

PHYSICAL BASIS OF REMOTE SENSING

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Summary

Remote sensing is the measurement and recording of the electromagnetic radiation emanating from the earth's environment by sensors mounted on a platform at a vantage point above the earth's surface. Remote sensing provides a synoptic view that carries a continuous record of the environment that is consistent. It works by exploiting the electromagnetic radiation from a source that interacts with targets on the earth's surface in a unique fashion, depending on its physical, chemical, and biological properties, to be reflected, emitted, or backscattered towards a sensor.

Effective use of the electromagnetic radiation measured by the sensor depends on understanding the physical processes that control the transmission of the electromagnetic radiation from the source to the target and to the sensor. Here there are four main components that require an understanding of characteristics and properties: electromagnetic radiation, Earth surface targets, atmospheric effects, and the sensor.

1. Overview of Remote Sensing and Common Remote Sensing Systems

Remote sensing is the means by which a target on the earth's surface can be studied using a device separated from it by some distance. Within the context of geoinformatics, the remote sensing definition can be refined to focus on the measurement and recording of the electromagnetic radiation (EMR) emanating from the earth's environment (surface and atmosphere) by sensors mounted on a platform at a vantage point above the earth's surface. Remote sensing provides a synoptic view that carries a continuous record of the environment that is consistent. This record can be more accurate than that derived by traditional representation by interpolation of limited field observations. The aim of this article is to provide a comprehensive overview of the topic.

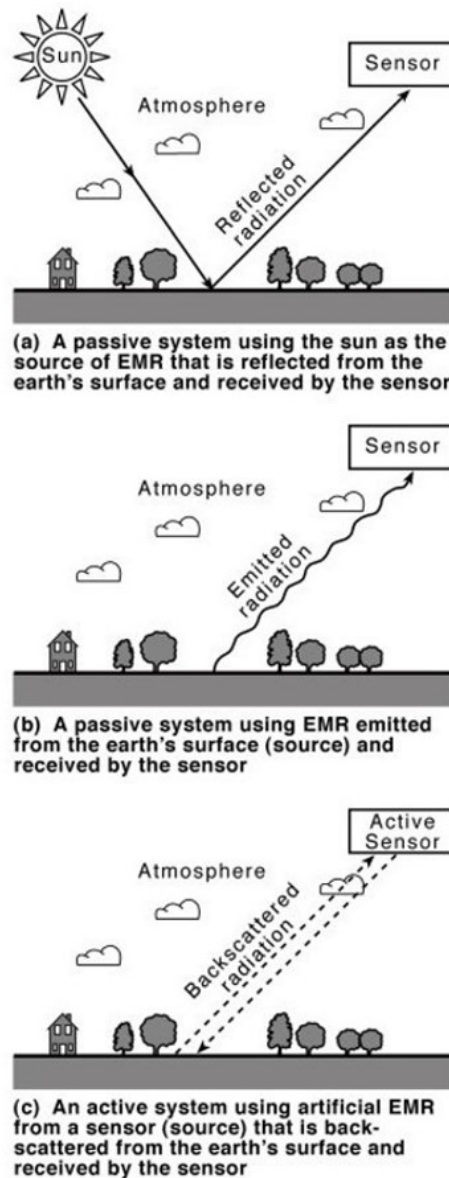


Figure 1. Common remote sensing systems

Remote sensing through the medium of EMR comprises four components, all of which are linked through the transfer of radiation. These components are EMR source, Earth surface targets, atmospheric effects, and the sensor. Commonly there are three remote sensing systems (Figure 1a, 1b, and 1c) used in remote sensing and each of these features the four components of remote sensing in different ways.

The first component of a remote sensing system is the source of EMR. It is natural, originating from the sun or the earth by emission, or artificial. The second component of a remote sensing system refers to the earth surface targets that determine the EMR received by the remote sensor. The essential physical, chemical, and biological properties of the targets determine the amount of radiation from it and measured by a sensor at a particular wavelength. EMR may also interact with the atmosphere between the earth's surface and the sensor, contributing to or modifying the radiation reaching the sensor, and this constitutes the third component of a remote sensing system. The final component of a remote sensing system is the sensor, which measures remotely the radiation from the earth's environment.

2. Electromagnetic Radiation

EMR provides the link between each component of a remote sensing system. It is a form of energy transfer from one target to another through space and media and behaves in two inseparable ways: as regular waves of energy and as rapidly moving and indivisible particles or photons. The former is described by the basic wave theory, the latter by quantum theory.

