Chapter 1 Fundamentals of Remote Sensing

1.1 Concept of Remote Sensing

Remote Sensing is defined as the science and technology by which the characteristics of objects of interest can be identified, measured or analyzed the characteristics without direct contact.

Electro-magnetic radiation which is **reflected** or **emitted** from an object is the usual source of remote sensing data. However any media such as gravity or magnetic fields can be utilized in remote sensing.

A device to detect the electro-magnetic radiation reflected or emitted from an object is called a "remote sensor" or "**sensor**". Cameras or scanners are examples of remote sensors.

A vehicle to carry the sensor is called a "**platform**". Aircraft or satellites are used as platforms.

The technical term "remote sensing" was first used in the United States in the 1960's, and encompassed photogrammetry, photo-interpretation, photo-geology etc. Since Landsat-1, the first earth observation satellite was launched in 1972, remote sensing has become widely used.

The characteristics of an object can be determined, using reflected or emitted electro-magnetic radiation, from the object. That is, "each object has a unique and different characteristics of reflection or emission if the type of deject or the environmental condition is different."Remote sensing is a technology to identify and understand the object or the environmental condition through the uniqueness of the reflection or emission.

This concept is illustrated in figure 1.1.1 while figure 1.1.2 shows the flow of remote sensing, where three different objects are measured by a sensor in a limited number of bands with respect to their, electro-magnetic characteristics after various factors have affected the signal. The remote sensing data will be processed automatically by computer and/or manually interpreted by humans, and finally utilized in agriculture, land use, forestry, geology, hydrology, oceanography, meteorology, environment etc.

In this chapter, the principles of electro-magnetic radiation are described in sections 1.2-1.4, the types of remote sensing with respect to the spectral range of the electro-magnetic, radiation in section 1.5, the definition of radiometry in section 1.6, black body radiation in section 1.7, electro-magnetic characteristics in sections 1.8 and 1.9, solar radiation in section 1.10 and atmospheric behavior in sections 1.11 and 1.12.

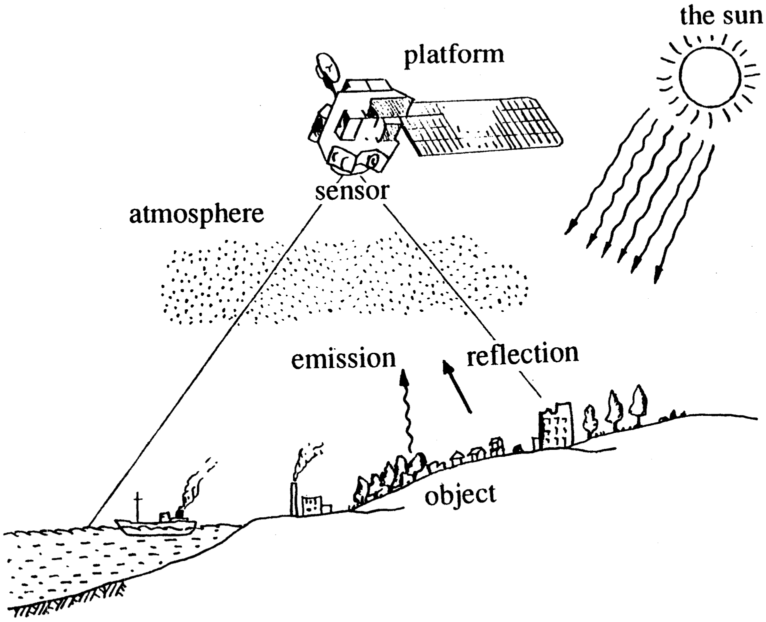


Figure1.1.1 Data collection by remote sensing

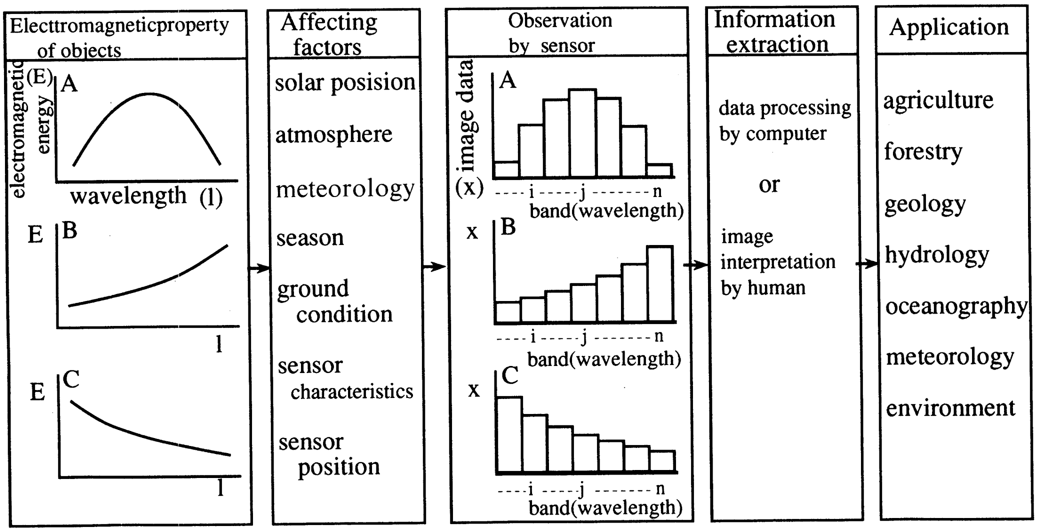


Figure1.1.2 Flow of remote sensing

1.2 Characteristics of Electro-Magnetic Radiation

Electro-magnetic radiation is a carrier of electro-magnetic energy by transmitting the oscillation of the electro-magnetic field through space or matter. The transmission of electro-magnetic radiation is derived from the Maxwell equations. Electro-magnetic radiation has the characteristics of both wave motion and particle motion.

(1) Characteristics as wave motion

Electro-magnetic radiation can be considered as a transverse wave with an electric field and a magnetic field. A plane wave for an example as shown in Figure 1.2.1 has its electric field and magnetic field in the perpendicular plane to the transmission direction. The two fields are located at right angles to each other. The **wavelength** λ, **frequency** ν and the velocity v have the following relation.

$$\lambda = v / \nu$$

Electro-magnetic radiation is transmitted in a vacuum of free space with the velocity of light c, (= 2.998×10^8 m/sec) and in the atmosphere with a reduced but similar velocity to that in a vacuum. The frequency ν is expressed as a unit of hertz (H_z), that is the number of waves which are transmitted in a second.

(2) Characteristics as particle motion

Electro-magnetic can be treated as a photon or a light quantum. The energy E is expressed as follow.

$$E = h\nu$$

where h : Plank's constant

ν : frequency

The photoelectric effect can be explained by considering the electro-magnetic radiation as composed of particles. Electro-magnetic radiation has four elements of frequency (or wavelength), **transmission direction**, **amplitude** and **plane of polarization**. The amplitude is the magnitude of oscillating electric field. The square of the amplitude is proportional to the energy transmitted by electro-magnetic radiation. The energy radiated from an object is called radiant energy. A plane including electric field is called a plane of polarization. When the plane of polarization forms a uniform plane, it is called linear polarization.

