

Thermal Imagers and System Considerations

Chapter Outline

Brief History (Basic Concepts)	101	Thermal Sensitivity	110
Thermal Image	103	Spatial Resolution	111
Performance Parameters	105	Range	116
Spectral Response	106	Thermal Resolution	117
Signal-to-Noise Ratio	108		

There are many different types of infrared detectors but those used in thermal imagers need fast response time, ruggedness if they will be used outdoors, and the ability to be fabricated into arrays so that the requirements associated with thermal sensitivity can be met. These detectors fall into two classes: thermal detectors and photon or quantum detectors. When conducting animal surveys in the field it is necessary to be able to detect animals at relatively long ranges based primarily on the animal's size and its temperature difference with respect to the background. This is basically a surveillance application that depends on the performance specifications of the imager being used coupled with several special conditions to deal with the local atmospheric conditions. For surveillance applications the primary goal is to optimize the ability to see spatial distributions based on the temperature difference in the scene being viewed. Other applications might require the monitoring of thermal distributions and making temperature measurements to seek information about the well-being of living organisms or to provide methods of monitoring products for quality assurance in manufacturing. For these types of applications the most important performance parameters for a thermal imaging camera can be reduced to the spatial resolution and the noise equivalent temperature difference (NETD) although using an imager for making absolute temperature measurements must respond linearly with temperature and be equipped with an absolute temperature reference.

BRIEF HISTORY (BASIC CONCEPTS)

Thermal imaging systems are not new. In fact, they are used regularly in a number of application areas. Originally developed by the military for detecting, recognizing, and identifying enemy personnel and equipment, they are now

routinely used in police work, firefighting activities, border patrol crossings, perimeter surveillance, and environmental work (monitoring for pollution control and energy conservation) as well as a variety of medical, industrial, and construction applications. Thermal imagers can be used to image objects both large and small such as tanks deployed on the battlefield (landscape scale) to components that comprise a printed circuit board. They are infrared radiation detectors that may be used to perform noncontact thermal mapping of any device, system, object, or animal that emits infrared radiation (heat).

Infrared detector focal plane arrays (FPAs) can be either photon detectors or thermal detectors that are capable of converting infrared energy into electrical signals, which after multiplexing can be read out in a video format. Thermal detectors (bolometers) (Wolfe and Kruse, 1995; Vollmer and Mollmann, 2010) can be either resistive or capacitive in nature and sense the incident radiation by way of absorption and ancillary temperature change in the detector that produces an electrical charge or signal that mimics the incident infrared energy distribution. The capacitive devices are known as pyroelectric vidicons. Pyroelectric detectors require the incoming scene to be modulated, usually by a mechanical chopper, so a change in the capacitance of the device will produce a change in the stored electrical charge pattern on the detector (Garn and Sharp, 1974). Bolometric systems are now commercially available with uncooled detector arrays that offer moderate performance at a moderate price. A number of these systems have been used in the field for ground-based surveys and behavioral studies (Boonstra et al., 1994, 1995; Focardi et al., 2001, 2013; Franzetti et al., 2012; McCafferty et al., 1998; McCafferty, 2013). Recently these imagers have been used to detect signs of rabies infection in raccoons (Dunbar and MacCarthy, 2006) and were used in airports to scan and detect passengers infected with the swine flu (Shenkenberg, 2009). While imagers equipped with thermal detectors are suitable for a wide range of applications, the sensitivity and performance necessary to conduct surveys under a wide variety of field conditions (particularly airborne surveys) requires that we look to infrared (IR) imagers using photon detectors as opposed to thermal detectors.

The first thermal imaging systems employing photon detectors were in use nearly 35 years ago. The precursors of today's thermal imagers had moderate resolutions and were large, heavy, complex, cryogenically cooled, and very expensive. Since that time new technologies have been developed that have resulted in a new breed of infrared imaging systems featuring high resolution; the lightweight units are no larger than modern camcorders. For the most part, these advances were made due to the development of high-resolution FPAs and concomitantly the development of Stirling cycle micro-coolers that allow the detectors to be cooled to $\sim 75\text{ K}$ (-189°C), which eliminated the need for cryogenic cooling (Kozlowski and Kosonocky, 1995). These new IR imagers can produce hundreds of images per second. The units are now commercially available from several vendors and while the cost of the units has come down considerably they are still somewhat expensive. Before we continue with describing what features

and performance characteristics a camera must have to produce good thermal images, we need to look at a thermal image and think about what would actually make it suitable for a particular application.

Thermal Image

All objects above absolute zero ($T > 0$ K) radiate heat and the amount of heat radiated is determined by the temperature and surface condition of the object. Modern thermal imaging cameras are IR cameras that are capable of measuring the heat radiating from objects. Since heat transfer by radiation occurs at the speed of light images of the objects can be formed. One can record thermal images captured by the IR camera on video, view the camera display on a TV monitor, or simply view the objects of interest through a viewfinder as one could with a conventional camcorder. The only difference here is that the IR camera senses and displays a spatial distribution of thermal (heat) energy instead of visible light. This allows one to see in total darkness, through smoke, and other low visibility, low-contrast situations. These cameras can also be used during daylight hours to see heat-generated images when visual observation is inadequate to distinguish a heat-emitting object from its background. The imager sees all objects in a particular scene that radiate infrared energy. A protocol must be established to determine if the objects imaged are objects of interest for any particular survey.

