Lecture 1.

The nature of electromagnetic radiation.

1. Basic introduction to the electromagnetic field:
   - Dual nature of electromagnetic radiation
   - Electromagnetic spectrum
2. Basic radiometric quantities: intensity and flux.
3. Introductory survey: passive and active remote sensing; general characteristics of satellite platforms (orbits, resolutions, types of sensors).

Required reading:

S: 2.1-2.2

Recommended reading:

Petty: Chapters 2-3

Additional reading:

CCRS online tutorial. Chapter 2 - Satellites and Sensors

http://ccrs.nrcan.gc.ca/resource/tutor/fundam/chapter2/01_e.php

NASA online tutorial: Sections: Overview, The Concept of Remote Sensing, and History of Remote Sensing; Remote Sensing Systems

http://www.fas.org/irp/imint/docs/rst/

1. Basic introduction to electromagnetic field.

Electromagnetic (EM) radiation is a form of energy propagated through free space or through a material medium in the form of electromagnetic waves.

EM radiation is so-named because it has electric and magnetic fields that simultaneously oscillate in planes mutually perpendicular to each other and to the direction of propagation through space.

- ✓ Electromagnetic radiation has the **dual nature**:
  its exhibits **wave properties** and **particulate (photon) properties**.

- **<u>Wave nature of radiation:</u>** Radiation can be thought of as **a traveling transverse wave.**

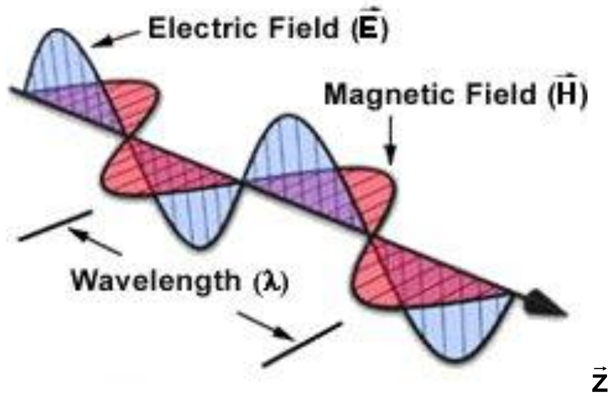


Figure 1.1 A schematic view of an electromagnetic wave propagating along the $\vec{z}$ axis. The electric $\vec{E}$ and magnetic $\vec{H}$ fields oscillate in the x-y plane and perpendicular to the direction of propagation.

- As a transverse wave, EM radiation can be polarized. **Polarization** is the distribution of the electric field in the plane normal to propagation direction.

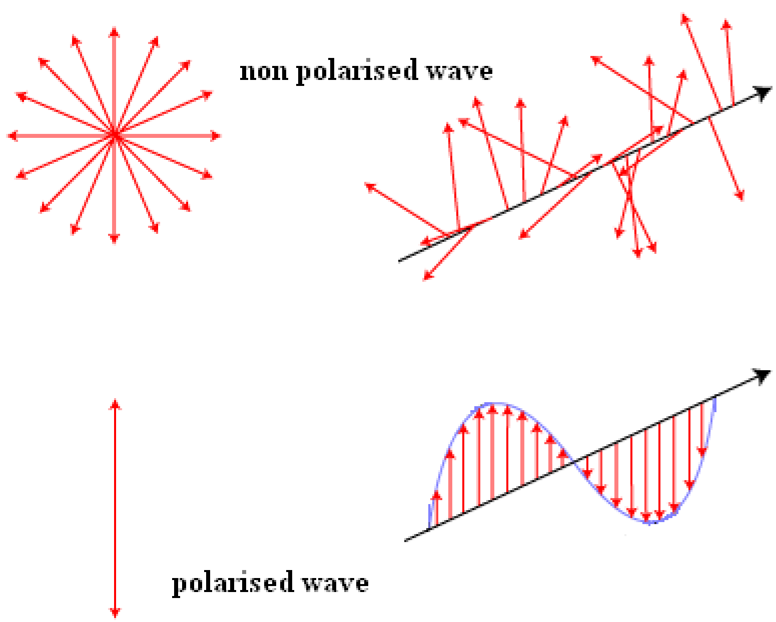


Figure 1.2 Electric field $\vec{E}$ orientation for polarized and non polarized electromagnetic waves.

Poynting vector gives the flow of radiant energy and the direction of propagation as (in the cgs system of units)

$$\vec{S} = c^2 \varepsilon_0 \vec{E} \times \vec{H} \quad [1.1]$$

here c is the speed of light in vacuum (c = 2.9979x10^8 m/s ≅ 3.00x10^8 m/s) and ε_0 is vacuum permittivity (or dielectric constant). $\vec{S}$ is in units of energy per unit time per unit area (e.g., W m^{-2})

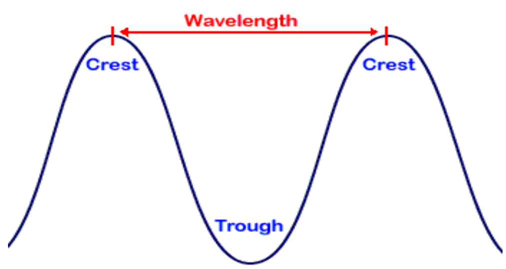
NOTE: $\vec{E} \times \vec{H}$ means a **vector product** of two vectors.

- $\vec{S}$ is often called **instantaneous Poynting vector**. Because it oscillates at rapid rates, a detector measures its average value <*S*> over some tome interval that is a characteristic of the detector.

- **Waves** are characterized by **frequency, wavelength, speed** and **phase**.

Frequency is defined as the number of waves (*cycles*) per second that pass a given point in space (symbolized by $\tilde{\nu}$).

Wavelength is the distance between two consecutive peaks or troughs in a wave (symbolized by the λ).