The four elements of electro-magnetic radiation are related to different information content as shown in Figure 1.2.2. Frequency (or wavelength) corresponds to the color of an object in the visible region which is given by a unique characteristic curve relating the wavelength and the radiant energy. In the microwave region, information about objects is obtained using the Doppler shift effect in frequency, that is generated by a relative motion between an object and a platform. The spatial location and shape of objects are given by the linearity of the transmission direction, as well as by the amplitude. The plane of polarization is influenced by the geometric shape of objects in the case of reflection or scattering in the microwave region. In the case of radar, horizontal polarization and vertical polarization have different responses on a radar image.

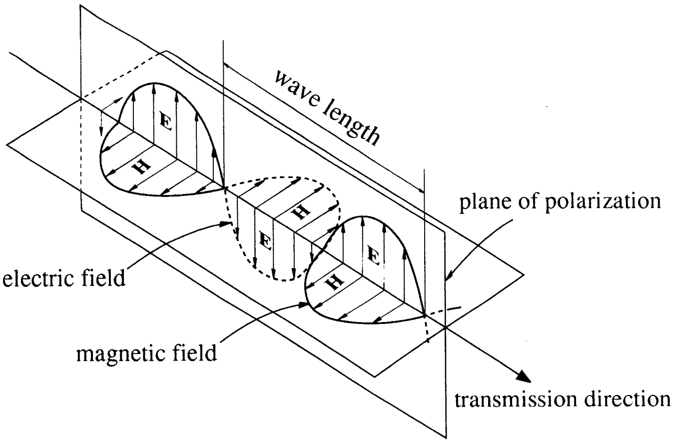


Figure 1.2.1 Electromagnetic radiation

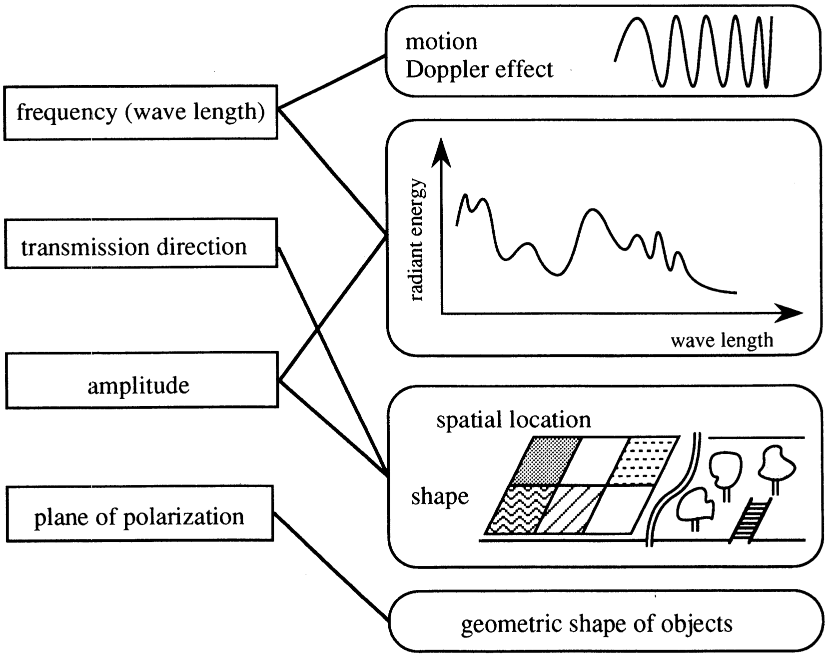


Figure 1.2.2 Information derived from elements of electromagnetic radiation

1.3 Interactions between Matter and Electro-magnetic Radiation

All matter reflects, absorbs, penetrates and emits electro-magnetic radiation in a unique way. For example, the reason why a leaf looks green is that the chlorophyll absorbs blue and red spectra and reflects the green spectrum (see 1.9). The unique characteristics of matter are called **spectral characteristics** (see 1.6).

Why does an object have a peculiar characteristic of reflection, **absorption** or emission? In order to answer the question, one has to study the relation between molecular, atomic and electro-magnetic radiation. In this section, the interaction between hydrogen atom and absorption of electro-magnetic radiation is explained for simplification.

A hydrogen atom has a nucleus and an electron as shown in Figure 1.3.1. The inner state of an atom depends on the inherent and discrete energy level. The electron's orbit is determined by the energy level. If electro-magnetic radiation is incident on an atom of H with a lower **energy level** (E_1), a part of the energy is absorbed, and an electron is induced by **excitation** to rise to the energy level (E_2) resulting in the upper orbit.

The electro-magnetic energy E is given as follow.

$$E = hc / \lambda$$

where h : Plank's constant c : velocity of light λ : wavelength

The difference of energy level

$$\Delta E = E_2 - E_1 = hc / \lambda_H$$ is absorbed.

In other words, the change of the inner state in an H-atom is only realized when electro-magnetic radiation at the peculiar wavelength λ_H is absorbed in an H-atom. Conversely electro-magnetic radiation at the wavelength λ_H is **radiated** from an H-atom when the energy level changes from E_2 to E_1.

All matter is composed of atoms and molecules with a particular composition. Therefore, matter will emit or absorb electro-magnetic radiation at a particular wavelength with respect to the inner state.

The types of inner state are classified into several classes, such as ionization, excitation, molecular vibration, molecular rotation etc. as shown in Figure 1.3.2 and Table 1.3.1, which will radiate the associated electro-magnetic radiation. For example, visible light is radiated by excitation of valence electrons, while infrared is radiated by molecular vibration or lattice vibration.

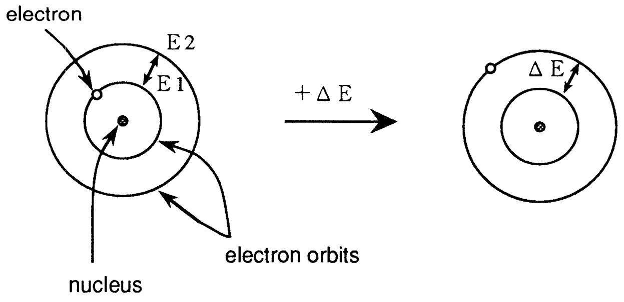
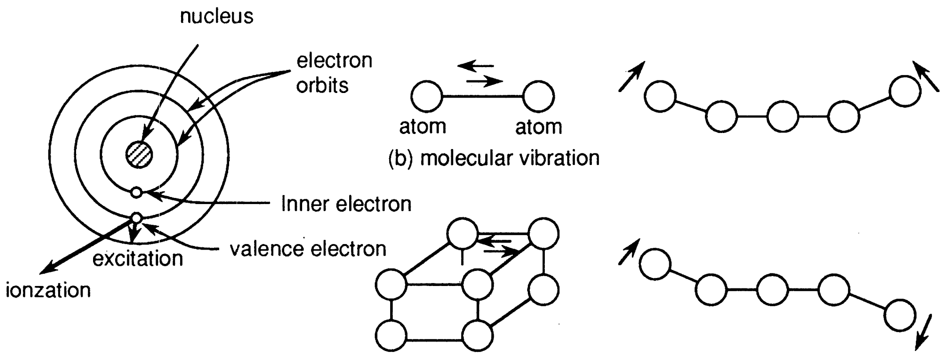


Figure 1.3.1 Change in energy level of the electron of a H atom according to absorption of electromagnetic radiation wavelength λ H

