PHOTOMETRY FORM

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2. History of Infrared

Less than 200 years ago the existence of the infrared portion of the electromagnetic spectrum wasn't even suspected. The original significance of the infrared spectrum, or simply 'the infrared' as it is often called, as a form of heat radiation is perhaps less obvious today than it was at the time of its discovery by Herschel in 1800.

Sir William Herschel (1738–1822)

The discovery was made accidentally during the search for a new optical material. Sir William Herschel – Royal Astronomer to King George III of England, and already famous for his discovery of the planet Uranus – was searching for an optical filter material to reduce the brightness of the sun's image in telescopes during solar observations. While testing different samples of colored glass which gave similar reductions in brightness he was intrigued to find that some of the samples passed very little of the sun's heat, while others passed so much heat that he risked eye damage after only a few seconds' observation.

Herschel was soon convinced of the necessity of setting up a systematic experiment, with the objective of finding a single material that would give the desired reduction in brightness as well as the maximum reduction in heat. He began the experiment by actually repeating Newton's prism experiment, but looking for the heating effect rather than the visual distribution of intensity in the spectrum. He first blackened the bulb of a sensitive mercury-in-glass thermometer with ink, and with this as his radiation detector he proceeded to test the heating effect of the various colors of the spectrum formed on the top of a table by passing sunlight through a glass prism. Other thermometers, placed outside the sun's rays, served as controls.

As the blackened thermometer was moved slowly along the colors of the spectrum, the temperature readings showed a steady increase from the violet end to the red end. This was not entirely unexpected, since the Italian researcher, Landriani, in a similar experiment in 1777 had observed much the same effect. It was Herschel, however, who was the first to recognize that there must be a point where the heating effect reaches a maximum, and those measurements confined to the visible portion of the spectrum failed to locate this point.

Marsilio Landriani (1746–1815)

Moving the thermometer into the dark region beyond the red end of the spectrum, Herschel confirmed that the heating continued to increase. The maximum point, when he found it, lay well beyond the red end – in what is known today as the 'infrared wavelengths'.

When Herschel revealed his discovery, he referred to this new portion of the electromagnetic spectrum as the 'thermometrical spectrum'. The radiation itself he sometimes referred to as 'dark heat', or simply 'the invisible rays'. Ironically, and contrary to popular opinion, it wasn't Herschel who originated the term 'infrared'. The word only began to appear in print around 75 years later, and it is still unclear who should receive credit as the originator.

Herschel's use of glass in the prism of his original experiment led to some early controversies with his contemporaries about the actual existence of the infrared wavelengths. Different investigators, in attempting to confirm his work, used various types of glass indiscriminately, having different transparencies in the infrared. Through his later experiments, Herschel was aware of the limited transparency of glass to the newly-discovered thermal radiation, and he was forced to conclude that optics for the infrared would probably be doomed to the use of reflective elements exclusively (i.e. plane and curved mirrors). Fortunately, this proved to be true only until 1830, when the Italian investigator, Melloni, made his great discovery that naturally occurring rock salt (NaCl) – which was available in large enough natural crystals to be made into lenses and prisms – is remarkably transparent to the infrared. The result was that rock salt became the principal infrared optical material, and remained so for the next hundred years, until the art of synthetic crystal growing was mastered in the 1930's.

Macedonio Melloni (1798–1854)

Thermometers, as radiation detectors, remained unchallenged until 1829, the year Nobili invented the thermocouple. (Herschel's own thermometer could be read to 0.2 °C (0.036 °F), and later models were able to be read to 0.05 °C (0.09 °F)). Then a breakthrough occurred; Melloni connected a number of thermocouples in series to form the first thermopile. The new device was at least 40 times as sensitive as the best thermometer of the day for detecting heat radiation – capable of detecting the heat from a person standing three meters away.

The first so-called 'heat-picture' became possible in 1840, the result of work by Sir John Herschel, son of the discoverer of the infrared and a famous astronomer in his own right. Based upon the differential evaporation of a thin film of oil when exposed to a heat pattern focused upon it, the thermal image could be seen by reflected light where the interference effects of the oil film made the image visible to the eye. Sir John also managed to obtain a primitive record of the thermal image on paper, which he called a 'thermograph'.

Samuel P. Langley (1834–1906)

The improvement of infrared-detector sensitivity progressed slowly. Another major breakthrough, made by Langley in 1880, was the invention of the bolometer. This consisted of a thin blackened strip of platinum connected in one arm of a Wheatstone bridge circuit upon which the infrared radiation was focused and to which a sensitive galvanometer responded. This instrument is said to have been able to detect the heat from a cow at a distance of 400 meters.

An English scientist, Sir James Dewar, first introduced the use of liquefied gases as cooling agents (such as liquid nitrogen with a temperature of -196 °C (-320.8 °F)) in low temperature research. In 1892 he invented a unique vacuum insulating container in which it is possible to store liquefied gases for entire days. The common 'thermos bottle', used for storing hot and cold drinks, is based upon his invention.

Between the years 1900 and 1920, the inventors of the world 'discovered' the infrared. Many patents were issued for devices to detect personnel, artillery, aircraft, ships – and even icebergs. The first operating systems, in the modern sense, began to be developed during the 1914–18 war, when both sides had research programs devoted to the military exploitation of the infrared. These programs included experimental systems for enemy intrusion/detection, remote temperature sensing, secure communications, and 'flying torpedo' guidance. An infrared search system tested during this period was able to detect an approaching airplane at a distance of 1.5 km (0.94 miles), or a person more than 300 meters (984 ft.) away.

The most sensitive systems up to this time were all based upon variations of the bolometer idea, but the period between the two wars saw the development of two revolutionary new infrared detectors: the image converter and the photon detector. At first, the image converter received the greatest attention by the military, because it enabled an observer for the first time in history to literally 'see in the dark'. However, the sensitivity of the image converter was limited to the near infrared wavelengths, and the most interesting military targets (i.e. enemy soldiers) had to be illuminated by infrared search beams. Since this involved the risk of giving away the observer's position to a similarly-equipped enemy observer, it is understandable that military interest in the image converter eventually faded.

The tactical military disadvantages of so-called 'active' (i.e. search beam-equipped) thermal imaging systems provided impetus following the 1939–45 war for extensive secret military infrared-research programs into the possibilities of developing 'passive' (no search beam) systems around the extremely sensitive photon detector. During this period, military secrecy regulations completely prevented disclosure of the status of infrared-imaging technology. This secrecy only began to be lifted in the middle of the 1950's, and from that time adequate thermal-imaging devices finally began to be available to civilian science and industry.

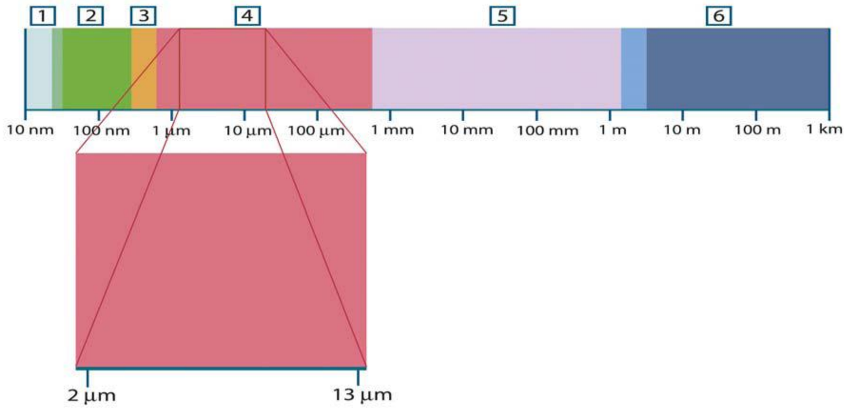
3. Theory of Thermography

3.1. Introduction

The subjects of infrared radiation and the related technique of thermography are still new to many who will use an infrared camera. In this section the theory behind thermography will be given.

3.2. The Electromagnetic Spectrum

The electromagnetic spectrum is divided arbitrarily into a number of wavelength regions, called bands, distinguished by the methods used to produce and detect the radiation. There is no fundamental difference between radiations in the different bands of the electromagnetic spectrum. They are all governed by the same laws and the only differences are those due to differences in wavelength.



The Electromagnetic Spectrum
1: X-ray; 2: UV; 3: Visible; 4: IR; 5: Microwaves; 6: Radiowaves.

Thermography makes use of the infrared spectral band. At the short-wavelength end the boundary lies at the limit of visual perception, in the deep red. At the long wavelength end it merges with the microwave radio wavelengths, in the millimeter range.

The infrared band is often further subdivided into four smaller bands, the boundaries of which are also arbitrarily chosen. They include: the near infrared (0.75–3 µm), the middle infrared (3–6 µm), the far infrared (6–15 µm) and the extreme infrared (15–100 µm). Although the wavelengths are given in µm (micrometers), other units are often still used to measure wavelength in this spectral region, e.g. nanometer (nm) and Ångström (Å).

The relationships between the different wavelength measurements is:

$$10\ 000\ \text{Å} = 1\ 000\ \text{nm} = 1\ \mu = 1\ \mu\text{m}$$

3.3. Blackbody Radiation

A blackbody is defined as an object which absorbs all radiation that impinges on it at any wavelength. The apparent misnomer black relating to an object emitting radiation is explained by Kirchhoff’s Law (after Gustav Robert Kirchhoff, 1824–1887), which states that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation.

Gustav Robert Kirchhoff (1824–1887)

The construction of a blackbody source is, in principle, very simple. The radiation characteristics of an aperture in an isotherm cavity made of an opaque absorbing material represents almost exactly the properties of a blackbody. A practical application of the principle to the construction of a perfect absorber of radiation consists of a box that is light tight except for an aperture in one of the sides. Any radiation which then enters the hole is scattered and absorbed by repeated reflections so only an infinitesimal fraction can possibly escape. The blackness which is obtained at the aperture is nearly equal to a blackbody and almost perfect for all wavelengths.

By providing such an isothermal cavity with a suitable heater it becomes what is termed a cavity radiator. An isothermal cavity heated to a uniform temperature generates blackbody radiation, the characteristics of which are determined solely by the temperature of the cavity. Such cavity radiators are commonly used as sources of radiation in temperature reference standards in the laboratory for calibrating thermographic instruments, such as a FLIR Systems camera for example.

If the temperature of blackbody radiation increases to more than 525 °C (977 °F), the source begins to be visible so that it appears to the eye no longer black. This is the incipient red heat temperature of the radiator, which then becomes orange or yellow as the temperature increases further. In fact, the definition of the so-called color temperature of an object is the temperature to which a blackbody would have to be heated to have the same appearance. Now consider three expressions that describe the radiation emitted from a blackbody.