Relation between λ and $\tilde{\nu}$: $\boxed{\lambda \tilde{\nu} = c}$ [1.2]

- Since all types of **electromagnetic radiation** travel at the speed of light, short-wavelength radiation must have a high frequency.
- Unlike speed of light and wavelength, which change as electromagnetic energy is propagated through media of different densities, frequency remains constant and is therefore a more fundamental property.

Wavenumber is defined as a count of the number of wave crests (or troughs) in a given unit of length (symbolized by ν):

$$\nu = \tilde{\nu}/c = 1/\lambda \qquad [1.3]$$

UNITS:

Wavelength units: length

Angstrom (A) : 1 A = $1\text{x}10^{-10}$ m;

Nanometer (nm): 1 nm=$1\text{x}10^{-9}$ m;

Micrometer (μm): 1 μm = $1\text{x}10^{-6}$ m;

Wavenumber units: inverse length (often in cm^{-1})

NOTE: Conversion from the wavelength to wavenumber:

$$\nu[cm^{-1}] = \frac{10{,}000 cm^{-1}\mu m}{\lambda[\mu m]} \qquad [1.4]$$

Frequency units: unit cycles per second 1/s (or s^{-1}) is called hertz (abbreviated Hz)

Table 1.1 Frequency units

Unit	Frequency, (cycles/sec)
Hertz, Hz	1
Kilohertz, KHz	10^3
Megahertz, MHz	10^6
Gigahertz, GHz	10^9

- **Particulate nature of radiation:**

Radiation can be also described in terms of particles of energy, called **photons**

The energy of a **photon** is given as:

$$\boldsymbol{\varepsilon}_{\text{photon}} = \boldsymbol{h}\,\tilde{\nu} = \boldsymbol{h}\,c/\lambda = \boldsymbol{hc}\nu \qquad [1.5]$$

where $\boldsymbol{h}$ is Plank's constant (h = $6.6256\text{x}10^{-34}$ J s).

- Eq. [1.5] relates energy of each photon of the radiation to the electromagnetic wave characteristics ($\tilde{\nu}$ and λ).
- Photon has energy but it has no mass and no charge.

NOTE: The quantized nature of light is most important when considering absorption and emission of electromagnetic radiation.

PROBLEM: A light bulb of 100 W emits at 0.5 μm. How many photons are emitted per second?

Solution:

Energy of one photon is ε_{photon} = hc/λ, thus, using that 100 W = 100 J/s, the number of photons per second, N, is

$$N(s^{-1}) = \frac{100(Js^{-1})\ \lambda(m)}{h(Js)\ c(ms^{-1})} = \frac{100\ \times 0.5\times 10^{-6}}{6.6256\times 10^{-34}\times 2.9979\times 10^{8}} = 2.517\times 10^{20}$$

NOTE: Large number of photons is required because Plank's constant ***h*** is very small!!!

➢ **<u>Spectrum of electromagnetic radiation:</u>**

The electromagnetic **spectrum** is the distribution of electromagnetic radiation according to energy or, equivalently, according to the wavelength or frequency.

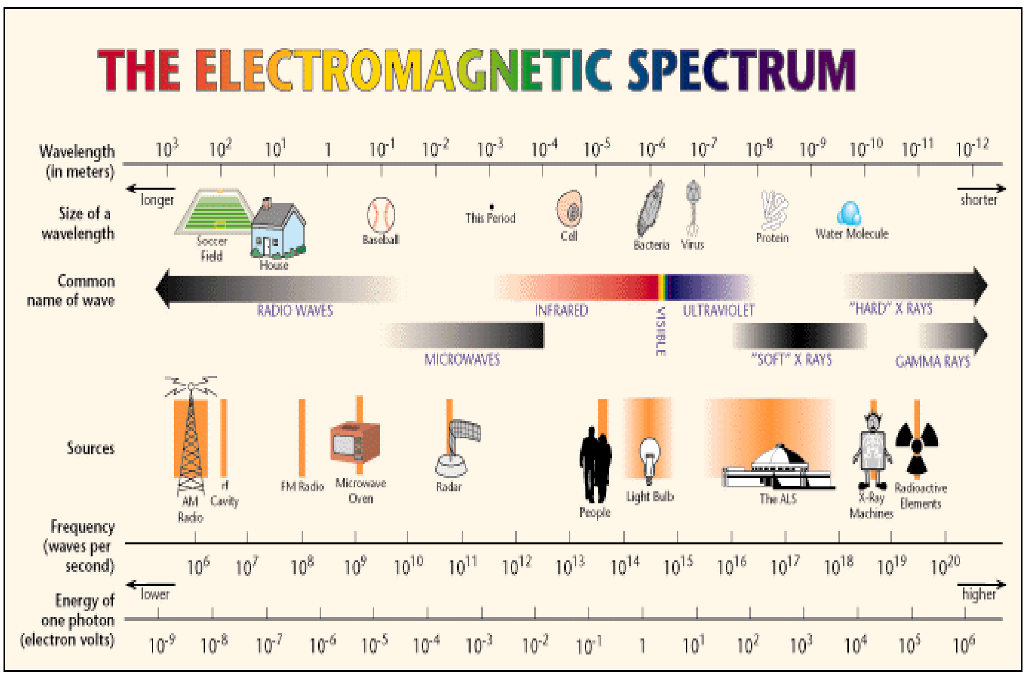


Figure 1.3 Schematic representation of the electromagnetic spectrum.

