1 Imaging – an introduction

Imaging is a process that produces an image of some part of our surroundings - while visualization – the rendering an image of a mathemathical function - is not considered to be imaging. The image that is produced may be projected onto a screen for viewing, or it may be captured on film or some digital detector matrix for storage and processing.

The image stored may be a two-dimensional matrix of intensity values, one such matrix for each of a number of wavelengths – giving a three-dimensional dataset, one such set for each of several instances in time – giving a four-dimensional dataset. Or it may be a three-dimensional image depicting physical properties, obtained by e.g. CT or MR-scanning of a human body or seismic exploration of the limestone deep down under the North Sea. If the 3D dataset is obtained at several frequencies, we may regard it as a 4D set. If the 4D set is repeated at several instances in time, we may regard it as a 5D dataset.

The data stored is not necessarily an image matrix containing intensities or absorption values. It may just as well be a matrix of coefficients that may later be transformed into an image. And the imaging may occur at wavelengths where we are used to see images using our own visual system – the eye and the brain, or it may occur at completely different wavelengths, giving images that are not obtainable by the naked eye.

1.1 Passive imaging

In passive imaging we utilize energy sources that are not part of the imaging system – usually sources that are naturally available. We then either image the sources that are present in the scene, or let the energy source light up the objects within the scene.

An example of the former is infrared (IR) imaging of heat sources or leaks in a construction, or IR images of people at night. Such passive imaging of heat sources has a number of military as well as civilian applications. Astronomical images of visual as well as gamma, X-ray, UV, IR, microwave and radio sources also belong in this category.

If an energy source lights up the objects of a scene, we will image that part of the radiation that is reflected at a given wavelength, or absorbed and then reemitted at a different wavelength. Different objects or different parts of the same object may have different absorption- and reflection properties. Highly absorbing objects may then look dark, and the spectral distribution of the absorption will determine the apparent color of the object. The reflection properties will determine whether the objects acts as a highly reflective mirror or a matte and diffuse surface. And the orientation of the surface, its shape and fine structure, will influence how the object is imaged.

The result of a passive imaging is obviously very dependent on the nature of the energy source. The most frequently used source is sunlight, which is only available when the Sun is not too far below the horizon. And although the Sun may be considered as a constant source of energy, the amount and color of the light received depends on several factors, like atmospheric phenomena, the time of day, our position on the Earth, as well as on the time of year, as exemplified in figure 1-1.

Figure 1-1. Midnight sun at 69° northern latitude.

1.2 Active imaging

In active imaging we have to provide the energy source to illuminate the scene that is to be imaged, and then either image the radiation that is reflected from the objects, or image the fraction of the energy that passes through the object. Thus, active imaging is not hampered by unpredictable variations in the light source, and we are able to obtain images regardless of time of day or time of year. However, the total process is often more complex and costly, since it also includes the generation and emission of a calibrated amount of energy.

Active imaging is found in radar, sonar and seismic, where an emitted pulse of energy is reflected from a number of different objects or interfaces between different objects. The time it takes for the reflected pulse to reach the detector – together with the direction of the reflected energy – helps us construct an image. Usually, a large number of pulses are transmitted, and patterns encoded into each pulse helps us keeping track of the reflected pulses that are received.

Active imaging is utilized in many medical applications – like ultrasound, X-ray, CT, MR and PET-imaging, which we will describe later.

1.3 Spectral distribution of radiation

Before entering into the realms of optics, it may be instructive to include a couple of facts about electromagnetic radiation in general and visible light in particular, how energy is distributed over wavelength, as well as how we can characterize the color of light by measuring the intensity at a few wavelengths. Figure 1-2 shows typical wavelengths and frequencies for different parts of the electromagnetic spectrum. Note that visible light is only a tiny fraction of the whole spectrum.