3.4. Planck's Law

Max Planck (1858–1947)

Max Planck (1858–1947) was able to describe the spectral distribution of the radiation from a blackbody by means of the following formula:

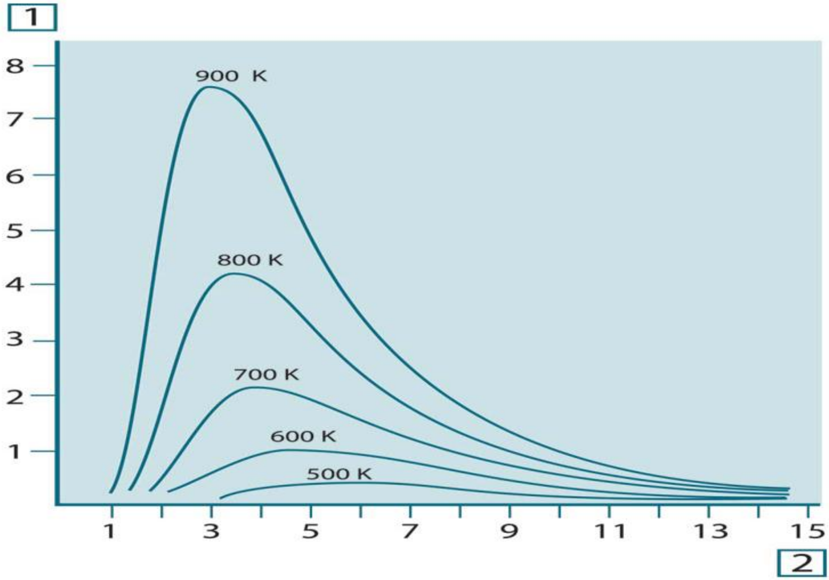
$$W_{\lambda b} = \frac{2\pi hc^{3}}{\lambda^{5}\left(e^{hc/\lambda kT} - 1\right)} \times 10^{-6} \left[Watt/m^{2}\mu m\right]$$

Where:

- Wλb = Blackbody spectral radiant emittance at wavelength λ.
- c = Velocity of light = 3 × 108 m/s
- h = Planck's constant = 6.6 × 10-34 Joule sec.
- k = Boltzmann's constant = 1.4 × 10-23 Joule/K.
- T = Absolute temperature (K) of a blackbody.
- λ = Wavelength (μm).

Note The factor 10-6 is used since spectral emittance in the curves is expressed in Watt/m2m. If the factor is excluded, the dimension will be Watt/m2μm.

Planck's formula, when plotted graphically for various temperatures, produces a family of curves. Following any particular Planck curve, the spectral emittance is zero at λ = 0, then increases rapidly to a maximum at a wavelength λmax and after passing it approaches zero again at very long wavelengths. The higher the temperature, the shorter the wavelength at which maximum occurs.



Blackbody spectral radiant emittance according to Planck's law, plotted for various absolute temperatures. 1: Spectral radiant emittance (W/cm2 × 103(µm)); 2: Wavelength (µm)

3.5. Wien's Displacement Law

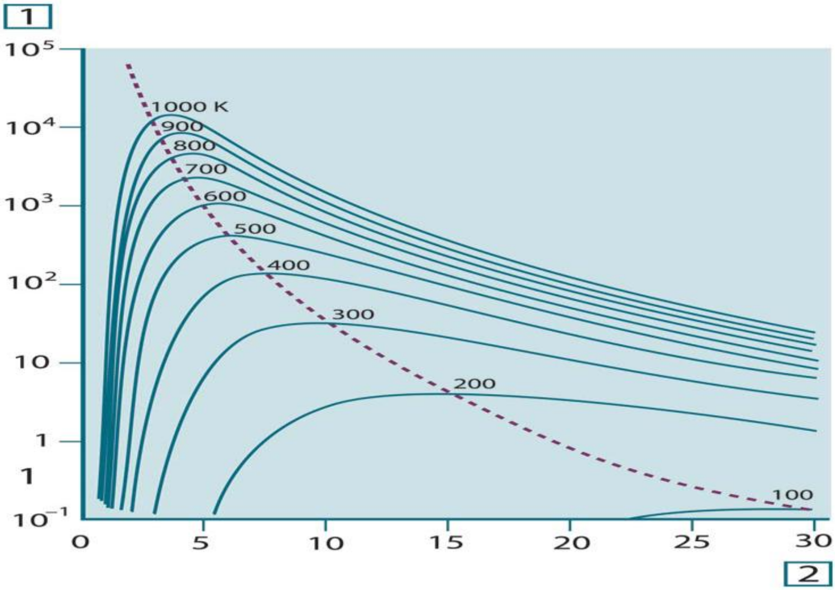
By differentiating Planck's formula with respect to λ, and finding the maximum, we have:

$$\lambda_{\max} = \frac{2898}{T}[\mu m]$$

This is Wien's formula (after Wilhelm Wien, 1864–1928), which expresses mathematically the common observation that colors vary from red to orange or yellow as the temperature of a thermal radiator increases. The wavelength of the color is the same as the wavelength calculated for λmax. A good approximation of the value of λmax for a given blackbody temperature is obtained by applying the rule-of-thumb 3 000/T µm. Thus, a very hot star such as Sirius (11 000 K), emitting bluish-white light, radiates with the peak of spectral radiant emittance occurring within the invisible ultraviolet spectrum at wavelength 0.27 µm.

Wilhelm Wien (1864–1928)

The sun (approx. 6 000 K) emits yellow light, peaking at about 0.5 μm in the middle of the visible light spectrum.
At room temperature (300 K) the peak of radiant emittance lies at 9.7 μm, in the far infrared, while at the temperature of liquid nitrogen (77 K) the maximum of the almost insignificant amount of radiant emittance occurs at 38 μm, in the extreme infrared wavelengths.



Planckian curves plotted on semi-log scales from 100 K to 1000 K. The dotted line represents the locus of maximum radiant emittance at each temperature as described by Wien's displacement law. 1: Spectral radiant emittance (W/cm2 (μm)); 2: Wavelength (μm).

3.6. Stefan-Boltzmann's Law

By integrating Planck's formula from λ = 0 to λ = ∞, we obtain the total radiant emittance (Wb) of a blackbody:

$$W_b = \sigma T^4 \ [\mathrm{Watt/m^2}]$$

This is the Stefan-Boltzmann formula (after Josef Stefan, 1835–1893, and Ludwig Boltzmann, 1844–1906), which states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. Graphically, Wb represents the area below the Planck curve for a particular temperature. It can be shown that the radiant emittance in the interval λ = 0 to λmax is only 25 % of the total, which represents about the amount of the sun's radiation which lies inside the visible light spectrum.


Josef Stefan (1835–1893), and Ludwig Boltzmann (1844–1906)

Using the Stefan-Boltzmann formula to calculate the power radiated by the human body, at a temperature of 300 K and an external surface area of approx. 2 m2, we obtain 1 kW. This power loss could not be sustained if it were not for the compensating absorption of radiation from surrounding surfaces, at room temperatures which do not vary too drastically from the temperature of the body – or, of course, the addition of clothing.

3.7. Non-Blackbody Emitters

So far, only blackbody radiators and blackbody radiation have been discussed. However, real objects almost never comply with these laws over an extended wavelength region – although they may approach the blackbody behavior in certain spectral intervals. For example, a certain type of white paint may appear perfectly white in the visible light spectrum, but becomes distinctly gray at about 2 µm, and beyond 3 µm it is almost black. There are three processes which can occur that prevent a real object from acting like a blackbody: a fraction of the incident radiation α may be absorbed, a fraction ρ may be reflected, and a fraction τ may be transmitted. Since all of these factors are more or less wavelength dependent, the subscript λ is used to imply the spectral dependence of their definitions. Thus:

- The spectral absorptance α_λ= the ratio of the spectral radiant power absorbed by an object to that incident upon it.
- The spectral reflectance ρ_λ = the ratio of the spectral radiant power reflected by an object to that incident upon it.
- The spectral transmittance τ_λ = the ratio of the spectral radiant power transmitted through an object to that incident upon it.

The sum of these three factors must always add up to the whole at any wavelength, so we have the relation:

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$

For opaque materials $\tau_\lambda = 0$ and the relation simplifies to:

$$\alpha_\lambda + \rho_\lambda = 1$$

Another factor, called the emissivity, is required to describe the fraction ε of the radiant emittance of a blackbody produced by an object at a specific temperature. Thus, we have the definition: The spectral emissivity ε_λ= the ratio of the spectral radiant power from an object to that from a blackbody at the same temperature and wavelength.

Expressed mathematically, this can be written as the ratio of the spectral emittance of the object to that of a blackbody as follows:

$$\varepsilon_\lambda = \frac{W_{\lambda o}}{W_{\lambda b}}$$

Generally speaking, there are three types of radiation source, distinguished by the ways in which the spectral emittance of each varies with wavelength.

- A blackbody, for which $\varepsilon_\lambda = \varepsilon = 1$
- A graybody, for which $\varepsilon_\lambda = \varepsilon$ = constant less than 1
- A selective radiator, for which ε varies with wavelength