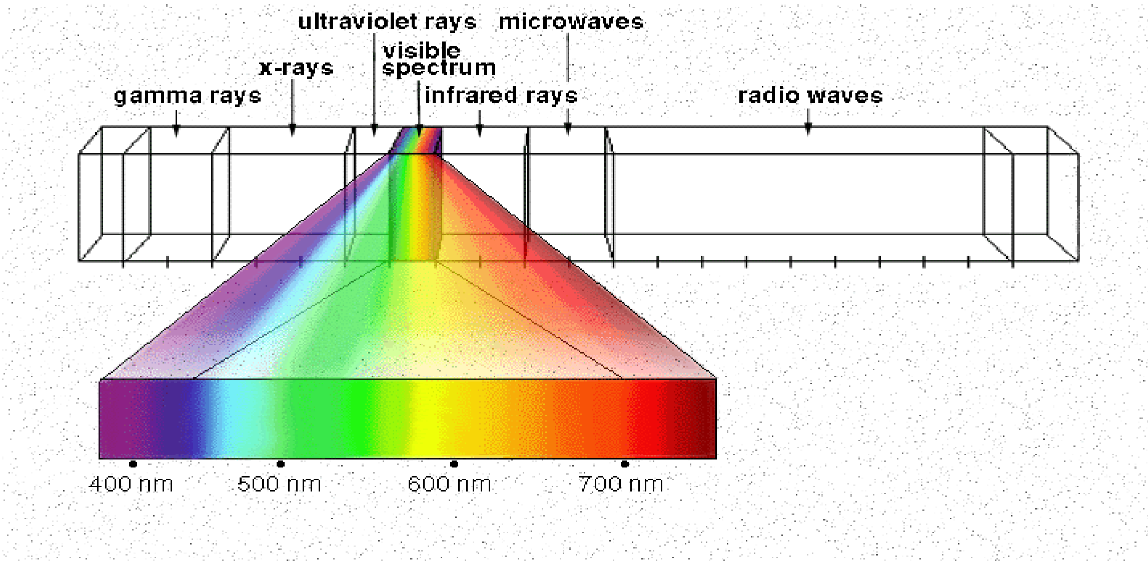


Figure 1.4 Visible region of the electromagnetic spectrum.

NOTE: In remote sensing, sensor's spectral bands in the visible are often called by their color (e.g., blue, green, and read channels)

Effects of atmospheric gases:

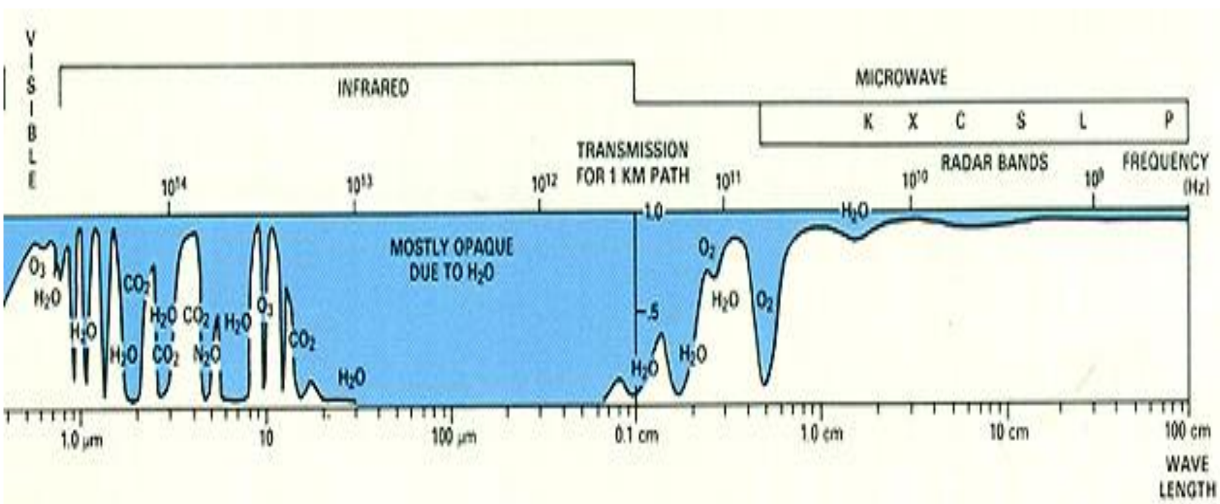


Figure 1.5 A generalized diagram showing relative atmospheric radiation **transmission** at different wavelengths. Blue zones show low passage of incoming and/or outgoing radiation and white areas show atmospheric windows, in which the radiation doesn't interact much with air molecules and hence, isn't absorbed.

Table 1.2 Common names and relationships between radiation components.

Name of spectral region	**Wavelength region, μm**	**Spectral equivalence**
Solar	0.1 - 4	Ultraviolet + Visible + Near infrared = Shortwave
Terrestrial	4 - 100	Far infrared = Longwave
Infrared	0.75 - 100	Near infrared + Far infrared
Ultraviolet	0.1 - 0.38	Near ultraviolet + Far ultraviolet = UV-A + UV-B + UV-C + Far ultraviolet
Shortwave	0.1 - 4	Solar = Near infrared + Visible + Ultraviolet
Longwave	4 - 100	Terrestrial = Far infrared
Visible	0.38 - 0.75	Shortwave - Near infrared - Ultraviolet
Near infrared	0.75 - 4	Solar - Visible - Ultraviolet = Infrared - Far infrared
Far infrared	4 - 100	Terrestrial = Longwave = Infrared - Near infrared
Thermal	4 - 100 (up to 1000)	Terrestrial = Longwave = Far infrared
Microwave	10^3 - 10^6	Microwave
Radio	> 10^6	Radio

Table 1.3 Microwave frequency bands used in remote sensing

Bands "Old"	**Bands** "New"	**Frequency [GHz]**
L	D	1-2
S	E, F	2-4
C	G, H	4-8
X	I, J	8-12
Ku	J	12-18
K	J	18-26
Ka	K	26-40

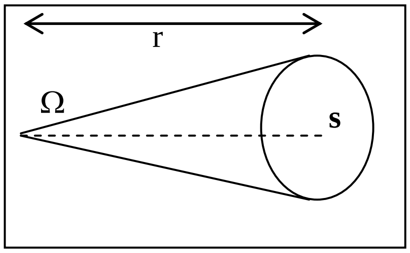
Example: L-band is used onboard American SEASAT and Japanese JERS-1 satellites.