Generally speaking, the camera provides a display of the spatial distribution of the thermal energy emanating from a scene (thermal image) and the individual objects of interest within the scene are referred to as thermal signatures. Each signature is a composition of the spectral distribution (wavelength band of infrared-radiation), spatial distribution (size and shape), and intensity distribution (temperature) that allows us to distinguish it from other signatures and the background of the scene. There is also a temporal component associated with these distributions, which can be used to aid in the interpretation of collected imagery. The objects of interest may be moving, for example. There are a number of factors that can influence these distributions that will be considered in later sections. It is instructive to examine a typical thermal image to get a feel for some of these factors. Since thermal images are formed by the radiated intensity difference between objects and their backgrounds it is important to recognize that the temperature and the surface of the object play a major role in the recorded energy distribution that the camera captures. In other words, it is more than just a temperature difference but an “apparent” temperature difference that produces the image since the surface moderates the emissivity and the resulting energy distribution emanating from the object. We will also see that reflected and scattered ambient radiation also contributes to the energy distribution responsible for the imagery.

A thermal image is shown in [Figure 7.1](#). The image contains a thermal signature of a house cat (Sniper), which is depicted as a white silhouette on a



FIGURE 7.1 A thermal image of a house cat in a forested setting. The thermal signature of Sniper was captured with an InfraCAM® model A 3–5 μm infrared camera. The photo shown here was taken with a 35 mm camera of a single frame from 8 mm video of the thermal imagery displayed on a TV monitor.

somewhat darker (cooler) background, yet the image was collected during daylight hours. Other objects (trees, deadfall, and ground litter) in this scene are also radiating thermal energy and those images are also recorded. The gain of the 3–5 micron thermal imager was reduced in this image to provide a suitable apparent temperature difference for this infrared image. Note that the large log in the photograph is radiating a significant amount of heat and is comparable to that being radiated by Sniper yet the thermal signature of Sniper exhibits nice contrast when compared to the shady cool under-story provided by the forest canopy. The log was heated during the day due to the absorption of considerable amounts of thermal radiation from the sun (solar loading). The key difference here is that Sniper is his own source of radiant energy while the other objects are merely reradiating energy that was previously absorbed from sunlight. It should be noted that the polarity of the thermal camera could be reversed so that the collected imagery could also be presented as black signatures on a nearly white background.

There are a number of books with good discussions of infrared imaging systems and their uses (Maldague, 1992; Kaplan, 1999; Burney et al., 1988; Holst, 2000; Williams, 2009; Vollmer and Mollmann, 2010). However, they contain very little information on the use of infrared cameras for observing animals in the wild.

There is a plethora of factors that can influence the quality of thermal images collected in the field. An infrared imager is a complex electro-optical system (Seyrafi, 1973) that derives its performance from the intrinsic properties of detector materials (quantum efficiency), signal processing techniques, and human observation/interpretation of signals near the noise level of the system, all of which is extracted from a simple optical input. These cameras are rugged devices that meet the specifications for physical and mechanical robustness

demanded by the military. Even so, a few precautions taken during the data-gathering phase will help to secure quality imagery. If the imagery is being recorded on and from a moving observation platform (vehicle, aircraft, watercraft) then the recording equipment should be soft-mounted to eliminate noise and vibrations associated with the moving platform. In the field an observer is typically viewing a TV monitor whose display must be of sufficient brightness and contrast and be close enough to the observer so that visual acuity is preserved. In this phase of data collection, as with visual surveys, observer experience will play a role that may be influenced by training, workload, and fatigue. The significant difference here is that the data is also being recorded to video for comprehensive analysis at a later time. Fortunately, the issues involving image observation/interpretation can be significantly reduced or eliminated by using the proper methodology that will in turn negate the need for extensive training or experience on the part of the observer.

A review of past work in which IR thermal imagers were used for animal surveys reveal two significant facts: (1) the performance of the IR imagers used prior to 1995 was only marginal in actual field studies and surveys, and (2) for the most part the methods used to collect the imagery in these efforts did not fully exploit the strengths that the earlier imagers actually offered. There was, however, significant progress made in these early efforts toward identifying the limitations of the technology. Advances made in the performance capability of the cameras and changes in the proposed methodology for using these cameras have minimized these limitations significantly.

PERFORMANCE PARAMETERS

The performance of thermal imaging cameras can be characterized by a handful of parameters. However, the extraction of useful imagery from a state-of-the-art infrared imager is a complex process. It involves much more than just conducting surveys with the best imager available. It is not enough to simply view an image to determine if it is optimized. In addition to the performance capability built into the cameras we must also consider a number of other miscellaneous factors that ultimately affect the image quality. We need to keep in mind that there is a clear distinction between seeing a spatial distribution of thermal energy (detection) and seeing the detail in that thermal energy distribution (resolution). We will discuss later how the atmospheric transmittance, the scene content, observer experience, subordinate equipment, aircraft type, ambient illumination, ambient temperature, and other factors affect image quality. These factors are not necessarily mutually independent of one another, which contributes to the complexity of interpreting image quality. For example, the atmospheric transmittance (an optical phenomenon) and the ambient temperature (a thermal phenomenon) both affect the image quality captured by an infrared imager and both of these are affected by rainfall. If we just consider the performance parameters associated with the imaging

camera we intuitively want the IR camera to be capable of forming thermal images of small objects that have small temperature differences with respect to their backgrounds.

