The reflection of two fields – Electromagnetic radiation and its role in (aerial) imaging

Article · October 2017

DOI: 10.5281/zenodo.3534245

Geert J. Verhoeven
University of Vienna

ISSN 1756-753X

AARGnews

Number 55 October 2017

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Several months ago Geert Verhoeven asked if AARGnews *would be interested in a series of technical contributions, to which my reply was "Yes please". The text below is his introduction explaining his aims for the series and its contents.*

If any readers want a more technical version, it can be found as part of Geert's paper in Stylianidis, E and Remondino, F., 2016. *3D Recording, Documentation and Management of Cultural Heritage*. Whittles Publishing: Dunbeith.

Geert's aerial pixel corner

In this "corner", I will try to share some insights about the rather technical world of remote sensing. The idea of this column is to unveil some of the most useful principles of digital imaging and provide easy-to-understand explanations of abstract but archaeologically-relevant image processing concepts. That is why I will try to keep an informal style while using ample illustrations. I sincerely hope that the reader gets a better understanding of the topics at hand, which might in turn help them to recognise and solve their own digital image processing needs.

The first article will address the nature of electromagnetic radiation and explain how its various ways of reflection determine image creation. In the next contribution, I will address the fundamental building block of all digital imagery: the pixel. What is this concept we call "pixel"? Why is it often explained wrongly to be a square and how can a more accurate description improve our general understanding of images?

In future volumes of *AARGnews*, we will draw upon both these concepts and explain how a monochromatic, two-band, three-band, multi- and hyperspectral pixel stores some form of spectral reflectance data. These concepts will prove helpful in debunking some major myths about spatial, radiometric and spectral image resolution, while also aiding a low-tech explanation of image sharpening and deblurring algorithms.

Afterwards, I plan to explain two abundantly used but ill-understood image processing techniques: principal component analysis and the computation of vegetation indices.
It goes without saying that I remain open for any suggestion about future topics and that I welcome any addition, doubt or criticism you might have on these scribbles.

Happy reading.

Geert

The reflection of two fields – Electromagnetic radiation and its role in (aerial) imaging

Geert Verhoeven[1]

Since air- or spaceborne imaging usually records how an object or a scene interacts with solar radiant energy (amongst many other interactions such as those taking place in the atmosphere and inside the camera), it is advisable to start our journey with a concise exploration of the world of electromagnetic energy. This entry will give some highly simplified insights into the properties of electromagnetic radiation and explain how they are harnessed when creating a digital image from a terrestrial or aloft platform. These insights should serve as essential building blocks for future entries. Since the latter will focus on the imaging pipeline of a digital camera and tackle related concepts such as spatial, spectral and radiometric resolution, they will build upon the concepts introduced here.

1 What is light?

1.1 Light is fast

Everybody knows the expression "the speed of light" and some people might even remember that it is about 300 000 km per second. Well, to be accurate, this "speed of light" should be denoted "the speed of light in vacuum" because the velocity of light will decrease when travelling in air, glass, water or other transparent substances. Moreover, this speed is not exclusively related to light. Any massless particle will always travel at this velocity in a vacuum. If scientists did not discover gravitation waves in 2016 but already two centuries before, this speed might nowadays be denoted "the gravitational wave velocity". However, since light was the only massless physical entity that was known in the 1800s, this velocity is currently known as the speed of light and symbolised by *c*. Moreover, *c* is exactly 299,792,458 m/s. Why exactly? Because this is the number that physicists agreed upon to be the vacuum speed of light. This fixed quantity has also been used to redefine a "metre". Today, the official definition of one meter is 1 / 299,792,458th of the distance travelled by light in a vacuum in 1 second. As a consequence, one cannot remeasure and redefine the speed of light in vacuum, since one must use the definition of a meter to measure it, but the latter definition relies on the speed of light in vacuum.

This speed of light in vacuum is very special. Everybody will observe anything massless travelling at this speed irrespective of their motion. For example, if one would be in a high-speed rocket flying along a green laser beam, one would come up with the same velocity of that light beam as when standing still on Earth. This vacuum speed of light is, therefore, said to be **invariant for any possible observer** and as such also known as the invariant speed of relativity theory.

Finally, it is also wrong to state that the speed of light in a vacuum is the fastest observable phenomenon. If one would quickly sweep an Earth-bounded laser beam across the moon, the velocity of the laser spot could easily exceed the vacuum speed of light. In addition, some physicists also hypothesise about **tachyons**: particles that, at least in theory, travel faster than light in vacuum.