According to Kirchhoff’s law, for any material the spectral emissivity and spectral absorptance of a body are equal at any specified temperature and wavelength. That is:

$$\varepsilon_\lambda = \alpha_\lambda$$

From this we obtain, for an opaque material (since $\alpha_\lambda + \rho_\lambda = 1$):

$$\varepsilon_\lambda + \rho_\lambda = 1$$

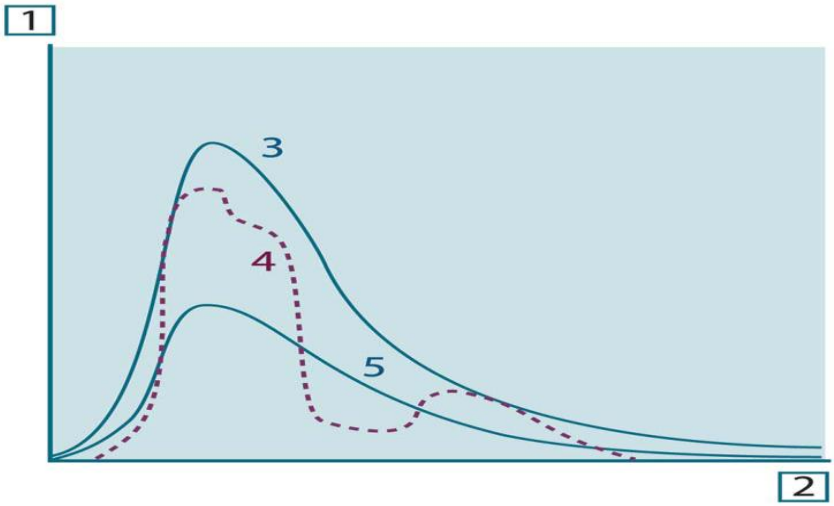
For highly polished materials ε_λ approaches zero, so that for a perfectly reflecting material (i.e. a perfect mirror) we have:

$$\rho_\lambda = 1$$

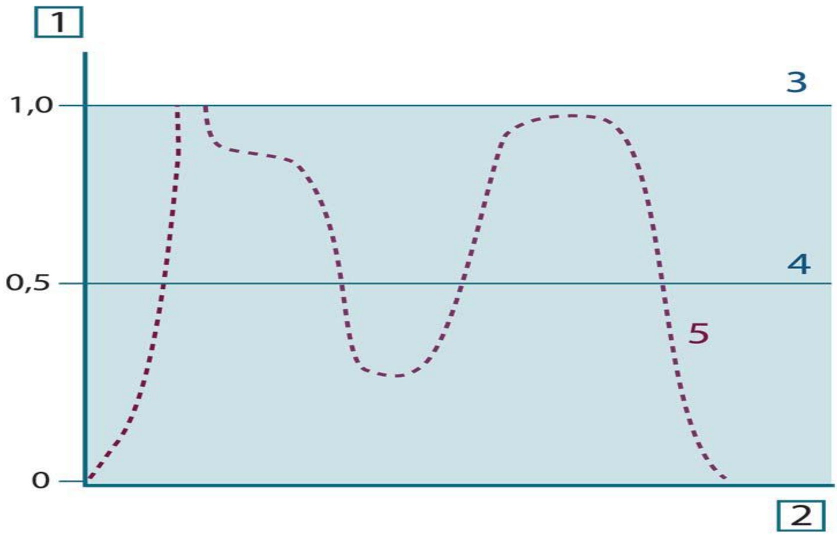
For a graybody radiator, the Stefan-Boltzmann formula becomes:

$$W = \varepsilon\sigma T^4 \; [\mathrm{Watt/m^2}]$$

This states that the total emissive power of a graybody is the same as a blackbody at the same temperature reduced in proportion to the value of ε from the graybody.



Spectral radiant emittance of three types of radiators. 1: Spectral radiant emittance; 2: wavelength; 3: Blackbody; 4: Selective radiator; 5: Graybody.



Spectral emissivity of three types of radiators. 1: Spectral emissivity; 2: Wavelength; 3: blackbody; 4: Graybody; 5: Selective radiator.

3.8. Infrared Semi-Transparent Materials

Consider now a non-metallic, semi-transparent body – let us say, in the form of a thick flat plate of plastic material. When the plate is heated, radiation generated within its volume must work its way toward the surfaces through the material in which it is partially absorbed. Moreover, when it arrives at the surface, some of it is reflected back into the interior. The back-reflected radiation is again partially absorbed, but some of it arrives at the other surface, through which most of it escapes; part of it is reflected back again. Although the progressive reflections become weaker and weaker they must all be added up when the total emittance of the plate is sought. When the resulting geometrical series is summed, the effective emissivity of a semi-transparent plate is obtained as:

$$\varepsilon_\lambda = \frac{\left(1-\rho_\lambda\right)\left(1-\tau_\lambda\right)}{1-\rho_\lambda\tau_\lambda}$$

When the plate becomes opaque this formula is reduced to the single formula:

$$\varepsilon_\lambda = 1-\rho_\lambda$$

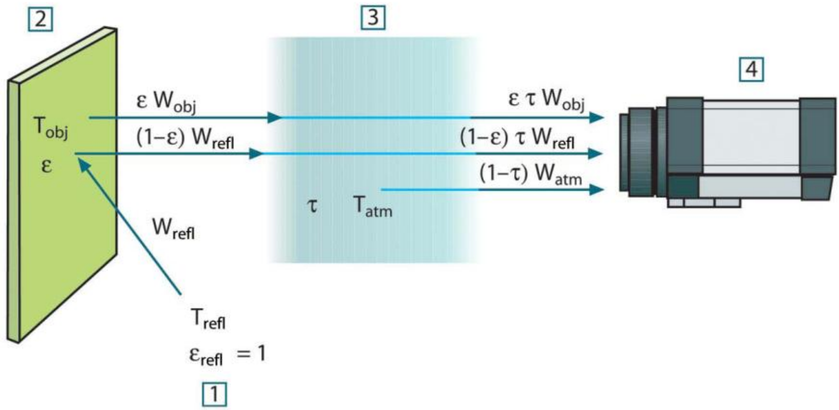
This last relation is a particularly convenient one, because it is often easier to measure reflectance than to measure emissivity directly.

4. The Measurement Formula

As already mentioned, when viewing an object, the camera receives radiation not only from the object itself. It also collects radiation from the surroundings reflected via the object surface. Both these radiation contributions become attenuated to some extent by the atmosphere in the measurement path. To this comes a third radiation contribution from the atmosphere itself.

This description of the measurement situation, as illustrated in the figure below, is so far a fairly true description of the real conditions. What has been neglected could for instance be sun light scattering in the atmosphere or stray radiation from intense radiation sources outside the field of view. Such disturbances are difficult to quantify, however, in most cases they are fortunately small enough to be neglected. In case they are not negligible, the measurement configuration is likely to be such that the risk for disturbance is obvious, at least to a trained operator. It is then his responsibility to modify the measurement situation to avoid the disturbance e.g. by changing the viewing direction, shielding off intense radiation sources etc.

Accepting the description above, we can use the figure below to derive a formula for the calculation of the object temperature from the calibrated camera output.



A schematic representation of the general thermographic measurement situation.1: Surroundings; 2: Object; 3: Atmosphere; 4: Camera

Assume that the received radiation power W from a blackbody source of temperature T_{source} on short distance generates a camera output signal U_{source} that is proportional to the power input (power linear camera). We can then write (Equation 1):

$$U_{source} = CW\left(T_{source}\right), \text{or with simplified notation: } U_{source} = CW_{source}$$

Where C is a constant.

Should the source be a graybody with emittance ε, the received radiation would consequently be εW_{source}.

We are now ready to write the three collected radiation power terms:

1. Emission from the object = $\varepsilon\tau W_{obj}$, where ε is the emittance of the object and τ is the transmittance of the atmosphere. The object temperature is T_{obj}.
2. Reflected emission from ambient sources = $(1 - \varepsilon)\tau W_{refl}$, where $(1 - \varepsilon)$ is the reflectance of the object. The ambient sources have the temperature T_{refl}.

It has here been assumed that the temperature Trefl is the same for all emitting surfaces within the half sphere seen from a point on the object surface. This is of course sometimes a simplification of the true situation. It is, however, a necessary simplification in order to derive a workable formula, and Trefl can – at least theoretically – be given a value that represents an efficient temperature of a complex surrounding.

Note also that we have assumed that the emittance for the surroundings = 1. This is correct in accordance with Kirchhoff's law: All radiation impinging on the surrounding surfaces will eventually be absorbed by the same surfaces. Thus the emittance = 1.

Note: Though that the latest discussion requires the complete sphere around the object to be considered.

3. Emission from the atmosphere = $(1 - \tau)\tau W_{atm}$, where $(1 - \tau)$ is the emittance of the atmosphere. The temperature of the atmosphere is T_{atm}.

The total received radiation power can now be written (Equation 2):

$$W_{tot} = \varepsilon\tau W_{obj} + (1-\varepsilon)\tau W_{refl} + (1-\tau)W_{atm}$$

We multiply each term by the constant C of Equation 1 and replace the CW products by the corresponding U according to the same equation, and get (Equation 3):

$$U_{tot} = \varepsilon\tau U_{obj} + (1-\varepsilon)\tau U_{refl} + (1-\tau)U_{atm}$$

Solve Equation 3 for U_{obj} (Equation 4):

$$U_{obj} = \frac{1}{\varepsilon\tau}U_{tot} - \frac{1-\varepsilon}{\varepsilon}U_{refl} - \frac{1-\tau}{\varepsilon\tau}U_{atm}$$

This is the general measurement formula used in all the FLIR Systems thermographic equipment. The voltages of the formula are:

- U_{obj} = Calculated camera output voltage for a blackbody of temperature Tobj i.e. a voltage that can be directly converted into true requested object temperature.

- U_{tot} = Measured camera output voltage for the actual case.
- U_{refl} = Theoretical camera output voltage for a blackbody of temperature Trefl according to the calibration.
- U_{atm} = Theoretical camera output voltage for a blackbody of temperature T_{atm} according to the calibration.

The operator has to supply a number of parameter values for the calculation:

- The object emittance ε,
- T_{atm}
- Object distance (D_{obj})
- The (effective) temperature of the object surroundings, or the reflected ambient temperature T_{refl}, and
- The temperature of the atmosphere T_{atm}

This task could sometimes be a heavy burden for the operator since there are normally no easy ways to find accurate values of emittance and atmospheric transmittance for the actual case. The two temperatures are normally less of a problem provided the surroundings do not contain large and intense radiation sources.

A natural question in this connection is: How important is it to know the right values of these parameters? It could though be of interest to get a feeling for this problem already here by looking into some different measurement cases and compare the relative magnitudes of the three radiation terms. This will give indications about when it is important to use correct values of which parameters.

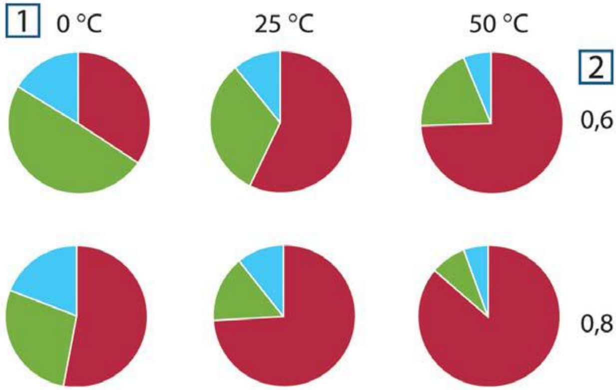
The figures below illustrates the relative magnitudes of the three radiation contributions for three different object temperatures, two emittances, and two spectral ranges: SW and LW. Remaining parameters have the following fixed values:

- τ = 0.88
- Trefl = +20 °C (+68 °F)
- Trefl = +20 °C (+68 °F)

- It is obvious that measurement of low object temperatures are more critical than measuring high temperatures since the 'disturbing' radiation sources are relatively much stronger in the first case. Should also the object emittance be low, the situation would be still more difficult.