Additionally, for animal censusing, we would want to be able to resolve images from a considerable distance and over a considerable area (i.e., from an aircraft flying transects). As a first step in choosing an IR imager for use in animal studies and population surveys in the wild we would want to examine the performance parameters provided by both mid-wave IR band (MWIR) and long wavelength IR band (LWIR) imagers, which feature high thermal sensitivity, spatial resolution, and thermal resolution. Another parameter of importance is the signal-to-noise ratio that can be used to give physical insight into the significance of these parameters and how they relate to features we see in images, such as contrast. In addition to these obvious parameters there is the minimum detectable temperature difference (MDTD), which is important for animal counting applications when the species is known. Perhaps the most important parameters are the minimum resolvable temperature difference (MRTD), which depends on the spatial resolution of the imager, the noise equivalent temperature difference (NETD), and human observation/interpretation. The MRTD allows discrimination of animals based on the range and atmospheric conditions in the field.

Spectral Response

Thermal imagers are designed to operate in two specific wavelength bands in the infrared. The first thermal imaging band covers the (3–5 μm) or MWIR and the second thermal imaging band covers the (8–12 μm) or LWIR. In general, a system is an LWIR system if it is responsive somewhere in the LWIR region and likewise a system is an MWIR system if it responds somewhere in the MWIR region. When imagery is collected with either system it is only using a small portion of the total emitted radiation represented by the blackbody curves presented in Figure 5.1. Thermal imaging systems were designed to operate in these two spectral bands because they are the two primary transmission windows in the atmosphere suitable for thermal imaging applications.

The atmospheric transmittance depends on the amount of water vapor, gases, and aerosols that are present in the atmosphere. They interact through absorption and scattering with the radiation emanating from an object as it travels from the object to the imaging system. This loss in radiation is the atmospheric transmittance. For example, the strong drop in transmittance at 4.2 μm is due to absorption by carbon dioxide (CO_2). Both the upper and lower spectral limits of the MWIR and LWIR regions are determined by absorption due to water vapor. Since the makeup of the atmosphere is continually changing it is impractical to assign a value to the transmittance unless the measurement is made in a laboratory environment and as a result the curves in Figure 7.2 are only representative of typical atmospheric conditions.

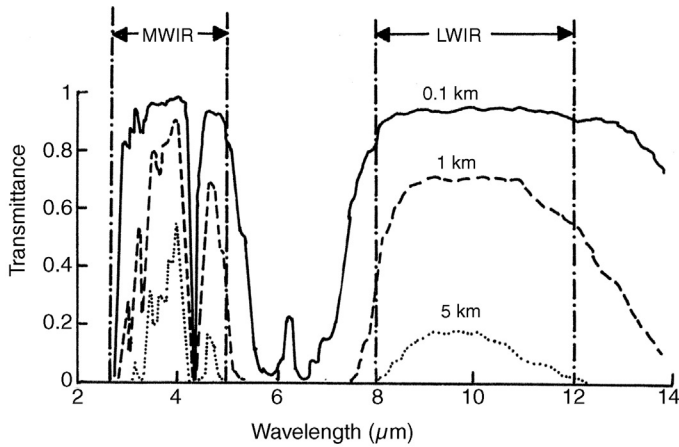


FIGURE 7.2 The atmospheric transmittance as a function of wavelength over 100 m and 1-km path lengths. The actual transmittance is continually changing, depending upon the presence of airborne particulates (dust, fog, and haze) and gases and the path length from the object to the thermal imaging system. This is a representative curve since the conditions in the field, which give rise to the atmospheric transmittance, can change within minutes.

The atmospheric transmission is high when there are only small amounts of water vapor, gases, and aerosols present in the atmosphere. At these times the sky will appear cold to the thermal imager since deep space is very cold. Under these conditions (viewing the zenith) the self-emission of the atmosphere is low and the average temperature of the background viewed by the imager is low. As the imager is lowered from the zenith to smaller elevation angles more aerosols and gases at ambient temperature are encountered along the line of sight, resulting in an average temperature close to that of the earth's surface. For most of the detection and survey work encountered in the field, small elevation angles are the norm. Down-looking angles from aircraft will experience the same high average temperatures associated with atmospheric layers close to the surface of the earth. Under these circumstances, atmospheric constituents degrade the thermal resolution. Both scattering and absorption in the line of sight reduce the magnitude of the thermal signature of the object to be detected, located, recognized, or identified. On the other hand, scattering of radiation into the line of sight and self-emission from the atmosphere in the line of sight both serve to reduce the thermal contrast between the object and the background. Since nearly all fieldwork involving censusing will utilize relatively long path lengths, the self-emission and scattering by the atmosphere in the path could be significant and must be taken into consideration. For short path lengths (<20 m) the transmittance for both the LWIR and MWIR windows can be considered as unity. The directional dependence and the amount of background radiation (both emitted and reflected) that the imager will encounter is another important factor that must be incorporated into the overall methodology.

Signal-to-Noise Ratio

The signal-to-noise ratio (S/N) is more important in detection systems than it is in imaging systems (Seyrafi, 1973, p. 269). For even low signal-to-noise-ratios a human observer can overlook a great deal of random noise flickering in an image displayed on an observation monitor. The human eye easily pulls very weak well-defined signatures from noisy images because it provides a powerful temporal and spatial integration capability. Observers will be able to identify relatively persistent brightness contours and shapes that form easily recognized geometric shapes (e.g., circles, triangles, rectangles, stars, or alphanumeric characters).

