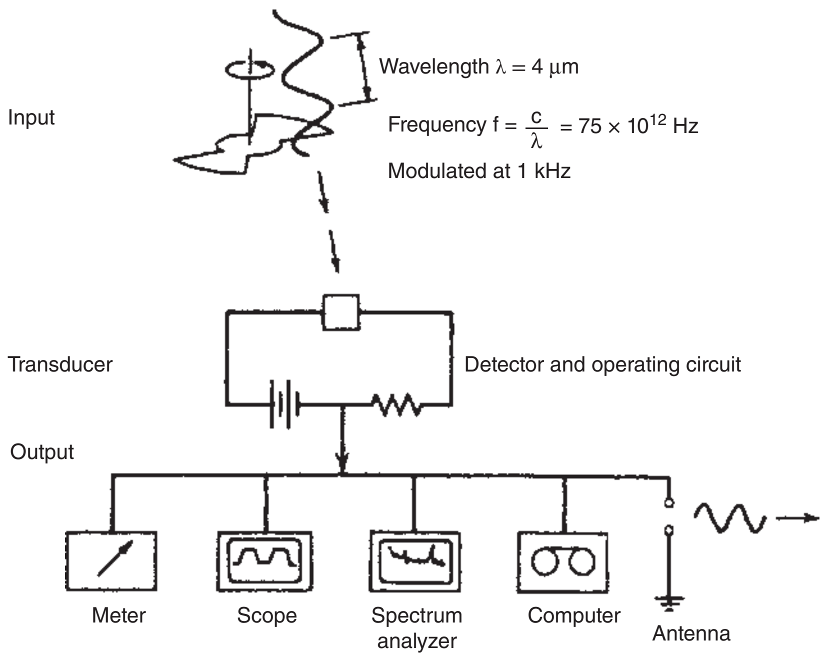

Figure 1.5 IR detectors are transducers.

1.8 DETECTOR PARAMETERS: DEFINITIONS

Before beginning our discussion of detectors, consider the parameters that describe how well the detectors perform. In this section, we define these parameters in terms of the detector outputs and the radiometric inputs and other test conditions. Later – after we have described the various detection mechanisms – we discuss theoretical formulas that attempt to predict what these parameters will be. Later still, we discuss the measurement of those parameters. The parameters used to characterize an IR detector are the following:

Responsivity: electrical output for a given IR input

Noise: the "clutter" that tends to hide the true signal

Signal-to-noise ratio: A measure of the fidelity or "cleanliness" of a signal pattern

Noise-equivalent power (NEP): The minimum IR power a detector can accurately "see" (There are other similar figures of merit: noise-equivalent irradiance (NEI), noise-equivalent differential temperature (NEdT))

Specific detectivity (D^*): The signal-to-noise ratio that would result if the performance of your detector were scaled to a detector of a standard size, under standardized test conditions

Linearity: How well the output signal "tracks" the IR power

Dynamic range: The range of IR signal levels for which the detector is useful

Frequency response: How the responsivity changes with electrical frequency

Spectral response: How the responsivity varies with the wavelength of the IR power

Modulation transfer function (MTF): How the responsivity varies as smaller and smaller targets are focused on the detector

Minimum resolvable temperature difference (MRTD): The minimum temperature difference that we can resolve – this is a function of spatial frequency (small or finely spaced features are harder to resolve than large, widely spaced ones); it combines the noise equivalent temperature difference and the MTF

Crosstalk: Apparent signal from one detector due to a large signal on a nearby detector

1.8.1 Responsivity

The basic function of a detector is to convert radiant input to an output signal of some convenient type. For our purposes, that output is always electrical – either a current or a voltage. The responsivity $\mathcal{R}$ is the ratio between the output signal and the radiant input (see Figure 1.6).

We will often work in terms of the *irradiance* E – the flux density at our detector, expressed either in watts per square centimeter of detector area (W/cm^2) or photons per second per square centimeter [photons/(cm^2 s)]. The radiant input is the product of the irradiance and the detector area A_d.