The energy emitted by a given source of radiation at a given wavelength depends on the temperature of the source. Our primary source of energy, the Sun, may serve as an example. It behaves like a “black body” radiator with temperature $T \approx 5780$ K. The

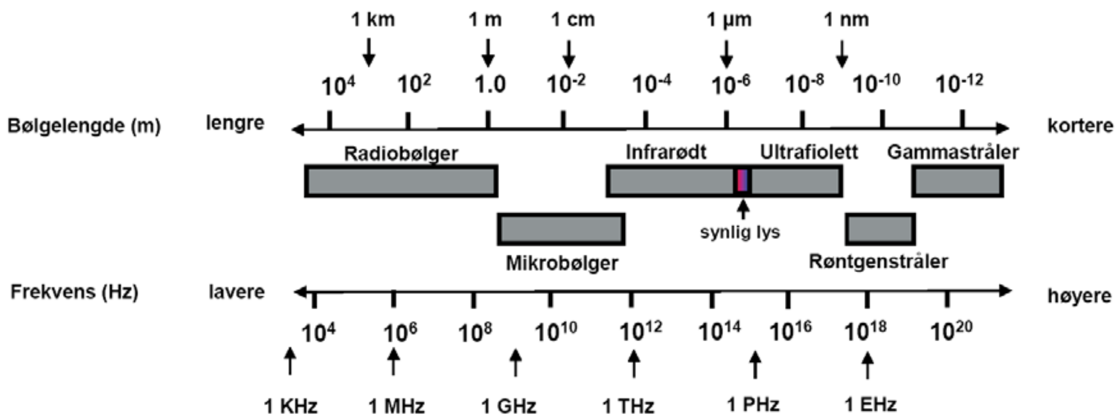


Figure 1-2. Wavelengths and frequencies for different parts of the spectrum.

emitted energy varies with wavelength according to Planck's equation

$$M(\lambda,T) = \frac{2hc^2}{\lambda^5} \cdot \frac{\pi}{e^{\frac{hc}{\lambda kT}} - 1}$$

where

- λ is the wavelength (m)
- T is the temperature (K)
- h is Planck's constant = $6.6260693 \cdot 10^{-34}$ Js,
- c is the speed of light = $2.99792458 \cdot 10^{8}$ m/s,
- k is Boltzmann's constant = $1.3806505 \cdot 10^{-23}$ J/K

M is the spectral emittance, given as energy (W) per unit area (m^2) per wavelength (m).

For a blackbody radiator, the wavelength of maximum emission is given by Wien's displacement law

$$\lambda_{\max} = \frac{2897}{T}$$

where λ_{max} is the wavelength of maximum emittance, given in µm. We see that as the Sun has an average surface temperature of T≈ 5780 K, we get λ_{max} = 2897/5780 ≈ 0.5 µm. The average temperature of the Earth's surface is about 287 K, so its emission spectrum peaks in the infrared part of the spectrum, around 10 µm.

The Earth only receives a small fraction of the total radiation emitted by the Sun, since the energy passing through the spherical surface of the Sun is spread out evenly over a sphere having a radius equal to the distance of the Earth from the Sun. Thus, the exo-atmospheric solar spectral irradiance, E_0, i.e., the amount of solar radiation incident at the top of the Earth's atmosphere, is given by

$$E_0(\lambda,T) = \frac{2hc^2}{\lambda^5} \cdot \frac{\pi}{e^{\frac{hc}{\lambda kT}} - 1} \left(\frac{r}{d}\right)^2$$

where

- r is the radius of the Sun = 6.96 $\bullet 10^{8}$ m
- d is the mean distance Earth – Sun = 1.5 $\bullet 10^{11}$ m.

Figure 1-3 shows this spectral irradiance in units of W/m^2/µm.