[1] Geert.Verhoeven@archpro.lbg.ac.at

Although relativity theory does not forbid their existence, they are highly debatable since they could violate causality by sending signals to the past.

1.2 Light is wave-like and part of a wider spectrum

However, what exactly is light? Light is a tiny part of the phenomenon we call electromagnetic radiation. It bears that name because electricity and magnetism are intimately related. Moving a magnet around an electric wire "pushes" electrons in the wire and creates an electric current. The reverse relationship also holds. Just as a moving magnetic field generates an electric field, a moving electric field will produce a magnetic field. Since both "fields" create each other, they oscillate together and create a so-called electromagnetic wave (Figure 1). The Scottish physicist James Clerk Maxwell (1831-1879) found out that this is the very nature of light. He was the first to accurately describe the relationship between these magnetic and electric fields in a famous set of equations.

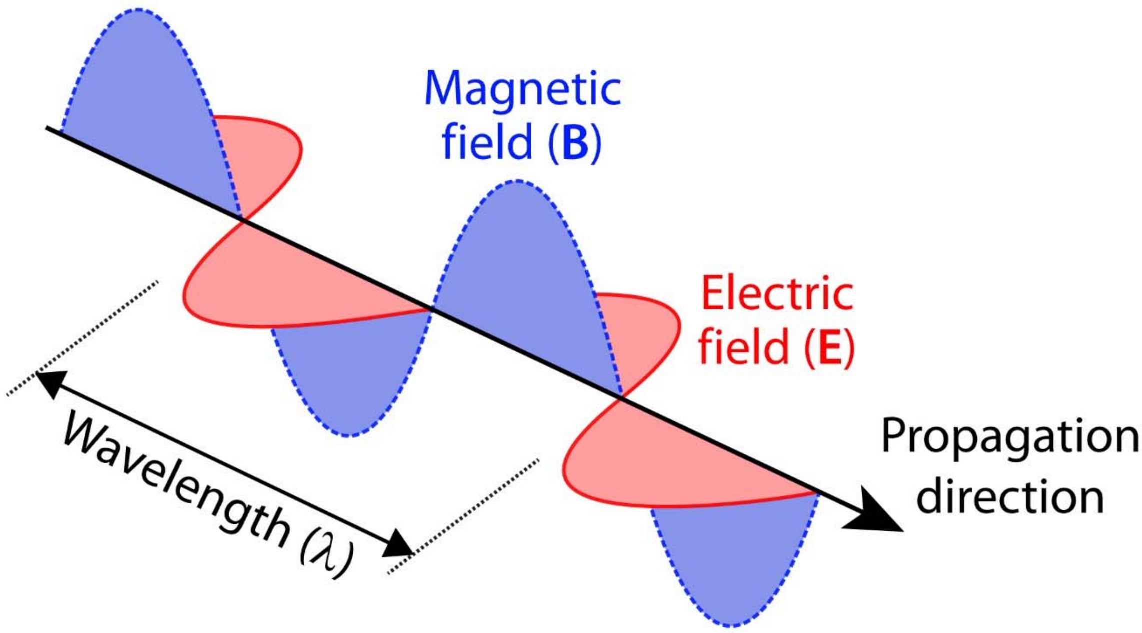

Figure 1 – An electromagnetic wave consisting of electric and magnetic oscillating fields. In this example, the oscillating electric field vectors are indicated in red, while the blue lines represent the magnetic field vectors.

Being a wave-like phenomenon, electromagnetic radiation can be distinguished by the length of its waves, called the wavelength (λ). Electromagnetic radiation with a wavelength between 400 nm ($400 * 10^{-9}$ m) to 700 nm ($700 * 10^{-9}$ m) is called visible light or simply light. Light is thus only a very narrow spectral band out of all possible electromagnetic radiation and the only wavelengths to which human eyes respond with a visual sensation.

In the visible wavelength range, each wavelength of light correlates with a sensory impression of a particular colour (or more technically correct "hue", but that is for another time). Even though colour is thus not a physical property of the electromagnetic radiation itself, the light spectrum may be divided roughly as indicated in Figure 2. The latter shows that the light spectrum contains all hues that are visible in a rainbow: varying from Red on the long-wavelength side over Orange, Yellow, Green and Blue to Violet on the short-wavelength side. For the sake of simplicity, the visible spectrum is usually considered to consist of only three bands: Blue (400 nm – 500 nm), Green (500 nm – 600 nm) and Red (600 nm – 700 nm). Although a coarse approximation, many image-related devices such as digital cameras and monitors base their physical working principles on this subdivision.