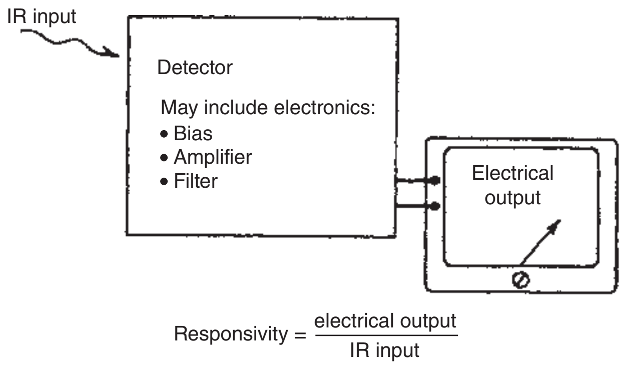

Figure 1.6 Responsivity of a detector.

DEFINITION OF RESPONSIVITY

$$\mathcal{R} = \frac{\text{signal output}}{\text{IR input}} \tag{1.1a}$$

$$= \frac{S}{EA_d} \tag{1.1b}$$

Example: Given that a 30-mV signal results when a detector of area 25×10^{-6} cm^2 is exposed to an irradiance of 120×10^{-6} W/cm^2, what is the responsivity?

The incident power is

$$P = EA_d = (120 \times 10^{-6}\,\text{W/cm}^2)(25 \times 10^{-6}\,\text{cm}^2)$$
$$= 3 \times 10^{-9}\,\text{W}$$

The responsivity is

$$\mathcal{R} = (30\,\text{mV})/(3 \times 10^{-9}\,\text{W})$$
$$= 10^7\ \text{V/W}$$

■

Responsivity is an important parameter for a detector. It allows the users to determine ahead of time how sensitive a measuring circuit they will require to "see" the expected output, or how much amplifier gain they need to boost the signal to a satisfactory level. Alternatively, it tells them how to determine from the output signal what the detected irradiance level was.

It is most common to express the output signal in volts and the IR input in watts, so the usual units of responsivity are volts/watt (V/W). However, depending on the application and the customer's preferences, the output may be either current or voltage, and the IR input may be stated in terms of total power, power density, photon arrival rate, or photon flux density. The concept is still the same: responsivity equals output divided by input. Examine the units carefully to make sure that you know what is intended.

In addition to the choices for measuring input and output, it is sometimes agreed to refer the output to what it would be if some different (idealized) circuit or spectral content were used. The nomenclature may warn you that some additional manipulation is meant.[1] Some examples are the following:

Short-circuit current responsivity
Open-circuit voltage responsivity
Peak spectral responsivity.

Specific examples of this kind are discussed in Section 2.2.5 (spectral responsivity) and Section 4.10.3 (circuits).

Low responsivity is not an insurmountable problem; it is always possible to increase the signal levels by adding amplifiers to the signal processing circuit. A limitation that cannot be overcome with additional gain is the presence of noise.

1.8.2 Noise

Noise refers to an electrical output other than the desired signal. It is unavoidable, but we strive to keep it as low as possible. Once noise enters the output, it can obscure or completely hide small signals (Figure 1.7). It is very difficult (or impossible) to find those signals again.

Some noise sources are fundamental and cannot be avoided. Some of the sources of these fundamental noises are the following:

- Photons do not arrive at an absolutely constant rate (the arrival rate fluctuates slightly);
- Atoms in the detector vibrate slightly, even at low temperatures;
- Electrons move randomly in the detector, not like well-drilled soldiers.

Other noise sources arise externally and can be eliminated if we are careful:

[1]On the other hand, you cannot count on the use of proper or even consistent nomenclature – we often encounter vague or incorrect requirements. To be safe, get someone who knows what is meant to give you a sample calculation. If they say, "Well, you know, just the responsivity … ," you need to poke a little more because they don't know exactly what they want.

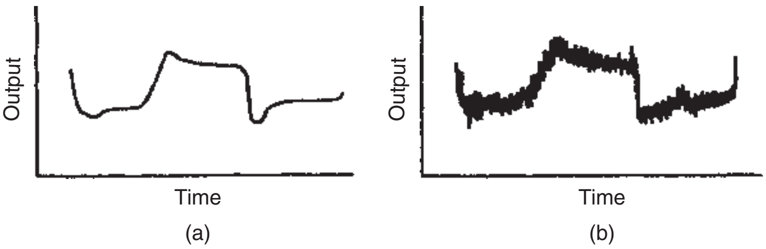

Figure 1.7 Noise is "clutter" that degrades signal fidelity: (a) with little noise: (b) with more noise.