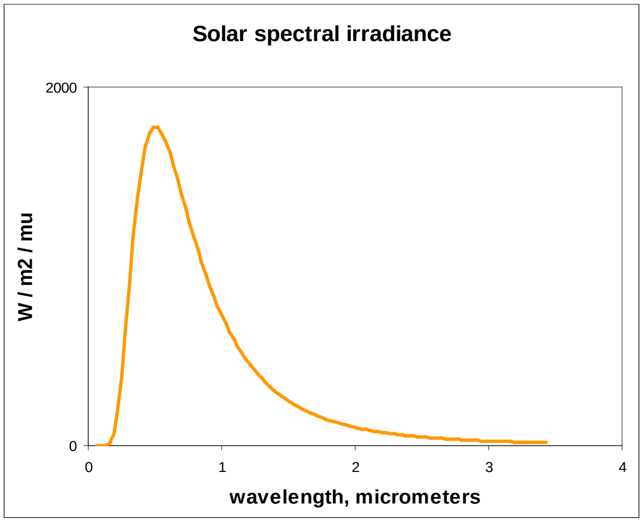


Figure 1-3. Exo-atmospheric solar spectral irradiance, E_0 – i.e., the amount of energy incident at the top of the Earth's atmosphere per unit area per wavelength interval.

Now, only a part of the total exo-atmospheric solar irradiance reaches the Earth surface. Some is absorbed by gases and particles in the atmosphere, some is scattered back out to space by aerosols and clouds. The combined effect is to attenuate the incident solar radiation as it passes down through the atmosphere.

The fraction of incident solar radiation that is absorbed by atmospheric gases varies as a function of wavelength, but is relatively stable over time and space. Figure 1-4 shows the transmittance of the standard atmosphere when light travels vertically down through the atmosphere to sea level. Note that absorption is strong in the ultraviolet and in some bands in the infrared.

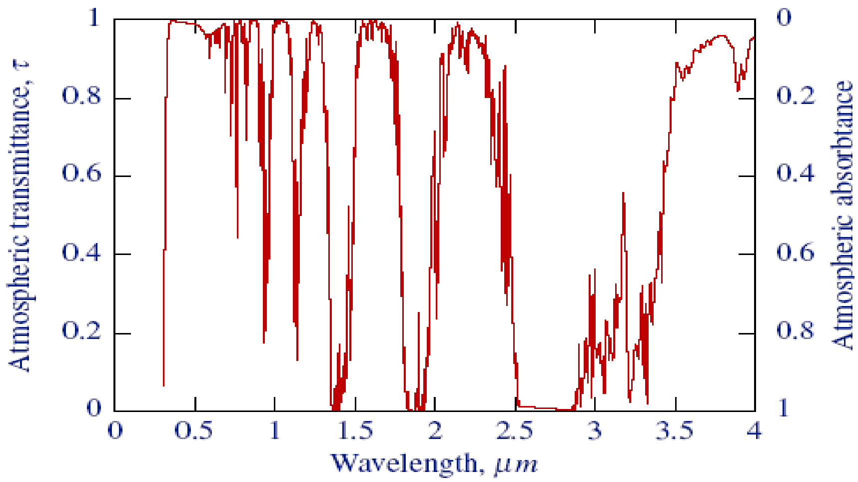


Figure 1-4. Atmospheric transmittance (left) and corresponding absorbtance (right).

The actual attenuation depends on the path length that the radiation has to travel through the atmosphere. This again depends on the altitude of the terrain and the angle of the Sun above the horizon, which is itself a function of the latitude of the site and the time of day and year.

The direct and the diffuse solar radiation incident on a horizontal surface are given by

$$I_{total} = I_{direct} + I_{diffuse}; \quad I_{direct} = E_0 \tau^m \cos(z); \quad I_{diffuse} = 0.3 E_0 \left(1 - \tau^m\right) \cos(z)$$

where τ is the atmospheric transmittance, m is the air mass and z is the solar zenith angle (i.e. the angle of the Sun relative to a point directly above the observer). For a flat atmosphere, the air mass at sea level, m, is given by

$$m = \frac{1}{\cos(z)}$$

The solar zenith angle, z, varies with latitude, time of year and time of day:

$$\cos z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos H$$

where ϕ is the geographical latitude of the site, δ is the solar declination angle (its angular distance from the celestial equator) and H is the hour angle of the Sun (its angular distance from the local meridian), given by $H \approx 15(12\text{-}h)$, where h is the local solar time in hours. The solar declination angle varies as a function of the time of year, i.e.:
$\delta = -23.4° \cos(360(D + 10)/365))$ where D is the day of year.