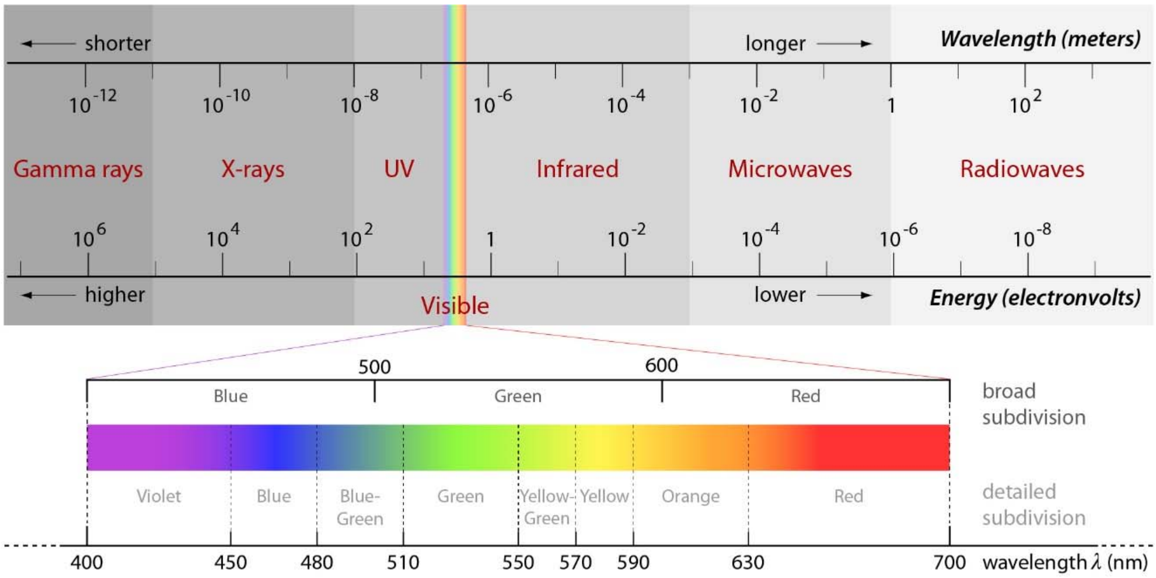

Figure 2 – The complete electromagnetic spectrum with the spectral subdivisions of the visible waveband.

Nonetheless, the complete electromagnetic spectrum consists of far more particular wavebands with characteristic wavelengths that are not perceivable by the unaided normal human eye. As an example, radio waves are also electromagnetic radiation. However, we have to build specific sensors (e.g. ground-penetrating radars) to utilise those wavelengths, since they are useless for the human eye. To both sides of the visible band resides radiation that does not produce a visual sensation: gamma rays, X-rays and ultraviolet radiation with shorter-than-visible wavelengths, while the long-wavelength region encompasses infrared radiation, microwaves and radiowaves (Figure 2).

1.3 Light is particle-like

In addition to the wave properties mentioned above, electromagnetic radiant energy is known to exhibit particle-like behaviour. The latter leads many to write that one can conceptualise electromagnetic radiation also as a travelling bundle of indivisible particles or photons. These photons are discrete energy packets with energy levels that differ according to the wavelength. In this sense, electromagnetic radiation can be considered a vehicle for transporting energy from the radiation source to a destination, photons or quanta being the particles of the radiant energy. Since all photons travel at the vacuum speed of light and nothing with mass can ever attain that speed according to Einstein's special theory of relativity, photons must be massless.

Creating a more intense beam of radiant energy while keeping the wavelength the same means a tighter packing of the photons in that beam so that the radiant flux (i.e. the amount of photons passing a given point in a given time) increases. Even so, each photon in the more intense beam has the equal amount of energy as those in the less intense beam. Due to this quantization, a visible photon with a wavelength of 650 nm will always have 1.9 eV of energy, while photons with quantum energies of 3.6 eV characterise 345 nm ultraviolet radiation. From these numbers, it is evident that shorter wavelengths have higher radiative energies (see also Figure 2). This also explains why highly energetic ultraviolet radiation causes sunburns.

1.4 Is light now a wave or a particle?

None of the wave-like and particle-like descriptions of electromagnetic radiation is complete by itself, but each of them a valid description of some aspects of its behaviour. This wave-particle duality is still one of the key concepts in quantum mechanics, which states that all things are both waves and particles at the same time and that nothing can be predicted or known with absolute certainty. Despite being mind-blowing, one could as well forget about this wave-particle duality if in need for absolute physical accuracy. In essence, there are no waves and no particles, just quantised fields with discrete excitations. That is also the reason why quantum field theory is the theoretical framework behind the standard model of particle physics. However, to understand how solar radiant energy contributes to the imaging process, this naïve interpretation of electromagnetic radiation as both "waves" and "particles" is satisfying enough.