2.1. Basic Wave Theory

The basic wave theory describes EMR as an electric field and a magnetic field that are orthogonal to each other, travelling from the source in a harmonic, sinusoidal wave-like fashion at the velocity of light (Figure 2). The waves can be characterised through a number of variables:

- (i) Wavelength (λ) represents the distance between successive peaks (or troughs) of a wave.
- (ii) Frequency (ν) refers to the number of peaks or troughs of waves passing a fixed point in a given period of time. Frequency is often measured in hertz (Hz) (i.e. units equivalent to 1 cycle per second) and multiples of hertz.
- (iii) Speed: all electromagnetic waves travel at the speed of light (c), in a vacuum.
- (iv) The amplitude (A) of a wave is the maximum distance attained by a wave from its mean position (i.e. the height of a wave peak).

The three variables of wavelength, frequency, and speed are related to each other by the general equation:

$$c = \nu\lambda. \quad (1)$$

Since c is a constant (approximately $3 \times 10^8 \text{ m s}^{-1}$), frequency and wavelength for any given wave are related inversely, and either can be used to categorise any wave.

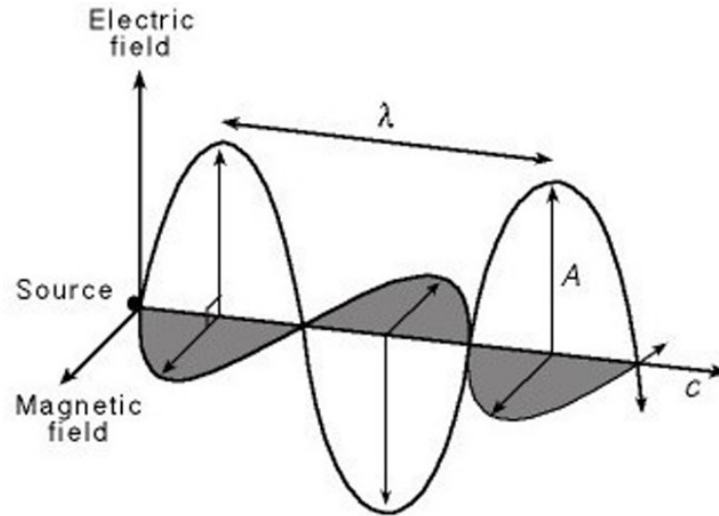


Figure 2. The basic wave theory of EMR

2.2. Quantum Theory

Quantum theory describes EMR as composed of many discrete units called quanta or photons. The radiant energy of a quantum is expressed as:

$$Q = h\nu, \quad (2)$$

where Q = radiant energy of a quantum and h = Planck's constant, 6.626×10^{-34} J sec. The rate at which quanta strike a target is known as the radiant flux (ϕ_e), measured in watts (W). This describes the time rate of the flow of radiant energy. Irradiance (E_e) defines the amount of radiant energy delivered to an area of surface (i.e. the radiant flux per unit area (measured in watts per square metre (W m^{-2}))).

The use of the basic wave and quantum theory of EMR are complementary and useful for understanding the physical basis of remote sensing. Each theory can be related by combining Eqs. (1) and (2) to give:

$$Q = hc/\lambda. \quad (3)$$

As described by Eq. (3), the energy of a quantum is inversely proportional to its wavelength. Thus, all other variables being equal, wavelengths that are low in energy will be harder to sense remotely and sensors operating at these wavelengths therefore view relatively large areas of the earth's surface in order to obtain a detectable energy signal. Thus, knowledge of the properties of EMR is crucial in the design of the remote sensors that record EMR from the earth's surface.

3. The Electromagnetic Spectrum

The electromagnetic spectrum refers to the wavelength distribution of EMR in a continuous array from short rays wavelength (at $<10^{-6}$ micrometers (μm)), high

frequency cosmic waves through to long wavelength (low frequency) radio waves (at $10^8 \mu\text{m}$) and beyond. The spectrum of EMR is commonly divided into regions for convenience and by tradition within the field of remote sensing. Table 1 features some of the characteristics of the regions described in the illustration of the electromagnetic spectrum in Figure 3 and their relative location.