We can put the sensitivity improvements achieved with staring FPAs into perspective by examining the signal-to-noise ratio of a system when operating under the same average atmospheric conditions. The Beer-Lambert law determines the attenuation of the atmospheric transmittance, τ , by absorption and scattering. Figure 7.2 shows the results of the strong attenuation associated with absorption and scattering as a function of wavelength. We can write the atmospheric transmittance, τ , as

$$I = I_0 e^{(-kR)} \quad (7.1)$$

where k (1/km) is the extinction coefficient and R (km) is the path length or range. The extinction coefficient is wavelength dependent and accounts for both absorption and scattering losses in the atmospheric transmittance for any given path length. $k(\lambda)$ can be separated into its absorptive $k_A(\lambda)$ and scattering $k_S(\lambda)$ components as $k(\lambda) = k_A(\lambda) + k_S(\lambda)$. The transmittance curve in Figure 7.2 shows the wavelength dependence of the attenuation caused by absorption (primarily CO₂ and H₂O vapor) and scattering from the atmosphere. The most prominent attenuation mechanisms caused by the atmosphere are linear absorption, elastic scattering (Rayleigh scattering), and scattering from particulates (Mie scattering). Equation (7.1) can be rewritten by defining an average attenuation coefficient, $\beta = e^{-k}$. As a result we can write the transmittance as

$$I = \beta^R = e^{(-kR)} \quad (7.2)$$

Both β and k have the units of 1/km and in the limit of a completely transparent atmosphere ($k = 0$) then $\beta = 1$ and $I = 1$. From Figure 7.2 we see that generally for $R \approx 1$ km the values relating to $k_A(\lambda)$ and $k_S(\lambda)$ are small in the 3–5 μm and 8–12 μm range. However, the average attenuation coefficient β has values ranging from 0.70/km to 0.95/km, depending on whether the conditions are poor or excellent. Topics relating to the importance of atmospheric effects on collecting thermal images and their quality will be discussed in more detail in Chapter 11.

The signal-to-noise ratio (S/N) of a system operating during average atmospheric conditions can be written as

$$S/N = \Delta T(\beta^R)/\text{NETD}. \quad (7.3)$$

Here the signal is just the thermal contrast $\Delta T = (T_O - T_B)$ between an object and its background that is attenuated by the average atmospheric transmission (β) at some range R . The noise is given by the noise equivalent temperature difference that is a function of background temperature. As the temperature of the environment drops NETD increases and system noise increases, which reduces the signal-to-noise ratio. Both MWIR and LWIR detector performances are degraded due to the lack of photon production at the lower temperatures (the MWIR more so than the LWIR).

We can get an idea of how the local atmospheric conditions can influence the range of an imager by using equation (7.3) and the specifications for a typical thermal imaging system to compare values of the range for different average attenuation coefficients. Holst (2000) provides average attenuation values β for weather conditions ranging from poor to excellent for a hypothetical local environment, which can be used to compare range estimates. The weather quality and average attenuation β are given as: poor (0.70/km), fair (0.80/km), average (0.85/km), good (0.90/km), and excellent (0.95/km). For the 3–5 μm thermal imager (InfraCAM[®]) the following specifications apply: NETD = 0.7°C @ 23°C; IFOV = 0.6 mrad; FOV = 8 × 8 degrees; and we let S/N = 5, $T_B = 23^\circ\text{C}$, and $\Delta T = 4^\circ\text{C}$. We can rewrite equation (7.3) as

$$R = \{\log(S/N) - \log(\Delta T) + \log(\text{NETD})\} / \log(\beta) \quad (7.4)$$

Table 7.1 gives the calculated values of the range R obtained from equation (7.4) for the attenuation coefficients representing the weather conditions from poor to excellent and the parameters given for NETD, ΔT , and S/N.

From these rough calculations one can easily see the dramatic effect that the atmospheric attenuation can have on the range. Clearly water vapor is one of the most problematic obstacles that confront researchers using thermal imagers in the infrared.

TABLE 7.1 Estimates of the Range Calculated from Equation (7.4) for Various Atmospheric Attenuation Conditions

Range (m)	β/km	Conditions
370	0.70	Poor
590	0.80	Fair
820	0.85	Average
1270	0.90	Good
2600	0.95	Excellent

The values of the range R calculated from (7.4) for hypothetical atmospheric attenuation coefficients associated with various local weather conditions. S/N = 5, $\Delta T = 4^\circ\text{C}$, NETD = 0.7°C

Thermal Sensitivity

The output of an IR detector is a manifestation of a complex relationship involving many interdependent quantities. This makes it very difficult to compare imagers of different designs and different detector materials. In an infrared imager the detector is the most important component in the unit. For the most part, the significant improvements gained in the thermal sensitivity of modern IR imagers come about from advances in detector technology, specifically FPA. Imagers equipped with FPA technology do not require mechanical scanning mechanisms or choppers as do conventional IR imagers. Typically, a mosaic can be constructed consisting of 65,536 discrete detectors arranged in a 256×256 pattern to form an FPA. Each element (pixel) in the array appears as a point or resolution element in each image. Conventional IR imagers used in the early experiments for animal surveys had a single detector or a small array of detectors that were rapidly scanned over the entire scene so that the detector only received radiation during a very short period of time. By comparison each detector in an FPA stares continuously at the scene so it is “on” continuously. This allows it to receive a larger number of infrared photons from the scene, thereby providing a very high thermal sensitivity.

Thermal sensitivity refers to the smallest temperature differential that can be detected by the imager. A laboratory measurement of the thermal sensitivity is the NETD, defined as the temperature difference in the object scene that produces a change in output signal that is equal to the system root mean square noise. Basically, the radiant temperature increment in the object scene must be capable of producing a response from the detector that is sufficient to overcome the noise of the system. For most comparisons it is sufficient to use the temperature difference that produces a signal-to-noise ratio of unity at the sensor output.