Table.1.3.1 Relation between characteristic state and electromagnetic radiation

Characteristic state	energy (eV)	associated electromagnetic wave
Nuclear transmission and disintegrations	$10^7 \sim 10^5$	γ - ray
Ionization by inner electron removal	$10^4 \sim 10^2$	X - ray
Ionization by outer electron removal	$10^2 \sim 4$	Ultra - violet
Excitation of valence electrons	$4 \sim 1$	Visible
Molecular vibration, Lattice vibration	$10 \sim 10^{-5}$	Infrared
Molecular rotations, electron spin resonance	$10^{-4} \sim 10^{-5}$	Microwave
Nuclear spin resonance	10^{-7}	Meter wave

[unit] energy of 1eV = 1.60219 × 10^{-19} Joule wavelength of 1eV light = 1.23985 μm



(b) molecular vibration

(c) lattice vibration

(d) molecular rotation

Figure 1.3.2 Schematics of characteristic states associated with electromagnetic radiation

1.4 Wavelength Regions of Electro-magnetic Radiation

Wavelength regions of electro-magnetic radiation have different names ranging from γ ray, Xray, **ultraviolet** (UV), **visible light**, **infrared** (IR) to radio wave, in order from the shorter wavelengths. The shorter the wavelength is, the more the electro-magnetic radiation is characterized as particle motion with more linearity and directivity. (see 1.2).

Table 1.4.1 shows the names and wavelength region of electro-magnetic radiation. One has to note that classification of infrared and radio radiation may vary according to the scientific discipline. The table shows an example which is generally used in remote sensing.

The electro-magnetic radiation regions used in remote sensing are near UV(ultra-violet) (0.3-0.4 μm), visible light(0.4-0.7 μm), near shortwave and thermal infrared (0.7-14 μm) and micro wave (1 mm - 1 m).

Figure 1.4.1 shows the spectral bands used in remote sensing. The spectral range of **near IR** and **short wave infrared** is sometimes called the **reflective infrared** (0.7-3 μm) because the range is more influenced by solar reflection rather than the emission from the ground surface (see 1.5). In the thermal infrared region, emission from the ground's surface dominates the radiant energy with little influence from solar reflection (see 1.5 and 1.7).

Visible light corresponds to the spectral colors. They are, in order from the longer wavelengths in the visible region, the so called rainbow colors; red, orange, yellow, green, blue, indigo and violet are located with respect to the wavelength.

Short wave infrared has more recently been used for geological classification of rock types. Thermal infrared is primarily used for temperature measurement (see 1.7), while micro wave is utilized for radar and micro wave radiometry. A special naming of k band, X band, C band, L band etc. is given to the micro wave region as shown in Figure 1.4.1.

Table 1.4.1 Classification of electromagnetic radiations

class				wavelength	frequency
ultraviolet				100A ~ 0.4μm	750 ~ 3,000THz
visible				0.4 ~ 0.7μm	430 ~ 750THz
infrared	near infrared			0.7 ~ 1.3μm	230 ~ 430THz
	short wave infrared			1.3 ~ 3μm	100 ~ 230THz
	intermediate infrared			3 ~ 8μm	38 ~ 100THz
	thermal infrared			8 ~ 14μm	22 ~ 38THz
	far infrared			14μm ~ 1mm	0.3 ~ 22THz
radio wave	submillimeter			0.1 ~ 1mm	0.3 ~ 3THz
	micro wave	millimeter	(EHF)	1 ~ 10mm	30 ~ 300GHz
		centimeter	(SHF)	1 ~ 10cm	3 ~ 30GHz
		decimeter	(UHF)	0.1 ~ 1m	0.3 ~ 3GHz
	very short wave		(VHF)	1 ~ 10m	30 ~ 300MHz
	short wave		(HF)	10 ~ 100m	3 ~ 30MHz
	medium wave		(MF)	0.1 ~ 1km	0.3 ~ 3MHz
	long wave		(LF)	1 ~ 10km	30 ~ 300kHz
	very long wave		(VLF)	10 ~ 100km	3 ~ 30kHz

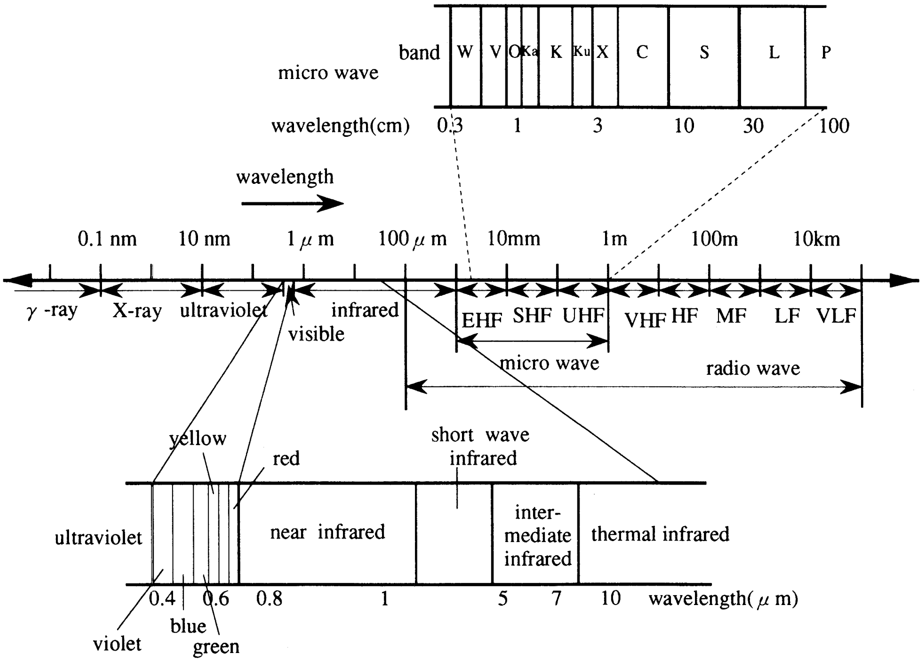


Figure 1.4.1 The bands used in remote sensing

1.5 Types of Remote Sensing with Respect to Wavelength Regions

Remote sensing is classified into three types with respect to the wavelength regions; (1)**Visible and Reflective Infrared Remote Sensing**, (2)**Thermal Infrared Remote Sensing** and (3)**Microwave Remote Sensing**, as shown in Figure 1.5.1.

The **energy source** used in the visible and reflective infrared remote sensing is the sun. The sun radiates electro-magnetic energy with a peak wavelength of 0.5 µm (see 1.7 and 1.10). Remote sensing data obtained in the visible and reflective infrared regions mainly depends on the **reflectance** of objects on the ground surface (see 1.8). Therefore, information about objects can be obtained from the spectral reflectance. However laser radar is exceptional because it does not use the solar energy but the laser energy of the sensor.

The source of radiant energy used in thermal infrared remote sensing is the object itself, because any object with a normal temperature will emit electro-magnetic radiation with a peak at about 10 µm (see 1.7), as illustrated in Figure 1.5.1.

One can compare the difference of spectral radiance between the sun (a) and an object with normal earth temperature (about 300°K), as shown in Figure 1.5.1. However it should be noted that the figure neglects atmospheric absorption (see 1.11), for simplification, though the spectral curve varies with respect to the reflectance, emittance and temperature of the object.

The curves of (a) and (b) cross at about 3.0 µm. Therefore in the wavelength region shorter than 3.0 µm, spectral reflectance is mainly observed, while in the region longer than 3.0 µm, **thermal radiation** is measured.