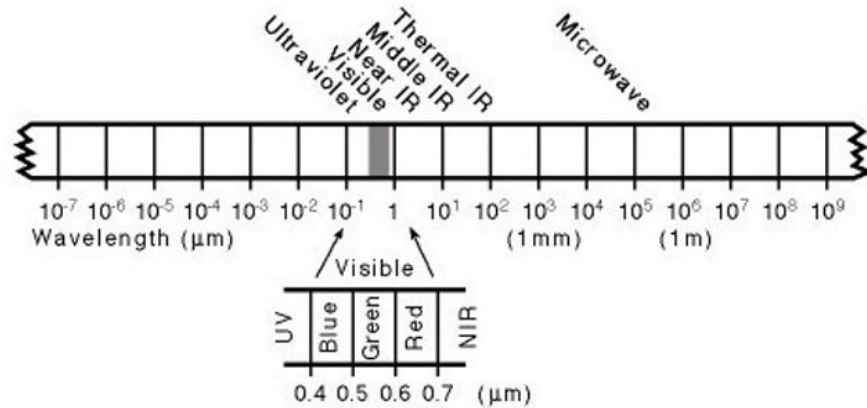


Figure 3. The electromagnetic spectrum showing the wavelengths of the main regions used in remote sensing

Region name	Wavelength range	Details
Ultraviolet (UV)	0.30–0.38 μm	Very narrow zone of electromagnetic radiation that lies between the X-ray region and visible region. It is largely scattered by atmospheric particles, thus is not readily used in remote sensing, having very specialised applications.
Visible	0.4–0.75 μm	Narrow but well-used region since the short wavelengths are of high frequency and high energy. Comprises the three additive primaries; blue (0.4–0.5 μm), green (0.5–0.6 μm) and red (0.6–0.7 μm).
Near infrared (NIR)	0.75–1.5 μm	Start of the region beyond the red wavelengths. Like the visible region, it is frequently used in remote sensing.
Middle infrared (MIR)	1.5–5.0 μm	Comprises two main portions: shortwave infrared (SWIR, 1.5–3.0 μm) and MIR (3.0–5.0 μm). MIR radiation measured by sensors can comprise a mixed signal of reflected solar radiation and radiation emitted from the earth's surface.
Thermal infrared (TIR)	5.0–15.0 μm	Comprised of long wavelengths of lower frequency and thus lower energy. Much of the thermal infrared signal is comprised of emitted radiation from the earth's surface.

Microwave	1 mm–1 m	Longest wavelengths used in remote sensing. Passive remote sensing is difficult as wavelengths have low energy, so some sensors that record microwave radiation in this region generate radiation artificially and measure radiation backscattered from the earth.
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Table 1. Main regions of the electromagnetic spectrum used in remote sensing

4. Sources of Electromagnetic Radiation

Remote sensing uses EMR from both natural sources and artificial sources.

4.1. Natural Sources of Electromagnetic Radiation

All objects with a temperature above absolute zero (-273°C , 0K) emit EMR continuously. In remote sensing, the sun is the most obvious source of EMR (solar radiation), although all terrestrial objects are also a source. The term radiant exitance (M_e) refers to the rate at which radiation is emitted from a unit area (W m^{-2}) of a source object. The distribution of the amount of radiation at each wavelength across the spectrum emitted from a target is not uniform, but depends on the temperature of that object. The exact nature of the EMR emitted can be described in several ways. The first way relates to Planck's radiation law:

$$M_{\lambda} = c_1/\lambda^5[\exp(c_2/\lambda T)-1], \quad (4)$$

where M_{λ} is the spectral radiant exitance per unit wavelength (measured in $\text{W m}^{-2} \mu\text{m}^{-1}$), T is absolute temperature (K), c_1 and c_2 are constants with values $c_1 = 3.742 \times 10^{-16} \text{ W m}^{-2}$ and $c_2 = 1.4388 \times 10^{-2} \text{ m K}$. This is illustrated in Figure 4 for objects at temperatures of 600° (the sun's temperature) and 30° (the earth's temperature). In each case, the object is assumed to be a blackbody (see Section 6.2. **Emitted Radiation**). It is further evident from Figure 4 that as the temperature of the source object increases so the wavelength at which the maximum spectral exitance is achieved is reduced. This can be described by Wien's displacement law, which gives the wavelength of maximum spectral exitance (λ_m) in terms of temperature:

$$\lambda_m = c_3/T, \quad (5)$$

where $c_3 = 2.898 \times 10^{-3} \text{ m K}$.