We have finally to answer a question about the importance of being allowed to use the calibration curve above the highest calibration point, what we call extrapolation. Imagine that we in a certain case measure Utot = 4.5 volts. The highest calibration point for the camera was in the order of 4.1 volts, a value unknown to the operator. Thus, even if the object happened to be a blackbody, i.e. Uobj = Utot, we are actually performing extrapolation of the calibration curve when converting 4.5 volts into temperature.

Let us now assume that the object is not black, it has an emittance of 0.75, and the transmittance is 0.92. We also assume that the two second terms of Equation 4 amount to 0.5 volts together. Computation of Uobj by means of Equation 4 then results in Uobj = 4.5 / 0.75 / 0.92 – 0.5 = 6.0. This is a rather extreme extrapolation, particularly when considering that the video amplifier might limit the output to 5 volts! Note, though, that the application of the calibration curve is a theoretical procedure where no electronic or other limitations exist. We trust that if there had been no signal limitations in the camera, and if it had been calibrated far beyond 5 volts, the resulting curve would have been very much the same as our real curve extrapolated beyond 4.1 volts, provided the calibration algorithm is based on radiation physics, like the FLIR Systems algorithm. Of course there must be a limit to such extrapolations.



Relative magnitudes of radiation sources under varying measurement conditions (SW camera).1: Object temperature; 2: Emittance; RED: Object radiation; BLUE: Reflected radiation; GREEN: atmosphere radiation. Fixed parameters: τ = 0.88; Trefl = 20 °C (+68 °F); Tatm = 20 °C (+68 °F).

5. Radiometry Basis

5.1. Solid angle

Definition

It is the angle that, seen from the centre of a sphere, includes a given area on the surface of that sphere. The value of the solid angle is numerically equal to the size of that area divided by the square of the radius of the sphere.

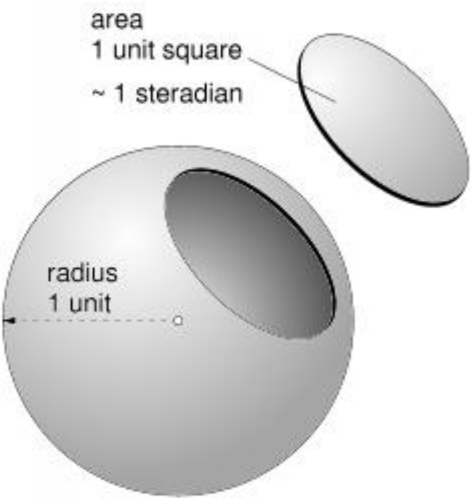


Figure 1

W = A / r², A is the area of the object, r is the radius

Even though the diagram might suggest it, the shape of the area doesn't matter at all. Any shape on the surface of the sphere that holds the same area will define a solid angle of the same size.

Also, the diagram only shows the elements that define a solid angle, not the solid angle itself. The solid angle is the quantitative aspect of the conical slice of space, which has the centre of the sphere as its peak, the area on the surface of the sphere as one of its spherical cross sections, and extends to infinity.

The maximum solid angle is ~12.57, corresponding to the full area of the unity sphere, which is $4\times\pi$.

Standard units of a solid angle are the **steradians (sr)**. (Mathematically, the solid angle is unitless, but for practical reasons, the steradian is assigned.)

Mathematical expression

- When the following hypothesis are verified:
  - The shape of the object can be considered flat
  - Its transverse dimensions are small in comparison with the observation distance

Then the solid angle is defined by:

$$\mathbf{d\Omega = \frac{dS' \cos\theta'}{d^2}}$$

dS' is the real surface of the object and **θ'** is the angle between the observation line and the normal line of the object (see the below drawing).

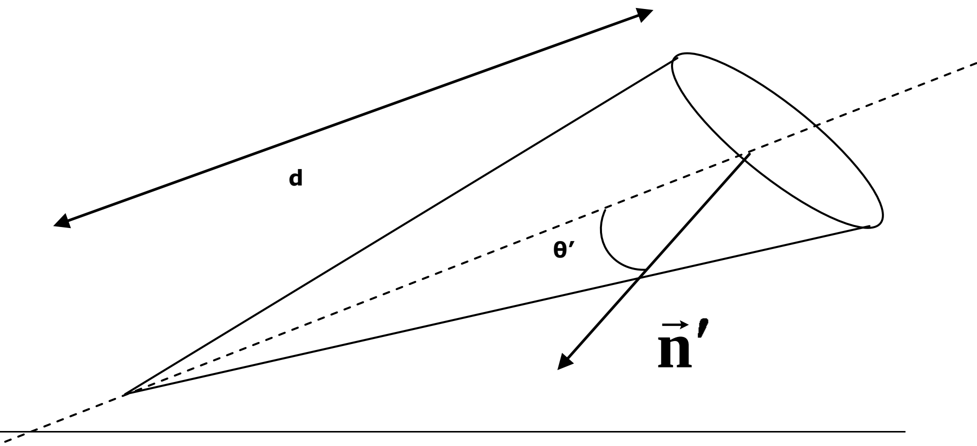


Figure 2

- When the following hypothesis are verified:
  - The shape of the object can be considered flat
  - Its transverse dimensions are small in comparison with the observation distance
  - The object is seen as a disc of small apparent radius α (see next drawing)

Then the solid angle is defined by:

$$d\Omega = \pi\alpha^2$$

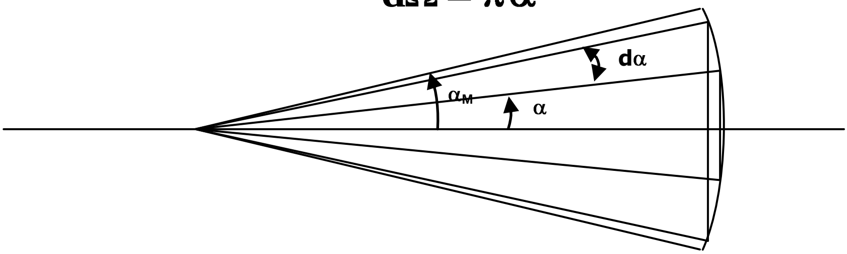


Figure 3

Therefore, the solid angle defined by the circular cone, which half angle at the top is α_M is equal to:

$$\Omega(\alpha_M) = 2\pi(1 - \cos\alpha_M)$$

5.2. Etendue

Definition

Literally, the French word "etendue" translates to "extent" or "space". In a radiometric context, it is used to specify the geometric capability of an optical system to transmit radiation, its throughput.

The numeric value of the etendue is a constant of the system and gets calculated as the product of the opening size and the solid angle that the system accepts light from.

In most practical situations, it is approximated by integrating over the two factors.

$$\mathbf{G} = \iint \mathbf{dA} \times \Omega$$

Quite often an engineer will be confronted with the need to optimize the arrangement of elements within a system in order to maximize the geometric etendue and thus its throughput.

Mathematical expression

Let us consider the following drawing.

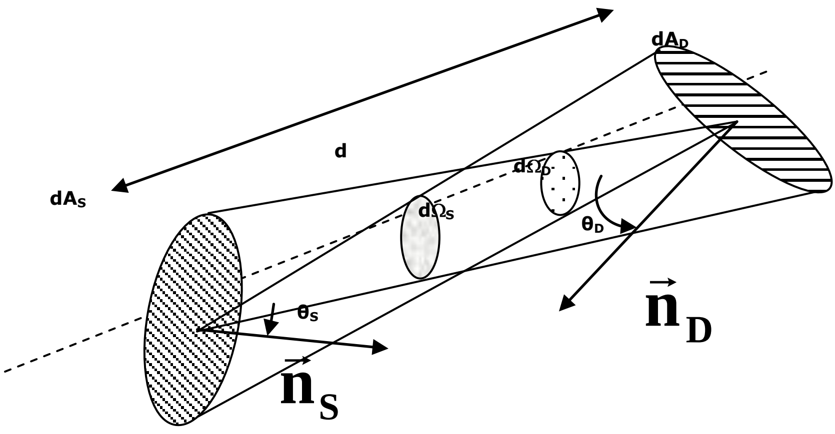


Figure 4

The index $_S$ means source, the index $_D$ means detector. If the solid angle of the emitted light is hold by the small area of the detector $\mathbf{dA_D}$ which is at a distance d from the source, the etendue between the two stops of respective area $\mathbf{dA_S}$ and $\mathbf{dA_D}$ has three different expressions:

$$\mathbf{d^2G = \frac{dA_S \cos\theta_S dA_D \cos\theta_D}{d^2} = dA_D \cos\theta_D d\Omega_D = dA_S \cos\theta_S d\Omega_S}$$

The source is seen by the detector with the solid angle $\mathbf{d\Omega_D}$, the detector is seen by the source with the solid angle $\mathbf{d\Omega_S}$.

The etendue units are $m^2.sr$ or $cm^2.sr$.

6. Radiometric basis for a camera

6.1. Focus in optics

In optics, a focus, also called an image point, is the point where light rays originating from a source in front of the camera converge. Although the focus is conceptually a point, physically the focus has a spatial extent, called the blur circle. A principal focus or focal point is a special focus: it is a point onto which collimated light parallel to the optical axis is focused. The distance in air from the lens principal plane to the focus is called the focal length.

Therefore, when a camera is well focused, that means that we have adjusted the focus distance so that the detector plane is placed on the focus plane.

6.2. Focal length of a camera

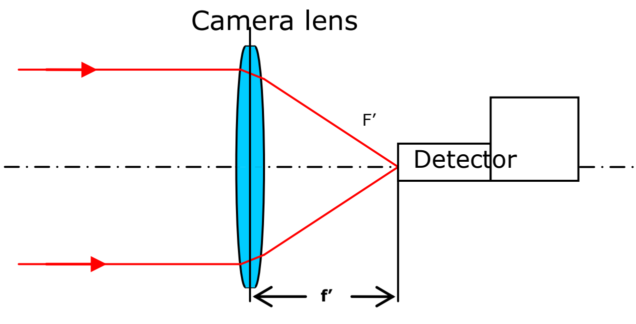


Figure 5

The focal length of a camera is a measure of how strongly it focuses the light. For a thin lens in air as shown in the drawing above, the focal length is the distance from the center of the lens to the principal foci (or focal points) of the lens. It is usually expressed in millimeters.

6.3. Field of view of a camera

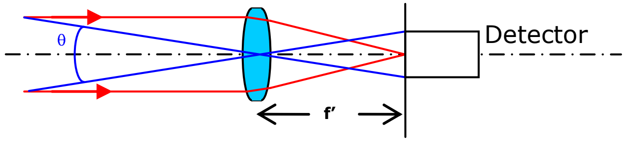


Figure 6

The angle of view or field view (usually marked as θ in optics) is the amount of a given scene shown on the detector. It is expressed in degrees of angular measurement. It highly depends on the size of the detector. Therefore, as the detector is usually rectangular, we are used to talk about horizontal and vertical field of view (θ_H and θ_V).