- Electrical interference: motors, AC power lines, and so on;
- Temperature fluctuations;
- Vibrations that cause electrical components to shift.

Since noise is a random deviation from the average signal output, some convention is required to decide how to assign a single number to a given noise pattern. The usual definition is the root-mean-square (rms) deviation: the square root of the mean (average) of the square of the *deviation* over a period of time. (The squaring process is necessary since the output shifts negative as often as it goes positive: a simple average would yield zero.) Meters and digital circuits are available that calculate rms values automatically. An algorithm for calculating noise from sampled data is provided in Section 11.4.4.

1.8.3 Frequency Spectrum of Noise

Some noise components will appear at very specific frequencies. A pump will vibrate a dewar a few times every second, and an AC power line near a critical amplifier will introduce noise at the line rate – 60 cycles per second (see Figure 1.8). The more fundamental noise sources, however, will add some noise more or less uniformly at all frequencies. This is referred to as *white noise*, by analogy to the fact that white light contains all wavelengths (frequencies) of light. Even if the noise is not quite white,

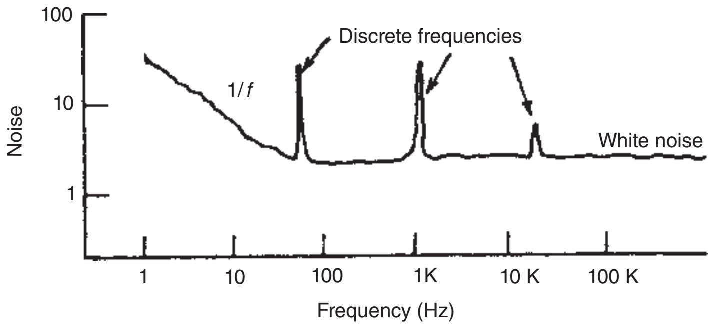

Figure 1.8 Frequency spectrum of noise.

it will generally contain a wide range of frequencies, and we can reduce the noise by eliminating unnecessary frequencies. For example, if our signal is at 200 Hz (200 cycles per second), eliminating all electrical output above 250 Hz and below 150 Hz would improve the noise situation. The remaining 100-Hz electrical bandwidth would contain less noise than the original wide-band signal.

1.8.3.1 Noise Spectral Density It can be shown that, for white noise, the total noise voltage or current is proportional to the square root of the bandwidth Δf. Even if the noise is not "pure white," the square root of bandwidth rule is often used:

$$\text{"in-band" noise} \sim \sqrt{\Delta f} \tag{1.2a}$$

> ***Example:*** If the original bandwidth in the case mentioned above was 40 kHz, we would have reduced the noise by a factor of about 20 when we reduced the bandwidth to 100 Hz:
>
> $$\sqrt{40}\,\text{kHz} = \sqrt{4 \times 10^4\,\text{Hz}} = 200\,\text{Hz}^{1/2}$$
>
> $$\sqrt{100}\,\text{Hz} = 10\ \ \text{Hz}^{1/2}$$ ■

To compare the noise in various pass bands, we use the noise spectral density n. It is the noise N divided by the square root of the bandpass Δf:

DEFINITION OF NOISE SPECTRAL DENSITY

$$n = \frac{N}{\sqrt{\Delta f}} \tag{1.2b}$$

The noise spectral density has units of volts per root hertz (V/Hz$^{1/2}$). Its numerical value is the noise that would occur if the electrical bandpass were reduced to 1 Hz.

