Chapter 2

Radiometric Overview

The purpose of this chapter is to highlight the radiometric concepts that are relevant to this study. It is not intended as a complete introduction to radiometry and it is therefore assumed that the reader is familiar with the basic radiometric quantities.

2.1 Object Parameters

A blackbody (Planckian) function describes the maximum energy that can be emitted by an object in equilibrium at a specific temperature and wavelength. According to Zissis, *et al.* [11, p8], the spectral radiant excitance can be calculated using

$$M_{\lambda,T} = \frac{c_1}{\lambda^5(e^x - 1)}, \tag{2.1}$$

where

$$x = \frac{c_2}{\lambda T}. \tag{2.2}$$

In equations (2.1) and (2.2) c_1 is the first radiation constant, c_2 is the second radiation constant and λ is the wavelength in μm. The values of c_1 and c_2 are given by Leuschner [12] as:

$$\begin{aligned} c_1 &= 2\pi c^2 h = 3.7417749 \times 10^8 \quad [W\mu m^4 m^{-2}], \\ c_2 &= \frac{hc}{k} = 14387.69 \quad [\mu m K]. \end{aligned}$$

A radiator under equilibrium conditions is limited by the blackbody relationship. Emissivity describes the efficiency with which it radiates energy, absorptivity the efficiency with which it absorbs energy, reflectivity the efficiency with which it reflects energy and transmissivity the efficiency with which it transmits energy.

Kirchhoff [11, p26] pointed out that under equilibrium the sum of the absorbed, reflected and transmitted power is equal to the incident power, so that one can write

$$\alpha + \rho + \tau = 1, \tag{2.3}$$

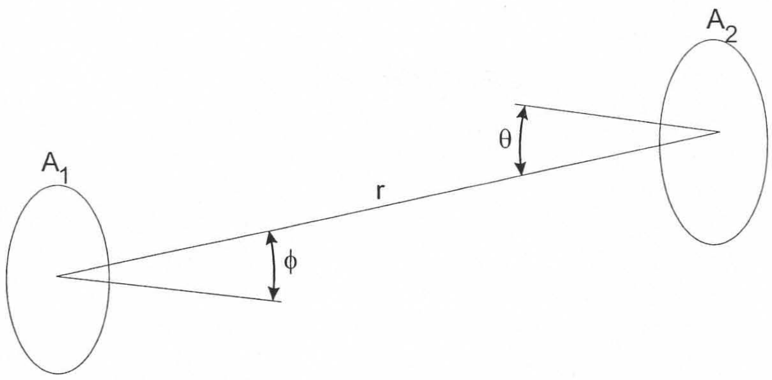

Figure 2.1: Flux transfer between a source and a detector

with α the absorptivity, ρ the reflectivity and τ the transmissivity.

Equation (2.3) is true for total power and under equilibrium conditions it is true for spectral quantities.

2.2 Flux transfer

The flux that is transferred from Surface A_1 to Surface A_2 in Figure 2.1 is given by Wyatt [13, p54] as:

$$\partial^2\Phi_\lambda = \frac{L_{1,\lambda}\partial A_1 \cos\phi \partial A_2 \cos\theta \tau_\lambda}{r^2}, \tag{2.4}$$

with L_1 the radiance from surface A_1, τ the transmittance of the medium between A_1 and A_2 and ϕ and θ the angle between the surface's normal and the vector connecting the two surfaces. The subscript λ is included to indicate spectrally variant sources and transmittance paths.

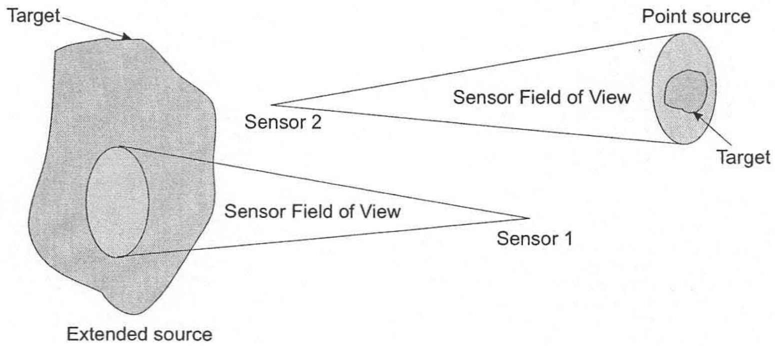

Figure 2.2: Comparison between a point and extended source

2.2.1 Irradiance on a pixel from an extended source

If the size of an object in a sensor's field of view is larger than the sensor's field of view, as shown in Figure 2.2, the object is called an extended source. In the case of an extended source, Equation (2.4) can be simplified to give

$$E_{source,\lambda} = L_{source,\lambda}\Omega_{sensor}\tau_{\lambda,atm}\tau_{\lambda,sys}. \tag{2.5}$$