The number of pixels ($\mathbf{N_H}$ and $\mathbf{N_V}$), the pitch **p** of the detector and the focal length **f'** is necessary to calculate the horizontal and vertical field of view of the camera.

$$\theta_H = 2 \times \mathrm{Arc\,tan}\frac{N_H p}{2f'} \quad \text{and} \quad \theta_V = 2 \times \mathrm{Arc\,tan}\frac{N_V p}{2f'}$$

Beware: the pitch **p** and the focal length **f'** must have the same units.

6.4. The instantaneous field of view of a camera

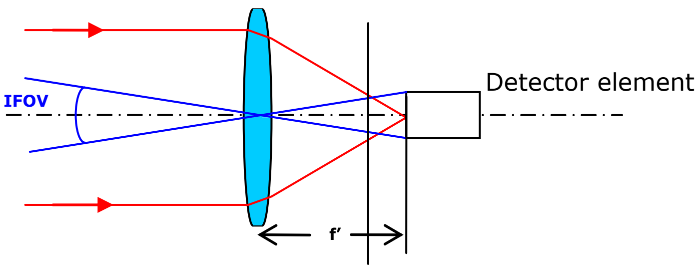


Figure 7

The instantaneous field of view of a camera or detector angular substance (usually known as **IFOV**) is the amount of a given scene shown on one pixel of the detector. It is often used to describe the spatial resolution of systems when the detector is the limiting subsystem.

It is usually expressed in **milliradians** of angular measurement. It highly depends on the size of the detector element. Therefore, as each detector element is usually square, we use the following formula to calculate it:

$$\mathbf{IFOV} = \mathbf{2} \times \mathbf{Arc\,tan}\,\frac{\mathbf{p}}{\mathbf{2f'}} \approx \frac{\mathbf{p}}{\mathbf{f'}}$$

Beware: the pitch **p** is in µm whereas the focal length **f'** is in millimeters. Thus, the **IFOV** is in milliradians.

6.5. Geometric aperture of a lens

To make it simple, we consider a thin lens and the space that holds the lens and the image made by the lens.

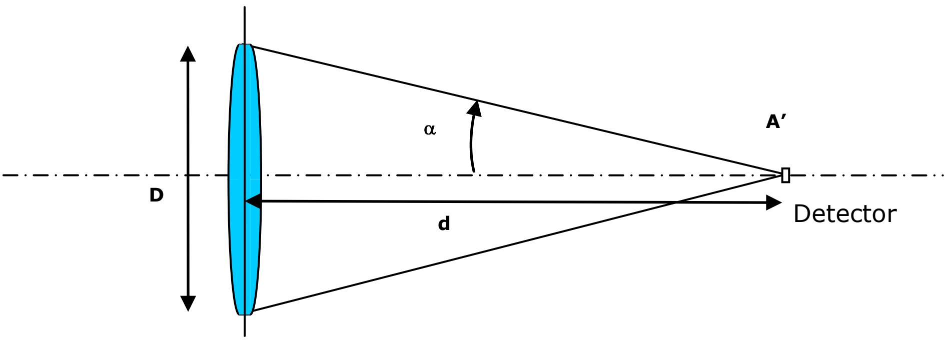


Figure 8

D is the diameter of the entrance pupil. The image is located at a distant **d** from the lens entrance pupil. In this configuration, the geometric aperture of the lens which is the angle α is defined by the following formula:

$$\sin\alpha = \frac{\mathbf{D}}{\mathbf{2d}}$$

When the observed object is far enough from the camera to be considered lying at an infinite distance, the image **A'** lies on the focal point of the camera. Therefore, the distance **d** is equal to the focal length of the lens and:

$$\sin\alpha = \frac{D}{2f'} = \frac{1}{2N}$$

N is defined below.

Though the way to obtain these equations is slightly more difficult in a case of a more complex optical lens (more than one lens), the last formula above remains valid, considering that **D** is your entrance pupil diameter and **f'** the effective focal length of your lens.

6.6. Numerical aperture

Definition for a lens

We have previously defined the geometric aperture for any kind of imaging situation. When the object lies at a distance big enough to be considered infinite, we know that the image is located in the focal plane of the lens. Only in this condition can we easily express the numerical aperture, called **N**, of a lens.

$$N = \frac{1}{2\sin\alpha} = \frac{f'}{D}$$

- **f'** is the focal length of the lens. The units are m.
- **D** is the diameter of the entrance pupil in m (see **Figure 8** above).
- **N** is unitless.

Definition for a detector

We can consider the **Figure 8** above, but the lens entrance pupil is replaced by a virtual entrance pupil which has no specific diameter nor is located at a specific distance. The numerical value given by the detector manufacturer corresponds to the following relation.

$$N = \frac{d}{D}$$

No object outside the solid angle hold by the pupil of diameter **D** located at distance d from the detector will be seen.

6.7. Solid angle

The camera is now equipped with a lens and we have the following configuration.

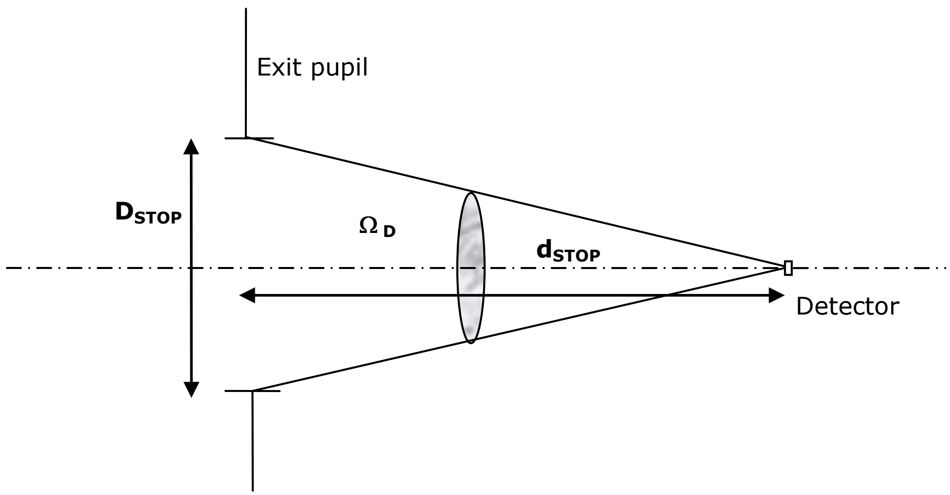


Figure 9

Careful, except for the thin lens, the exit pupil is different than the entrance pupil so $\mathbf{D_{STOP}} \neq \mathbf{D}$
The detector solid angle is then defined by the following relation:

$$\Omega_D = \frac{\pi D_{STOP}^{\ 2}}{4d_{STOP}^{\ 2}} = \pi \sin^2 \alpha$$

- α is the geometric aperture defined above.

If the object can be considered lying at an infinite distance, we have:

$$\Omega_D = \frac{\pi D^2}{4f'^2} = \frac{\pi}{4N^2}$$

- **f'** is the focal length of the lens. The units are m.
- **D** is the diameter of the entrance pupil in m (see **Figure 8** above).
- **N** is unitless.

6.8. Etendue

The camera is now equipped with a lens and we have the following configuration.

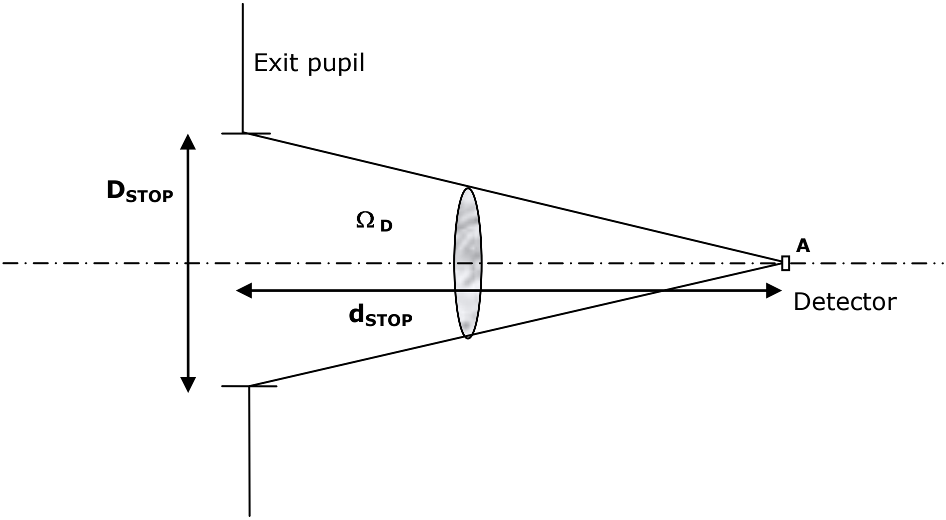


Figure 10

Careful, except for the thin lens, the exit pupil is different than the entrance pupil so $\mathbf{D_{STOP}} \neq \mathbf{D}$

The etendue is then defined by the following relation:

$$G_D = \frac{\pi A D_{STOP}^{\ 2}}{4 d_{STOP}^{\ 2}} = \pi A \sin^2 \alpha$$

- **A** is the area of the detector, usually the area of the pixel. The units are m².
- α is the geometric aperture defined above.
- **GD** units are m².sr or cm².sr.

If the object can be considered lying at an infinite distance, we have:

$$\mathbf{G_D = \frac{\pi A D^2}{4f'^2} = \frac{\pi A}{4N^2}}$$

- **f'** is the focal length of the lens. The units are m.
- **D** is the diameter of the entrance pupil in m (see **Figure 8** above).
- **N** is unitless.

7. Radiometric calculations

7.1. The Planck relation

The energetic spectral radiance

The Planck law gives us the energetic spectral radiance of a blackbody which temperature is set to **T** as shown below:

$$\left[\frac{dL_e}{d\lambda}\right]_{CN}^{T}(\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} = \frac{1.191\times 10^{14}}{\lambda^5}\frac{1}{e^{\frac{1.44\times 10^4}{\lambda T}}-1}$$

- λ is the wavelength. Beware the units are in µm.
- **T** is the blackbody temperature. **T** is in Kelvin (K).

This is the energetic spectral radiance and the units are W/m²/µm/sr. It depends on the wavelength λ.

The photonic spectral radiance

Sometimes, it is necessary to know how many photons are emitted by the source and to calculate the power in ph/s received by each pixel (see below for this calculation).