In the microwave region, there are two types of micro wave remote sensing, passive microwave remote sensing and active remote sensing. In passive microwave remote sensing, the **microwave radiation** emitted from an object is detected, while the **back scattering coefficient** is detected in active micro wave remote sensing. (see 3.4).

Remarks: the two curves (a) and (b) in Figure 1.5.1 show the black body's spectral radiances of the sun at a temperature of 6,000°K and an object with a temperature of 300°K, without atmospheric absorption.

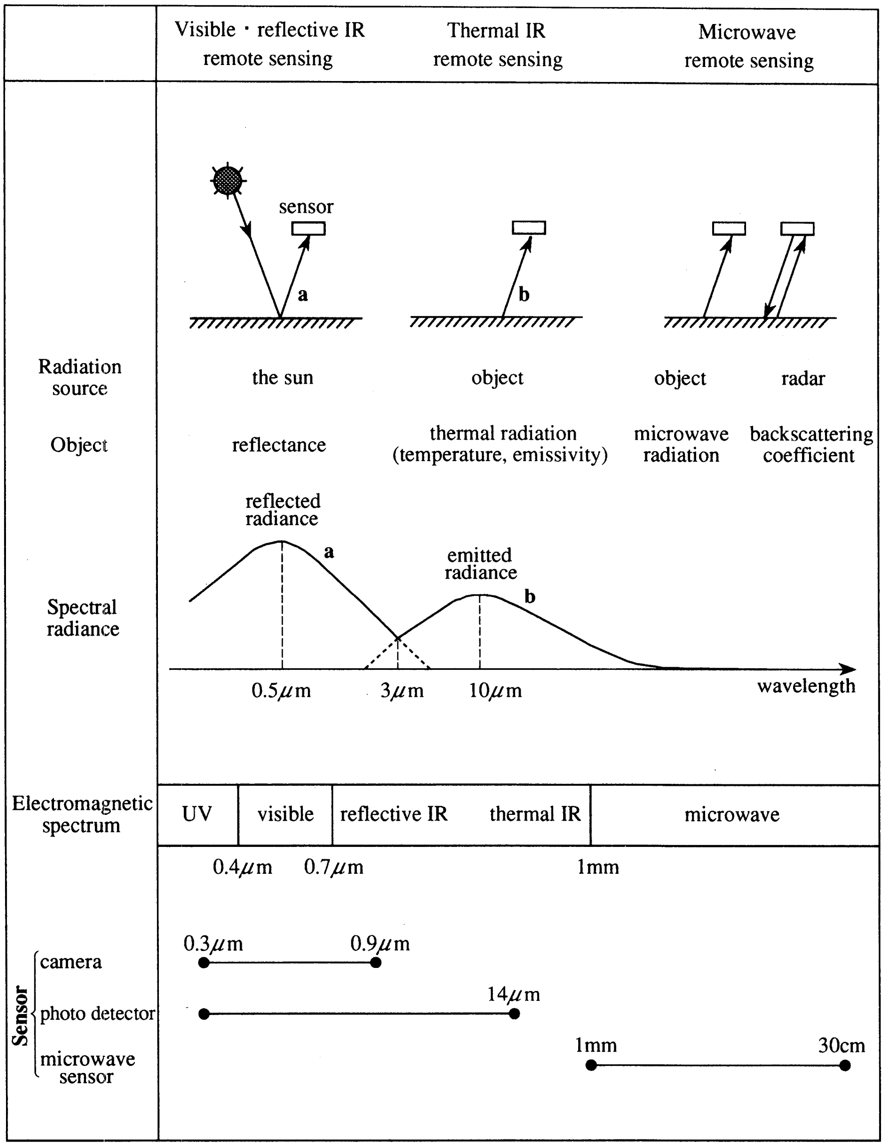


Figure 1.5.1 Three types of remote sensing with respect to wavelength regions

1.6 Definition of Radiometry

In remote sensing, electro-magnetic energy reflected or emitted from objects is measured. The measurement is based on either **radiometry** or **photometry**, with different technical terms and physical units.

Radiometry is used for physical measurement of a wide range of radiation from x-ray to radio wave, while photometry corresponds to the human perception of visible light based on the **human eye's sensitivity** as shown in Figure 1.6.1 (see Appendix).

Figure 1.6.2 shows the radiometric definitions of radiant energy, radiant flux, radiant intensity, irradiance, radiant emittance and radiance.

Table 1.6.1 shows the comparison with respect to the technical terms, symbols and units between radiometry and photometry.

One can add an adjective "Spectral" before the technical terms of radiometry when defined as per unit of wavelength. For example, one can use spectral radiant flux ($W\ \mu m^{-1}$) or spectral radiance ($Wm^{-2}\ sr^{-1}\ \mu m^{-1}$).

Radiant energy is defined as the energy carried by electro- magnetic radiation and expressed in the unit of joule (J).

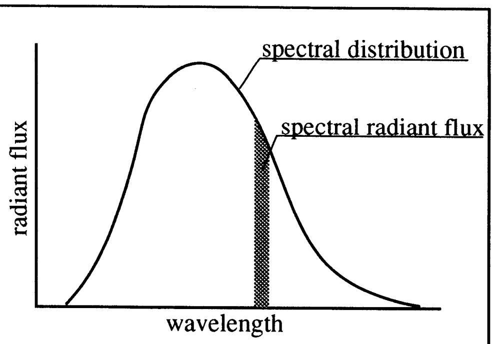
Radiant flux is radiant energy transmitted as a radial direction per unit time and expressed in a unit of watt (W). **Radiant intensity** is radiant flux radiated from a point source per unit solid angle in a radiant direction and expressed in the unit of Wsr^{-1}. **Irradiance** is radiant flux incident upon a surface per unit area and expressed in the unit of Wm^{-2}. **Radiant emittance** is radiant flux radiated from a surface per unit area, and expressed in a unit of Wm^{-2}. **Radiance** is radiant intensity per unit projected area in a radial direction and expressed in the unit of Wm^{-2} $s\gamma^{1}$.

Radiant energy *Qe*

The energy carried by electromagnetic radiation

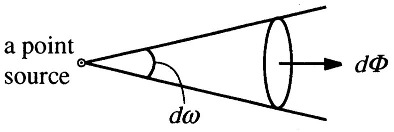
Radiant flux Φ

Radiant energy transmitted per unit time



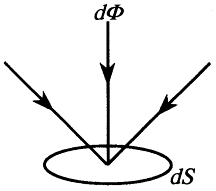
Radiant intensity *Ie*

Radiant energy radiated from a point source per solid angle in a radial direction per unit time



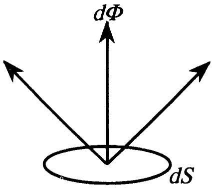
Irradiance *Ee*

Radiant energy incident upon a unit area per unit time



Radiant emittance *Me*

Radiant energy radiated from a unit area per unit time



Radiance *Le*

Radiant energy radiated from a unit projected area per unit solid angle in a radial direction per unit time

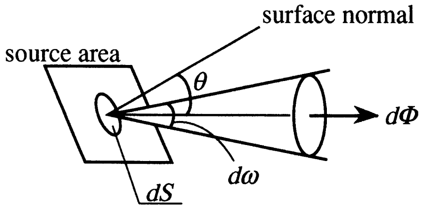


Figure 1.6 Summary of radiometric definitions

1.7 Black Body Radiation

An object radiates unique spectral radiant flux depending on the temperature and emissivity of the object. This radiation is called **thermal radiation** because it mainly depends on temperature. Thermal radiation can be expressed in terms of **black body** theory.

A black body is matter which absorbs all electro-magnetic energy incident upon it and does not reflect nor transmit any energy. According to **Kirchhoff's law** the ratio of the radiated energy from an object in thermal static equilibrium, to the absorbed energy is constant and only dependent on the wavelength and the temperature T. A black body shows the maximum radiation as compared with other matter. Therefore a black body is called a perfect radiator.

Black body radiation is defined as thermal radiation of a black body, and can be given by **Plank's law** as a function of temperature T and wavelength as shown in Figure 1.7.1 and Table 1.7.1.

In remote sensing, a correction for **emissivity** should be made because normal observed objects are not black bodies. Emissivity can be defined by the following formula-

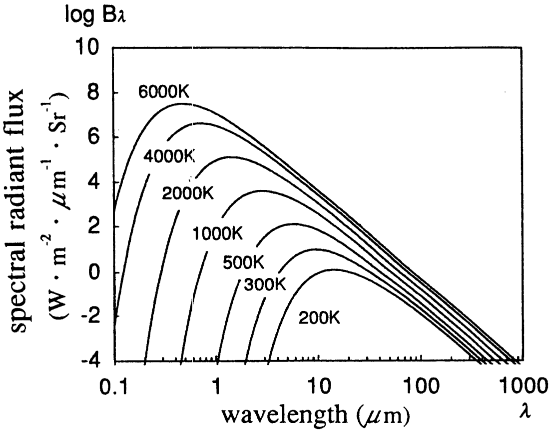
$$\text{Emissivity} = \frac{\text{Radiant energy of an object}}{\begin{array}{l}\text{Radiant energy of a black body with}\\ \text{the same temperature as the object}\end{array}}$$

Emissivity ranges between 0 and 1 depending on the dielectric constant of the object, surface roughness, temperature, wavelength, look angle etc. Figure 1.7.2 shows the spectral emissivity and spectral radiant flux for three objects that are a black body, **a gray body** and a selective radiator.

The temperature of the black body which radiates the same radiant energy as an observed object is called the **brightness temperature** of the object.

Stefan-Boltzmann's law is obtained by integrating the spectral radiance given by Plank's law, and shows in that the radiant emittance is proportional to the fourth power of absolute temperature (T^4). This makes it very sensitive to temperature measurement and change.

Wien's displacement law is obtained by differentiating the spectral radiance, which shows that the product of wavelength (corresponding to the maximum peak of spectral radiance) and temperature, is approximately 3,000 (μm°K). This law is useful for determining the optimum wavelength for temperature measurement of objects with a temperature of T. For example, about 10 μm is the best for measurement of objects with a temperature of 300°K.



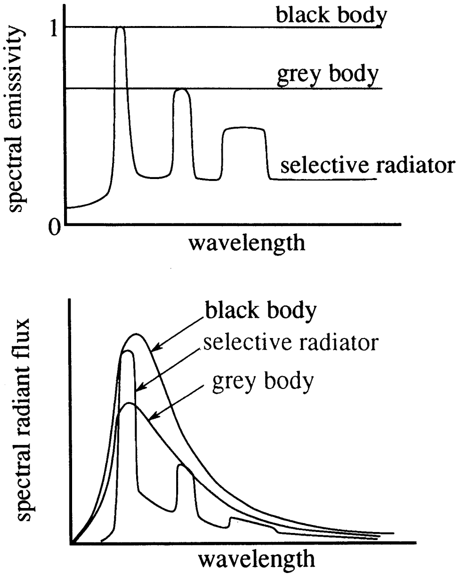


Figure 1.7.1 Plank's law of radiation

Figure 1.7.2 Radiators

Table 1.7.1 Plank's law of radiation

spectral radiance of black body $B\lambda$ is given as follows.

$$B\lambda = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp(hc/k\lambda T) - 1}$$

$B\lambda$	:	black body spectral radiance ($W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$)		
T	:	absolute temperature of Black body (K)		
λ	:	wavelength (μm)		
c	:	velocity of light	2.998×10^8	($m \cdot s^{-1}$)
h	:	plank's constant	6.626×10^{-34}	($J \cdot s$)
k	:	Boltzmann's constant	1.380×10^{-23}	($J \cdot K^{-1}$)

1.8 Reflectance

Reflectance is defined as the ratio of incident flux on a sample surface to reflected flux from the surface as shown in Figure 1.8.1. Reflectance ranges from 0 to 1. Reflectance was originally defined as a ratio of incident flux of white light to reflected flux in a hemisphere direction. Equipment to measure reflectance are called spectrometers (see 2.6).

Albedo is defined as the reflectance using the incident light source from the sun. **Reflectance factor** is sometime used as the ratio of reflected flux from a sample surface to reflected flux from a perfectly diffuse surface.

Reflectance with respect to wavelength is called **spectral reflectance** as shown for a vegetation example in Figure 1.8.2. A basic assumption in remote sensing is that spectral reflectance is unique and different from one object to an unlike object.

Reflectance with a specified incident and reflected direction of electro-magnetic radiation or light is called **directional reflectance**. The two directions of incident and reflection have can be directional, conical or hemispherical making nine possible combinations.

For example, if incident and reflection are both directional, such reflectance is called bidirectional reflectance as shown in Figure 1.8.3. The concept of bidirectional reflectance is used in the design of sensors.

Remarks; A perfectly diffuse surface is defined as a uniformly diffuse surface with a reflectance of 1, while the uniformly diffused surface, called a Lambertian surface, reflects a constant radiance regardless of look angle.

The Lambert cosine law which defines a Lambertian surface is as follows:

$$I(\theta) = I_n . \cos\theta$$

where $I(\theta)$: luminous intensity at an angle of θ from the normal to the surface.