The spectral irradiance on the sensor from the source is given by E_λ, $L_{source,\lambda}$ is the spectral radiance of the source, Ω_{sensor} is the solid angle in steradian viewed by the sensor and $\tau_{\lambda,atm}$ is the spectral transmittance of the medium between the source and the sensor. In the case of a spectrally variant detector, the detector's spectral response is included in the value of $\tau_{\lambda,sys}$. The irradiance due to the atmospheric path between the source and the sensor is given by Equation (2.6).

$$E_{path,\lambda} = L_{path,\lambda}\Omega_{sensor}\tau_{\lambda,sys}. \tag{2.6}$$

When the path is uniform, this term is given by

$$E_{path,\lambda} = L_{blackbody,\lambda}\ \Omega_{sensor}\tau_{\lambda,sys}\ (1-\tau_{\lambda,atm}). \tag{2.7}$$

$L_{blackbody,\lambda}$ is the radiance from a blackbody source at the temperature of the atmospheric path. The term $(1-\tau_{\lambda,atm})$ defines the emissivity of this source. The irradiance on the sensor varies as a function of the transmittance of the medium between the source and the sensor.

2.2.2 Irradiance on a pixel from a point source

When the source is subtending an angle smaller than the sensor's field of view, also shown in Figure 2.2 the irradiance is given by

$$E = E_{source} + E_{path,sourcetosensor} + E_{background} + E_{path,backgroundtosensor}. \tag{2.8}$$

The irradiance from the components of Equation (2.8) is given in Equation (2.10). The irradiance from the source is given by

$$E_{source,\lambda} = \frac{L_{source,\lambda}Area_{source}\tau_\lambda}{r^2}, \tag{2.9}$$

with $Area_{source}$ the projected area of the source, L the radiance of the source and r the distance between the sensor and the source. If the sensor's responsivity is spectrally variant, τ_λ includes the detector's spectral responsivity. The irradiance from the source varies as a function of the distance between the source and sensor, as well as the transmittance of the medium between the source and the sensor.

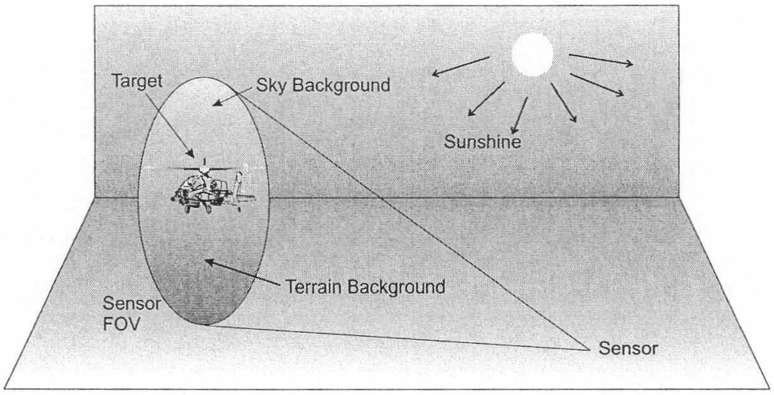

Figure 2.3: Some of the sources of radiance in a scenario

2.3 Elements of the radiometric environment

A radiometric scene can be a complex combination of sources, a detector and propagating medium. The radiance generated, reflected and transmitted by these objects combine to form the irradiance measured by the sensor. A typical scenario is shown in Figure 2.3.

2.3.1 Blackbody, graybody and spectral sources

In Section 2.1 a blackbody is defined as a perfect emittter, with an emissivity $\varepsilon = 1$. A graybody is defined as an emitter with a constant emissivity, at a value smaller than one. A spectral source is defined as an emitter with an emissivity that is varying as a function of wavelength. These concepts are illustrated in Figure 2.4.

