1. Electromagnetic Spectrum and Remote Sensing.

Electromagnetic radiation is characterized by the amplitude, wavelength, frequency and phase of the signal. There is a continuum of wavelengths referred to as the electromagnetic spectrum (EM). Different regions of the EM have different names. There is no precise boundary between the regions. In the middle region of the EM spectrum the EM wave is described by its wavelength. At very high energies the wavelength is very short and the frequency is very high. In these regions the EM wave is described by it the energy of its photons. Examples would be x-rays and gamma rays. At very low energies the wavelengths are long and the EM wave is described by its frequency [Richards, 2001, preface]

The following table gives some information about the electromagnetic spectrum [Simonett, 1983, pp. 40, Elachi, 1987, pp. 22].

Table 1. Electromagnetic Spectrum

Wavelength in meters	Frequency Hz	Frequency name		Name	Common Users
	10	Hertz		Extremely Low Frequency	generators
10^7	30	cycles per		ELF	
	$100 = 10^2$	second			
10^6	300			Voice Frequency	voice
	1	Kilohertz		VF	
10^5	3				radio
	$10 = 10^4$			Very Low Frequency	
10^4	30			VLF	
	$100 = 10^5$			Low Frequency	
10^3	300			LF	
	1	Megahertz		Medium Frequency	
10^1	3			MF	television
	$10 = 10^7$			High Frequency	
10	30			HF	
	$100 = 10^8$			Very High Frequency	
1	300			VHF	
	1	Gigahertz		Ultra High Frequency	radar
10^{-1}	3			UHF	microwave
	$10 = 10^{10}$			Super High Frequency	emitters
10^{-2}	30			SHF, centimeter waves	
	$100 = 10^{11}$			Extremely High Frequency	lasers
10^{-3}	300			EHF, millimeter waves	
	1	Epahertz		submillimeter waves	
10^{-4}	3				
	$10 = 10^{13}$			far infrared	
10^{-5}	30				
	$100 = 10^{14}$	1 ev	photon	intermediate infrared	
10^{-6}			energy	near infrared	
	10^{15}	10 ev	in	visible	
10^{-7}			electro n	near ultraviolet	
	10^{16}	100 ev	volts	vacuum ultraviolet	
10^{-8}					
	10^{17}	1 kev			
10^{-9}	10^{18}	10 kev		soft x-rays	x-ray tubes
10^{-10}	10^{19}	100 kev		hard x-rays	
10^{-11}	10^{20}	1 Mev		soft gamma rays	linear
10^{-12}	10^{21}	10 Mev		hard gamma rays	accelerators
10^{-13}	10^{22}	100 Mev		gamma rays	
10^{-14}	10^{23}	1 Gev		from cosmic rays	

Radio waves exist from 1 kilohertz (1000 cycles per second) to about 1 gigahertz (10^9 cycles per second). The wavelengths range between 300,000 meters to .3 meters. These frequencies are not used in remote sensing. We do not image at wavelengths longer than 1m because antennas cannot be adequately focused.

The near-infrared (NIR) and the near-ultraviolet (NUV) regions are next to the visible area of the EM spectrum. NIR photons do not have energy required to stimulate the eye sensors and our eye lens block UV light. Hence humans do not see these bands of light [Richards, 2001, pp. 1].

IR, visible, and UV lie in the middle of the EM spectrum using a log scale. This might be called medium light. Medium light is strongly emitted and absorbed by atoms and molecules in matter [Richards, 2001, pp. 51] and may not penetrate more than a few millimeters of solid material. Very short and very long wavelengths of light may penetrate much deeper into materials. An example is x-ray imaging that has high energy. This light passes through skin but is absorbed by denser objects. Light in the long wavelength regions can penetrate sand and ice for kilometers. There are many applications that utilize different regions of the EM spectrum.

1.1 Visible Spectrum

The visible part of the spectrum is shown below. The visible spectrum has been defined to be from 380 to 790 nm by the International Commission on Illumination.

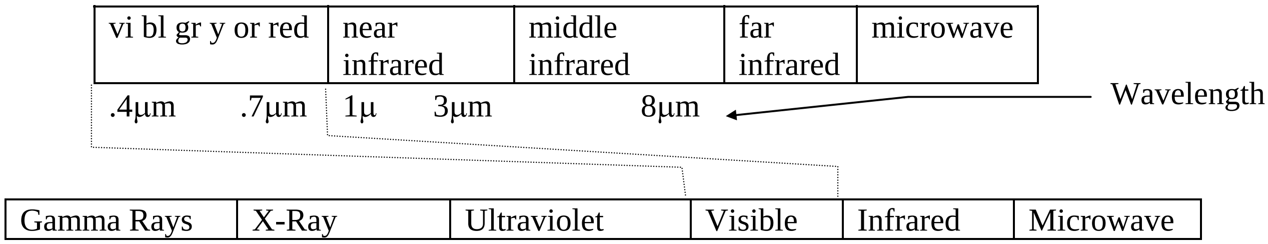

Figure 1. Electromagnetic Spectrum

The wavelengths for different colors are given in the following table [Weeks, 1996, pp. 230].

Table 2. Wavelengths for some visible colors

color	wavelength
violet	0.38 – 0.45 µm
blue	0.45 - 0.48 µm
cyan	0.48 - 0.49 µm
green	0.49 - 0.56 µm
yellow	0.56 – 0.58 µm
orange	0.58 – 0.60 µm
red	0.60 – 0.79 µm

The visible part of the EM spectrum covers the region from .38 to .79 microns. The human eye has its peak sensitivity at .55 microns, which is approximately the peak of the emission curve of the sun. The atmosphere scatters blue light and hence the sky appears blue in visible light. The scattering is Rayleigh scattering by the atmospheric molecules (primarily oxygen and nitrogen). The sun appears red at sunset because we are looking through a thick atmosphere that removes the blue with scattering leaving a red appearing sun.

1.2 Infrared Spectrum

The infrared (IR) part of the EM spectrum goes from about .79 microns to 100 microns in wavelength. It borders the visible spectrum at the red end. This region is often broken into subregions. The near IR (NIR) region is from .79 to 1.3 microns, the middle IR is from 1.3 to 7.0 microns, the far IR is from 7.0 to 15 microns. The extreme IR is from 15 to 100 microns [NASA, 2000a]. The middle IR includes the short wavelength IR (SWIR) and the midwave (MWIR) regions. Another name for the far IR is the longwave IR. This region is also called the thermal IR region [NASA, 2000b]. See the following table. Some other subdivisions are the reflected IR (.7-3.0 microns), photographic IR (.7-.9 microns), thermal IR bands at 3-6 microns, and thermal IR bands at 8-14 microns. NASA often refers to the visible and near IR (VNIR) that includes the visible and near IR spectrum. These subdivisions are approximate and not universally agreed upon as to their boundaries.

Table 3. IR regions of the EM spectrum

visible	near IR NIR	short wave IR SWIR	midwave IR MWIR	far IR thermal IR longwave IR LWIR	extreme IR
.38-.79μm	.79-1.3μm	1.3-2.5μm	2.5-7μm	7-15μm	15-100μm

The near and middle IR radiated energy is primarily from the sun and hence is often called the reflective-infrared part of the spectrum. The far IR or thermal IR radiated energy is primarily from objects on the earth and not the sun. Near IR radiation is only emitted by very hot bodies such as our sun. Most satellite near IR sensors are designed to passively detect reflected IR energy coming from the sun. The long wavelengths consisting of the far and intermediate infrared region are the only regions useful for sensing temperature on the earth. A body of 20 degrees Celsius emits its radiant energy in the region from 4 to 90 microns in wavelength with the peak at 9.8 microns. All objects reflect, transmit, and emit energy. The intensity of an object's emitted IR energy is proportional to its temperature. The term emissivity is used to describe an object's energy emitting characteristics. Every object emits an optimum amount of IR energy at a specific point in the IR band. The atmosphere is nearly opaque to EM radiation in part of the mid-IR and all of the far IR. Water has absorption bands at 760, 970, 1190, and 1450nm bands. Red light is also absorbed by water [Richards, 2001, pp. 22]. The atmosphere contains water vapor and may absorb radiation in these bands.