In Chapter 5 we noted that the emitted power differential ΔP from an object and its background can be very small and that the sensitivity of the camera can be marginally effective. As a result, the camera must have sufficient gain so that the difference in the detector output voltage between the object and the background is a measurable quantity. This is a very important parameter and determines the fundamental limit of the camera. It is therefore a fundamental goal to reduce detector noise, which is usually defined as the noise equivalent power (NEP) and is expressed as $NEP = V_{RMS}/R_d$ where V_{RMS} is the root mean square noise and R_d is the detector responsivity. The basic output signal from the detector is a voltage V_d proportional to the power incident on the detector according to $V_d = \kappa R_d P$ where κ is a constant particular to the camera design and R_d is the responsivity of the detector. For small ΔT the differential camera output is

$$(\Delta V_d / \Delta T) = \kappa R_d (\Delta P / \Delta T). \quad (7.5)$$

Recall from above that $NEP = V_{RMS}/R_d$ and that the NEP is the signal level that produces a S/N of unity. Ignoring the atmospheric conditions ($\beta = 1$) we can use equation (7.3) as

$$S/N = \Delta T (\beta^R) / NETD$$

to get $\text{NETD} = \Delta T$ when $S/N = \text{unity}$. Since the NETD is the input ΔT that produces the S/N of unity then $(\Delta V_d) = V_{\text{RMS}}$ where V_{RMS} is the root mean square value of the noise. We can rewrite equation (8.1) as

$$V_{\text{RMS}} = kR_d (\Delta P / \Delta T) \text{NETD}. \quad (7.6)$$

where ΔT is the noise equivalent temperature difference NETD and the detector signal level ΔV_d is the root mean square value of the noise V_{RMS} . The sensitivity NETD is a function of the background temperature T_b since $(\Delta P / \Delta T)$ is evaluated at a specific background temperature.

$$\text{NETD} = V_{\text{RMS}} \{kR_d (\Delta P / \Delta T)\}^{-1}. \quad (7.7)$$

Note that the NETD decreases as the background temperature increases and therefore the minimum detectable temperature difference decreases or the system becomes more sensitive at warmer temperatures. Conversely, as the power differential available to the detector gets smaller due to the decrease in background temperature, the NETD increases or the system gets noisier and the temperature resolution decreases. Remember that small NETD is preferable and that generally the NETD becomes excessively large in the MWIR region as the background temperature drops below 0°C .

An FPA allows the detectors to collect photons for a longer period of time than a scanning system. This allows materials with modest quantum efficiency to easily produce signals above the noise of the system. The NETD is a function of the background temperature and is usually expressed as a temperature difference at ambient temperature. The NETD is also a function of the radiation collecting optics or the lens f-number, so that changing the lenses of the system can change the NETD. A typical value of the NETD for a 3–5 μm spectral band staring focal plane array fabricated either from indium antimonide (InSb) or from platinum silicide (PtSi) is 0.025 or 0.07°C @ 23°C . This can be compared to 0.2°C @ 23°C typical of the 8–12 μm scanning IR imagers that have been used in most of the animal survey work to date. This is approximately an order of magnitude improvement in thermal sensitivity over the scanning units used in earlier animal surveys conducted from the early 1960s to the middle of the 1990s.

Spatial Resolution

The spatial resolution of an IR imager does not uniquely determine the image quality. However, high spatial resolution is needed to acquire quality images since it furnishes important information with respect to the finest detail in an image that can be discerned. Since the spatial resolution of the system (detector array and optics) is unrelated to the system noise it is therefore independent of the thermal sensitivity discussed earlier. The spatial resolution of an IR imager is usually specified by the instantaneous field-of-view (IFOV) of the system or by the diameter of the bright central disk of the diffraction pattern (Airy disk)

formed by an ideal optical system. While either may be used it is important to note that both contribute to the resolution of the system, which can be detector limited (IFOV) or optics limited (Airy disk).

Detector-Limited Resolution

The size of the FPA ($D_{\text{HORIZONTAL}} \times D_{\text{VERTICAL}}$), the individual detector size, the number of pixels, and the center-to-center spacing (detector pitch) of the pixels characterize detector arrays. The IFOV specifies the angular resolution of the camera and is expressed as the angle in milliradians (mrad) over which the detector senses radiation. The parameters needed to determine the IFOV are the focal length, f , of the optical system and the width of the detector's active area, w . From this, the angle θ_D subtended by the detector can be estimated in the small angle approximation as $\theta_D = \theta_{\text{IFOV-H}}$ (horizontal instantaneous FOV).

$$\theta_D = w/f \quad (7.8)$$

If the detector is not square then the angular resolution would be an average θ_a of the horizontal and vertical resolutions or $\theta_a = (\theta_{\text{IFOV-H}} \times \theta_{\text{IFOV-V}})^{1/2}$ where w and h are the horizontal and vertical dimensions of the detector (see Figure 7.3). In this case θ_a would be the instantaneous field-of-view of a square detector with the same area as a rectangular detector having area (wh). Figure 7.3 is an illustration of section of a focal plane array delineated into an array of individual pixels with detector elements. The “fill-factor” or the ratio of the area of detector to the area of a pixel is shown for the array and the difference in the subtended angle by each is compared. The comparison of the detector angular subtense θ_D and the pixel angular subtense θ_P is shown for only one dimension (width).

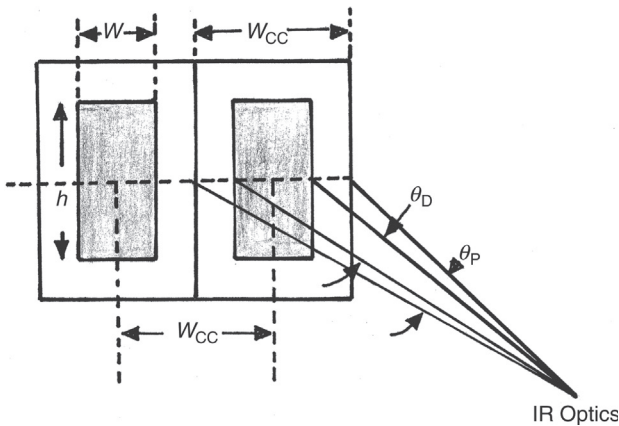


FIGURE 7.3 An illustration showing two pixels in a staring focal plane array showing a fill-factor (less than 100%) and the resulting differences in the subtended angles associated with a pixel and a detector.

For a 100% fill factor $\theta_D = \theta_p$. However, in general the detector angular subtense θ_D is smaller than the pixel angular subtense θ_p and this difference is proportional to the fill-factor. For example, a 60% fill-factor means that $\theta_D = (0.6)\theta_p$ and the relationship between the IFOV for a pixel as given above for a staring FPA is different than the IFOV for a detector that does not fill the area defined as a pixel. State of the art photon detector focal plane arrays have fill factors of over 90% and microbolometers focal plane arrays greater than 80%, so for modern imagers $\theta_D \approx \theta_p$.

In order to determine the IFOV of an IR imaging system using a staring FPA we need to know some specifics about the FPA. If the number of pixels and the array size is known the pixel size (center-to-center spacing) can be calculated. For a staring focal plane array the IFOV is determined by the angle subtended by a pixel θ_p so the IFOV is given by

$$\theta_{\text{IFOV}} = 2 \tan^{-1}(w_{\text{CC}}/2f) = \theta_p = W_{\text{CC}}/f \quad (7.9)$$

where w_{CC} is the detector pitch or center-to-center spacing of the pixels. This is a very useful parameter since it allows us to estimate the size of the smallest perceptible thermal signature we can detect with the camera. Conversely, if the size or spatial extent of the object is known we can determine the maximum distance at which the object can be resolved. In this context the spatial resolution of the system is given by the following relationship

$$X_{\text{min}} = \theta_{\text{IFOV}}(R) \quad (7.10)$$

Where R is the distance from the thermal object and X_{min} is the minimum size object that can be detected for a given distance R . If the focal length f of the lens system is changed then the value of X_{min} changes according to

$$X_{\text{min}} = (w_{\text{CC}}/f) \times (R). \quad (7.11)$$

We can now make an estimate of the smallest object X_{min} (Figure 7.4) that will be detected at a given range R for a 3–5 μm thermal imager with a staring focal plane array having an IFOV = 0.6 mrad by using equation (7.11).

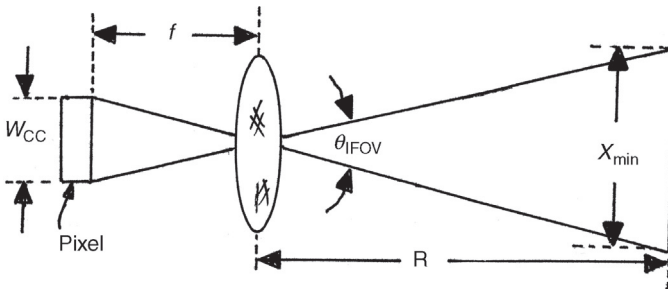


FIGURE 7.4 The instantaneous field-of-view and spatial resolution as determined from the detector angular subtense.

TABLE 7.2 The Calculated Estimates from Equation (7.11) of the Minimum Detectable Object Size for a Series of Ranges

Range, R (m)	Minimum Object Size, X_{\min} (m)
50	0.03
100	0.06
200	0.12
500	0.30
1000	0.60
2000	1.20
5000	3.00

The influence of atmospheric attenuation was not taken into account for these estimates. Minimum detectable object size X_{\min} for a thermal imager with a focal plane array having detector pitch $w_{cc} = 30 \mu\text{m}$, focal length $f = 50 \text{ mm}$, and IFOV = 0.6 mrad for different ranges R .

Table 7.2 gives the minimum detectable object sizes X_{\min} for a set of ranges from 50 m to 5 km for a thermal imager with these specifications. Note that these are optimal values since we have not included any effects due to atmospheric conditions (e.g., we have assumed that the atmospheric transmittance $\tau = 1$), which usually is never the case (see the range estimations given in Table 7.1 when the atmospheric attenuation is included in the range calculations). In Chapter 11 we discuss ways to achieve the best ranges possible for a variety of conditions.

Optics-Limited Resolution

The diameter of the bright central disk (Airy disk) of the diffraction pattern formed by a good optical system can be determined from diffraction theory (Hecht and Zajac, 1979, pp. 350–354). For MWIR imagers with an average wavelength of $\lambda_a \sim 4 \mu\text{m}$ and a system lens diameter D , the Airy disk diameter θ_{Airy} (expressed as an angle in mrad) is

$$\theta_{\text{Airy}} = 2.44(\lambda_a / D) \quad (7.12)$$

which gives a value of X_{\min} as

$$X_{\min} = \theta_{\text{Airy}}(R) = 2.44(\lambda_a / D)(R) \quad (7.13)$$

From this we can calculate a value for X_{\min} at a specified range and that it only depends on the optics and wavelength of the radiation and has no reference to the detectors at all. Furthermore, by increasing the size (D = diameter of the optics) we can improve the resolution by reducing the lens f -number ($F\#$). $F\# = f/D$, where f is the focal length of the lens. Most infrared detectors employ optical systems with $F\#$ s between 1 and 4. For example, a

typical imager such as the 3–5 μm Inframetrics InfraCAM[®] is equipped with a (F# 1.3) 50 mm lens and the FLIR Systems MilCAM-Recon[®] 3–5 μm camera uses a 50 mm F# 4 lens system as standard. As the ratio of the F# and the width of the detector changes the factors determining the limiting resolution also change. In actuality the system resolution is a combination of the optics and the detector and the transition from optic-limited to detector-limited resolution is gradual. The detector output should always be as large as possible so that objects with a small ΔT can be detected and reducing the F# will increase the detector output. However, since most IR optical systems are equipped with F#s larger than 1 and given that large diameter infrared optics are impractical from an economic standpoint we can, for all practical purposes, use the IFOV (either θ_D or θ_P) rather than θ_{Airy} to specify the spatial resolution of a staring array.

The spatial resolution and thermal sensitivity are independent of one another since the resolution does not include the effects of system noise nor thermal contrast but the thermal sensitivity does. However, the image resolution achieved with cameras using staring FPA technology is considerably better than that achieved with scanning systems because the thermal sensitivity is better. That is, the system resolution is greatly improved by allowing smaller IFOVs to be used with FPAs than with scanning systems. FPAs are comprised of large numbers of individual detector elements, each with differing signal responsivities (gain and offsets) and these differences must be accounted for to obtain quality imagery. The spread in the gain and offset values causes a spread in the detectivity for different pixels receiving the same incident radiant power and if this nonuniformity is large then the imagery obtained is generally not very useful. A correction process referred to as the nonuniformity correction (NUC) is carried out during the camera calibration process where the gain and offset of each pixel is adjusted and the correction parameters are stored in the camera. For example, the FLIR SC8000 HS[®] Series MWIR camera comes equipped with a 1024×1024 InSb FPA with an 18 μm pitch and has built-in NUC for on camera nonuniformity corrections.

Typically, the scanning systems used in early animal surveys had IFOVs between 1.0 mrad and 3.0 mrad. With the introduction of 3–5 μm and 8–12 μm staring FPAs, longer focal length optics were incorporated into the systems and the spatial resolution was improved by more than an order of magnitude to values ranging between 0.05 mrad and 0.6 mrad. Modern 8–12 μm imagers using a 4-element HgCdTe (mercury cadmium telluride) detector are equipped with both wide field-of-view (WFOV) and narrow field-of-view (NFOV) optics, providing IFOVs of 1.2 mrad and 0.3 mrad. These small IFOVs allow surveys of much smaller objects to be conducted from higher altitudes over greater areas. Since modern infrared imagers are equipped with superb optics we find that using the IFOV to estimate ranges or the smallest discernable object size commensurate with a given field application is appropriate in most cases.

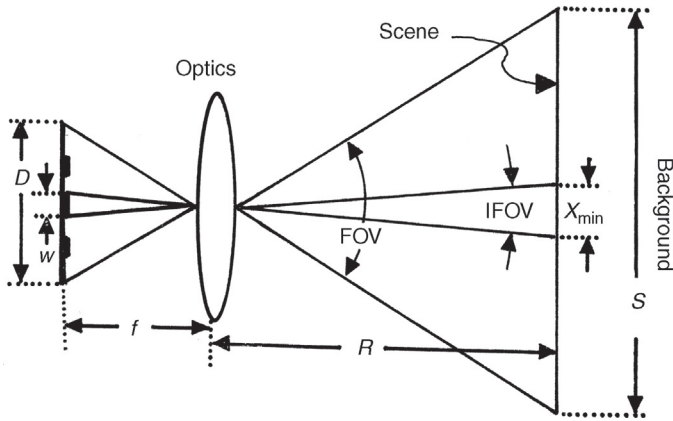


FIGURE 7.5 A two-dimensional view of the geometrical relationships of the FOV, IFOV, and the focal plane array in a thermal imager.

The FOV of the system (Figure 7.5) is the total viewing area of the system measured in radians. The FOV is determined by the size of the focal plane array D and the focal length of the optics f as

$$\text{FOV} = 2 \tan^{-1}(D/2f) \quad (7.14)$$

The FOV determines the swath width S when censusing from aircraft and is sometimes given as a length at a certain altitude above ground level (agl). The swath or scene dimension is determined by the FOV of the imager and range R as $S = 2R \tan(\text{FOV}/2)$. If the focal plane array is not square (see Section “Detector-Limited Resolution” of this chapter) then the FOV of an imager is given for both the horizontal (HFOV) and vertical (VFOV) views in degrees and the swath will take on horizontal and vertical dimensions.

Most systems are equipped with a WFOV and an NFOV capability. This is normally accomplished by changing the lens on the front of the camera. When the lens is changed, however, the IFOV of the system is also changed since IFOV depends on the focal length of the lens system, according to equation (7.6). The smaller the IFOV for a given FOV, the more detailed the images. We can therefore select the IFOV and choose either a narrow mode (narrow ground swath but good resolution) or a wide mode (wide ground swath but less resolution). If there were an object in the background of a scene that was in the FOV of the imager it would be detected if its size exceeded X_{\min} .

Range

What does it take to see through adverse atmospheric conditions and to what extent or how far can we see with thermal imagers? What is the range under conditions of fog, haze, aerosols (particulates of all sizes), rain, and dust? For

fieldwork, these are very important questions that can greatly influence the outcome. For the MWIR CO_2 and H_2O vapor is the most attenuating species. The actual range of an IR camera is affected by a number of things, including the camera and the atmospheric conditions at the time of usage. Range predictions can be estimated based on the signal-to-noise ratio (Table 7.1) based on attenuation and we can also include the effective contribution from radiation scattered forward into the imaging camera from the atmosphere (path radiance), which is essentially part of the background radiation and will diminish contrast in the imagery.

In the above expressions X_{\min} gives a value for the minimum object size for 50% probability of detection. We shall address this situation in Chapter 9 when we discuss the issues concerning differences associated with detection, recognition, and identification of objects when using thermal imagers under a specific set of representative conditions (Johnson, 1958). Within this context, detection does not mean finding so called “hot spots” in a scene but rather finding “thermal signatures” of interest that warrant a closer look according to some pre-established criterion. For example, we can compare the values of X_{\min} computed for imagers used in early experiments with those used more recently. For $R = 1000$ m and $\theta_{\text{IFOV}} = 2.5$ mrad (typical for early thermal imaging fieldwork) we can detect with 50% probability an object having a spatial extent of 2.5 m. Using an imager with a $\theta_{\text{IFOV}} \approx 0.5$ mrad we could easily detect objects of 0.5 m spatial extent with the same probability. New cameras have IFOVs an order of magnitude less than we used in this work. The actual threshold for the spatial resolution achievable with cameras using new FPAs is determined by the pointing stability of the camera. Ways of dealing with this threshold point will be addressed in Chapter 11.

Thermal Resolution

The minimum resolvable temperature difference (MRTD) depends on the thermal sensitivity, NETD, the background temperature, and the spatial resolution. The MRTD depends on the background temperature in the same way as the NETD: as the background temperature increases the MRTD decreases. As such it is the most meaningful parameter for comparing image quality from one imager to another. The MRTD is probably the most important measure of an infrared system’s ability to detect and identify a thermal anomaly in a particular scene. The MRTD is not an absolute value since it takes into account the visual acuity of the observer and quality and settings of the display device (typically a TV monitor). As a result, the MRTD should be considered as a perceivable temperature differential relative to a given background and not something that is mandated by optics and electronics. Williams (2009) presents several concepts that have been formalized to replace the subjective measurement with ways to objectively measure parameters suitable to model the performance of a human observer. These models provide a relatively good match to the subjectively

measured MRTD and may produce far more repeatable and reliable results resolving targets than the subjective measurements. Additionally, the minimum detectable temperature difference (MDTD) can also be predicted from a model similar to that of the MRTD. The parameters are treated with a slightly different algorithm because of the difference between being able to recognize (resolve) a target and being able to detect the presence of a target in a scene.

The MRTD of a system is determined in a laboratory by human observers who make a determination of the minimum temperature that they can recognize by viewing a standard 4-bar pattern (Johnson, 1958). The spatial frequency (cycles/mrad) or spacing between the bars of the pattern and the temperature of the bar pattern relative to the background temperature are varied. Human observers determine the temperature difference at which the bar pattern is indistinguishable from the background by the imaging system. The temperature differential is determined as a function of the spatial frequency in both the horizontal and vertical directions and can then be compared to other systems at a particular spatial frequency. When comparing MRTDs a low temperature difference at a high spatial frequency is desirable. Typical values for today's handheld 3–5 μm imagers using InSb or PtSi focal plane arrays are 0.05°C @ 0.5 cy/mrad or 0.025°C @ 0.5 cy/mrad when 50 mm optics are used. By comparison a modern commercially available 8–12 μm imager using a 4-element HgCdTe (mercury cadmium telluride) detector has a MRTD of 0.22°C @ 0.375 cy/mrad.

Note that the MRTD may be considered as being inversely proportional to the spatial resolution since as the separation of the bars in the pattern becomes smaller (higher spatial resolution) the MRTD becomes larger. The degradation in the MRTD by increasing the spatial resolution results due to the incident radiation required to produce a response by the detector above the system noise, which depends on the thermal sensitivity or NETD. As the IFOV decreases there are fewer IR photons impinging upon the detector and at some point the system noise overshadows the thermal sensitivity. For these very small IFOV cases there are simply not enough photons reaching the detector to produce a signal regardless of the thermal contrast between the animals and their background. This particular problem was especially restrictive of the performance for scanning imagers since they have their detectors exposed to the scene radiation for only a short period of time (scan time) as compared to staring FPAs that continually stare at the scene and collect photons.

There is a big distinction between thermal imagers that utilize quantum detectors as the sensitive element as opposed to detectors that rely on thermal effects to generate an image. The differences are enormous for censusing and surveying, particularly on a landscape scale. For the most part, for applications requiring higher sensitivities and/or time resolutions, such as in R&D, cameras with photon detector FPAs cooled to liquid nitrogen temperature ($T = 77\text{ K}$) are used for the MWIR and LWIR spectral region. These photon detector arrays exhibit a much larger responsivity/detectivity and a spectral response varying with wavelength. Cameras using photon detectors have smaller NETD values and

are also capable of higher frame rates than cameras fitted with microbolometers arrays. The practical issues concerning the use of both photon detectors and bolometric cameras will be contrasted in Chapter 8. Physical features (weight and size) as well as cost issues associated with the desired performance will be discussed. There are a number of interrelated issues to be aware of when deciding what imager would be best suited for any particular application.