Figure 1-5 shows the irradiance ($W/m^2/\mu m$) outside the atmosphere, and at sea level for m=1.5. If the Sun closer to the horizon, the curve is almost flat in the visible range of 400-700 nm, so sunlight may be described as "white".

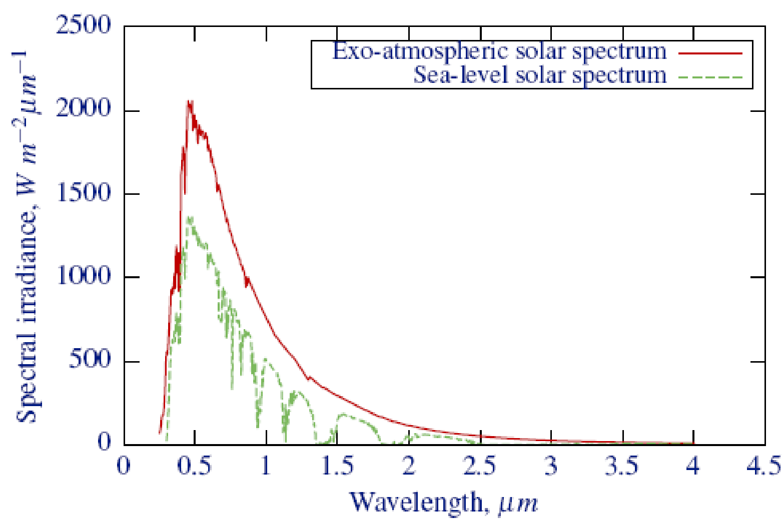


Figure 1-5. The solar spectral irradiance above the atmosphere together with the spectral irradiance at sea level for 1.5 air mass.

1.4 The color of images

The perceived color of an object is determined by the light reflected from the object. Thus, the color is a function of both the color of the light falling onto the object and the reflection properties of the surface of the object. Visible light is only a tiny fraction of the electromagnetic spectrum, but if the object is reflecting approximately equal amounts of all visible wavelengths, it will appear white or gray, while an object reflecting only a small part of the visible spectrum will appear to have some color. The wavelength range of seven different colors is indicated in figure 1-6.

Red	~ 625 - 740 nm
Orange	~ 590 - 625 nm
Yellow	~ 565 - 590 nm
Green	~ 500 - 565 nm
Cyan	~ 485 - 500 nm
Blue	~ 440 - 485 nm
Violet	~ 380 - 440 nm

Figure 1-6. Typical wavelengths (in nanometers) for seven different colors.

The retina of our eye is sensitive to light having wavelengths between approximately 350 and 760 nanometer (nm = 10^{-9} meter). There are three types of color-sensitive cones responsible for our *photopic* (high intensity) vision:

- S-cones (”short wavelength cones”) are most sensitive to violet light; their light sensitivity function peaks at 420 nm, and they are therefore called “blue” cones. Only 2% of the cones are of this type, but they have the highest sensitivity.

The two other types are both sensitive to light that we perceive as shades of green.

- L-cones (“long wavelength cones”) are most sensitive to yellow-green light. Their sensitivity curve peaks at 564 nm, but as they are closest to red of the two, they are called ”red” cones. 65% of the cones are this type.
- M-cones (”middle wavelength cones”) are most sensitive to green light. Their sensitivity curve peaks at 534 nm, thus they are called ”green” cones. 33% of the cones are this type.

Figure 1-7 shows the spectral distribution of the normalized light sensitivity curves for the three retinal cone types, as well as the spectral distribution of the several thousand times more sensitive retinal rods, responsible for our *scotopic* – low intensity – vision. The bell-shaped cone sensitivity curves overlap considerably, but they reduce the spectrum of light falling onto the retina into three *tristimulus*-values – so that we may perceive the color of the light. Thus, it is natural to describe color by three components. The same scheme is used in RGB color cameras.