> ***Example:*** If a noise of 7.5 µV is observed in a bandwidth of 50 Hz, the average noise spectral density in that pass band is about 1.1 µV/Hz$^{1/2}$.
>
> $$\begin{aligned} n &= \frac{N}{\sqrt{\Delta f}} \\ &= \frac{7.5\,\mu\text{V}}{\sqrt{50}\,\text{Hz}} \\ &= \frac{7.5\,\mu\text{V}}{7\,\text{Hz}^{1/2}} \\ &\approx 1.1\,\mu\text{V}/\text{Hz}^{1/2} \end{aligned}$$ ■

1.8.4 Signal-to-Noise Ratio

The *signal-to-noise* (*S*/*N*) *ratio* is a simple way to describe the "cleanliness" or "fidelity" of a given signal. It is simply the signal voltage divided by the rms noise voltage. An oscilloscope trace with an *S*/*N* ratio of 100 or more is a very clean pattern; the "contamination" is imperceptible when viewed with a gain that displays the entire signal. With an *S*/*N* ratio of 10, the main features are clear but most details are lost. A ratio of 3 is only roughly useful. These are illustrated in Figure 1.9.

The signal-to-noise ratio by itself does not tell us about the detector. We can get a better *S*/*N* ratio for the same detector just by applying more signal irradiance. *S*/*N does* describe the conditions under which you are working: if you are trying to collect data with an *S*/*N* ratio of 3, I would not trust your results as much as if you had an *S*/*N* of 30, or, better yet, 300.

1.8.5 Noise-Equivalent Power

NEP is a measure of the ultimate sensitivity of a given detector, and it is a convenient number to estimate what your *S*/*N* ratio will be if you know the power available. NEP is the power that must fall on the detector to cause an *S*/*N* of 1. If you have a power available 10 times the NEP, your *S*/*N* will be 10.

NEP is determined by dividing the system noise by the responsivity (using the output per power input definition of responsivity):

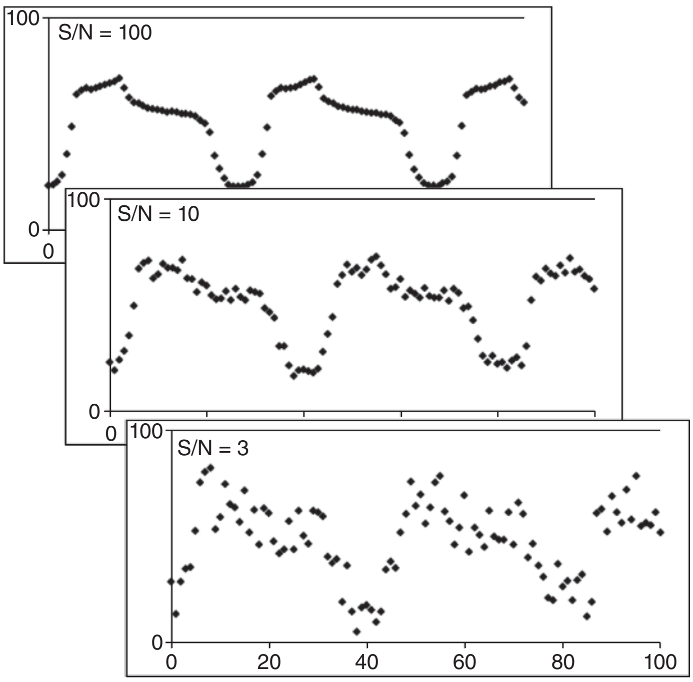

Figure 1.9 Detector output with varying signal-to-noise ratios.

DEFINITION OF NOISE EQUIVALENT POWER

$$\text{NEP} = \frac{\text{noise}}{\text{responsivity}} \tag{1.3}$$

The units of NEP are watts.

Example: For a detector with 7.5 μV of noise and responsivity 10^7 V/W, the NEP is 7.5×10^{-13} W:

$$\begin{aligned} \text{NEP} &= 7.5\,\mu\text{V}/10^7\,\text{V/W} \\ &= 7.5 \times 10^{-13}\,\text{W} \end{aligned}$$

A variant uses the *noise spectral density* instead of the noise in the NEP formula. The resulting units are watts per root hertz ($\text{W/Hz}^{1/2}$). If this parameter is used, it is especially important to display the units to help readers understand what you have done. ■

1.8.6 Specific Detectivity (D^*)

The NEP formula (1.3) is convenient for predicting the minimum power a given system can detect, but it has some undesirable features. A good detector will have a small NEP, and detectors of different sizes and noise bandwidths will have different NEPs, so we cannot say in general what NEP a good detector should have unless we specify the area and noise bandwidth.