So the Planck law is a little modified to express the photonic spectral luminance.

$$\left[\frac{dL_p}{d\lambda}\right]_{CN}^{T}(\lambda) = \frac{2c}{\lambda^4}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} = \frac{6\times 10^{8}}{\lambda^4}\frac{1}{e^{\frac{1.44\times 10^4}{\lambda T}}-1}$$

This is the photonic spectral luminance and the units are ph/s/m²/µm/sr. This is the energetic spectral radiance and the units are W/m²/µm/sr. It depends on the wavelength λ.

The radiance

The calculation of the radiance is little less simple as it supposed that you know some information on your system.

First, let us start with a little word on the spectral range, for instance the spectral range of a lens.

The spectral range of the lens is defined as the spectral domain for which the transmission of the lens goes from zero to its maximum value.

If it the transmission is not zero at the lower value and/or at the upper value of your spectral range, then it means that you have only a part of the spectral range of your lens.

Of course, the spectral radiance is not the most interesting value as it depends on the wavelength. Indeed, we need the radiance of the source for a specific spectral range (usually 0.8 to 2.5 µm, 3 to 5 µm, 8 to 12 µm) to calculate the power received by a pixel (see below).

To be accurate in the calculation, it is necessary to know the spectral range of your camera. That means that you must know the spectral range of your lens, the one of your filter and the one of your detector.

Then you consider the <u>highest minimum value</u> of each spectral range as a lower limit (λ_{min}) and the <u>lowest maximum value</u> as your upper limit (λ_{max}).

Once you have this, the calculation is given by this following formula, which works for both the energetic and photonic luminance.

$$\mathbf{L} = \int_{\lambda_{min}}^{\lambda_{max}} \left[\frac{\mathbf{dL}}{\mathbf{d\lambda}}\right]_{\mathbf{CN}}^{\mathbf{T}} (\lambda)\, \mathbf{d\lambda}$$

As it not easy to manipulate integral, the best way is to divide your spectral range into **N** little spectral range to approximate your calculation, **N** is as great as possible.

Thus, we have:

$$\Delta\lambda = \frac{\lambda_{max} - \lambda_{min}}{\mathbf{N}}$$

Let us consider the centre wavelength λ_i of the i^{th} little spectral range. We have:

$$\lambda_i = \lambda_{min} + i \times \Delta\lambda$$

Therefore, the formula becomes:

$$L = \int_{\lambda_{min}}^{\lambda_{max}} \left[\frac{dL}{d\lambda}\right]_{CN}^{T} (\lambda)\, d\lambda = \Delta\lambda \times \sum_{i=1}^{N-1} \left(\frac{\left[\frac{dL}{d\lambda}\right]_{CN}^{T} (\lambda_{i+1}) + \left[\frac{dL}{d\lambda}\right]_{CN}^{T} (\lambda_i)}{2} \right)$$

NB: $\sum_{i=1}^{3} f(i) = f(1) + f(2) + f(3)$

The units of the energetic radiance are W/m²/sr. The units of photonic radiance are ph/s/m²/sr.

7.2. Power

The source in most of the case is a blackbody and we have seen in the paragraph 4.1 how to calculate the radiance **L** of the source.

Therefore, if we would like to calculate the power that **a pixel in the center of the camera detector** is receiving, we have to use the following formula:

$$F = \tau \times \tau_{OP} \times L \times G = \pi \times \tau \times \tau_{OP} \times A \times L \times \sin^2 \alpha$$

- τ is the atmospheric transmission of the air between the source and the camera.
- τ_{OP} is the optical transmission: it is the product of the lens transmission and the filter transmission.
- **L** is the radiance of the source. If the radiance is energetic, then the power **F** will be expressed in watt (W). If the radiance is photonic, the power **F** is in ph/s.

- **A** is the area of the detector (usually the square of the pitch). Beware, the units are m.
- **G** is the etendue as defined in paragraph 3.4.

If the source is placed at an infinite distance from the camera, the formula gets a little easier to manipulate:

$$\mathbf{F} = \frac{\pi \times \tau \times \tau_{\mathbf{OP}} \times \mathbf{A} \times \mathbf{L}}{\mathbf{4N^2}}$$

7.3. Irradiance

The calculation of the irradiance of the pixel at the detector centre is quite similar to the one of the power.

$$\mathbf{E} = \frac{\mathbf{F}}{\mathbf{A}} = \tau \times \tau_{\mathbf{OP}} \times \mathbf{L} \times \Omega = \pi \times \tau \times \tau_{\mathbf{OP}} \times \mathbf{L} \times \mathbf{sin^2}\,\alpha$$

- τ is the atmospheric transmission of the air between the source and the camera.
- $\tau_{\mathbf{OP}}$ is the optical transmission: it is the product of the lens transmission and the filter transmission.
- **L** is the radiance of the source. If the radiance is energetic, then the irradiance E will be expressed in W/m². If the radiance is photonic, the irradiance E is in ph/s/m².
- **A** is the area of the detector (usually the square of the pitch). Beware, the units are m.
- Ω is the solid angle as defined in paragraph 3.3.

8. Performance of an infrared camera

8.1. Detectivity

Infrared detectors are called BLIP detectors. BLIP is the acronym of Background Limited Infrared Detectors. Therefore, knowing the spectral range of the camera, the detectivity D is expressed as:

$$D(\lambda) = \frac{1}{hc}\frac{1}{\sqrt{A}\sin\alpha}\sqrt{\frac{\eta}{2\pi L_p}}\sqrt{\frac{1}{\Delta\upsilon}}\lambda$$

- **A** is the area of the detector (usually the square of the pitch). Beware, the units are cm.
- **sin**α is the geometric aperture of the lens (see paragraph 2.1).
- η is the quantum efficiency of the detector. Usually, it is a value given by the detector manufacturer.
- $\mathbf{L_p}$ is the photonic radiance (see paragraph 3.1 for the calculation)
- $\mathbf{\Delta\nu}$ is the bandwidth of the detector. The units are Hz. It is defined by the following form:

$$\Delta\upsilon = \frac{1}{2t_i}$$

- $\mathbf{t_i}$ is the integration time of the detector.

The detectivity is equal to zero outside the camera spectral range.

To normalize the detector metrology and to provide equity when comparing detectors, the spectral specific detectivity **D*(**λ**)** is used. It represents the spectral detectivity of a detector per unit of surface (Beware A = 1 cm²) and per bandwidth ($\Delta\nu$ = 1 Hz).

Hence:

$$D^*(\lambda) = \frac{1}{hc}\frac{1}{\sin\alpha}\sqrt{\frac{\eta}{2\pi L_p}}\lambda$$

It is a figure-of merit that combines responsivity with detector noise. It stands for the spectral detectivity of a detector per unit of surface (Beware: the units of surface are here 1 cm²) and for a bandwidth of 1 Hz. So it does not depend on the integration time but…

…when the light is monochromatic (laser, narrow-band filter, monochromator), D* value is easy to get. When the light has a larger spectral domain, we usually consider the average specific detectivity.

D* units are cm/W/√Hz.

8.2. NEP (Noise Equivalent Power)

This quantity gives us the minimum optical power that must be received by the detector to be equal to its noise. Therefore, the NEP units are Watts.

$$\mathbf{NEP} = \frac{\sqrt{\mathbf{A} \times \Delta\upsilon}}{\mathbf{D}^{*}(\lambda)}$$

- **D*** is the specific detectivity of the detector.
- **A** is the area of the detector (usually the square of the pitch). Beware, the units are cm².
- **Δν** is the bandwidth of the detector. The units are Hz. It is defined by the following form:

$$\Delta\upsilon = \frac{1}{2t_i}$$

- t_i is the integration time of the detector.

For the calculation of the NEP, the integration time value is the same one as the one for which the detectivity is measured.

8.3. NEI (Noise equivalent irradiance)

This notion is quite equivalent to the former one. It is used for a complete infrared system and details about the lens need to be known.

The units are W.cm^{-2}.

$$\mathbf{NEI} = \frac{\sqrt{\mathbf{A} \times \Delta\upsilon}}{\mathbf{S_p D^*(\lambda)\tau_{OP}}} = \frac{\sqrt{\mathbf{A} \times \Delta\upsilon}}{\pi \frac{\mathbf{f'^2}}{\mathbf{4N^2}} \mathbf{D^*(\lambda)\tau_{OP}}}$$

- **Sp** is the entrance pupil diameter of the lens. The units are cm².
- $\boldsymbol{\tau_{op}}$ is the optical transmission of the lens. It is unitless.
- **f'** is the focal length of the lens. Beware, the units are cm.
- **N** is numerical aperture of the lens. It is unitless.

The other parameters are described above.

8.4. The NETD (Noise Equivalent Temperature Difference)

This corresponds to the minimal temperature that can be detected by the camera. This value is very similar to the NEP. The units are Kelvin (K).

$$\mathbf{NETD} = \frac{\mathbf{4N^2}\sqrt{\Delta\upsilon}}{\sqrt{\mathbf{A}}} \frac{\mathbf{1}}{\int_{\lambda_a}^{\lambda_b} \frac{\mathbf{d}\left(\frac{\mathbf{dR}}{\mathbf{d\lambda}}\right)}{\mathbf{dT}} \cdot \mathbf{D^*(\lambda)} \cdot \tau_{\mathbf{OP}}(\lambda) \cdot \mathbf{d\lambda}}$$

- **R** is given by the Planck formula.
- **λ_a and λ_b** are the spectral domain limits.

The other parameters are described above.

9. Numerical values

Let us consider the characteristics of a usual camera.

Camera	Detector pitch (µm)	Detector area (cm²)	Integration time (ms)	Bandwidth (Hz)
Silver MW	30	9×10^{-6}	4	167
Camera	Detectivity (W/cm/√Hz)	Focal length (cm)	Numerical aperture	Optical transmission
Silver MW	4.4×10^{11} for Ti = 3 ms	2.72	3	0.9

The usual values to characterize this infrared system are the following ones. We consider that the system is observing a source located at an infinite distance from the camera.

Geometric aperture	Detection solid angle	Detection etendue	NEP	NEI	NETD
α (rad)	Ω (sr)	G (cm².sr)	(W)	(W/cm²)	(K)
0.17 (=9.6°)	0.087	7.85×10^{-7}	8.8×10^{-14}	1.5×10^{-13}	0.017 (measured)

10. Emissivity table

This section presents a compilation of emissivity data from the infrared literature and FLIR Systems own measurements.