2. Basic radiometric quantities: intensity and flux.

Solid angle is the angle subtended at the center of a sphere by an area on its surface numerically equal to the square of the radius

$$\Omega = \frac{s}{r^2} \qquad [1.6]$$

UNITS: of a solid angle = steradian (sr)



A differential solid angle can be expressed as

$$d\Omega = \frac{ds}{r^2} = \sin(\theta)d\theta d\phi,$$

using that a differential area is

$ds = (r\, d\theta)\,(r \sin(\theta)\, d\phi)$

Example: Solid angle of a unit sphere = 4π

PROBLEM: What is the solid angle of the Sun from the Earth if the distance from the Sun to the Earth is $d=1.5\text{x}10^8$ km? Sun's radius is $R_s = 6.96\text{x}10^5$ km.

SOLUTION: $\Omega = \frac{\pi R_s^2}{d^2} = 6.76x10^{-5} sr$

Intensity (or radiance) is defined as radiative energy in a given direction per unit time per unit wavelength (or frequency) range per unit solid angle per unit area perpendicular to the given direction:

$$I_\lambda = \frac{d\varepsilon_\lambda}{ds \cos(\theta) d\Omega dt d\lambda} \qquad [1.7]$$

I_λ is referred to as the **monochromatic** intensity.

- Monochromatic does not mean at a single wavelengths λ, but in a very narrow (infinitesimal) range of wavelength $\Delta\lambda$ centered at λ.

NOTE: <u>*same name*</u>: intensity = specific intensity = radiance

UNITS: from Eq.[1.7]:

(J sec^{-1} sr^{-1} m^{-2} μm^{-1}) = (W sr^{-1} m^{-2} μm^{-1})

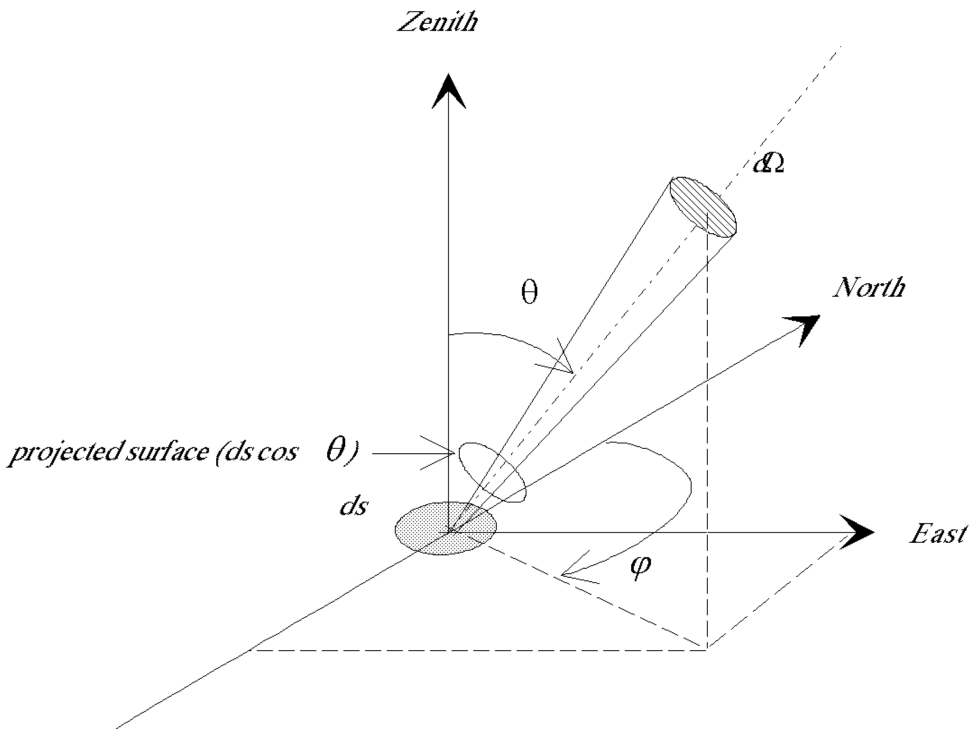


Figure 1.6 Intensity is the flow of radiative energy carried by a beam within the solid angle $d\Omega$.

Properties of intensity:

a) In general, intensity is a function of the coordinates ($\vec{r}$), direction ($\vec{\Omega}$), wavelength (or frequency), and time. Thus, it depends on seven independent variables: three in space, two in angle, one in wavelength (or frequency) and one in time.

b) In a transparent medium, the intensity is constant along a ray.

- If intensity does not depend on the direction, the electromagnetic field is said to be **isotropic.**
- If intensity does not depend on position the field is said to be **homogeneous**.

<u>Flux (or irradiance)</u> is defined as radiative energy in a given direction per unit time per unit wavelength (or frequency) range per unit area perpendicular to the given direction:

$$F_\lambda = \frac{d\varepsilon_\lambda}{dtdsd\lambda} \qquad [1.8]$$

UNITS: from Eq.[1.8]:
(J sec^{-1} m^{-2} μm^{-1}) = (W m^{-2} μm^{-1})

From Eqs. [1.7]-[1.8], the flux is integral of normal component of radiance over some solid angle

$$F_\lambda = \int_\Omega I_\lambda \cos(\theta) d\Omega \qquad [1.9]$$

NOTE: Many satellite sensors have a narrow viewing angle and hence measure the intensity (not flux). To measure the flux, a sensor needs to have a wide viewing angle.