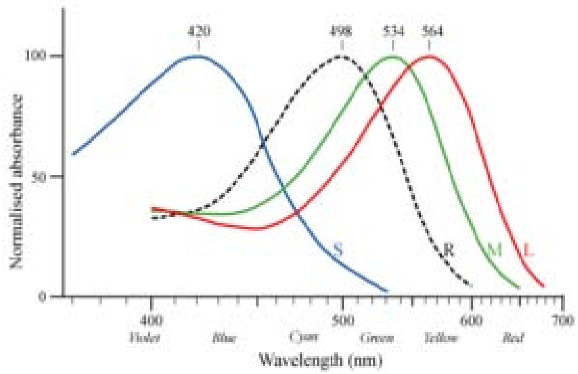


Figure 1-7. Normalized light sensitivity curves for retinal cones (S, M, L) and rods (R).

To make a color image of an object, for example the fruit in figure 1-8, light from a light source, e.g. the Sun, having a spectral distribution E(λ) must fall on the object. The surface of the object does not reflect the same amount of radiation at all wavelengths; it has a spectral reflection function S(λ). And the reflected light entering the eye is detected by the three cone types, each having a spectral sensitivity function (q) that varies with the wavelength – as we saw in figure 1-7. The "Commision Internationale de l'Eclairage" (CIE) has defined the primary colors of the RGB system: Blue = 435.8 nm, Green = 546.1 nm, and Red = 700.0 nm, and has also provided standard light sensitivity curves for the three color components. The three resulting analog signals may be expressed as three simple integrals giving a three-channel image:

$$R = \int E(\lambda)\, S(\lambda)\, q_R(\lambda)\, d\lambda$$

$$G = \int E(\lambda)\, S(\lambda)\, q_G(\lambda)\, d\lambda$$

$$B = \int E(\lambda)\, S(\lambda)\, q_B(\lambda)\, d\lambda$$

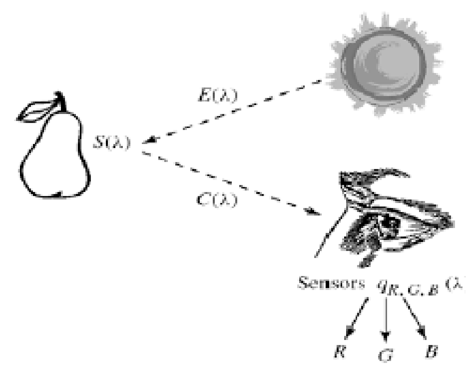


Figure 1-8. Color perception. (From Li and Drew: Fundamentals of Multimedia, 2004)

1.5 Pseudo-color and false-color images

Pseudo-color images are single-channel (graylevel) images where a color has been assigned to each graylevel. The sunspot image of figure 1-9 shows an example of this technique. The original image has been obtained using a narrow band (monochromatic) filter – in order to as sharp an image as possible – and has been recorded as a graylevel image. Thereafter, a lookup-table is used to map each graylevel to an RGB-value in order to display the single-channel image as a pseudo-color image that looks more natural.

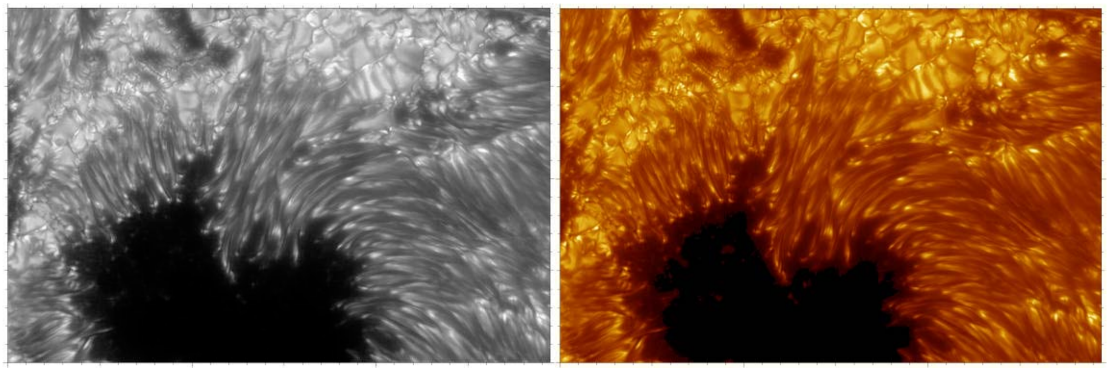
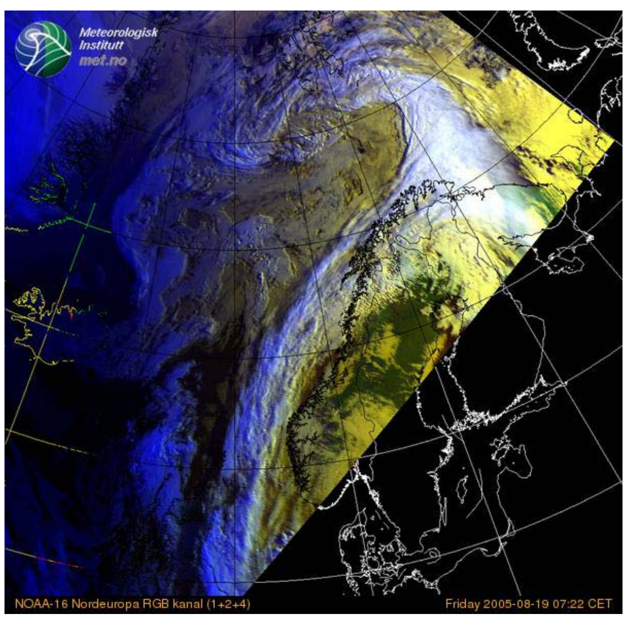
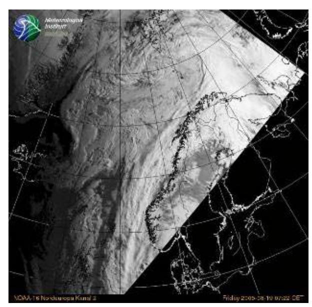


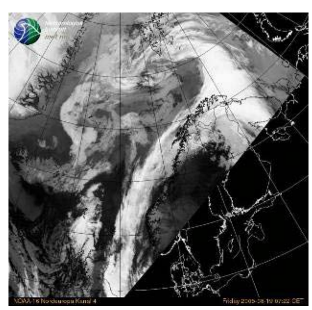
Figure 1-9. A graylevel sunspot image (left), and the same image in pseude-color (right). © Royal Swedish Academy of Sciences.

In ***false-color*** images we have e.g. three graylevel images from three different wavelengths, and assign each of them to the primary colors R, G and B, even though the wavelengths used did not correspond to R, G, and B. The result is an image of the observed scene using colors that are different from those actually observed. An example is the NOAA AVHRR satellite images often displayed by weather services on TV or internet. Figure 1-10 shows an example of such an image. Three graylevel images of the same area – two in the visual wavelength range (channel 1: 580-680 nm, channel 2: 725 – 1 000 nm), and one in the near infrared (channel 4: 1 030 – 1 130 nm) are displayed as an RGB image. And since the three channels do not observe radiation at the defined RGB-wavelengths of 700 nm, 546.1 nm and 435.8 nm, this is a *false-color image.*





Channel 2



Channel 4

Channel 1+2+4 as RGB

Figure 1-10. A NOOA AVHRR satellite image, where channel 1 + 2 + 4 are shown as an RGB-image, i.e., a false-color image. The image shows the cloud cover of 19.08.2005, together with land contours. © Norwegian Meteorological Institute.