2.3.2 Sources of radiance

The irradiance on a sensor is a combination of self-emitted and reflected radiance from the source, radiance from the background and the atmospheric path as well as radiance from objects in the scenario such as terrain that often contribute to the clutter in the scene. A possible sensor view is shown in Figure 2.3. The irradiance on the sensor is given by

$$\begin{aligned} E \;=\; & \int_{\lambda_0}^{\lambda_1} L(\lambda)_{target} S_\lambda \Omega_{target} (\tau_{\lambda,target}) d\lambda \\ & + \int_{\lambda_0}^{\lambda_1} L(\lambda)_{background} S_\lambda \Omega_{background} (\tau_{\lambda,background}) d\lambda \\ & + \int_{\lambda_0}^{\lambda_1} L(\lambda)_{path\ sensor\ to\ target} S_\lambda \Omega_{target} (1-\tau_{\lambda,target}) d\lambda \\ & + \int_{\lambda_0}^{\lambda_1} L(\lambda)_{path\ sensor\ to\ background} S_\lambda \Omega_{background} (1-\tau_{\lambda,background}) d\lambda \qquad (2.10) \end{aligned}$$

Figure 2.5 shows a simulation of the implementation of Equation (2.10). S_λ represents the spectral response of system. The irradiance from the different components were calculated