- Depending on its **spectral resolution**, a detector measures electromagnetic radiation in a particular wavelength range, Δλ. The intensity $\boldsymbol{I_{\Delta\lambda}}$ and flux $\boldsymbol{F_{\Delta\lambda}}$ in this range are determined by integrating over the wavelength the monochromatic intensity and flux, respectively:

$$I_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} I_\lambda d\lambda \qquad\qquad F_{\Delta\lambda} = \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda \qquad [1.10]$$

<u>3. Introductory survey: passive and active remote sensing; general characteristics of satellite platforms (orbits, resolutions, types of sensors).</u>

<u>Types of platforms used for remote sensing:</u>
Ground-based platforms: ground, vehicles and/or towers => up to 50 m
<u>Examples</u>:
DOE ARM (Atmospheric radiation Program): http://www.arm.gov/
NASA AERONET (AErosol Robotic NETwork): http://aeronet.gsfc.nasa.gov/

Airborne platforms: airplanes, helicopters, high-altitude aircrafts, balloons => up to 50 km

Examples:

NCAR, NOAA, and NASA research aircrafts

http://www.eol.ucar.edu/raf/

Spaceborne: rockets, satellites, shuttle => from about 100 km to 36000 km

Space shuttle: 250-300 km

Space station: 300-400 km

Low-level satellites: 700-1500 km

High-level satellites: about 36000 km

Examples:

NASA current and planned Earth's observing satellite missions:

http://science.hq.nasa.gov/missions/earth.html

http://earthobservatory.nasa.gov/MissionControl/#

NOAA weather satellites: http://www.noaa.gov/satellites.html

DOD satellites: http://www.nrlmry.navy.mil/NEXSAT.html

NPOESS (National Polar-orbiting Operational Environmental Satellite System):

http://www.ipo.noaa.gov/

Passive sensors measure natural radiation emitted by the target material or/and radiation energy from other sources reflected from the target.

Two main natural sources of radiation: Sun and Earth's thermal emission

Examples:

Passive microwave radiometer that detects naturally emitted microwave energy.

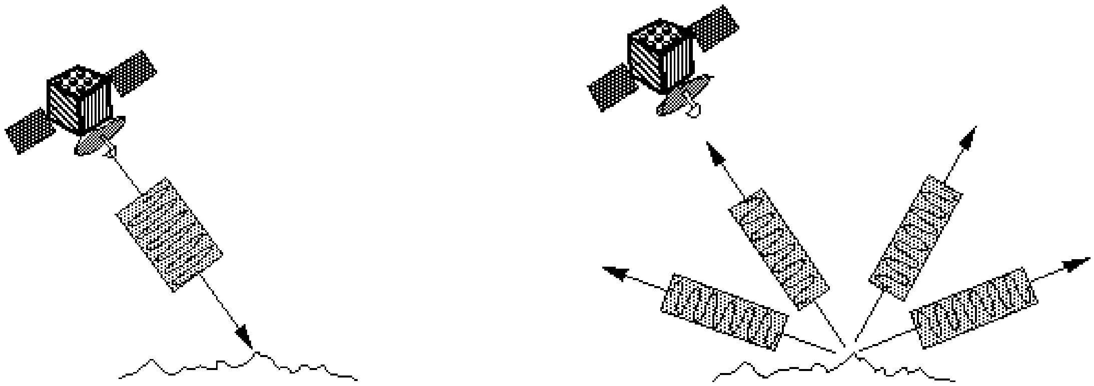
Radiometers that measure reflected (or backscattered) sun light from the atmosphere and ocean.

Active sensors transmit their own signal and measure the energy that is reflected (or scattered back) from the target material.

Examples:

Lidar (LIght Detection And Ranging)

Radar (RAdio Detection And Ranging)



Radar transmits a pulse and *measures reflected echo (backscatter)*

<u>Satellite platforms: orbits, resolutions, sensor types.</u>

- **<u>Satellites orbits: low-level and high-level</u>**

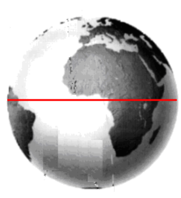
Low-level (700-1500 km) Earth observation satellites (called LEO) fall into three broad groups:

i). Equatorial orbiting satellites

ii). Polar orbiting satellite

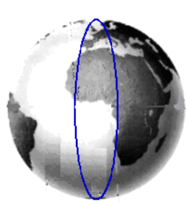
iii). Oblique orbiting (or near-polar) satellites

- LEO satellites are often on **sun-synchronous** orbits. **Sun-synchronous** means that the satellite remains fixed with respect to the Sun with the Earth rotating under the satellite (i.e., satellite passes over its target on the Earth at roughly the same local time).



Equatorial orbiting satellites, whose orbits are within the plane of the Equator

<u>Example:</u> TRMM



Polar orbiting satellites, whose orbits are in the plane of the Earth's polar axis

