How to Interpret Images from Infrared Cameras?

A field campaign. A laboratory testbed. A volcano. Different applications of infrared cameras, but the very same *modus operandi*. Turn the camera on, point it toward the scene, and get images on the screen. It looks so simple! And the image is even calibrated in real temperature units. Great!

Real life conditions are unfortunately a bit more complex. Accurate interpretation of the infrared images may be achieved, but it requires a good knowledge of the measurement conditions along with some radiometry skills. The goal of the present note is to describe how simple scene models may be established, how their limitations are determined, and how can we use them to estimate physical parameters like the thermodynamic temperature of the objects we are looking at.

This technical note is divided into 2 parts. The first one deals with the most important effect a camera user is faced with: the object emissivity. In the second, we discuss the contribution of the semi-transparent atmosphere through which the object is observed.

Realistic operating conditions

For most of the applications, the operating conditions may be summarised as follows: a distant scene is observed through the ambient atmosphere and a camera equipped with a lens producing an image on its detector. Through calibration data the user may view an image representing some physical quantity, like the *radiometric temperature* or the *in-band radiance*, which is the spectral radiance integrated over the spectral range of the camera.

These conditions gather all the important elements that have to be considered to fully understand infrared measurements. However, most of them are hiding some details that prevent any easy quantitative interpretation of the images. In the following pages, we will go through the different steps needed to understand *what* we are measuring and *how* we are measuring it. Once these steps are known, we will be able to determine what can be done in order to estimate the physical parameters, such as the thermodynamic temperature, of any scene constituent.

From the scene to the camera

At first, we must consider the radiometric aspects of the observed scene. The notions required to understand the concepts presented in this section have been summarised in a different technical note published by Telops [1].

Figure 1 depicts a simple view of the typical measurement setup. The infrared camera is pointed toward an object, itself surrounded by its normal environment.

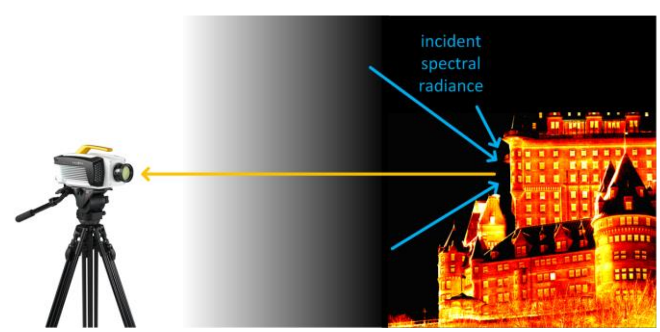

Figure 1 Simple model of an infrared camera looking at a distant scene.

Let's start with the object itself. The spectral radiance leaving any object involves 2 contributions as shown in Eq.1 :

Equation 1

$$L_{\text{obj}}(\lambda) = \varepsilon_{\text{obj}}(\lambda) L_{\text{Pl}}\big(\lambda, T_{\text{obj}}\big) + \big[1 - \varepsilon_{\text{obj}}(\lambda)\big] L_{\text{inc}}(\lambda) \, .$$

The first term corresponds to the thermal emission of the surface, and is defined by the object temperature T_{obj} and by its emissivity $\varepsilon_{\text{obj}}(\lambda)$. However, since the object is not a blackbody (a blackbody being defined as $\varepsilon \equiv 1$), it reflects part of the radiation incident on its surface $R_{\text{obj}}(\lambda) = 1 - \varepsilon_{\text{obj}}(\lambda)$ (see [1, Eq. 9]). Natural surfaces are usually diffuse reflectors, so they reflect radiation coming from a single direction in all directions. Similarly, when looking at an object in a single direction, a camera receives reflections of radiation coming from all directions. This is represented by the global incident spectral radiance on the object $L_{\text{inc}}(\lambda)$, usually measured with a diffuse reflector (Infragold®). The last term of Eq. 1 thus represents the radiation reflected by the surface.

From the setup depicted in Figure 1, we now know that the spectral radiance $L_{\text{obj}}(\lambda)$ is the quantity truly measured by the camera. However, the camera is not a spectrometer, so it does not provide a measurement of a spectrum, but rather measures the total amount of flux that each pixel of the focal-plane array detects. Through calibration with reference sources, such as high-quality commercial blackbodies, this quantity is converted into radiometric temperature (RT) or in-band radiance (IBR), both linked through the following definition:

Equation 2

$$\mathbb{L}_{\text{Pl}}(T) \equiv \int_{\lambda_{\text{l}}}^{\lambda_{\text{h}}} L_{\text{Pl}}(\lambda; T) \, \mathrm{d}\lambda \, ,$$

where $\mathbb{L}_{\text{Pl}}(T)$ stands for the bijective function linking radiometric temperature and in-band radiance:

Equation 3

$$\text{RT} = T \mapsto \mathbb{L}_{\text{Pl}}(T) = \text{IBR} \, .$$

Equation 2 gives the total blackbody radiance, as seen through the spectral range of the camera, integrated from the cut-on wavelength λ_{l} to the cut-off wavelength λ_{h} (parameters `LowCut` and `HighCut`, respectively, given in the camera image headers).