Specific detectivity (D^*)[2] was introduced to eliminate those two "faults" – a large D^* is good, and for a given field of view and scene temperature all good thermal detectors should have about the same D^*.

D^* and NEP are really appropriate for thermal detectors, but some people still use them and ask that they be reported, even for photon detectors.

D^* is the responsivity times the square root of the area, divided by the noise spectral density (1.4a), or it can be thought of as a normalized signal-to-noise ratio (1.4b):

DEFINITION OF SPECIFIC DETECTIVITY

$$D^* = \frac{\text{responsivity} \times \sqrt{\text{area}}}{\text{noise}/\sqrt{\Delta f}} = \frac{\mathcal{R}\sqrt{A_d}}{N/\sqrt{\Delta f}} \tag{1.4a}$$

$$= \frac{\text{signal/power}}{\text{noise}/\sqrt{A_d\ \Delta f}} \tag{1.4b}$$

The units of D^* are $\text{cm Hz}^{1/2}/\text{W}$.

[2] R. Clark Jones (1960) defined three "Detectivities," with symbols D, D^*, and D^{**}. Only the second – *Specific detectivity* (D^*) – is used now, and we generally just call it "Detectivity" or "D-star."

Example: If a 25×10^{-6} cm^2 detector has a responsivity of 10^7 V/W and a noise of 7.5 μV in a 50-Hz bandwidth, the D^* is about 4.7×10^{10} cmHz$^{1/2}$/W:

$$D^* = \frac{10^7 \ \mathrm{V/W} \times \sqrt{25 \times 10^{-6}}\,\mathrm{cm}^2}{7.5 \ \mu\mathrm{V}/\sqrt{50 \ \mathrm{Hz}}}$$
$$= 4.7 \times 10^{10} \ \mathrm{cm\text{-}Hz^{1/2}/W}$$ ■

Example of the Use of D*: D^* is useful in predicting *S/N* for a given test environment: Suppose that we had a detector of the same material as the one in the preceding example but with an area of 100×10^{-6} cm^2. If we used it with a circuit whose noise bandwidth was 200 Hz and an irradiance of 10 μW/cm^2, the resulting signal-to-noise ratio would be about 335:

$$\frac{S}{N} = D^* \frac{\text{irradiance} \times \sqrt{\text{area}}}{\sqrt{\Delta f}}$$
$$= 4.7 \times 10^{10} \ \mathrm{cm\text{-}Hz^{1/2}/W} \times \frac{10\,\mu\mathrm{W/cm^2} \times \sqrt{100 \times 10^{-6}\,\mathrm{cm}^2}}{\sqrt{200\,\mathrm{Hz}}}$$
$$= 335$$ ■

1.8.7 Linearity and Saturation

Detector outputs will increase linearly with input signal over some range of irradiances, but fail to be linear at some large irradiance. That is, a plot of electrical signal versus radiometric input will start out as a straight line but will eventually level off (see Figure 1.10). Linearity describes the exactness with which this is true. Linearity requirements are not always specified in the same way, but one way would be to state how far a graph of measured signal versus irradiance would be allowed to deviate from the best-fit straight line.

A major source of deviation from linearity is saturation of the detector or electronic circuit. By this we mean that, as the irradiance and signal increase, some physical constraint is reached, and the signal cannot continue to increase. This could be due to the electrical breakdown of the detector itself or of some electronic components. More generally, there is an amplifier in the circuit that will put out only a limited voltage. For example, many operational amplifiers are powered by 6-V supplies and cannot support more than a 6-V output signal.

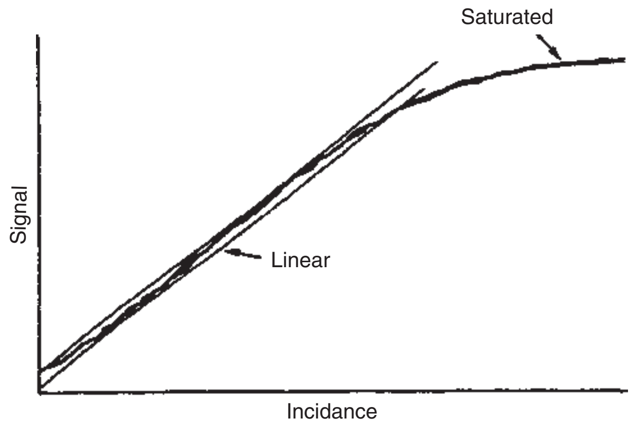

Figure 1.10 Signal versus irradiance plot showing linear and saturated regions.