I_n : luminous intensity at the normal angle

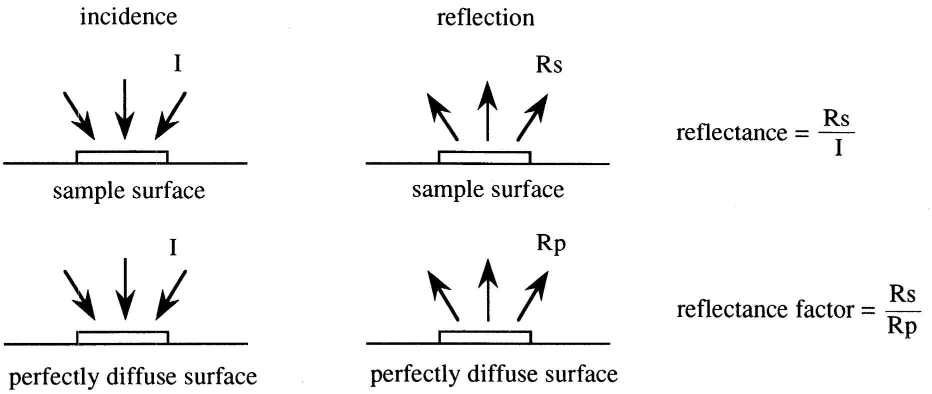


Figure 1.8.1 Reflectance and reflectance factor

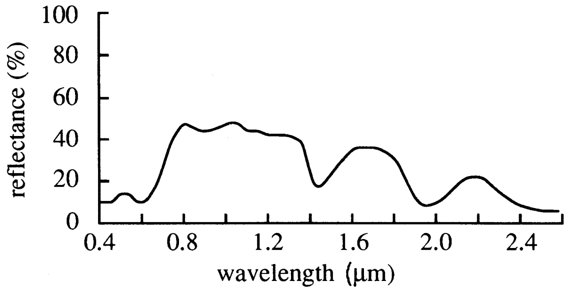


Figure 1.8.2 Spectral reflectance of vegetation

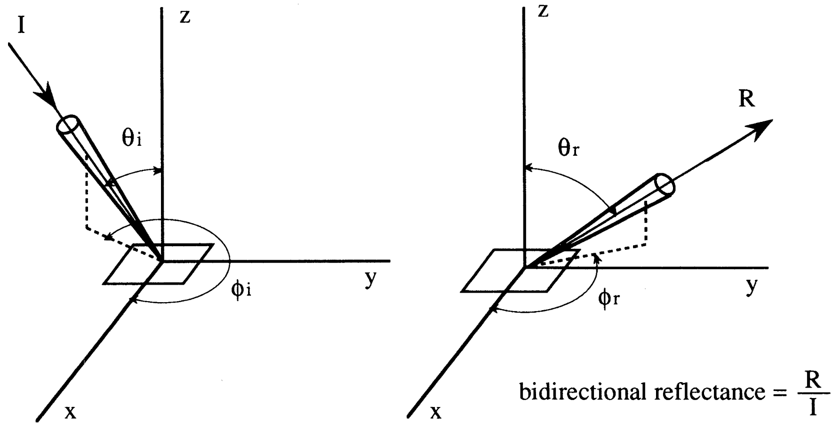


Figure 1.8.3 Bidirectional reflectance

1.9 Spectral Reflectance of Land Covers

Spectral reflectance is assumed to be different with respect to the type of land cover, as explained in 1.3 and 1.8. This is the principle that in many cases allows the identification of land covers with remote sensing by observing the spectral reflectance or spectral radiance from a distance far removed from the surface.

Figure 1.9.1 shows three curves of spectral reflectance for typical land covers; vegetation, soil and water. As seen in the figure, vegetation has a very high reflectance in the near infrared region, though there are three low minima due to absorption.

Soil has rather higher values for almost all spectral regions. Water has almost no reflectance in the infrared region.

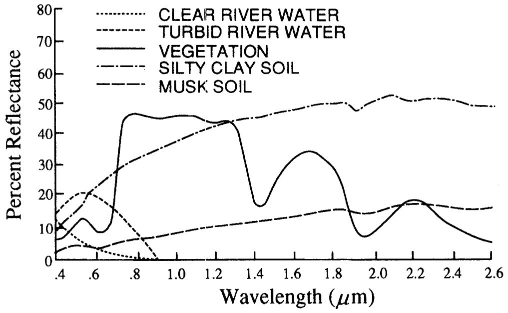
Figure 1.9.2 shows two detailed curves of leaf reflectance and water absorption. Chlorophyll, contained in a leaf, has strong absorption at 0.45 µm and 0.67 µm, and high reflectance at near infrared (0.7-0.9 µm). This results in a small peak at 0.5-0.6 (green color band), which makes vegetation green to the human observer.

Near infrared is very useful for vegetation surveys and mapping because such a steep gradient at 0.7-0.9 µm is produced only by vegetation.

Because of the water content in a leaf, there are two absorption bands at about 1.5 µm and 1.9 µm. This is also used for surveying vegetation vigor.

Figure 1.9.3 shows a comparison of spectral reflectance among different species of vegetation.

Figure 1.9.4 shows various patterns of spectral reflectance with respect to different rock types in the short wave infrared (1.3-3.0 µm). In order to classify such rock types with different narrow bands of absorption, a multi-band sensor with a narrow wavelength interval is to be developed. Imaging spectrometers (see 2.12) have been developed for rock type classification and ocean color mapping.



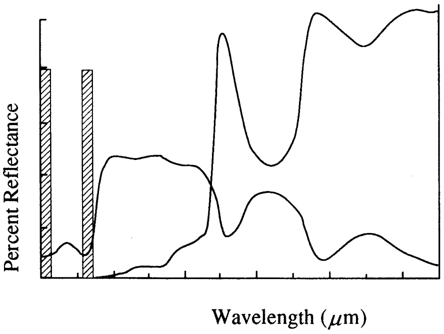
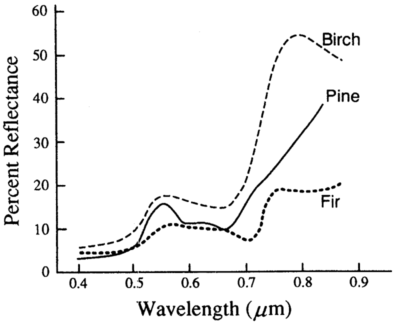


Figure 1.9.1 Spectral reflectance of vegetation, soil and water

Figure 1.9.2 Spectral reflectance of a green leaf



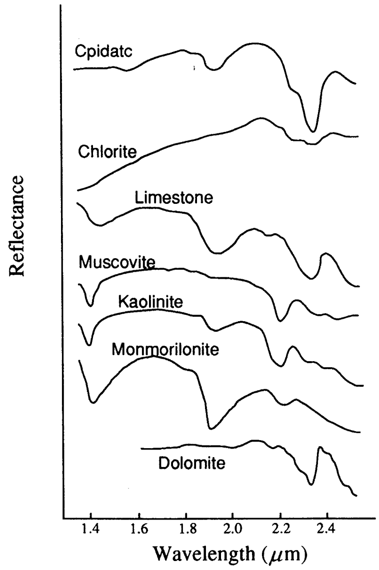


Figure 1.9.3 Spectral reflectance of different kind of plants

Figure 1.9.3 Spectral reflectance of rocks and minerals

1.10 Spectral Characteristics of Solar Radiation

The sun is the energy source used to detect reflective energy of ground surfaces in the visible and near infrared regions.

Sunlight will be absorbed and scattered by ozone, dust, aerosols, etc., during the transmission from outer space to the earths surface (see 1.11 and 1.12). Therefore, one has to study the basic characteristics of solar radiation.

The sun is considered as a black body with a temperature of 5,900°K. If the annual average of solar spectral irradiance is given by $FeO(\lambda)$, then the solar spectral irradiance $Fe(\lambda)$ in outer space at Julian day D, is given by the following formula.

$$Fe(\lambda) = FeO(\lambda)\{1 + \cos \varepsilon (2\pi (D-3)/365)\}^2$$

where ε : 0.167 (eccentricity of the Earth orbit) λ : wavelength

D-3: shift due to January 3 as apogee and July 2 as perigee

The **sun constant** that is obtained by integrating the spectral irradiance for all wavelength regions is normally taken as $1.37 Wm^{-2}$. Figure 1.10.1 shows four observation records of solar spectral irradiance. The values of the curves correspond to the value at the surface perpendicular to the normal direction of the sun light. To convert to the spectral irradiance per m^2 on the Earth surface with a latitude of ϕ, multiply the following coefficient by the observed values in Figure 1.10.1.

$$\alpha = (L_0 / L)^2 \cos z \qquad \cos z = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos h$$

where z : solar zenith angle δ : declination h : hour angle,

L : real distance between the sun and the earth

L_0: average distance between the sun and the earth

The incident solar radiation at the earth's surface is very different to that at the top of the atmosphere due to atmospheric effects, as shown in 1.10.2, which compares the solar spectral irradiance at the earth's surface to black body irradiance from a surface of temperature 5900°K.

The solar spectral irradiance at the earth's surface is influenced by the atmospheric conditions and the zenith angle of the sun. Figure 1.10.3 shows several different curves of solar spectral irradiance on the surface with respect to different angles, with the curve, $m = 0$, showing the solar spectral irradiance in outer space.(ie. above the atmosphere)

Beside the direct sunlight falling on a surface, there is another light source called sky radiation, diffuse radiation or skylight, which is produced by the scattering of the sunlight by atmospheric molecules and aerosols.

The skylight is about 10 percent of the direct sunlight when the sky is clear and the sun's elevation angle is about 50 degree. The skylight has a peak in its spectral characteristic curve at a wavelength of 0.45 μm.

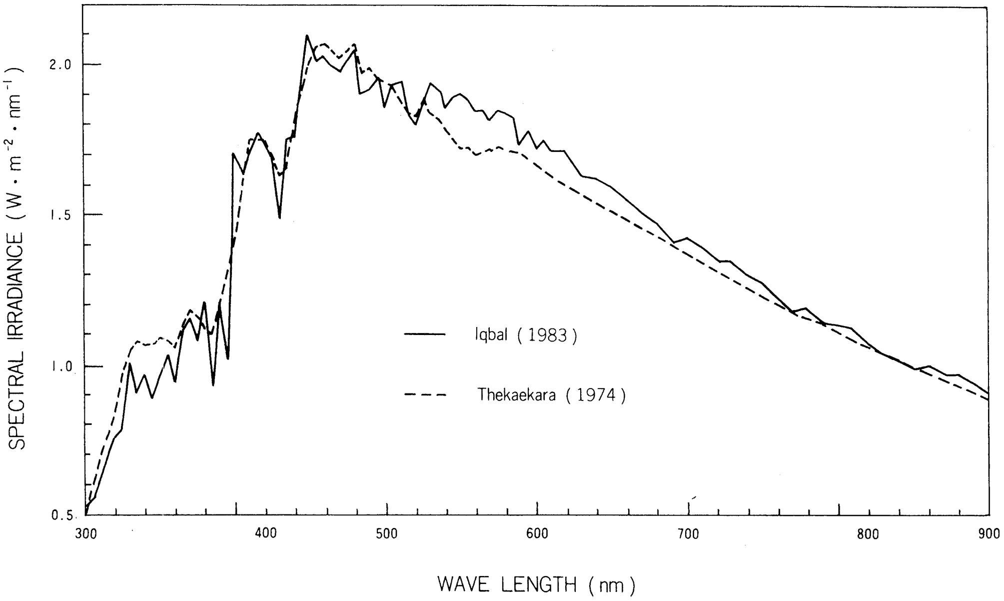


Figure 1.10.1 Solar irradiance at the top of atmosphere (annual mean)

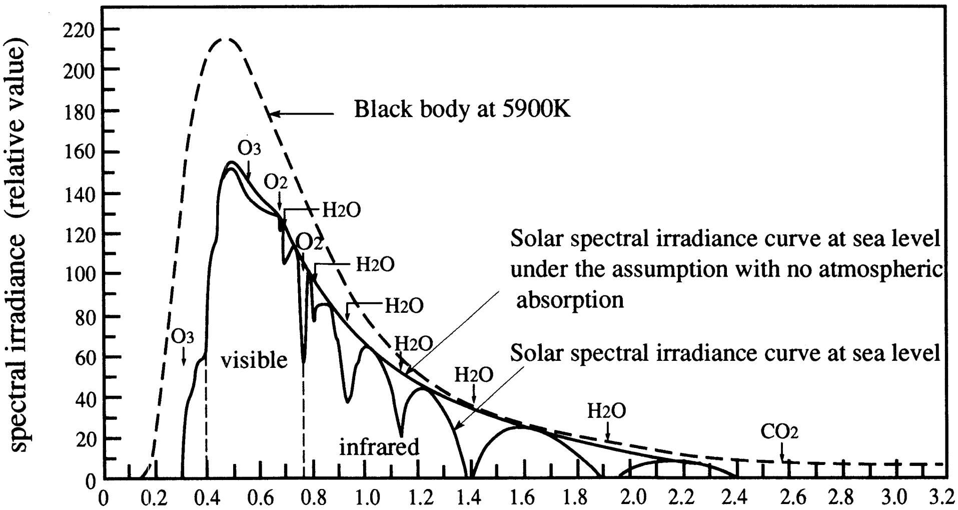


Figure 1.10.2 Comparison of spectral irradiance of solar light at sea level with black body radiation

1.11 Transmittance of the Atmosphere

The sunlight's transmission through the atmosphere is affected by **absorption** and **scattering** of atmospheric molecules and aerosols. The reduction of sunlight intensity is called extinction. The rate of **extinction** is expressed as **extinction coefficient** (see 1.12).

The **optical thickness** of the atmosphere corresponds to the integrated value of the extinction coefficient at each altitude by the atmospheric thickness. The optical thickness indicates the magnitude of absorption and scattering of the sunlight. The following elements will influence the transmittance of the atmosphere.

a. Atmospheric molecules(smaller size than wavelength):
carbon dioxygen, ozone, nitrogen gas, and other molecules

b. Aerosols (larger size than wavelength):
water drops such as fog and haze, smog, dust and other particles with a bigger size

Scattering by atmospheric molecules with a smaller size than the wavelength of the sunlight is called **Rayleigh scattering**. Rayleigh scattering is inversely proportional to the fourth power of the wavelength.

The contribution of atmospheric molecules to the optical thickness is almost constant spatially and with time, although it varies somewhat depending on the season and the latitude.

Scattering by aerosols with larger size than the wavelength of the sunlight is called **Mie scattering**. The source of aerosols will be suspended particles such as sea water or dust in the atmosphere blown from the sea or the ground, urban garbage, industrial smoke, volcanic ashes etc., which varies to a great extent depending upon the location and the time. In addition, the optical characteristics and the size distribution also changes with respect to humidity, temperature and other environmental conditions. This makes it difficult to measure the effect of aerosol scattering.

Scattering, absorption and transmittance of the atmosphere are different for different wavelengths. Figure 1.11.1 shows the spectral transmittance of the atmosphere. The low parts of the curve show the effect of absorption by the molecules described in the figure. Figure 1.11.2 shows the spectral transmittance, or conversely absorption, with respect to various atmospheric molecules. The open region with higher transmittance in called "an atmospheric window".

As the transmittance partially includes the effect of scattering, the contribution of scattering is larger in the shorter wavelengths. Figure 1.11.3 shows a result of simulation for resultant transmittance multiplied by absorption and scattering which would be produced for a standard "clean atmospheric model" in the U.S.A. The contribution by scattering is dominant in the region less than 2mm and proportional according to the shorter wavelength. The contribution by absorption is not constant but depends on the specific wavelength.