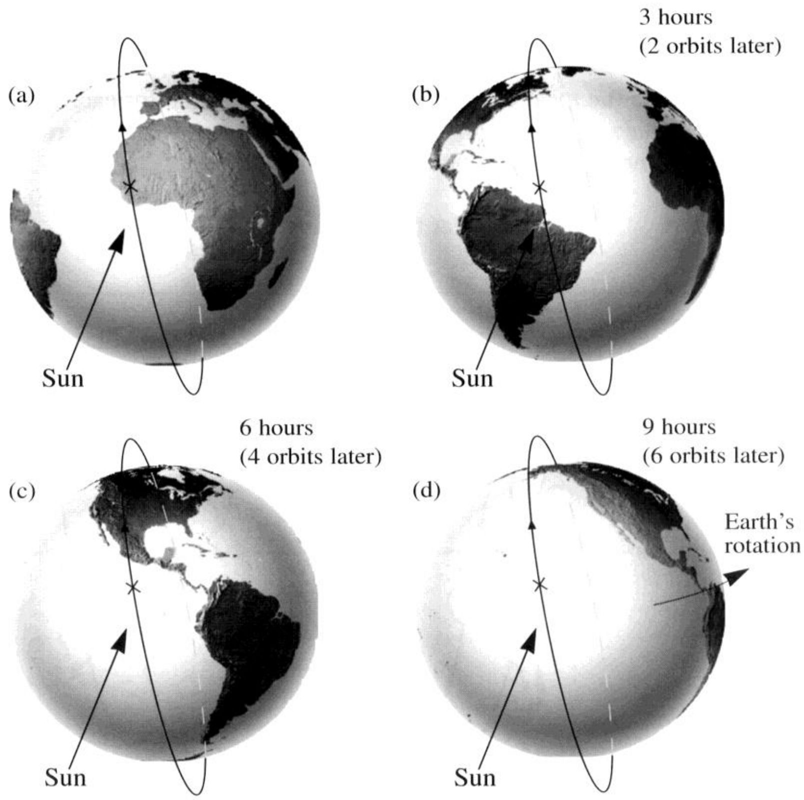


Figure 1.7 Oblique orbiting (near-polar orbiting) satellites: Sun-synchronous orbits (each 3 hours)

- Ascending pass is when the satellite travels from south to north, and descending when the satellite travels from north to south.
- Oblique orbiting satellites can be launched eastwards into direct (called prograde) orbit (so called because the movement of such satellites is in the same direction as the rotation of the Earth), or westwards into retrograde orbit.
- The inclination of an orbit is specified in terms of the angle between its ascending track and the Equator.
- Prograde orbits regress while retrograde orbits precess with respect to the planes of their initial orbits because the Earth is not a perfect sphere and it causes a gyroscopic influence on satellites in oblique orbits.

High-level (about 36000 km) satellites:

Geostationary satellites (often called weather satellites) are “fixed” above a given point on the Earth surface because their circular orbits above the equator have rotation period equals to the earth’s rotation period.

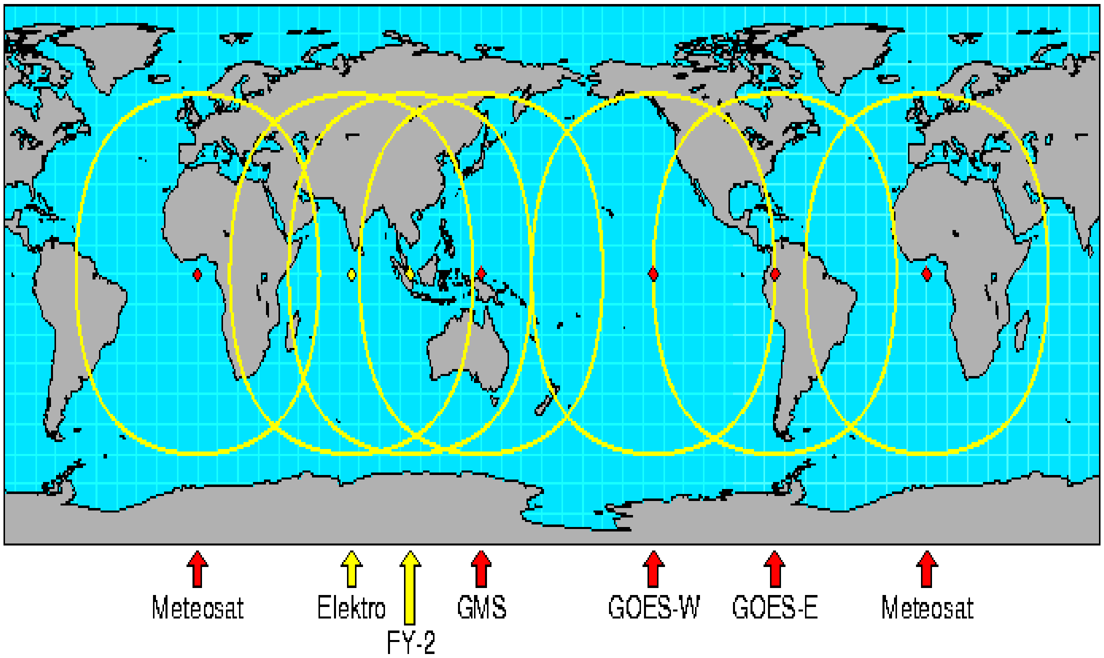


Figure 1.8 Example of geostationary satellite coverage.