Table 5-1: T: Total spectrum; SW: 2–5 µm; LW: 8–14 µm, LLW: 6.5–20 µm; 1: Material; 2: Specification; 3: Temperature in °C; 4: Spectrum; 5: Emissivity: 6: Reference

1. Mikael A. Bramson: Infrared Radiation, A Handbook for Applications, Plenum press, N.Y.
2. William L. Wolfe, George J. Zissis: The Infrared Handbook, Office of Naval Research, Department of Navy, Washington, D.C.
3. Madding, R. P.: Thermographic Instruments and systems. Madison, Wisconsin:University of Wisconsin–Extension, Department of Engineering and Applied Science.
4. William L. Wolfe: Handbook of Military Infrared Technology, Office of Naval Research, Department of Navy, Washington, D.C.
5. Jones, Smith, Probert: External thermography of buildings..., Proc. of the Society of Photo-Optical Instrumentation Engineers, vol.110, Industrial and Civil Applications of Infrared Technology, June 1977, London.
6. Paljak, Pettersson: Thermography of Buildings, Swedish Building Research Institute, Stockholm 1972.
7. Vlcek, J: Determination of emissivity with imaging radiometers and some emissivities at l ~ 5 mm. Photogrammetric Engineering and Remote Sensing.
8. Kern: Evaluation of infrared emission of clouds and ground as measured by weather satellites, Defence Documentation Center, AD 617 417.
9. Ohman, Claes: Emittansmatningar med AGEMA E-Box. Teknisk rapport, AGEMA 1999. (Emittance measurements using AGEMA E-Box. Technical report, AGEMA 1999.)

1	2	3	4	5	6
Aluminum	anodized, black, dull	70	LW	0.95	9
Aluminum	anodized, black, dull	70	SW	0.67	9
Aluminum	anodized, light gray, dull	70	T	0.97	9
Aluminum	anodized, light gray, dull	70	T	0.61	9
Aluminum	anodized sheet	100	T	0.55	2
Aluminum	as received, plate	100	T	0.09	4
Aluminum	as received, sheet	100	T	0.09	2
Aluminum	cast, blast cleaned	70	LW	0.46	9
Aluminum	cast, blast cleaned	70	SW	0.47	9
Aluminum	dipped in HNO3, plate	100	T	0.09	4
Aluminum	Foil	27	3 µm	0.09	3
Aluminum	Foil	27	10 µm	0.04	3
Aluminum	oxidized, strongly	50-100	T	0.2-0.3	1
Aluminum	polished	50-100	T	0.04-0.06	1
Aluminum	polished, sheet	100	T	0.05	2
Aluminum	polished plate	100	T	0.05	4
Aluminum	roughened	27	3 µm	0.28	3
Aluminum	roughened	27	10 µm	0.18	3
Aluminum	rough surface	20-50	T	0.06-0.07	1
Aluminum	Sheet, 4 samples differently scratched	70	LW	0.03-0.06	9
Aluminum	Sheet, 4 samples differently scratched	70	SW	0.05-0.08	9
Aluminum	vacuum deposited	20	T	0.04	2
Aluminum	weathered, heavily	17	SW	0.83-0.94	5
Aluminum bronze		20	T	0.60	1
Aluminum hydroxide	powder		T	0.28	1
Aluminum oxide	activated, powder		T	0.46	1

Aluminum oxide	pure, powder alumina		T	0.16	1
Asbestos	Board	20	T	0.96	1
Asbestos	Fabric		T	0.78	7
Asbestos	floor tile	35	SW	0.94	1
Asbestos	Paper	40-400	T	0.93-0.95	1
Asbestos	Powder		T	0.40-0.60	1
Asbestos	Slate	20	T	0.96	8
Asphalt paving		4	LLW	0.967	1
Brass	dull, tarnished	20-350	T	0.22	9
Brass	oxidized	70	SW	0.04-0.09	9
Brass	oxidized	70	LW	0.03-0.07	2
Brass	oxidized	100	T	0.61	1
Brass	oxidized at 600 °C	200-600	T	0.59-0.61	1
Brass	polished	200	T	0.03	2
Brass	polished, highly	100	T	0.03	2
Brass	rubbed with 80- grit emery	20	T	0.20	1
Brass	Sheet, rolled	20	T	0.06	1
Brass	Sheet, worked with emery	20	T	0.2	5
Brick	Alumina	17	SW	0.68	5
Brick	common	17	SW	0.86-0.81	5
Brick	Dinas silica, glazed, rough	1100	T	0.85	1
Brick	Dinas silica, refractory	1000	T	0.66	1
Brick	Dinas silica, unglazed, rough	1000	T	0.80	1
Brick	firebrick	17	SW	0.68	5
Brick	Fireclay	20	T	0.85	1
Brick	fireclay	1000	T	0.75	1
Brick	fireclay	1200	T	0.59	1
Brick	masonry	35	SW	0.94	7
Brick	masonry, plastered	20	T	0.94	1
Brick	red, common	20	T	0.93	2

Brick	red, rough	20	T	0.88-0.93	1
Brick	refractory, corundum	1000	T	0.46	1
Brick	refractory, magnesite	1000-1300	T	0.38	1
Brick	refractory, strongly radiating	500-1000	T	0.8-0.9	1
Brick	refractory, weakly radiating	500-1000	T	0.65-0.75	1
Brick	Silica, 95 % SiO2	1230	T	0.66	1
Brick	sillimanite, 33 % SiO2, 64 % Al2O3	1500	T	0.29	1
Brick	waterproof	17	SW	0.87	5
Bronze	phosphor bronze	70	LW	0.06	9
Bronze	phosphor bronze	70	SW	0.08	9
Bronze	polished	50	T	0.1	1
Bronze	porous, rough	50-150	T	0.55	1
Bronze	Powder		T	0.76-0.80	1
Carbon	candle soot	20	T	0.95	2
Carbon	charcoal powder		T	0.96	1
Carbon	graphite, filed surface	20	T	0.98	2
Carbon	graphite powder		T	0.97	1
Carbon	lampblack	20-400	T	0.95-0.97	1
Chipboard	untreated	20	SW	0.90	6
Chromium	polished	50	T	0.10	1
Chromium	Polished	500-1000	T	0.28-0.38	1
Clay	Fired	70	T	0.91	1
Cloth	Black	20	T	0.98	1
Concrete		20	SW	0.92	2
Concrete	Dry	36	SW	0.95	7
Concrete	Rough	17	LLW	0.97	5
Concrete	Walkway	5	T	0.974	8
Copper	commercial, burnished	20	T	0.07	1
Copper	electrolytic, carefully polished	80	T	0.018	1
Copper	electrolytic, polished	-34	T	0.006	4
Copper	Molten	1100-1300	T	0.13-0.15	1

Copper	Oxidized	50	T	0.6-0.7	1
Copper	oxidized, black	27	T	0.78	4
Copper	oxidized, heavily	20	T		
Copper	oxidized to blackness		T	0.88	1
Copper	Polished	50-100	T	0.02	1
Copper	Polished	100	T	0.03	2
Copper	polished, commercial	27	T	0.03	4
Copper	polished, mechanical	22	T	0.015	4
Copper	pure, carefully prepared surface	22	T	0.008	4
Copper	Scraped	27	T	0.07	4
Copper dioxide	Powder		T	0.84	1
Copper oxide	red, powder		T	0.70	1
Ebonite			T	0.89	1
Emery	Coarse	80	T	0.85	1
Enamel		20	T	0.9	1
Enamel	Lacquer	20	T	0.85-0.95	1
Fiber board	hard, untreated	20	SW	0.85	6
Fiber board	Masonite	70	LW	0.88	9
Fiber board	Masonite	70	SW	0.75	9
Fiber board	particle board	70	LW	0.89	9
Fiber board	particle board	70	SW	0.77	9
Fiber board	porous, untreated	20	SW	0.85	6
Gold	Polished	130	T	0.018	1
Gold	polished, carefully	200-600	T	0.02-0.03	1
Gold	polished, highly	100	T	0.02	2
Granite	Polished	20	LLW	0.849	8
Granite	Rough	21	LLW	0.879	8
Granite	rough, 4 different samples	70	LW	0.77-0.87	9
Granite	rough, 4 different samples	70	SW	0.95-0.97	9
Gypsum		20	T	0.8-0.9	1
Ice: See Water			T		

Iron, cast	Casting	50	T	0.81	1
Iron, cast	Ingots	1000	T	0.95	1
Iron, cast	Liquid	1300	T	0.28	1
Iron, cast	Machined	800-1000	T	0.60-0.70	1
Iron, cast	Oxidized	38	T	0.63	4
Iron, cast	Oxidized	100	T	0.64	2
Iron, cast	Oxidized	260	T	0.66	4
Iron, cast	Oxidized	538	T	0.76	4
Iron, cast	oxidized at 600°C	200-600	T	0.64-0.78	1
Iron, cast	Polished	38	T	0.21	4
Iron, cast	Polished	40	T	0.21	2
Iron, cast	Polished	200	T	0.21	1
Iron, cast	Unworked	900-1100	T	0.87-0.95	1
Iron and steel	cold rolled	70	LW	0.09	9
Iron and steel	cold rolled	70	SW	0.20	9
Iron and steel	covered with red rust	20	T	0.61-0.85	1
Iron and steel	Electrolytic	22	T	0.05	4
Iron and steel	Electrolytic	100	T	0.05	4
Iron and steel	Electrolytic	260	T	0.07	4
Iron and steel	electrolytic, carefully polished	175-225	T	0.05-0.06	1
Iron and steel	freshly worked with emery	20	T	0.24	1
Iron and steel	ground sheet	950-1100	T	0.55-0.61	1
Iron and steel	heavily rusted sheet	20	T	0.69	2
Iron and steel	hot rolled	20	T	0.77	1
Iron and steel	hot rolled	130	T	0.60	1
Iron and steel	Oxidized	100	T	0.74	1
Iron and steel	Oxidized	100	T	0.74	4
Iron and steel	Oxidized	125-525	T	0.78-0.82	1
Iron and steel	Oxidized	200	T	0.79	2
Iron and steel	Oxidized	1227	T	0.89	4
Iron and steel	Oxidized	200-600	T	0.80	1
Iron and steel	oxidized strongly	50	T	0.88	1