The thermal band on the Landsat 4 and 5 satellites covers the range from 10.4 to 12.5 microns. Near infrared radiation is generated by hot bodies such as the sun. Hence most near IR systems are designed to detect passive radiation from the sun. The three non-thermal Landsat TM IR bands cover the region from .79 to 2.35 microns. The near IR region is useful for identification of surface materials. Many sensors cover the visible and near IR regions of the EM [Spencer, 1997].

In the NIR region healthy vegetation is highly reflective and appears bright or white. Diseased vegetation is not so reflective and appears darker [Richards, 2001, pp. 8].

This has applications to agriculture and forestry studies. Materials that have been colored to look like vegetation in the visible region appear dark in the NIR. This is relevant to military reconnaissance and camouflage applications. NIR and visible light are absorbed and transmitted differently. The NIR may penetrate materials that absorb visible light [Richards, 2001, pp. 10]. The SWIR region is used to examine documents. The NIR has forensic applications. One may recover writing or printing that has been marked over with pens or correcting fluid. One may examine old paintings to discover layers that have been covered with varnish or other paints. Varnish is transparent to IR light. Old documents may be read with light in the IR region. One may need tunable filters to see the most detail. Alcohol has absorption bands in the 1600-1900nm region. Flaming alcohol may occur in auto racing and cannot be seen in visible light. It may be seen with an IR camera [Richards, 2001, pp. 25].

There are many applications for thermal imaging [Richards, 2001, pp. 27,31]. If one heats an object it changes from red to white at it gets hotter. A body emits radiation depending upon its temperature. One must go to longer wavelengths to see energy emitted by bodies at near terrestrial temperatures. One cannot see the energy emitted by a person in the visible range. A person will appear bright in the MWIR and the LWIR regions. This is especially true at night when the radiant energy of the sun in the spectral ranges is not present. Light in these ranges can also penetrate smoke and mist. The IR region is not scattered by the atmosphere. The sky appears black in this spectral region. No animal can see in the MWIR and LWIR regions. Thermal IR cameras can detect .01 degree C differences [Richards, 2001, pp. 33, 43]. The MWIF region is good for measuring temperatures in the 0-200 degree C range. Glass is transparent to visible to opaque to MWIR-LWIR. Thermal imaging may detect differences in materials. Dense materials retain heat. One may be able to locate studs in houses, hidden compartments, or buried objects [Richards, 2001, pp. 40]. Thermal imaging is used locate heat build up in electrical circuits and to determine heat loss in buildings. In medical applications it is used to analyze blood flow since blood is warmer that tissue [Richards, 2001, pp. 45].

1.3 UV Spectrum

The ultraviolet (UV) covers the region from 10 to 380 nm. The radiation is detrimental to organic materials. It is strongly absorbed by ozone in the atmosphere and to a lesser extent by oxygen. It has been used to induce fluorescence in hydrocarbons such as thin films on water resulting from oil spills. It has also been used to prospect for minerals.

The near UV (NUV) region is from 200-380nm. There are a number of forensic applications in this spectral region. Fingerprints are often located in the NUV region. Finger oils are transparent to visible but reflect NUV light. This makes fingerprints distinct in NUV light [Richards, 2001, pp. 14]. Some materials fluoresce (emit radiant energy) when exposed to NUV light. This includes hair, fibers, and blood. Camouflage materials often reflect visible light but absorb NUV. Polar bears appear black in NUV light. Artic camouflage uniforms also appear black. NUV light does not penetrate human skin but is absorbed by the melanon pigment. This may cause damage but also allows the determination of diseased skin areas that do not absorb the NUV light [Richards, 2001, pp. 17].

The atmosphere has water content and hence absorbs at these bands. NUV has higher energy and is absorbed by glass that transmits visible, NIR, and SWIR. Hence glass is opaque to the NUV. Hair does not absorb the SWIR and hence appears white in this light but hair does absorb NUV and hence appears dark in this light. Methanol flames emit at 240-280nm range and may be seen with a NUV camera [Richards, 2001, pp. 25]. The corona around electrical connections in a strong electric field emits in the NUV and may be detected with a NUV camera. This fact is often utilized to locate broken connections in electrical power transmission applications.

1.4 TeraHz Spectrum

Another region frequently utilized is the terahertz region. This regions extends from .1 to 10THz or from 3000um to 30um. Recall that a terahertz is 10^{12} Hz and a gigahertz is 10^9 Hz. The region is between the visible/infrared and the microwave regions. It is used in biological applications.

There are a number of applications in the TeraHz range. Paper and cardboard are transparent in these images. The images can excite substances in a package and identify the substances. Substances absorb at these frequencies and can thereby be identified. Images a 230GHz or .23THz have been used to identify cancer from normal human tissue [Rowell, 2002].

1.5 Millimeter Spectrum

Microwaves occupy the region from .3 meters to about .0003 meters in wavelength. They pass through materials with low dielectric constants (nonconductors) but are reflected by materials such as rocks and soils containing water and metals. Some frequencies can penetrate clouds and jungle canopies. Passive systems sense microwaves emitted by the sun. RADAR technology and in particular SAR (Synthetic Aperture Radar) is an active technology. It has been used to detail surface topography irrespective of cloud cover and vegetation. It can penetrate dry desert sand to show subsurface topography.

Microwaves have long wavelengths with less energy. The following table describes these bands. The term sub-MMW refers to sub-millimeter bands. The term MMW refers to millimeter bands.

Table 4. Long wavelength regions

Sub-MMW	MMW	microwave	radiowave
100μm-1mm	1-10mm	10mm-1m	1m-1000m

Millimeter wave energy is emitted naturally at low intensities from objects at terrestrial temperatures. Microwave imaging requires active illumination by radar devices. The sub-millimeter, millimeter, and microwave regions can be used to see through material that is opaque to middle light. Microwave imaging can see through clouds and vegetation. Radar (24GHz) can also be used to see through wood, plaster, and concrete and detect humans on the other side of a wall. This is called through wall imaging. Microwave energy penetrates human tissue. Cancerous tissue absorbs 2 to 5 times as much microwave energy at 3GHz as normal tissue and can be used to characterize cancerous tissue [Hogan, 2000].

Millimeter imaging can see through clothing [Richards, 2001, pp. 51].

There are a number of applications for long wavelength imaging in the sub-MMW, MMW, and microwave regions [Richards, 2001, pp. 53]. Sub-millimeter imaging is referred to as T-imaging since it is in the terrahertz range. It is in the early stage of development. It has applications in inspection and security. Pulse of sub-millimeter light are transmitted through a sample and detected. The detected signal can determine the chemical properties of the sample because they affect the pulse shape. One can determine the contents of a package without opening it. MMW imaging is used for security applications [Richards, 2001, pp. 55] to detect guns, explosives, and drugs. Imaging with x-rays has safety concerns. There is a need to penetrate clothing safely. EM in the 3-mm band is emitted by the skin and penetrates clothing. Guns, explosive packets, and drug packets block the emitted MMW light and become visible. Cloth absorbs middle light that cannot be used for this application. Another application is seeing through fog. MMW light is not scattered by water droplets (fog) and these cameras can aid pilots in fog conditions [Richards, 2001, pp. 58]. MMW imaging can see through packaging, clothing, and many wall materials. It does not penetrate human skin and is safe to humans. Human skin does emit radiate energy at these frequencies.

1.6 X-ray and Gamma Ray Spectrum

Light at wavelengths shorter then the UV behaves like a particle or photon and has high energy [Richards, 2001, pp. 77]. These regions of the EM spectrum are called x-rays and gamma rays. X-rays cover the region from .01 microns to .00001 microns. They are dangerous to organisms. They are not used in remote sensing because of high atmospheric absorption and difficulty in focusing them. Gamma rays have wavelengths shorter than .00001 microns. They are emitted by celestial bodies as a by-product of thermonuclear reactions. These are the most energetic forms of EM radiation. Gamma rays are also emitted by natural radioactive elements such as uranium and potassium.