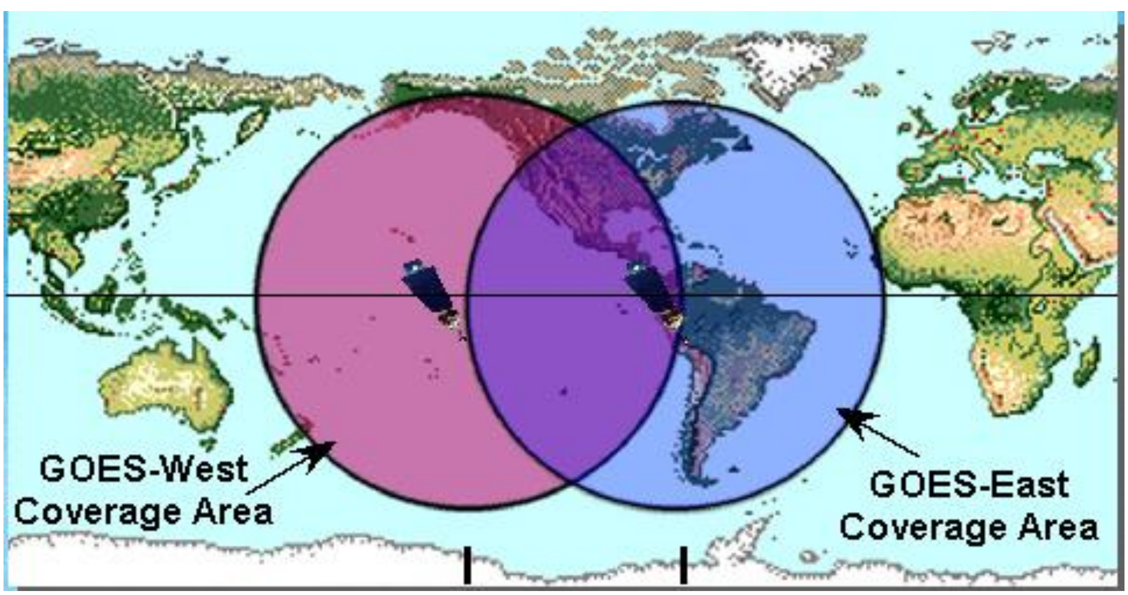


Figure 1.9 U.S. geostationary satellites: GOES

Polar orbiting vs. geostationary satellites (Example of NPOESS):

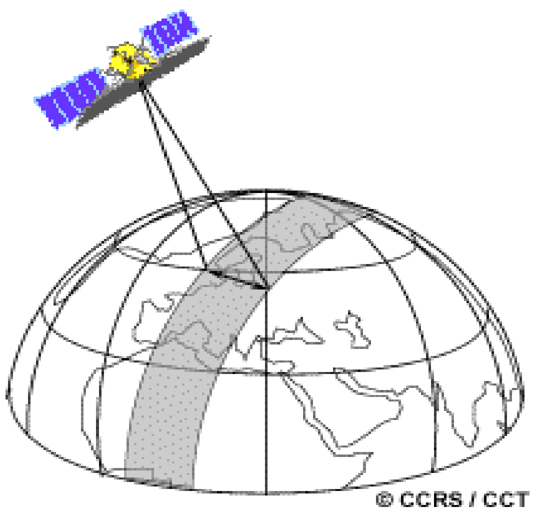
A polar orbiting satellite can provide an observational platform for the entire planet surface, while geostationary satellites are limited to approximately 60^0 of latitude at a fixed point over the earth. Polar orbiting satellites are able to circle the globe approximately once every 100 minutes. Relatively low orbit allows detection and collection of data, by instruments aboard a polar orbiting satellite, at a higher spatial resolution than from a geostationary satellite..

The NPOESS satellites are inserted into a sun-synchronous polar orbit. An early morning satellite will make its ascending pass over the equator in the early morning, independent of Earth's west to east rotation. For example, if a morning satellite flies over Washington, D.C. at 6:00 a.m. Eastern time, then roughly three hours later it will fly over California at 6:00 a.m. Pacific time. And later that day it will fly over Tokyo at 6:00 a.m. Japan time.

The label applied to a polar-orbiting satellite is determined by the local time as it crosses the equator. The crossing from north to south is labeled as its descending node time; from south to north is labeled as its ascending node time. The NPOESS satellite will be flying ascending node times of 1330, 1730, and 2130, i.e., they will cross the equator, from south to north, at 1:30 p.m., 5:30 p.m., and 9:30 p.m., respectively

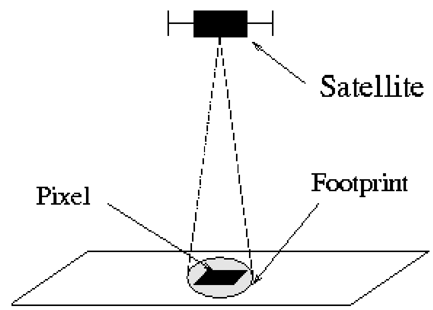
- **Resolutions: spatial, spectral, radiometric, and temporal**

Swath is the width of the track covered by a sensing system on the surface of the Earth. In general, swaths for spaceborne sensors vary between tens and hundreds of kilometers wide.



Spatial resolution is often defined as the ability to distinguish between two closely spaced objects on an image. No single definition for spatial resolution exists.

- Spatial resolution depends on the field of view (FOV), altitude and viewing angle of a sensor.



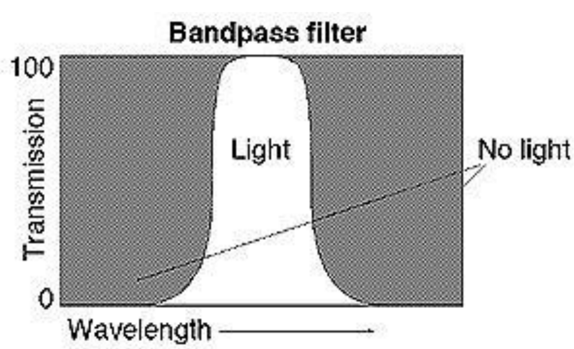
NOTE: small pixel => large spatial resolution

- The size of the pixel sets a lower limit on the spatial resolution.
- A measure of the size of the pixel is given by the instantaneous field of view

Instantaneous Field of View (IFOV) is the solid angle through which a detector is sensitive to radiation.

Spectral resolution refers to the dimension and number of wavelength regions (or bands) in the electromagnetic spectrum to which the sensor is sensitive.

- Based on the spectral resolution the sensors fall into the following broad groups: broad-band, narrow-band, spectral and hyperspectral sensors.



The narrower the bandwidth, the better the spectral resolution!