1.8.7.1 Dynamic Range The dynamic range is the ratio of the highest useful signal to the lowest measurable signal. *Highest useful signal* might be defined as the point at which a given linearity specification is exceeded, and *lowest measurable signal* might be the signal at which $S/N = 1$. Other criteria are possible, however.

1.8.8 Frequency Response

The detector or system (detector plus electronics) will generally respond equally well to a range of low frequencies, but will not respond as well to higher frequencies. The frequency response is described by a plot of the responsivity versus frequency (Figure 1.11). It can also be described by providing the corner frequency, in which case one implies that the frequency response curve obeys an equation of the form

$$S = S_0 \frac{1}{[1 + (f/f_c)^2]^{1/2}} \tag{1.5}$$

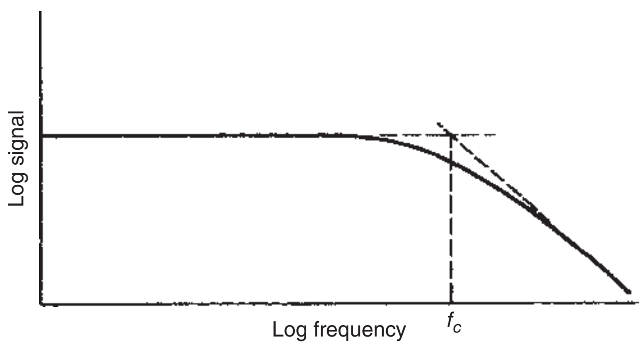

Figure 1.11 Frequency response.

Example: Given a detector with a 1200-Hz corner frequency and a signal of 100 mV at 25 Hz, the signal at 1800 Hz is about 55.5 mV. S_0 is 100 mV (25 Hz qualifies as a low frequency since it is well below the corner frequency), so

$$
\begin{aligned}
S &= 100\,\mathrm{mV} \times \frac{1}{[1 + (1800/1200)^2]^{1/2}} \\
&= 100\,\mathrm{mV} \times \frac{1}{(3.25)^{1/2}} \\
&= 55.5\,\mathrm{mV}
\end{aligned}
$$

■

When $f = f_c$, $S = S_0/\sqrt{2} = S_0 \times 0.707$. This is sometimes expressed by saying that, at the corner frequency, “the signal is down by 3 dB,” and the corner frequency is sometimes referred to as the 3-dB *frequency*.

1.8.9 Spatial Considerations

1.8.9.1 Uniformity of Response For some applications, it will matter whether the detector responsivity is uniform over its surface or whether some parts are more sensitive than others. Actually, no detector is *perfectly* uniform, so the question really is how nonuniform it is, and how much nonuniformity the customer can tolerate. In theory, a response profile (sometimes called a spot-scan- a plot of responsivity vs. position) is a good way to report uniformity[3]. This may be possible with some single-element detectors, but for most modern detectors the sensitive surface is so small that we cannot obtain an optical spot small enough to measure the response uniformity. Instead, we revert to the determination of MTF.

1.8.9.2 Modulation Transfer Function Consider a target made up of alternating hot and cold lines, with the hot lines repeating at some frequency k every millimeter: 2, 5, or 20 lines/mm. We call k the *spatial frequency* of the target, and the MTF (at spatial frequency k) is a measure of how much the detector signal will vary (be modulated) as we scan a target with that spatial frequency[4] For the example of Figure 1.12, note how the signal will fall off as k exceeds one cycle/mm. This detector will not “see” 0.1-mm features very well. Figure 1.13 is a graph of MTF versus frequency.

[3]We mention spot-scans for completeness and as an introduction to MTF, but they are not nearly as important now as they were in the 1960s. At that time many detectors were many millimeters in size – considerably larger than available spot sizes – so we could measure responsivity at many points across the detector, and plot responsivity versus position. Nonuniformities were often seen near the electrical contacts, for example. The size of most modern detectors is comparable, or smaller than, the smallest spots available. The theory described here still applies, but in practice it is not relevant.

[4]Actually, the MTF definition is based on sine-wave targets; however, some MTF measurements are made with bar pairs (a hot stripe and a cold stripe), so “lines per millimeter” is an acceptable way to begin to understand spatial frequency.

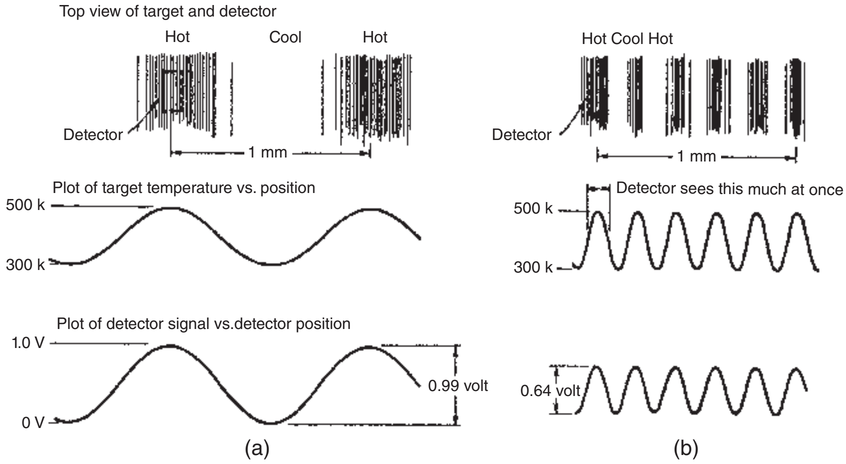

Figure 1.12 Signal generated by detector moving over IR sources: (a) target repeats once every millimeter ($k = 1 \sim /\text{mm}$); (b) target repeats five times every millimeter ($k = 5 \sim /\text{mm}$).

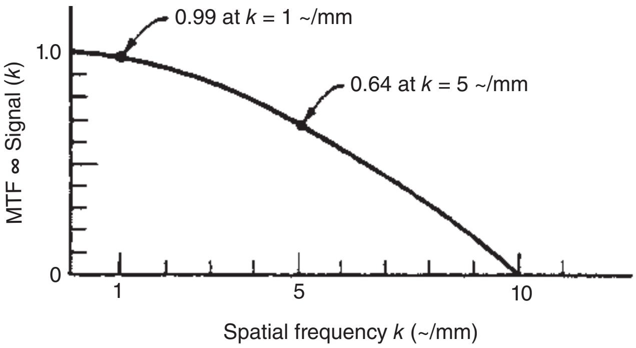

Figure 1.13 MTF of the detector of Figure 1.12.

MTF is sometimes called the spatial equivalent of the frequency response of a detector, or the *spatial frequency response*. It is a measure of how well the detector can sense small details. MTF depends on detector size and the uniformity of response across the detector. A small detector with uniform response will have better MTF and be able to see smaller features than a large one or one with a response that tapers off near the detector edges.

1.8.10 Crosstalk

If one has an array of detectors and images a spot on one detector, there should be no signal from the other detectors. In practice, some signal will be present on the others, but it should be very small. This excess signal is said to be due to *crosstalk*. Crosstalk is generally measured as a percentage of the input or driving signal. A requirement

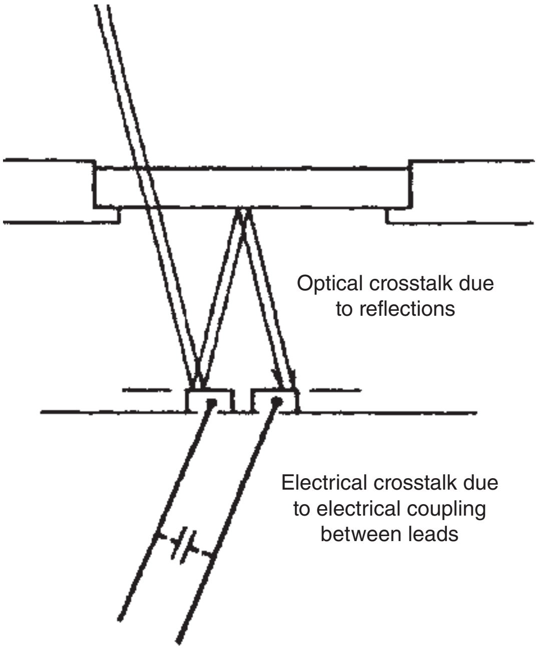

Figure 1.14 Crosstalk due to optical reflections and electrical coupling.