Medical applications make use of x-rays in radiography and computed tomography (CT) imaging. Light at these frequencies allows us to see through opaque materials. In normal x-ray imaging the source is on one side of the object and the detector the other side. Dense materials absorb the x-rays and create an image of the object. Backscatter x-ray detectors are on the same side as the source and detect the backscattered x-ray signals [Richards, 2001, pp. 91]. Gamma rays can penetrate steel containers. They are used for on site examination of nuclear warheads. PET scanners used in hospitals also use gamma rays. The patient takes a drug cocktail that causes the gamma ray emissions [Richards, 2001, pp. 96,98].

Table 5. High energy light

gamma rays	x-rays	ultra violet	visible
<.01 nm	.01-10nm	10-380nm	380-790nm

1.7 Thermoacoustics

Thermoacoustics is more than 100 years old. When photons strike an object sound is produced. The photons striking an object generate heat that results in a thermal wave in the object. The heat causes the object to expand and results in sound. A pulse of photons results in a pulse of sound. Turning the laser on and off generates a string of pulses and generates sound.

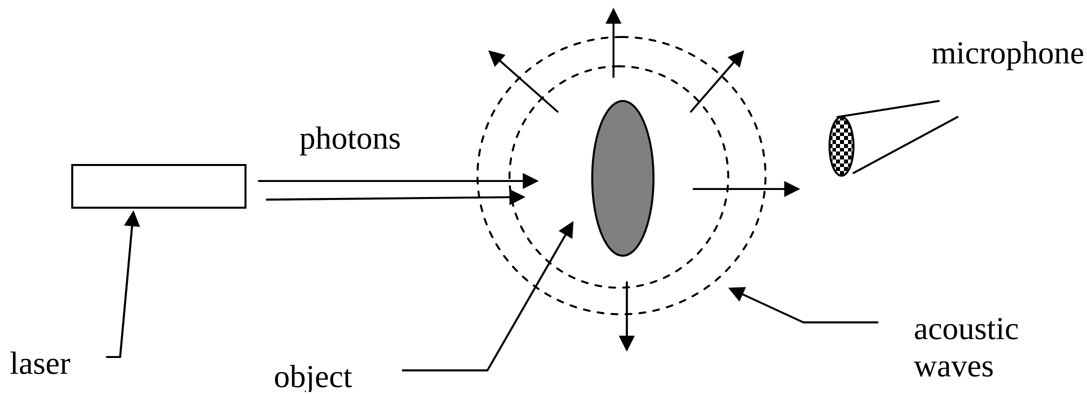

Figure 2. Thermoacoustic Detector

Thermoacoustics has been used in biomedical applications to determine malignant tumors and monitor glucose. Resolutions of .75mm have been obtained with 10μm a possibility. A pulsed beam of photons travel through tissue, when the bean strikes a tumor it produces a thermal wave and sound is produced that scatters in all directions. Software detects the sound and produces an image. Thermoacoustic computed tomography images have been created. Visible and infrared light suffer severe attenuation in tissue. Hence microwaves at a frequency of 3GHz are used. This gives better penetration and cancerous tissue absorbs two to five times as much microwave energy as noncancerous tissue[Hagan, 2000].

The same technology has been used to develop an "optical nose". The presence of trace amounts of ammonia, nitric oxide, aldehydes, and ketones, the breath has been linked to kidney/liver malfunction, asthma, diabetes, cancer, and ulcers. The ability to detect trace gases in patients breath is important in diagnosis and treatment. Methods have been developed based upon photoacoustic spectroscopy to detect and measure trace gases. The laser beam overlaps a spectral feature of the target molecule. The absorbed radiant energy is converted into heating and the resulting acoustic waves are monitored with a microphone. Carbon dioxide laser have been used that produce 120 discrete wavelengths between 9 and 11 μm that allows the detection of ammonia with a 9.22 μm absorption line [Patel and Mueller, 2002].