One may now couple Eqs. 1 and 2 to get the in-band radiance leaving the object and reaching the camera:

Equation 4

$$\begin{aligned}\mathbb{L}_{\text{obj}} &= \int_{\lambda_{\text{l}}}^{\lambda_{\text{h}}} L_{\text{obj}}(\lambda) \, \mathrm{d}\lambda \, , \\ &= \int_{\lambda_{\text{l}}}^{\lambda_{\text{h}}} \varepsilon_{\text{obj}}(\lambda) L_{\text{Pl}}\big(\lambda, T_{\text{obj}}\big) \, \mathrm{d}\lambda \\ &\qquad + \int_{\lambda_{\text{l}}}^{\lambda_{\text{h}}} \big[1 - \varepsilon_{\text{obj}}(\lambda)\big] L_{\text{inc}}(\lambda) \, \mathrm{d}\lambda \, .\end{aligned}$$

From this expression, we clearly see that while the object temperature T_{obj} does play a decisive role to determine the in-band radiance measured by the camera, its impact is submerged by the non-unitary object emissivity and consequently by the incident radiance. *Equation 4 thus cannot be directly inverted to recover the temperature from the radiance measurement.*

What about the object temperature?

In order to go further with Eq. 4, one has to make a few assumptions. The main one consists in ignoring the spectral dependence of the emissivity. In such a case, we need to approximate it by its average value over the spectral range of the camera $\overline{\varepsilon_{\text{obj}}}$ (such a hypothesis is called the grey body approximation[1]):

Equation 5

$$\int_{\lambda_l}^{\lambda_h} \varepsilon_{\text{obj}}(\lambda) L_{\text{Pl}}(\lambda, T_{\text{obj}})\, d\lambda \cong \overline{\varepsilon_{\text{obj}}} \times \int_{\lambda_l}^{\lambda_h} L_{\text{Pl}}(\lambda, T_{\text{obj}})\, d\lambda \;, \\ = \overline{\varepsilon_{\text{obj}}} \times \mathbb{L}_{\text{Pl}}(T_{\text{obj}}) \,.$$

Using a similar assumption for the second term of Eq. 1 gives:

Equation 6

$$\mathbb{L}_{\text{obj}} \cong \overline{\varepsilon_{\text{obj}}} \times \mathbb{L}_{\text{Pl}}(T_{\text{obj}}) + [1 - \overline{\varepsilon_{\text{obj}}}]\mathbb{L}_{\text{inc}} \,.$$

When we assume that the incident spectral radiance may be approximated by a blackbody spectral radiance, it means that it may simply be represented by its temperature:

Equation 7

$$\mathbb{L}_{\text{obj}} \cong \overline{\varepsilon_{\text{obj}}} \times \mathbb{L}_{\text{Pl}}(T_{\text{obj}}) + [1 - \overline{\varepsilon_{\text{obj}}}] \times \mathbb{L}_{\text{Pl}}(T_{\text{inc}}) \,.$$

This last result is of prime importance because, contrary to Eq. 4, it gives us a direct way to estimate the object temperature from a radiance measurement:

Equation 8

$$\mathbb{L}_{\text{Pl}}(T_{\text{obj}}) \cong \frac{\mathbb{L}_{\text{obj}} - [1 - \overline{\varepsilon_{\text{obj}}}] \times \mathbb{L}_{\text{Pl}}(T_{\text{inc}})}{\overline{\varepsilon_{\text{obj}}}} \,.$$

[1] It is normally expected that liquid and solid objects exhibit a slowly varying spectral emissivity as a function of wavelength, so the grey body approximation may be valid over a limited spectral range.

Once the in-band radiance of the object is known, its temperature can be calculated by inverting the IBR relation $\mathbb{L}_{\text{Pl}}(T_{\text{obj}})$ vs T_{obj}.