2 Remotely imaging optical radiation

2.1 Remote sensing

Remote sensing is the collection of data about a scene or object without having direct physical contact with it. In archaeology, remote sensing is a general name given to all techniques that use propagated signals to observe the Earth's surface from above. Based on their specific characteristics, remote sensing techniques can be classified in different ways: imaging versus non-imaging, passive versus active, optical versus non-optical, airborne versus spaceborne. Whereas passive remote sensing systems capture naturally occurring radiation, active systems produce their own radiation. Airborne systems operate from within the Earth's atmosphere, while spaceborne systems deploy a sensor mounted onboard a spacecraft (often a satellite) that orbits the Earth. When dealing with an imaging system, the output is an image, whereas non-imaging systems can deliver sounding data or emission spectra.

2.2 Optical remote imaging

Although exceptions exist, archaeological air- and spaceborne imaging generally refers to the amalgam of passive remote sensing techniques that capture a specific part of the Earth's reflected solar energy or self-emitted thermal energy and turn that into a (digital) image. In addition, these remote imagers only operate in the optical electromagnetic spectrum (Figure 3), which conventionally incorporates the complete ultraviolet to infrared bandwidth, comprising radiation with wavelengths between 10 nm (0.01 µm) to 1 mm (1000 µm). However, remotely-sensed imaging in the optical range usually begins at the visible waveband (i.e. 400 nm–700 nm). Together with the near-infrared (NIR; 700 nm–1100 nm) and short wavelength infrared (SWIR; 1.1 µm–3 µm), this waveband is known as the **solar-reflective** spectral range because reflected solar energy predominantly generates the imagery.

The neighbouring mid wavelength infrared (MWIR; 3 µm – 6 µm) range is considered an optical **transition zone**, as the solar-reflective behaviour slowly shifts in favour of **self-emitted thermal radiation**. In both the long wavelength infrared (LWIR; 6 µm to 15 µm) and far/extreme-infrared (FIR; 15 µm to 1 mm), thermal electromagnetic radiation emitted by the scene objects themselves almost uniquely governs the imaging process. As a result, the MWIR to FIR optical region is commonly denoted the thermal region.

Optical electromagnetic radiation

Division	Subdivision	Abbreviation	Cut-on (nm)	Cut-off (nm)	Division by imaging principle	
UltraViolet (UV)	Vacuum UV	VUV / UV-D*	10	200		
	Far UV	FUV / UV-C*	200	280		
	Middle-UV	MUV / UV-B	280	315		
	Near-UV	NUV / UV-A	315	400		
Visible (Vis)	Blue	B	400	500	*Solar-reflective spectral region*	
	Green	G	500	600		
	Red	R	600	700		
InfraRed (IR)	Near-IR	NIR	700	1 100		
	Short Wavelength IR	SWIR	1 100	3 000		
	Mid Wavelength IR	MWIR	3 000	6 000	*Transition zone*	*Thermal region*
	Long Wavelength IR	LWIR	6 000	15 000	*Self-emitted thermal radiation region*	
	Far/Extreme-IR	FIR	15 000	1 000 000		

Figure 3 – The divisions of the optical electromagnetic radiation (VUV does not perfectly correspond to UV-D. While VUV runs from 10 nm to 200 nm and FUV from 200 nm to 280 nm, UV-D encompasses the 10 nm to 100 nm region and UV-C the 100 nm to 280 nm zone).*

2.3 General principle of imaging

At the very origin of any imaging chain lies the interaction of electromagnetic radiation with the scene or object to be photographed. This interaction determines which portion and quantity of electromagnetic radiation the digital imaging sensor will detect, integrate and digitise. To better grasp this process, it is useful to understand that almost any form of optical imaging is the outcome of a three-variable process (see figure 4):

- electromagnetic radiation of a specific radiation source (such as the Sun) falls onto the object. This so-called spectral irradiance ***E*(λ)** is partly absorbed, transmitted and reflected by the object;
- in addition to the particular chemical and physical structure of the object, this interaction and the specific ratio of the three processes is wavelength dependent. The combination of both incoming energy ***E*(λ)** and the object's unique reflection ***R*(λ)** creates a spectral radiance distribution ***L*(λ)** [i.e. $L(\lambda) = E(\lambda) \times R(\lambda)$] that is sampled by an imaging sensor such as an airborne digital camera or a human eye;
- this imager also has its own spectral response(s). It will detect and integrate the incoming electromagnetic radiance in specific spectral regions. Digitising this integrated response yields a pixel with as many values as are there are spectral bands in the imager. For a standard digital photographic camera (as displayed in Figure 4), this means three values: one for the Blue, one for the Green and one for the Red spectral channel (hence denoted RGB values). In the entry about spectral resolution, we will delve deeper into their properties.

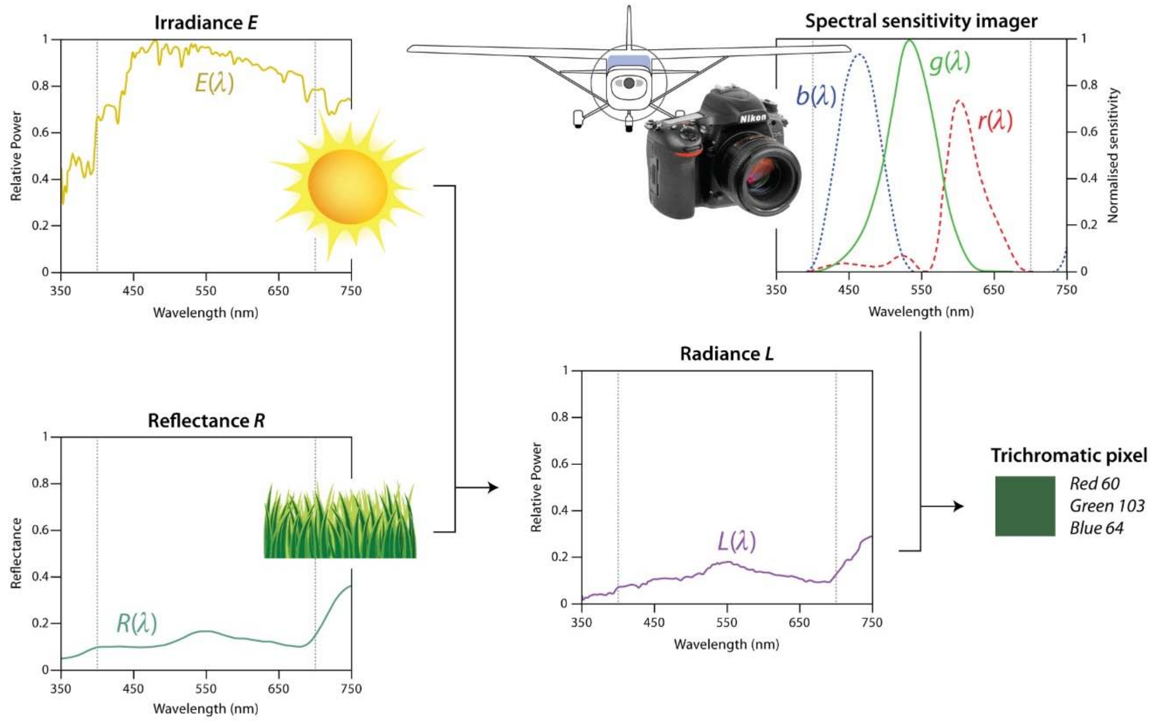

Figure 4 – Pixel values generated by an airborne RGB digital camera result in essence from a three-variable process.

When observing a hot object, the imaging process is ideally governed by just two variables since the thermal electromagnetic radiation emitted by the object itself should be the only radiation source. The principles of fluorescence imaging are similar to those of thermal imaging. In contrast to reflected or direct imaging, fluorescence imaging uses a radiation source to excite electromagnetic radiation of a wavelength longer than the incident wavelengths. Subsequently, only the emitted portion of the electromagnetic radiation is recorded.

To make things even more complicated, highly anisotropic reflectors of solar energy such as soils or vegetation have a spectral reflectance that is directionally non-uniform. This means that the soil and vegetation pixel values also depend on both the camera's angle of observation and the illumination geometry (i.e. the Sun's zenith and azimuth angle). As a result, the rendering of vegetation and soil marks varies both in our brain as well as in our digital cameras as we circle them.

Finally, also an atmosphere strongly interacts with both the irradiance and radiance signals. Since the amount of interaction depends on the thickness of this atmospheric layer, it influences spaceborne pixel values even more than their airborne counterparts (e.g. the contrast in spaceborne images can become very low). The next entry will tackle the actual nature of these pixels and debunk many of the misconceptions that surround them.