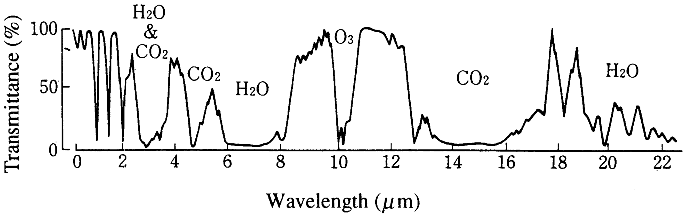


Figure 1.11.1 Characteristic of atmosphericspectral transmittance

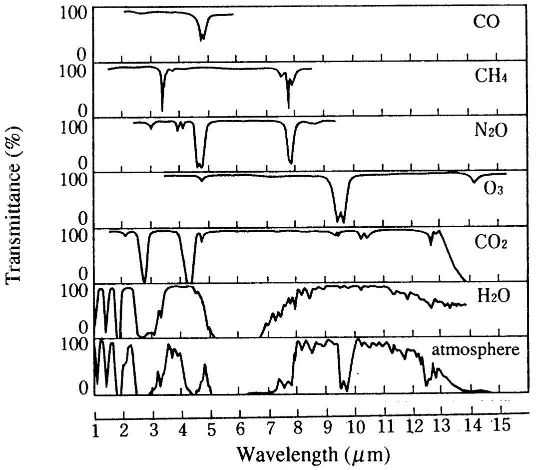


Figure 1.11.2 Characteristics of absorption in infrared region by atmospheric molecules

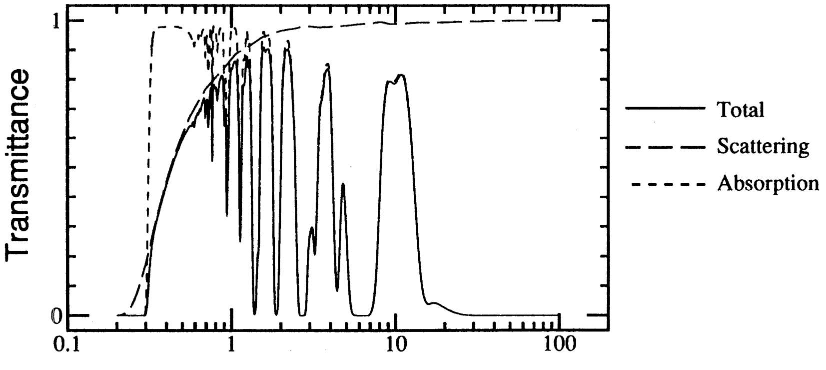


Figure 1.11.3 Atmospheric transmittance with contributions of absorption and scattering for "Clean" U.S. standard atmospheric model

1.12 Radiative Transfer Equation

Radiative transfer is defined as the process of transmission of the electro-magnetic radiation through the atmosphere, and the influence of the atmosphere. The atmospheric effect is classified into multiplicative effects and additive effects as shown in Table 1.12.1.

The multiplicative effect comes from the **extinction** by which incident energy from the earth to a sensor will reduce due to the influence of absorption and scattering. The additive effect comes from the **emission** produced by thermal radiation from the atmosphere and atmospheric scattering, which is incident energy on a sensor from sources other than the object being measured.

Figure 1.12.1 shows a schematic model for the absorption of the electro-magnetic radiation between an object and a sensor, while Figure 1.12.2 shows a schematic model for the extinction. Absorption will occur at specific wavelengths (see 1.11) when the electro- magnetic energy converts to thermal energy. On the other hand, scattering is remarkable in the shorter wavelength region when energy conversion does not occur but only the direction of the path changes.

As shown in Figures 1.12.3 and 1.12.4, additional energy by emission and scattering of the atmosphere is incident upon a sensor. The thermal radiation of the atmosphere which is characterized by **Plank's law** (see 1.7), is uniform in all directions. The emission and scattering of the atmosphere incident on the sensor, is indirectly input from other energy sources of scattering than those on the path between a sensor and an object.

The scattering depends on the size of particles and the direction of incident light and scattering.

Thermal radiation is dominant in the thermal infrared region, while scattering is dominant in the shorter wavelength region.

Generally, as extinction and emission occur at the same time,both effects should be considered together in the **radiative transfer equation** as indicated in the formula in Table 1.12.2.

Table 1.12.1 Atmospheric effects

Effects	Mechanism	Wavelength	Related physical variables
Multiplitive	Absorption	All region	Absorption coefficient, Absorber amount, Temperature Pressure
(Extinction)	Scattering	Visible & near IR	Scattering coefficient, Scatterer amount, Phase function
Additive	Thermal radiation	Thermal IR	Absorption coefficient, Absorber amount, Temperature Pressure
(Emission)	Scattering	Visible & near IR	Scattering coefficient, Scatterer amount, Phase function

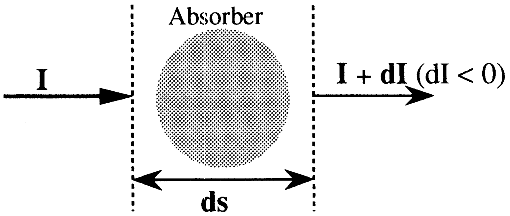


Figure 1.12.1 Absorption (extinction)

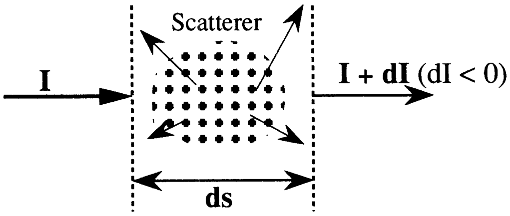


Figure 1.12.2 Scattering (extinction)

Definition of extinction coefficient K

$$\boxed{\mathbf{dI} = \rho \cdot \mathbf{K} \cdot \mathbf{I} \cdot \mathbf{ds}}$$

I : Incident radiance
dI : Increment of radiance
ρ : Absorber / Scatterer density
ds : Path length

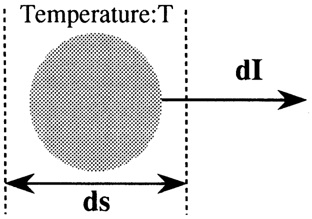


Figure 1.12.3 Thermal radiation (emission)

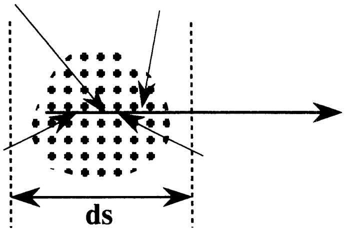


Figure 1.12.4 Scattering (emission)

Definition of emission coefficient j

$$\boxed{\mathbf{dI} = \rho \cdot \mathbf{j} \cdot \mathbf{ds}}$$

(1) Thermal radiation

$$\boxed{\mathbf{j} = \rho \cdot \mathbf{B(T)}}$$

ρ : Absorber density
B : Planck function
T : Temperature [K]

(2) Scattering

$$\boxed{\mathbf{j} = \omega_0 \frac{\mathbf{K}}{4\pi} \rho \int_{\Omega} \mathbf{P}(\Omega, \Omega)\, \mathbf{I}\,(\Omega')\, d\Omega}$$

ω_0 : Albedo for single scattering
ρ : Scatterer density
P : Phase function
Ω : Solid angle of incidence
Ω' : Solid angle of scattering
K : Extinction coefficient