In short

To summarize, in order to estimate the object temperature from an infrared camera measurement, we need to:

- measure the total IBR by looking at the object with the camera; if the radiometric temperature has been measured, we need to convert it into IBR using Eq. 3;
- compute the incident IBR from T_{inc} using Eq. 3[2];
- compute the average emissivity $\overline{\varepsilon_{\text{obj}}}$ of the object;
- use Eq. 8 to estimate the true object IBR;
- compute the object temperature from the true object IBR by inverting Eq. 3.

However, the user must remember the *conditions of validity* of the current approach:

- The object is a grey body, and it is represented by its average emissivity over the spectral range of the camera.
- The total incident spectral radiance on the object may be represented by a PLANCK's function.
- The atmosphere between the object and the camera is transparent in the infrared spectral range.

[2] T_{inc} is ideally based on the measurement of a diffuse reflector or based on the ambient temperature for a coarser approximation.

Considering the atmosphere

The simple scene model introduced in Figure 1 is assuming a transparent atmosphere. However, it is well known that at a given distance the atmosphere is not fully transparent since it contains many infrared active molecules [1]. So Eqs. 1 and 4 have to be generalised to include the limited transmittance of the medium standing between the object and the camera. Figure 2 illustrates such a more realistic model.

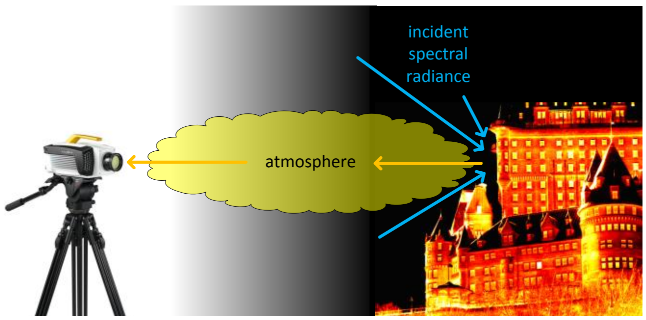

Figure 2 Model of an infrared camera looking at a distant scene through a semi-transparent atmosphere.

Equation 1 provides the radiance leaving the object. By application of BEER-LAMBERT's law [1, Eq. 11], the spectral radiance incident on the camera lens becomes:

Equation 9

$$L_{\mathrm{cam}}(\lambda) = \tau_{\mathrm{atm}}(\lambda) L_{\mathrm{obj}}(\lambda) + [1 - \tau_{\mathrm{atm}}(\lambda)] L_{\mathrm{Pl}}(\lambda, T_{\mathrm{atm}}) \,,$$

where the first term is the fraction of the object's spectral radiance transmitted by the atmosphere. $L_{\mathrm{obj}}(\lambda)$ is given by Eq. 1. The second term is the spectral radiance emitted by the atmosphere itself, at its own temperature T_{atm}. To avoid confusion with the temperature T_{atm}, the atmospheric transmittance is here denoted as $\tau_{\mathrm{atm}}(\lambda)$.

At this point, it is important to emphasize that the atmospheric transmittance does not only vary according to its molecular composition and concentration, but it is also dependent upon its thickness. Therefore, various objects in an infrared image may be seen through the same atmospheric content, but over different distances; they then undergo different spectral transmittances.

Performing the spectral integration of Eq. 9 gives:

Equation 10

$$\begin{aligned} \mathbb{L}_{\mathrm{cam}} = &\int_{\lambda_{\mathrm{l}}}^{\lambda_{\mathrm{h}}} \tau_{\mathrm{atm}}(\lambda) L_{\mathrm{obj}}(\lambda)\, \mathrm{d}\lambda \\ &+ \int_{\lambda_{\mathrm{l}}}^{\lambda_{\mathrm{h}}} [1 - \tau_{\mathrm{atm}}(\lambda)] L_{\mathrm{Pl}}(\lambda, T_{\mathrm{atm}})\, \mathrm{d}\lambda \,. \end{aligned}$$

As stated after presenting Eq. 4, the object temperature T_{obj} does impact the flux received by the camera, but in an obscured way due to the object's non-unitary emissivity and limited atmospheric transmittance.

Contrary to the spectral emissivity of a solid/liquid object, we are not expecting smooth spectral variations for the atmospheric transmittance. In fact, it is the opposite; resulting from the spectral signatures of distinct molecules, the transmittance is made of sharp peaks all across the spectrum (e.g. see [1, Figure 7]). The only way to translate Eq. 10 into a scalar relation (i.e. by performing the integration over the spectral range of the camera) is to suppose that the atmospheric transmittance should be represented by its average value. This constitutes a coarse approximation, but it has to be done in order to push the calculations further. Using average values for both the object emissivity and the atmospheric transmittance enables us to write:

Equation 11

$$\begin{aligned} \mathbb{L}_{\mathrm{cam}} &\cong \overline{\tau_{\mathrm{atm}}} \times \mathbb{L}_{\mathrm{obj}} + [1 - \overline{\tau_{\mathrm{atm}}}] \times \mathbb{L}_{\mathrm{Pl}}(T_{\mathrm{atm}}) \,, \\ &\cong \overline{\tau_{\mathrm{atm}}} \times \left\{ \overline{\varepsilon_{\mathrm{obj}}} \times \mathbb{L}_{\mathrm{Pl}}(T_{\mathrm{obj}}) + [1 - \overline{\varepsilon_{\mathrm{obj}}}] \mathbb{L}_{\mathrm{inc}} \right\} \\ &\quad + [1 - \overline{\tau_{\mathrm{atm}}}] \times \mathbb{L}_{\mathrm{Pl}}(T_{\mathrm{atm}}) \,, \end{aligned}$$

where $\mathbb{L}_{\mathrm{obj}}$ has been replaced by Eq. 6 in the second line. As above, assuming that the incident spectral radiance has a blackbody distribution, Eq. 11 can finally be written as:

Equation 12

$$\mathbb{L}_{\text{cam}} \cong \overline{\tau_{\text{atm}}} \times \left\{\overline{\varepsilon_{\text{obj}}} \times \mathbb{L}_{\text{Pl}}\left(T_{\text{obj}}\right) + \left[1 - \overline{\varepsilon_{\text{obj}}}\right]\mathbb{L}_{\text{Pl}}(T_{\text{inc}})\right\} + \left[1 - \overline{\tau_{\text{atm}}}\right] \times \mathbb{L}_{\text{Pl}}(T_{\text{atm}})\ .$$

Isolating the IBR at the object temperature gives:

Equation 13

$$\mathbb{L}_{\text{Pl}}\left(T_{\text{obj}}\right) \cong \frac{\mathbb{L}_{\text{cam}} - \overline{\tau_{\text{atm}}}\left[1 - \overline{\varepsilon_{\text{obj}}}\right] \times \mathbb{L}_{\text{Pl}}(T_{\text{inc}}) - \left[1 - \overline{\tau_{\text{atm}}}\right] \times \mathbb{L}_{\text{Pl}}(T_{\text{atm}})}{\overline{\tau_{\text{atm}}} \times \overline{\varepsilon_{\text{obj}}}}\ .$$

Again, as in the preceding section, the object temperature is finally calculated by inverting the IBR relation $\mathbb{L}_{\text{Pl}}\left(T_{\text{obj}}\right)$ vs T_{obj}.

In short

To summarize, in order to estimate the object temperature from an infrared camera measurement under a semi-transparent atmosphere, we need to:

- measure the total IBR by looking at the object with the camera; if the radiometric temperature has been measured, we need to convert it into IBR using Eq. 3;
- compute the incident IBR from T_{inc} using Eq. 3[2];
- compute the average emissivity $\overline{\varepsilon_{\text{obj}}}$ of the object;
- compute the opaque atmospheric IBR from T_{atm} using Eq. 3;
- compute the average transmittance $\overline{\tau_{\text{atm}}}$ of the atmosphere considering the distance between the object and the camera[3];
- use Eq. 13 to estimate the true object IBR;
- compute the object temperature from the true object IBR by inverting Eq. 3.

However, the user must remember the *conditions of validity* of this approach:

- The object is a grey body, and it is represented by its average emissivity over the spectral range of the camera.
- The total incident spectral radiance on the object may be represented by a PLANCK's function.
- The air content and the distance between the object and the camera must be known to estimate the average atmospheric transmittance.

The last approach can be generalized further to account for some optics that may be present between the object and the camera. In such a case, BEER-LAMBERT-BOUGUER's law may be applied recursively from the object to the camera to account for the different layers, each having its own temperature and transmittance (multi-layer approach).

Conclusion

In the present technical note, two approaches have been introduced to help an infrared camera operator estimate the real temperature of a distant object. At

[3] This step requires modelling the atmospheric transmittance by using spectroscopic databases such as MODTRAN and HITRAN. Distance and infrared active gases present in the atmosphere as well as their concentrations must be known.

first, the emissivity of the object itself is compensated. Then, in the more general approach, the atmospheric absorption is included. Anyone using these approaches must be fully aware that they both include important assumptions that are often very difficult to verify under practical situations. However, the calculations involved are simple and no deep modeling of the phenomenology is required. The user must thus remember that the estimated temperatures have limited accuracy and that care should be taken when interpreting their values.

References

[1] Telops, *Radiometry Primer*, Technical note, 2018.

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