Another way in which the nature of the EMR emitted from a source object can be described relates to the Stefan–Boltzmann radiation law. This provides the total spectral exitance (M) of a blackbody at temperature (T), which is the area below the curve for that value of T in Figure 4:

$$M = \sigma T^4, \quad (6)$$

where $\sigma = 5.6697 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$.

As Figure 4 illustrates, EMR the wavelength of maximum spectral exitance is located at 0.47 μm and 9.7 μm respectively for solar and earth radiation. EMR emitted by both the sun and the earth is a source of EMR used in remote sensing. Generally, solar-emitted EMR is used for remote sensing at ultraviolet (UV) to middle infrared (MIR) wavelengths and earth-emitted EMR is used for remote sensing at wavelengths beyond the MIR region of the EMS.

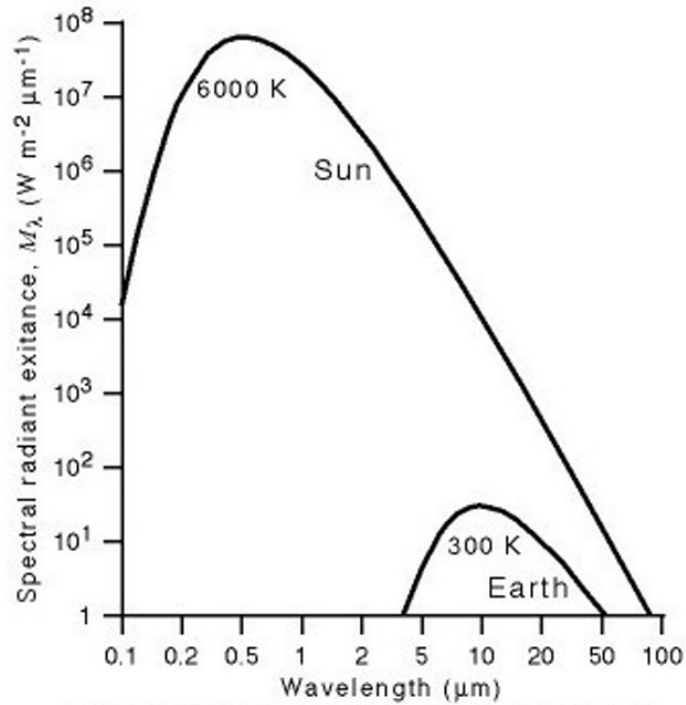


Figure 4. Spectral exitance curves for solar and earth-emitted radiation

4.2. Artificial Sources of Electromagnetic Radiation

Evident from Figure 4 is that at wavelengths beyond $\sim 20.0 \mu\text{m}$ the energy of the EMR from both the sun and the earth is so low that to use these wavelengths for remote sensing could prove problematic. Therefore, in many instances, active remote sensing is conducted. In this instance, EMR is produced artificially by the sensor rather than by natural sources. A sensor able to do this is the radar (radio detection and ranging), which transmits, usually sideways, short pulses of EMR at microwave wavelengths towards the earth's surface and then receives the radiation backscattered from the earth's surface. Here, two pieces of information are important. The first is the time taken for the radiation pulse to reach the target on the earth's surface and return, and the second is the strength and origin of the backscatter received from the targets within the sensor's field of view. The information on the time taken for the EMR to be backscattered indicates the location of targets on the earth's surface and the strength of the backscatter provides information on the targets' characteristics. The degree of backscatter is calculated using the radar equation:

$$\frac{\theta_r = \theta_t G_t^2 \lambda^2 \sigma}{(4\pi)^3 R^4}, \quad (7)$$

where θ_r = received power, θ_t = transmitted power, G_t = antenna gain, R = distance from transmitter to target, and σ = effective backscatter.

Other active systems are also used in remote sensing. For example, lidar (light detection and ranging) has grown in popularity for remote sensing from airborne platforms (see *Landform and Earth Surface*). This works on the same principle as radar with pulses of laser light, instead of microwaves, used to illuminate the earth's surface.

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Biographical Sketch

Dr. Doreen Boyd is currently senior lecturer in geography and environmental science at Kingston University, U.K. Her principal research interests are in remote sensing of vegetation, particularly within middle infrared wavelengths (3–5 μm). She is actively involved in many aspects of remote sensing as an editorial board member of *Electronic Geosciences* and a council member of the former Remote Sensing Society (now the Remote Sensing and Photogrammetry Society).