Iron and steel	oxidized strongly	500	T	0.98	1
Iron and steel	Polished	100	T	0.07	2
Iron and steel	Polished	400-1000	T	0.14-0.38	1
Iron and steel	polished sheet	750-1050	T	0.52-0.56	1
Iron and steel	rolled, freshly	20	T	0.24	1
Iron and steel	rolled sheet	50	T	0.56	1
Iron and steel	rough, plane surface	50	T	0.95-0.98	1
Iron and steel	rusted, heavily	17	SW	0.96	5
Iron and steel	rusted red, sheet	22	T	0.69	4
Iron and steel	rusty, red	20	T	0.69	1
Iron and steel	shiny, etched	150	T	0.16	1
Iron and steel	Shiny oxide layer, sheet	20	T	0.82	1
Iron and steel	Wrought, carefully polished	40-250	T	0.28	1
Iron galvanized	heavily oxidized	70	LW	0.85	9
Iron galvanized	heavily oxidized	70	SW	0.64	9
Iron galvanized	Sheet	92	T	0.07	4
Iron galvanized	sheet, burnished	30	T	0.23	1
Iron galvanized	sheet, oxidized	20	T	0.28	1
Iron tinned	Sheet	24	T	0.064	4
Lacquer	3 colors sprayed on Aluminum	70	LW	0.92-0.94	9
Lacquer	3 colors sprayed on Aluminum	70	SW	0.50-0.53	9
Lacquer	Aluminum on rough surface	20	T	0.4	1
Lacquer	Bakelite	80	T	0.83	1
Lacquer	black, dull	40-100	T	0.96-0.98	1
Lacquer	black, matte	100	T	0.97	2
Lacquer	black, shiny, sprayed on iron	20	T	0.87	1
Lacquer	heat–resistant	100	T	0.92	1
Lacquer	White	40-100	T	0.8-0.95	1
Lacquer	White	100	T	0.92	2
Lead	oxidized, gray	20	T	0.28	1

Lead	oxidized, gray	22	T	0.28	4
Lead	oxidized at 200 °C	200	T	0.63	1
Lead	Shiny	250	T	0.08	1
Lead	unoxidized, polished	100	T	0.05	4
Lead red		100	T	0.93	4
Lead red, powder		100	T	0.93	1
Leather	Tanned		T	0.75-0.80	1
Lime			T	0.3-0.4	1
Magnesium		22	T	0.07	4
Magnesium		260	T	0.13	4
Magnesium		538	T	0.18	4
Magnesium	Polished	20	T	0.07	2
Magnesium powder			T	0.86	1
Molybdenum		600-1000	T	0.08-0.13	1
Molybdenum		1500-2200	T	0.19-0.26	1
Molybdenum	Filament	700-2500	T	0.1-0.3	1
Mortar		17	SW	0.87	5
Mortar	Dry	36	SW	0.94	7
Nichrome	Rolled	700	T	0.25	1
Nichrome	Sandblasted	700	T	0.70	1
Nichrome	wire, clean	50	T	0.65	1
Nichrome	wire, clean	500-1000	T	0.71-0.79	1
Nichrome	wire, oxidized	50-500	T	0.95-0.98	1
Nickel	bright matte	122	T	0.041	4
Nickel	Commercially pure, polished	100	T	0.045	1
Nickel	Commercially pure, polished	200-400	T	0.07-0.09	1
Nickel	Electrolytic	22	T	0.04	4
Nickel	Electrolytic	38	T	0.06	4
Nickel	Electrolytic	260	T	0.07	4
Nickel	Electrolytic	538	T	0.10	4
Nickel	electroplated, polished	20	T	0.05	2

Nickel	Electroplated on iron, polished	22	T	0.045	4
Nickel	electroplated on iron, unpolished	20	T	0.11-0.40	1
Nickel	electroplated on iron, unpolished	22	T	0.11	4
Nickel	Oxidized	200	T	0.37	2
Nickel	Oxidized	227	T	0.37	4
Nickel	Oxidized	1227	T	0.85	4
Nickel	oxidized at 600 °C	200-600	T	0.37-0.48	1
Nickel	Polished	122	T	0.045	4
Nickel	Wire	200-1000	T	0.1-0.2	1
Nickel oxide		500-650	T	0.52-0.59	1
Nickel oxide		1000-1250	T	0.75-0.86	1
Oil, lubricating	0.025 mm film	20	T	0.27	2
Oil, lubricating	0.050 mm film	20	T	0.46	2
Oil, lubricating	0.125 mm film	20	T	0.72	2
Oil, lubricating	film on Ni base: Ni base only	20	T	0.05	2
Oil, lubricating	thick coating	20	T	0.82	2
Paint	8 different colors and qualities	70	LW	0.92-0.94	9
Paint	8 different colors and qualities	70	SW	0.88-0.96	9
Paint	Aluminum, various ages	50-100	T	0.27-0.67	1
Paint	cadmium yellow		T	0.28-0.33	1
Paint	chrome green		T	0.65-0.70	1
Paint	cobalt blue		T	0.7-0.8	1
Paint	Oil	17	SW	0.87	5
Paint	oil, black flat	20	SW	0.94	6
Paint	oil, black gloss	20	SW	0.92	6
Paint	oil, gray flat	20	SW	0.97	6
Paint	oil, gray gloss	20	SW	0.96	6
Paint	oil, various colors	100	T	0.92-0.96	1
Paint	oil based, average of 16 colors	100	T	0.94	2

Paint	plastic, black	20	SW	0.95	6
Paint	plastic, white	20	SW	0.84	6
Paper	4 different colors	70	LW	0.92-0.94	9
Paper	4 different colors	70	SW	0.68-0.74	9
Paper	Black		T	0.90	1
Paper	black, dull		T	0.94	1
Paper	black, dull	70	LW	0.89	9
Paper	black, dull	70	SW	0.86	9
Paper	blue, dark		T	0.84	1
Paper	coated with black lacquer		T	0.93	1
Paper	Green		T	0.85	1
Paper	Red		T	0.76	1
Paper	White	20	T	0.7-0.9	1
Paper	white, 3 different glosses	70	LW	0.88-0.90	9
Paper	white, 3 different glosses	70	SW	0.76-0.78	9
Paper	white bond	20	T	0.93	2
Paper	Yellow		T	0.72	1
Plaster		17	SW	0.86	5
Plaster	plasterboard, untreated	20	SW	0.90	6
Plaster	rough coat	20	T	0.91	2
Plastic	glass fibre laminate (printed circ. board)	70	LW	0.91	9
Plastic	glass fibre laminate (printed circ. board)	70	SW	0.94	9
Plastic	Polyurethane isolation board	70	LW	0.55	9
Plastic	Polyurethane isolation board	70	SW	0.29	9
Plastic	PVC, plastic floor, dull, structured	70	LW	0.93	9
Plastic	PVC, plastic for, dull, structured	70	SW	0.94	9
Platinum		17	T	0.016	4
Platinum		22	T	0.03	4
Platinum		100	T	0.05	4

Platinum		260	T	0.06	4
Platinum		538	T	0.10	4
Platinum		1000-1500	T	0.14-0.18	1
Platinum		1094	T	0.18	4
Platinum	pure, polished	200-600	T	0.05-0.10	1
Platinum	Ribbon	900-1100	T	0.12-0.17	1
Platinum	Wire	50-200	T	0.06-0.07	1
Platinum	Wire	500-1000	T	0.10-0.16	1
Platinum	Wire	1400	T	0.18	1
Porcelain	Glazed	20		0.92	1
Porcelain	white, shiny		T	0.70-0.75	1
Rubber	Hard	20	T	0.95	1
Rubber	soft, gray, rough	20	T	0.95	1
Sand			T	0.60	1
Sand		20	T	0.90	2
Sandstone	Polished	19	LLW	0.909	8
Sandstone	Rough	19	LLW	0.935	8
Silver	Polished	100	T	0.03	2
Silver	pure, polished	200-600	T	0.02-0.03	1
Skin	Human	32	T	0.98	2
Slag	Boiler	0-100	T	0.97-0.93	1
Slag	Boiler	200-500	T	0.89-0.78	1
Slag	Boiler	600-1200	T	0.76-0.70	1
Slag	Boiler	1400-1800	T	0.69-0.67	1
Snow: See Water					
Soil	Dry	20	T	0.92	2
Soil	saturated with water	20	T	0.95	2
Stainless steel	alloy, 8 % Ni, 18 % Cr	500	T	0.35	1
Stainless steel	Rolled	700	T	0.45	1
Stainless steel	Sandblasted	700	T	0.70	1
Stainless steel	sheet, polished	70	LW	0.14	9
Stainless steel	sheet, polished	70	SW	0.18	9
Stainless steel	sheet, untreated, somewhat scratched	70	LW	0.28	9

Stainless steel	sheet, untreated, somewhat scratched	70	SW	0.30	9
Stainless steel	type 18-8, buffed	20	T	0.16	2
Stainless steel	type 18-8, oxidized at 800 °C	60	T	0.85	2
Stucco	rough, lime	10-90	T	0.91	1
Styrofoam	Insulation	37	SW	0.60	7
Tar			T	0.79-0.84	1
Tar	Paper	20	T	0.91-0.93	1
Tile	Glazed	17	SW	0.94	5
Tin	Burnished	20-50	T	0.04-0.06	1
Tin	tin–plated sheet iron	100	T	0.07	2
Titanium	Oxidized at 540 °C	200	T	0.40	1
Titanium	Oxidized at 540 °C	500	T	0.50	1
Titanium	Oxidized at 540 °C	1000	T	0.60	1
Titanium	Polished	200	T	0.15	1
Titanium	Polished	500	T	0.20	1
Titanium	Polished	1000	T	0.36	1
Tungsten		200	T	0.05	1
Tungsten		600-1000	T	0.1-0.16	1
Tungsten		1500-2200	T	0.24-0.31	1
Tungsten	Filament	3300	T	0.39	1
Varnish	Flat	20	SW	0.93	6
Varnish	on oak parquet floor	70	LW	0.90-0.93	9
Varnish	on oak parquet floor	70	SW	0.90	9
Wallpaper	slight pattern, light gray	20	SW	0.85	6
Wallpaper	slight pattern, red	20	SW	0.90	6
Water	Distilled	20	T	0.96	2
Water	frost crystals	-10	T	0.98	2
Water	ice, covered with heavy frost	0	T	0.98	1
Water	ice, smooth	-10	T	0.96	2
Water	ice, smooth	0	T	0.97	1
Water	layer >0.1 mm thick	0-100	T	0.95-0.98	1

Water	Snow		T	0.8	1
Water	Snow	-10	T	0.85	2
Wood		17	SW	0.98	5
Wood		19	LLW	0.962	8
Wood	Ground		T	0.5-0.7	1
Wood	pine, 4 different samples	70	LW	0.81-0.89	9
Wood	pine, 4 different samples	70	SW	0.67-0.75	9
Wood	Planed	20	T	0.8-0.9	1
Wood	planed oak	20	T	0.90	2
Wood	planed oak	70	LW	0.88	9
Wood	planed oak	70	SW	0.77	9
Wood	plywood, smooth, dry	36	SW	0.82	7
Wood	plywood, untreated	20	SW	0.83	6
Wood	white, damp	20	T	0.7-0.8	1
Zinc	oxidized at 400 °C	400	T	0.11	1
Zinc	oxidized surface	100-1200	T	0.50-0.60	1
Zinc	Polished	200-300	T	0.04-0.05	1
Zinc	Sheet	50	T	0.20	1