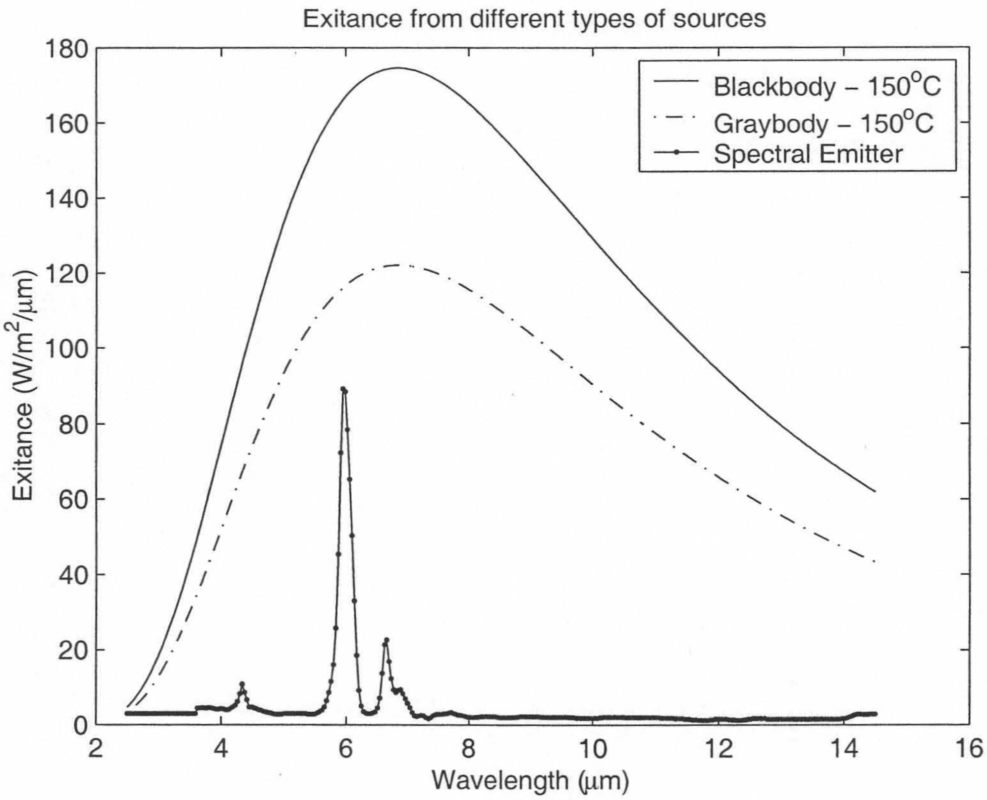

Figure 2.4: Spectral exitance of different types of sources

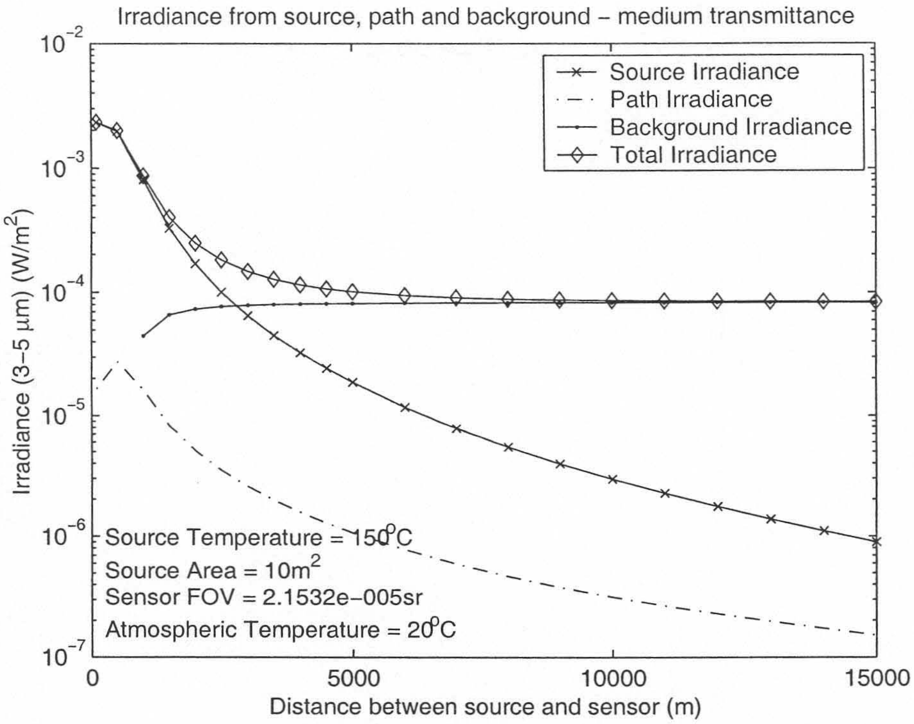

Figure 2.5: Simulation of the contribution of different sources to total irradiance at a sensor

spectrally and integrated to obtain the irradiance on a detector with the source at different distances from the detector. The input parameters that were used in the calculations are:

- Source temperature: 150°C
- Source Area: 10m^2
- Sensor Field of View: $2.1532\text{x}10^{-5}\text{sr} \equiv 0.3°$
- Atmospheric Temperature: 20°C

The source was initially an extended source, but became a point source after 681m, when the angle subtended by the source became smaller than the sensor's field of view. The contribution from the different components of the irradiance are shown in Figure 2.5.

2.3.3 Atmosphere

The atmosphere is an important factor in determining the performance of most electro-optical systems. Absorption, scattering and turbulence often determine the operational capability of electro-optical systems operating in the earth's atmosphere. From Smith [14], the atmospheric transmittance at a single wavelength is given by

$$\tau(r) = e^{(-\alpha r)}, \tag{2.11}$$

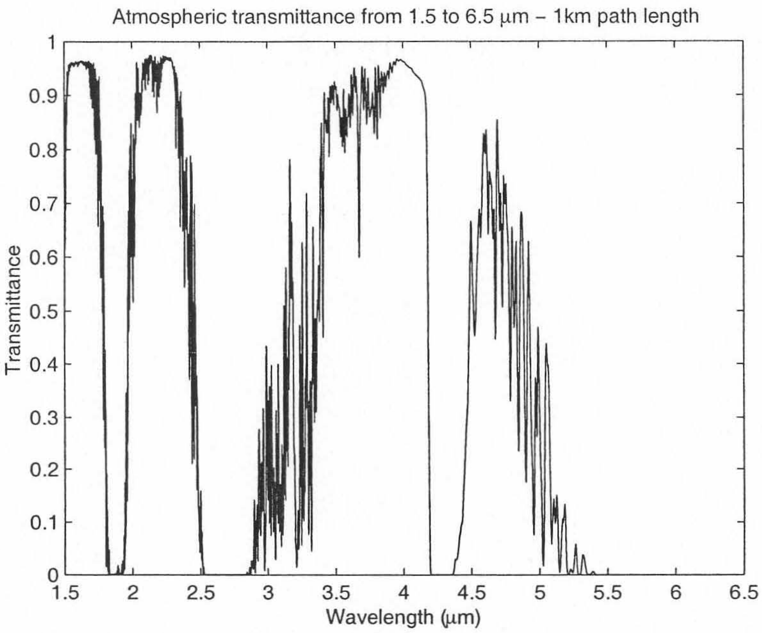

Figure 2.6: Example of atmospheric transmittance

with τ the atmospheric transmittance, r the distance and α the extinction coefficient. The extinction coefficient is highly dependent on the wavelength and atmospheric parameters such as humidity, temperature and air pressure. A number of models for atmospheric transmittance exist, examples include LOWTRAN, MODTRAN and FASCODE. An example of atmospheric transmittance over a 1 km path length is shown in Figure 2.6. The data was generated using MODTRAN 3. The input parameters were selected to represent an atmosphere that can be expected in Pretoria, South Africa, in the summer.

2.3.4 Detector characteristics

The detector in an electro-optical system is a transducer that converts electro-magnetic energy to a form that can be used in further processing. According to Wyatt [13, p79], electro-optical systems use two detector types: thermal detectors and photon detectors.

Thermal sensors make use of the heating effect of radiation. Their response is therefore dependent on the amount of energy absorbed, but not on the spectral content of the absorbed energy. Thermal sensors are used in thermocouples and in new generation imaging sensors such as uncooled bolometer arrays.

Photon detectors respond to photons that have more than a certain minimum energy. The response to photons at a wavelength is proportional to the rate at which photons of that energy are absorbed. Photon detectors include photoemissive detectors such as photomultiplier tubes, semiconductor photoconductive and photovoltaic detectors and photographic film.

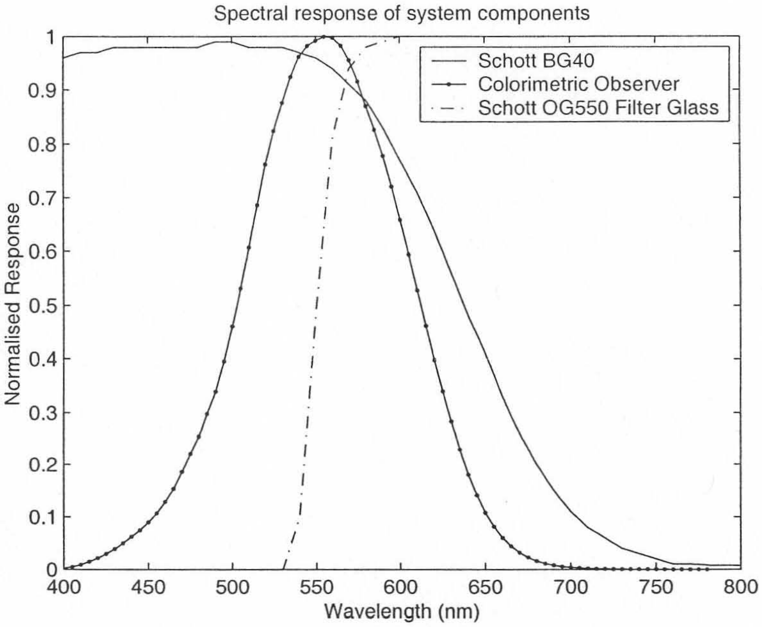

Figure 2.7: Normalised spectral response of the components of a sensor system

2.3.5 Spectral response of electro-optical sensors

The spectral response of a sensor system is determined by the response of the detector, the optical system and possible filter elements that can be introduced in the optical path. The response of the system is given by:

$$\mathcal{S} = \int_0^\infty R_{(\lambda,detector)} R_{(\lambda,opticalsystem)} R_{(\lambda,filter)} d\lambda. \tag{2.12}$$

The spectral responses for the components of a system are shown in Figure 2.7. The following components are used in this example system:

- **Schott BG40** is a filter glass passing short wavelengths with the normalised response shown in Figure 2.7.
- A **colorimetric observer** is a standard response based on the average response of the human eye. It is also known as the V_λ curve. The detector in this case is therefore the human eye.
- **Schott OG550** is a filter glass passing longer wavelengths with the normalised response shown in Figure 2.7.

The system's spectral response is shown in Figure 2.8.

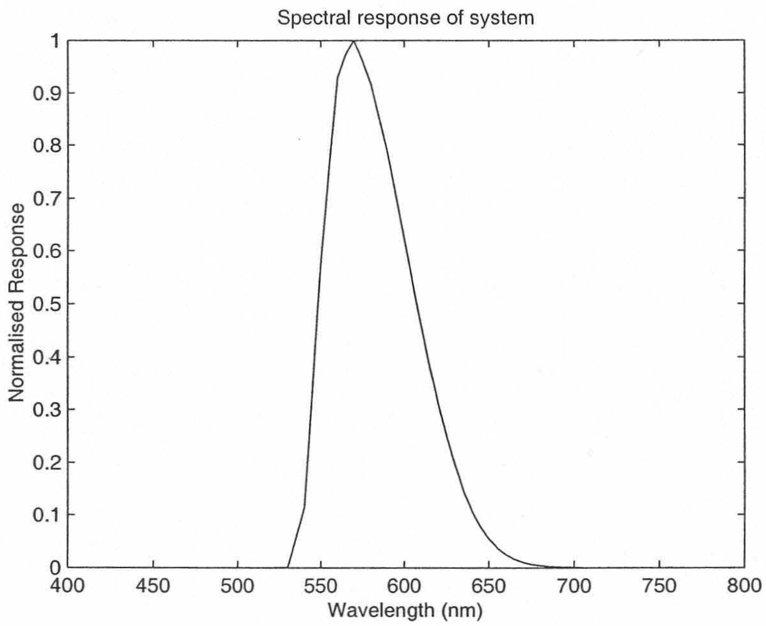

Figure 2.8: Normalised spectral response of a sensor system with the components shown in Figure 2.7

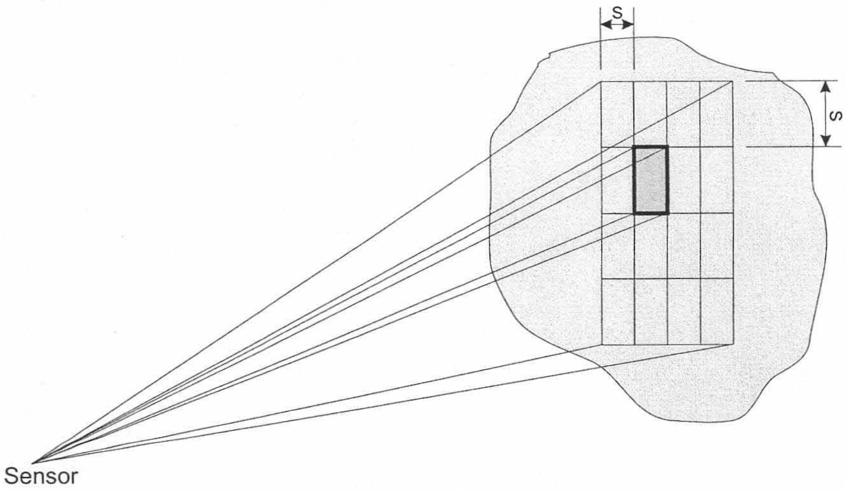

Figure 2.9: Image rendered at different pixel field of views

2.4 Irradiance conversion - different render resolutions

Rendering systems can be implemented where part of the scene is rendered at a higher resolution than the rest of the scene. The main advantage of such a scheme is that it can reduce the time required to render a scene, especially if parts of the scene do not contain a lot of detail. It is not necessary to render objects with low levels of detail at high resolution in order to generate realistic images. Figure 2.9 shows a case where a part of an image is rendered at two different resolutions. The high resolution pixel elements have a size of $s \times s$, whereas the low resolution pixel element has a resolution of $4s \times 4s$. The irradiance on the sensor for the low resolution case is given by:

$$E = L\Omega\tau, \quad (2.13)$$

$$= \frac{M}{\pi}\frac{(4s)^2}{r^2}\tau, \quad (2.14)$$

$$= 16\frac{Ms^2\tau}{\pi r^2}. \quad (2.15)$$

The radiance from a Lambertian source is given by $L = \frac{M}{\pi}$, with M the exitance of the source [13, p44]. The radiance value was substituted in Equation (2.13).

The distance between the sensor and the object is given by r, whereas the transmittance of the atmosphere is given by τ. The irradiance on the sensor in the high resolution case is given by:

$$E = L\Omega\tau, \quad (2.16)$$

$$= \frac{M}{\pi}\frac{(s)^2}{r^2}\tau, \quad (2.17)$$

$$= \frac{Ms^2\tau}{\pi r^2}. \quad (2.18)$$

The conclusion in Equation (2.18) can be generalised to the following statement: The irradiance on a lower resolution pixel is therefore the sum of the irradiance on higher resolution pixels, given that the field of view of the lower resolution pixel is the sum of the fields of view of the higher resolution pixels.

2.5 The generation of high-fidelity infrared images

Generating high-fidelity infrared images require the implementation of Equation (2.10) for each surface element in a detector's field of view. This process can be extremely time-consuming and the field of computer graphics developed to deal with this process. Chapter 3 is an overview of the elements of computer graphics that are relevant to this study. The implementation of an image rendering system in OpenGL is investigated. It was decided to implement the image rendering system in OpenGL due to its portability across operating systems such as Windows NT, Irix, Linux and Solaris, as well as hardware platforms such as personal computers, Sun machines and high-end graphics supercomputers from SGI.