that crosstalk be less than 5% would be fairly easy to meet, but a requirement of 0.05% would be very hard to meet.

Figure 1.14 illustrates two causes of crosstalk – optical effects (in this case we show reflections from the detector to the window and back to the detector) and electrical effects (in this example we show capacitance between the signal leads).

1.9 SOURCES OF ADDITIONAL INFORMATION

Numerous texts and articles in scientific journals discussing every aspect of the "IR business" and detection of electromagnetic radiation are available. We mention here a few that are of general interest. They are listed in chronological order, and we have provided some early papers for historical interest, as well as some more current papers.

Wolfe (1965) *The Handbook of Military Infrared Technology* edited by W. L. Wolfe, Office of Naval Research, Department of the Navy, Washington, DC. *This has been expanded and republished several times (with variants on the title) including recent web-based versions.*

Hudson (1969) *Infrared System Engineering* by R. D. Hudson, Jr., Wiley, New York. For many years this was the standard text on infrared engineering, and still is a valuable resource if you can find a copy.

Wolf and Zissus (1978) *The Infrared Handbook*, The Research Institute of Michigan. This was an outgrowth of the earlier *The Handbook of Infrared Military Technology* (Wolfe, 1965).

Dereniak and Crowe (1984) *Optical Radiation Detectors* by E. L. Dereniak and D. G. Crowe, Wiley, New York. This is an excellent introduction; it covers radiometry and detectors.

Accetta and Shumaker (1993) *The Infrared and Electro-Optical Systems Handbook* by J. S. Accetta and D. L. Shumaker, Executive Editors, copublished by Infrared Information Analysis Center, Environmental Research Institute of Michigan, P.O. Box 134001, Ann Arbor, Michigan 48113-4001 and SPIE Optical Engineering Press, P.O. Box 10, Bellingham, Washington 98227-0010 Copyright © 1993 The Society of Photo-Optical Instrumentation Engineers. The eight volumes are: (1) Sources of Radiation; (2) Atmospheric Propagation of Radiation; (3) Electro-Optical Components; (4) Electro-Optical Systems Design, Analysis and Testing; (5) Passive Electro-Optical Systems; (6) Active Electro-Optical Systems; (7) Countermeasure Systems; and (8) Emerging Systems and Technologies.

Lee (2010) *Thermal Design: Heat Sinks, Thermoelectrics, Heat Pipes, Compact Heat Exchangers, and Solar Cells* by H. Lee, John Wiley & Sons, Inc., Hoboken NJ. This book focuses on thermal engineering but we mention it here because it discusses several topics that are relevant to IR detection: thermal engineering and cryogenics (relates to our Chapter 12), and his chapter on solar cells covers radiation (like our Chapter 2 – Radiometry), semiconductor physics (relates to our Chapters 4 and 5). Lee covers these topics succinctly but in more detail than we can provide here.

The Ultimate Infrared Handbook for R&D Professionals (n.d.) published by FLIR Inc. Accessed September 2014 at http://www.flir.com/uploadedFiles/Thermography/MMC/Brochures/T559243/T559243_APAC.pdf. This 44-page "booklet" provides a succinct introduction to IR and specific tips on thermographic imaging.

REFERENCES

Eisberg (1961) *Fundamentals of Modern Physics* by R. M. Eisberg, Wiley, New York.

Hudson (1969) *Infrared System Engineering* by R. D. Hudson, Jr., Wiley, New York.

Wehr and Richards (1960) Physics of the At*om* by R. M. Wehr and J. A. Richards, Jr. Addison Wesley, Reading, MA.