***Examples*:**

Broad-band sensor: CERES (Clouds and the Earth's Radiant Energy System)

Three bands (channels): Solar region: 0.3 - 5.0 µm; IR window: 8 - 12 µm; and total: 0.3 to > 100 µm

Narrow-band sensor: MODIS (Moderate Resolution Imaging Spectroradiometer)

Table 1.4 MODIS spectral bands

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1.0	110
Ocean Color Phytoplankton Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21.0	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10.0	167
	18	931 - 941	3.6	57
	19	915 - 965	15.0	250
Surface/Cloud Temperature	20	3.660 - 3.840	0.45 (300K)	0.05
	21	3.929 - 3.989	2.38 (335K)	2.00
	22	3.929 -	0.67	0.07

		3.989	(300K)	
	23	4.020 - 4.080	0.79 (300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17 (250K)	0.25
	25	4.482 - 4.549	0.59 (275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16 (240K)	0.25
	28	7.175 - 7.475	2.18 (250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58 (300K)	0.05
Ozone	30	9.580 - 9.880	3.69 (250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55 (300K)	0.05
	32	11.770 - 12.270	8.94 (300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52 (260K)	0.25
	34	13.485 - 13.785	3.76 (250K)	0.25
	35	13.785 - 14.085	3.11 (240K)	0.25
	36	14.085 - 14.385	2.08 (220K)	0.35

** Footnotes:*
[1] Bands 1 to 19 are in nm; Bands 20 to 36 are in µm
[2] Spectral Radiance values are (W/m² -µm-sr)
[3] SNR = Signal-to-noise ratio
[4] NE(delta)T = Noise-equivalent temperature difference

<u>Radiometric</u> resolution is a measure of the sensitivity of a sensor to differences in the intensity of the radiation measured the sensor.

- The finer the radiometric resolution of a sensor, the more sensitive it is to detecting small differences in reflected or emitted energy.

<u>Technical definition</u>:

Radiometric resolution is a measure of how many grey levels are measured between pure black and pure white.

- The radiometric resolution is measured in bits: 1-bit system ($2^1 = 2$) measures only two radiation levels; 2-bit system measures ($2^2=4$) four levels, etc.

<u>Temporal</u> resolution is a measure of how often data are obtained for the same area (i.e., how often an area can be revisited).

- The temporal resolution varies from hours for some systems to about 20 days to others. High temporal resolution: daily or twice daily.

➢ **<u>Types of sensors.</u>**

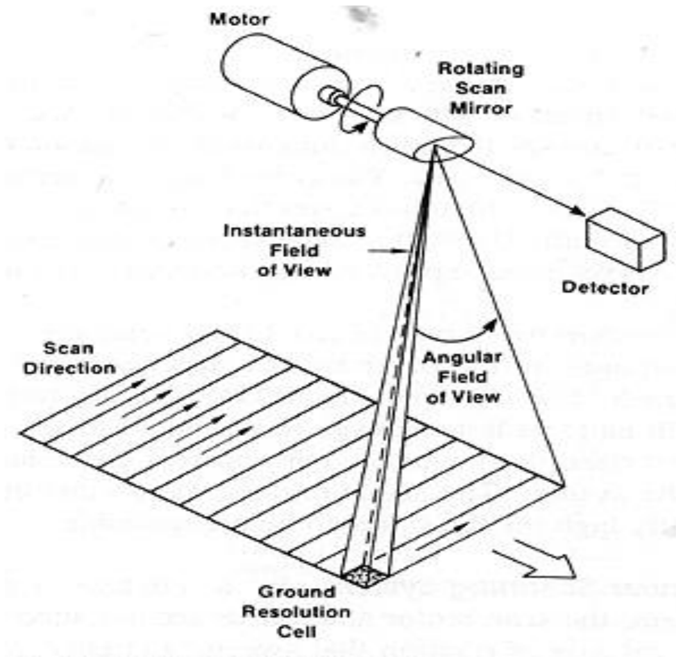
Classification based on energy source or generated product.

- Energy source: Passive (owns no energy source) or active (owns energy source in restricted spectral bands, like radar systems).

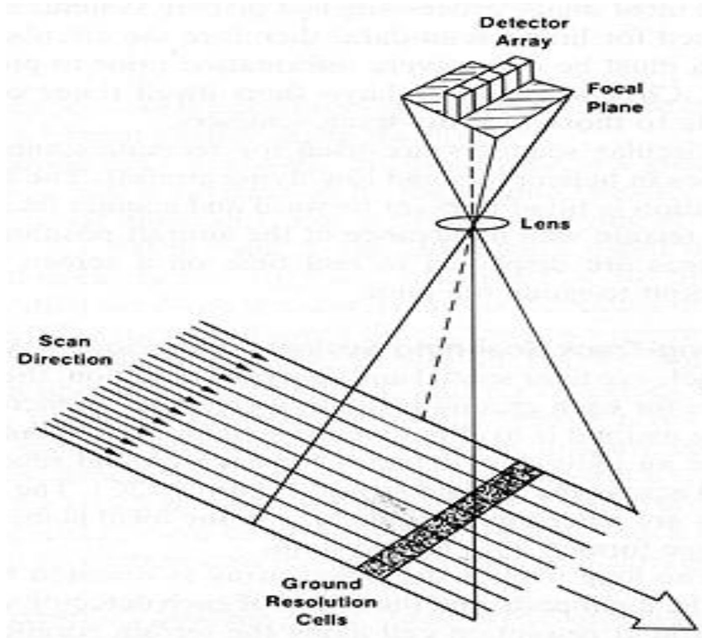
- Product:
    - No-imaging: Generates no images of the observed surface, used to collect precise spectral signature of objects.
    - Imaging: Generates images of the observed surface.
- Imaging systems are classified by:
    - Framing systems: acquisition of a whole image at the same time
    - Scanning systems: Scans lines to generate image

Scanning systems: cross-track scanners; spin scanners; along-track scanners side-scanning (or oblique scanners) (e.g., radar)

Examples:



A. CROSS–TRACK SCANNER.



C. ALONG–TRACK SCANNER.

Viewing geometry: