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**Euro-Mediterranean Wildland Fire Laboratory,
a “wall-less” Laboratory
for Wildland Fire Sciences and Technologies
in the Euro-Mediterranean Region**

Deliverable D-07-05

Infrared Cameras:

Principles and General Presentation

Juan MELÉNDEZ

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SUMMARY

This document is a general presentation of IR cameras. After a brief summary on the main general concepts in IR instrumentation (Chapter 1), the basic building blocks of an IR camera are described (Chapter 2) and its use for quantitative measurements is explained (Chapter 3). No specific mention to forest fire applications is made in this report (see list of associated documents for Eufirelab reports on IR applications to forest fires)

LIST OF ASSOCIATED DOCUMENTS

This document is self-contained but is related to other Eufirelab reports:

- D-07-03 Fire metrology: a state of the art
- D-07-04 Infra-red measurement devices: principles and basic results
- D-07-07 Infra red camera: an interesting tool for wildland fire monitoring

In addition, references are provided in the final section.

1 IR INSTRUMENTATION: GENERAL CONCEPTS

1.1 INTRODUCTION

The infrared region (IR) covers a wide section of the electromagnetic spectrum between the visible and the radio waves.

It is customary to include into it the wavelengths in a range from, approximately, 0.75 to 1000 μm (Figure 1-1).

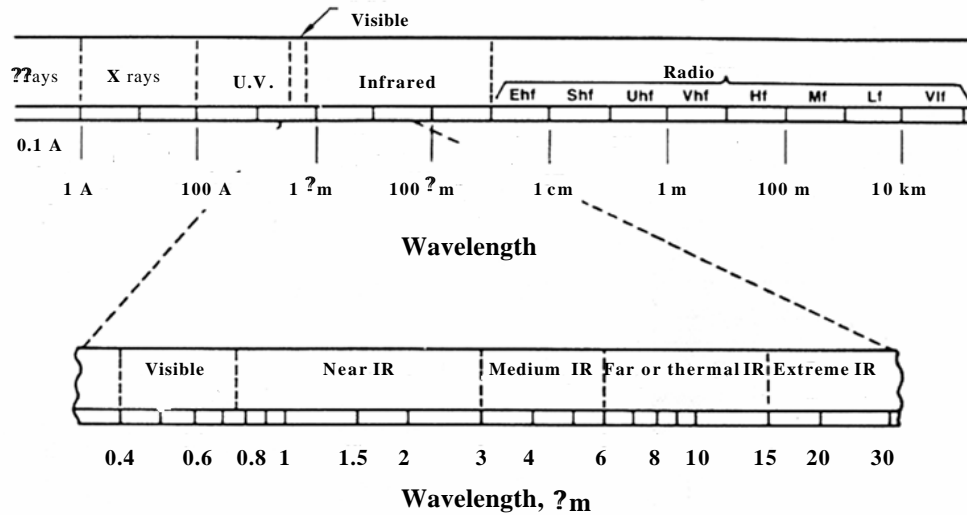


Figure 1-1: The IR portion of the electromagnetic spectrum

1.2 INFRARED DETECTORS

Infrared radiation can be detected by a large variety of IR detectors (VINCENT, 1990).

There are two main families, and both are used in IR instrumentation:

- *Thermal detectors* detect radiation indirectly, by a thermal effect produced by it. Historically they were the first IR detectors. (W. HERSCHEL discovered IR radiation in 1800 by observing its heating effect on a thermometer). Thermal detectors presently used include bolometers, thermopiles, pyro-electric detectors, Golay cells, etc. They are sensitive to the entire IR spectrum and may operate at room temperature.
- *Quantum detectors* are based on effects produced directly by the photons that constitute light. Their prototype is the photoelectric cell, whose operation was explained by EINSTEIN in 1905. Present day quantum detectors are usually photodiodes and photo-conductors that are made of semiconductors. They operate only in a specific spectral range, and usually require cooling at cryogenic temperatures.

Quantum detectors are much faster and more sensitive than thermal detectors, but their limitation in spectral sensitivity forces to use a different material for each spectral band.

Figure 1-2 compares the spectral sensitivity of different materials.

The figure of merit used for comparison is the intrinsic detectivity D^* , measured in $\text{cm}\cdot\text{Hz}^{1/2}/\text{W}$ (see (VINCENT, 1990) for definition).

Typical data for some thermal detectors are also plotted, showing no spectral dependence and smaller detectivities.

In quantum detectors, to decrease the temperature increases substantially the sensitivity for most materials.

Some of the methods used to refrigerate detectors are (HUDSON, 1969) (GAUSSORGUES, 1999):

- Use of liquefied gases (liquid Helium or, most frequently, liquid nitrogen (LN2))
- Refrigeration cycles, open (Joule-Thomson) or closed (Stirling)
- Thermoelectric cooling (Peltier effect)

The last method is very convenient because it is cheap and requires no moving parts, but it cannot reach very low temperatures (a minimum of approximately 173 K using six stages).

The cheapest and fastest method to reach low temperatures is to use LN2, but it has to be poured on a cryostat and refilled from time to time.

Therefore, Stirling cycle is becoming a standard, in spite of creating vibrations and being more expensive.

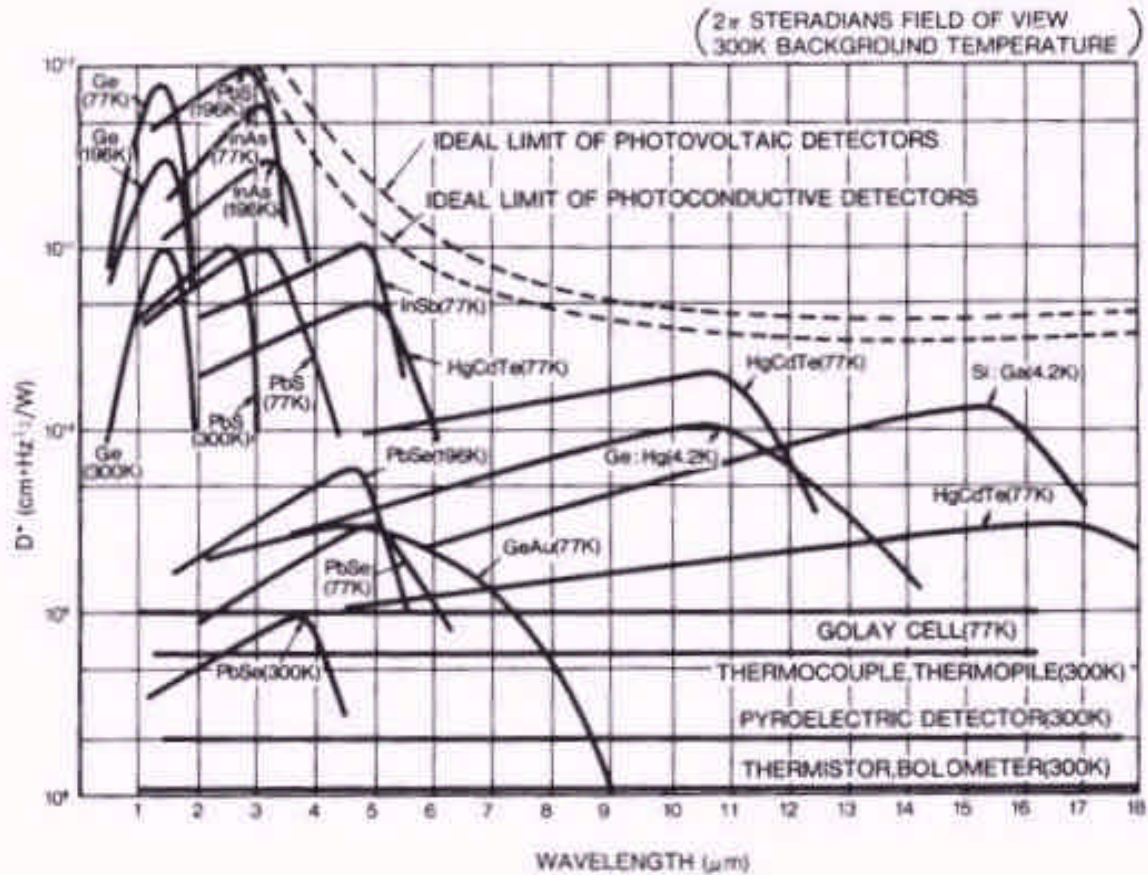


Figure 1-2: A comparison of the spectral sensitivity for different materials used as IR detectors (adapted from (Hudson1969) and (Papini1994)).

1.3 MAIN TYPES OF IR INSTRUMENTATION

Traditionally, there have been two families of IR instruments:

- Those with *spectral resolution (IR spectrometers)*; they integrate the incoming radiation over the whole field of view of the instrument, but discriminate between different wavelengths in the spectral range of operation; their output is a *spectrum*.
- Those with *spatial resolution (IR cameras)*; they integrate the incoming radiation over the whole spectral range of operation, but discriminate between different points within the field of view; their output is an *image*.

Recently, a new family has appeared that combines spectral and spatial resolution: the **imaging spectrometers**.

Their output, sometimes called a *spectral cube*, can be viewed as an image for each wavelength of the spectral range or, equivalently, as a spectrum for each point of the field of view.

In this report we will focus on basic principles and general features of infrared cameras.

More information on IR instrumentation can be found on references (JHA, 2000), (DRIGGERS et al, 1999) and (WOLFE, 1996), as well as in the reports (MELÉNDEZ et al, 2003) and (MELÉNDEZ et al, 2004).

2 IR CAMERAS

There are three main subsystems that can be distinguished in any IR camera: optics, detector, and electronics (Figure 2.1)

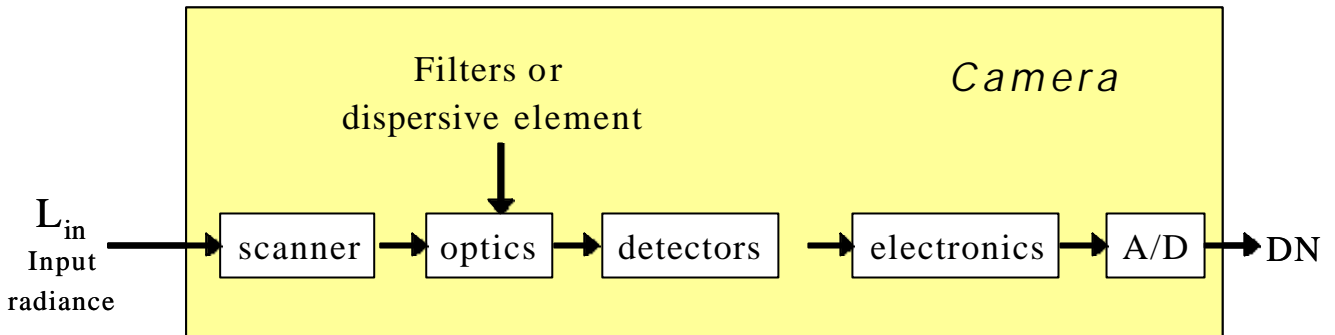


Figure 2-1: Subsystems in an IR camera

2.1 DETECTOR AND OPTICS SUBSYSTEMS

At the core of the camera there is the detector. As explained, detectors can be thermal or quantum.

But when considering the camera from the systems point of view, a more important distinction is that between *single detectors* (or monodetectors) and *detector arrays*.

Monodetectors are much easier to fabricate than detector arrays, and they were used by the first infrared cameras. In order to provide an image, it was necessary to scan the field of view using complex optical setups (see Figure 2-2)

In the last years, cameras based on two-dimensional arrays of detectors (*focal plane arrays* FPAs) have become the standard (WOLFE, 1999).

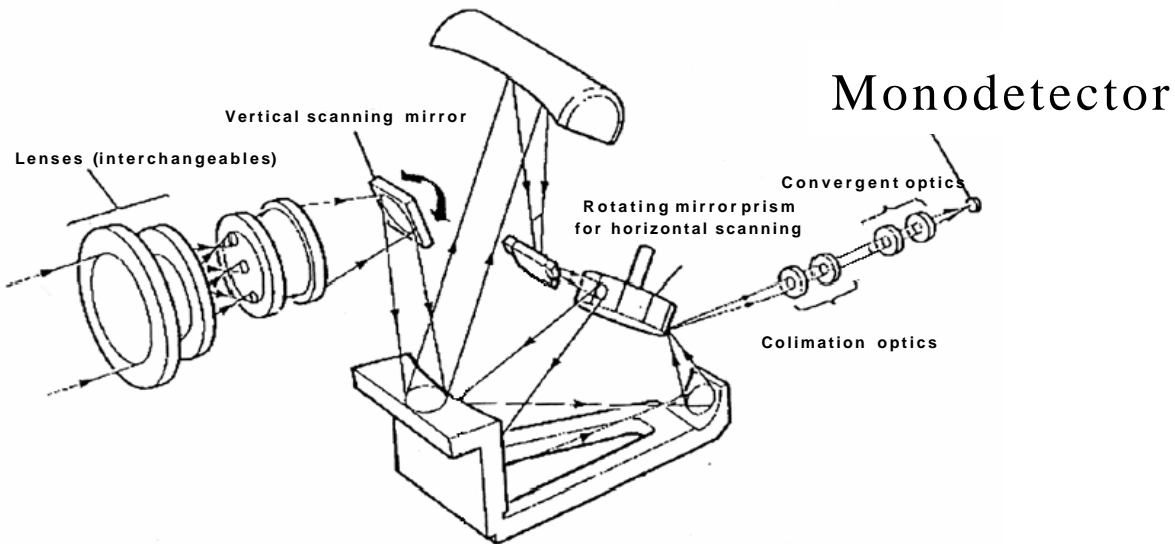


Figure 2-2: The scanning system of a IR camera using a monodetector (Adapted from (HAMRELIUS, 1991))

FPA's are much difficult to fabricate than single detectors, but this complication in the detector makes possible a great simplification the optical subsystem, whose design is now basically equal to that of a photographic camera (Figure 2-3).

It must be pointed out, however, that materials for IR optics are different and make them much more expensive than visible optics (commonly used materials are Ge and SeZn).

FPA based IR cameras are faster than those based on single detectors, because of the elimination of optical scanning.

A recent development in the readout electronics, the so-called *sub-windowing*, makes possible a further increase in velocity at the cost of a proportional reduction of the image size

Rates of acquisition in the range of a thousand frames per second are possible with this technique.

A disadvantage of FPA cameras is that they are more difficult to calibrate, because as a rule each individual detector in the array has a different response.

This lack of homogeneity must be corrected with a so-called Non Uniformity Correction (NUC) table that stores the calibration parameters for each pixel and applies them when visualising images.

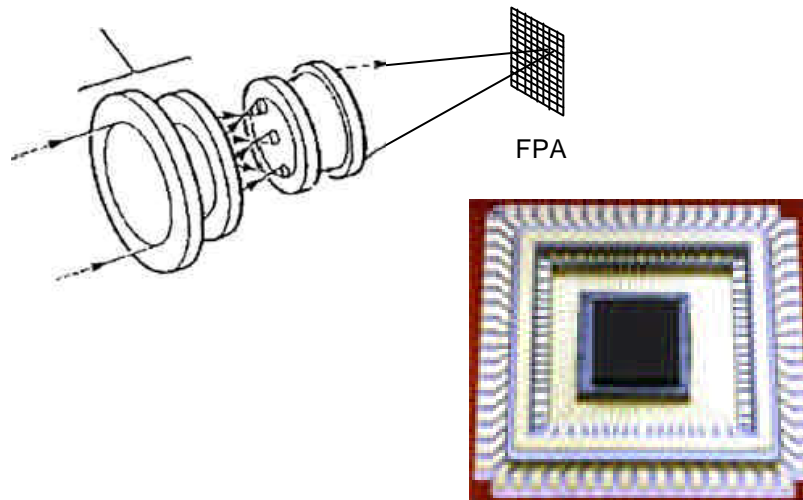


Figure 2-3: (Left) An IR camera using a focal plane array (FPA) needs no optical scanning (Right) A photograph of a FPA

2.2 ELECTRONICS SUBSYSTEM

Detectors provide a low level electric signal that must be amplified and conditioned by an electronics subsystem. For the user, the two most interesting parameters are:

- Number and type of data outputs: Most IR cameras have at least two outputs, a video output (for visualisation) and a digital output (for quantitative measurements).
- Dynamic range of the analog-to-digital converter (ADC). This determines the number of levels of the digital number (DN) of the output and therefore influences the sensitivity of the camera. Common values are 12 bits (4096 levels) or 14 bits (16384 levels).

2.3 SPECTRAL RANGE OF OPERATION

Figure 1-2 shows that there can be found detectors for any spectral range in the IR band.

However, for some spectral ranges atmospheric transmittance is very poor (see MELÉNDEZ et al 2004)) and thus IR cameras usually operate in one of the so-called atmospheric IR windows, MIR (3 to 5 microns) and TIR (8 to 12 microns).

This assures a good atmospheric transmittance, necessary for the camera to “see” at large distances.

Even cameras based on thermal detectors do not operate usually over all the IR band, but rather the transmittance of the optics select one or other of the spectral windows.

3 QUANTITATIVE MEASUREMENTS WITH IR CAMERAS

Many applications of IR cameras (for instance, monitoring of wildland fire propagation) do not require a quantitative output.

Using an IR camera for those applications is not very different from using a visible videocamera. However, IR cameras can provide also quantitative results on the IR emission of the target, and therefore on its temperature, emitted power and possibly other parameters.

To use an IR camera for quantitative studies requires special care and involves modelling of the IR scene. In this section we provide an introduction to these issues.

Note: this section has been adapted from reference (MELÉNDEZ et al, 2003)

3.1 BASIC CONSIDERATIONS

When an IR camera images an object (Figure 3.1) its output is a Digital Number (DN) for each point of the field of view (FOV).

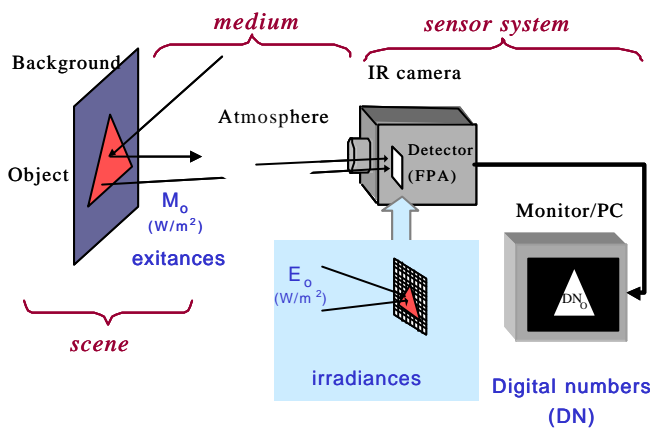


Figure 3-1: A standard measurement with an IR camera

This DN is related to the radiation emitted by each point of the imaged object.

When using the camera for quantitative measurements, this relationship must be made explicit.

This is conveniently done by means of two models:

3.1.1.1 A Sensor Model

It relates the irradiance that reaches the detector of the camera (we will call it E_D) to the digital number it provides (DN).

For the ordinary conditions of operation, it can be assumed a linear behaviour for the detector and the electronics, and thus:

$$DN = k_D \cdot E_D + k_{off} \quad (3.1)$$

Where k_D is the detector responsivity times the electronics gain.

3.1.1.2 A Radiometric Model

It relates the exitance at the object (M_o) to the irradiance at the detector (E_D).

A complete radiometric model can be very complex (SCHOWENGERDT, 1997), and therefore different approximations are used depending on the experimental circumstances.

In the next two sections we describe some of these approximations.

3.2 CASE OF TRANSPARENT MEDIUM

For a transparent medium ($\tau=1$), the invariance of radiance (See (MELÉNDEZ et al 2003)) guarantees that

$$L_o = L_D$$

Being L_o the radiance that leaves the object and L_D the incident radiance on the detector.

For ordinary values of f (focal length) and D (diameter of entrance pupil), and for objects at a distance much larger than f , it is easily shown that

$$L_D = E_D [2(f/\#)]^2 / \pi$$

Where $(f/\#)$ is the *f-number*, defined as $(f/\#) = f/D$.

Therefore,

$$E_D = k_G \cdot \pi \cdot L_o \quad (3.2a)$$

Where $k_G = [2 \cdot (f/\#)]^{-2}$.

We conclude that there is a fixed proportion between E_D and L_o , and according to (3.1), DN is a linear function of L_o .

Thus, if the atmosphere can be considered as transparent (measurements at short distances in an IR window), a camera provides a rather direct measurement of the radiance coming out of the imaged object.

If, in addition, the object is Lambertian (as for a blackbody), $M_o = L_o \cdot \pi$, and a direct relationship exists also with exitance:

$$E_D = k_G \cdot M_o \quad (3.2b)$$

In order to translate this exitance measurement into a temperature measurement (*thermography*), some additional hypotheses are needed.

We will consider two very simple models, that will be called zero-order model and first-order model.

3.2.1 Thermography: Zero order model

The simplest radiometric model is what we will call *Zero-order radiometric model*.

Here the imaged object is assumed to be a blackbody and the effects of the medium are ignored (i.e., it is considered as a vacuum, with $\tau = 1$).

With these approximations, the object exitance is simply (Stefan-Boltzmann law):

$$M_o = \sigma T_o^4 \tag{3.3}$$

Combining this with equation (3.2b) and with the sensor model (3.1), we get

$$DN = k_D k_G \sigma T_o^4 + k_{off} \tag{3.4}$$

This equation is easily inverted, making possible to measure temperatures using an infrared camera.

The relationship it furnishes between T and DN can be appreciated in Figure 3.2 for specific (arbitrary) values of k_D , k_G and k_{off} .

It is clear that the same ΔT gives larger ΔDN at large temperatures (in fact, $\Delta DN/DN = 4\Delta T/T$)

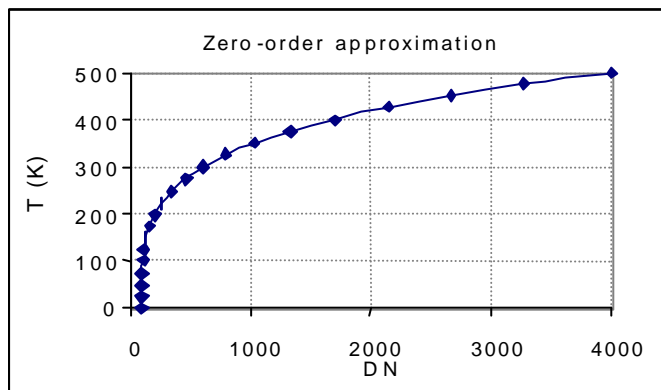


Figure 3-2: An example of the relationship between DN and temperature in the zero-order model

In the previous equations, we have neglected spectral dependence.

However, cameras are sensitive only through a specific spectral range.

Thus, instead of using the Stefan-Boltzmann law, the relevant emittance is given by Planck's law, integrated over the spectral range of the camera $\Delta\lambda$.

Therefore,

$$DN = \int_{\Delta\lambda} \{k_G k_D(\mathbf{I}) M_{BB}(T_o, \mathbf{I}) + k_{off}(\mathbf{I})\} d\mathbf{I} \tag{3.5}$$

- $M_{BB}(T_o, \lambda)$ stands for the spectral exitance of a blackbody at temperature T_o , and
- the spectral dependence of k_D and k_{off} has been shown explicitly.

In order to invert this equation, it is customary to make the approximation:

$$DN = Gain \cdot F(T_o) + Offset \tag{3.6}$$

$F(T)$ is an invertible "calibration function", usually depending on three parameters, that represents an approximation to the integral of Planck's function $M_{BB}(T_o, \lambda)$ over the spectral interval $\Delta\lambda$ of the camera.

3.2.2 Camera calibration: apparent brightness temperatures

If the calibration function is known, the parameters *Gain* and *Offset* can be determined by measuring at short distances a blackbody, and fitting the results (for several known blackbody temperatures) by the last equation.

This procedure is known as *camera calibration*.

After calibration, equation (3.6) can be used to provide object temperatures, which are called *apparent brightness temperatures*.

"Apparent" here means that no atmospheric corrections have been made.

"Brightness" means that an emittance $\epsilon = 1$ has been assumed.

3.2.3 Thermography: First order model

The zero-order model assumed $\epsilon = 1$ for the object and $\tau = 1$ for the atmosphere.

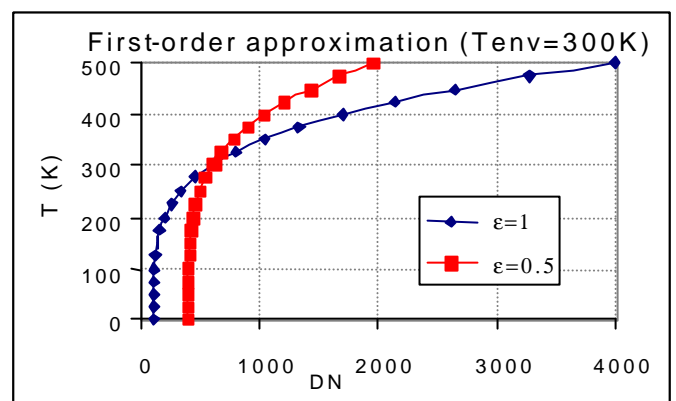


Figure 3-3: An example of the relationship between DN and temperature, for two different object emittances, in the first order model

The First-order radiometric model will:

- relax the condition $\epsilon = 1$ for the bodies and
- keep the approximation $\tau = 1$ for the atmosphere.

This is correct at short distances for a camera that operates in an atmospheric window.

Now the radiation that leaves the object is due not only to emission but also to reflection from the environment.

Assuming an opaque grey-body, $\rho = 1 - \epsilon$, and

$$M_o = \epsilon \sigma T_o^4 + (1 - \epsilon) \sigma T_{env}^4 \tag{3.7}$$

where T_{env} is the temperature of the environment.

Therefore,

$$DN = k_D k_G \sigma [\epsilon T_o^4 + (1 - \epsilon) T_{env}^4] + k_{off} \tag{3.8}$$

(see Figure 3.3)

Clearly, for $\epsilon = 1$, this model degenerates into the zero-order model.

If we now take into account the limited spectral range of the camera, a generalisation of equation (2.8) similar to (2.5) can be made.

However, a simple approximation of general validity like (2.6) will be possible only for grey-bodies.

For the general case, it is necessary to know the dependence $\varepsilon(\lambda)$ to make estimations of temperature.

Temperatures obtained in this model are no longer brightness temperatures, but are still *apparent temperatures* since no correction for the atmospheric effects has been made.

3.3 ATMOSPHERIC EFFECTS

When distances are long (i.e., in remote sensing measurements) atmospheric effects become appreciable even in the IR windows.

Two modifications are needed:

- the outgoing exitance is multiplied by the atmospheric transmittance;
- new radiation terms appear.

This point is explained with reference to Figure 3.4.

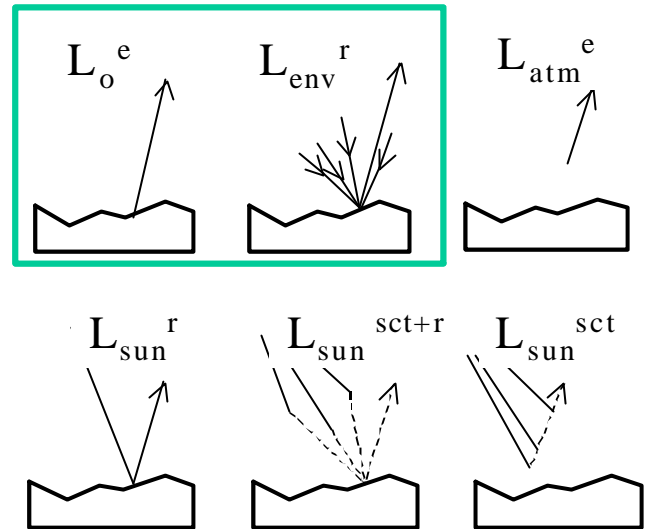


Figure 3-4: A scheme of the radiation components for a general remote sensing measurement (SCHOWENGERDT, 1997)

Up to now, in the zero-order model, we have considered the radiance emitted by the object (L_o^e).

In the first-order mode, we took into account also the radiance from the environment reflected by the object (L_{env}^r).

In a remote sensing measurement, it may be important also:

- the radiance emitted by the atmosphere between the object and the camera (L_{atm}^e),
- the solar radiance reflected by the object to the camera (solar glints, L_{sun}^r),
- the solar radiance scattered in the atmosphere and then reflected by the object (L_{sun}^{sct+r}), and
- the solar radiance scattered by the atmosphere to the camera (L_{sun}^{sct}).

The relative importance of these terms will depend on the specific measurement circumstances.

For an active forest fire, all the terms will be negligible as compared to L_o^e .

The atmospheric transmittance factor will be also negligible at short distances (some meters) but not at more than 100 m.

On the other hand, if careful temperature estimations need to be made for an object not very hot, all the terms may have to be reckoned.

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