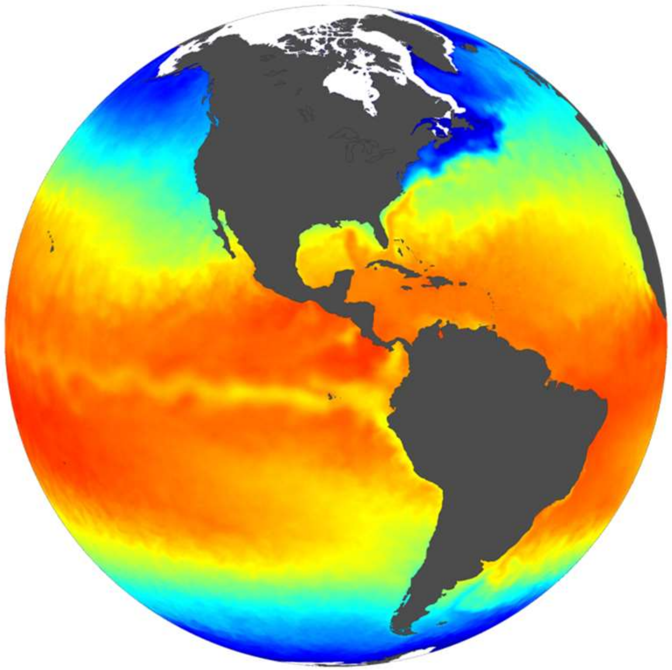

Infrared radiometry

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GHRSST SST Short Course
University of Cape Town
29-30 May 2014

To provide operational users and the science community with the SST measured by the satellite constellation

Outline

- Difference between passive and active measurements
- Review some concepts and definitions
- Emission (Planck's Function)
- Emissivity
- Kirchhoff's Law
- Effects of atmosphere
- Infrared radiometry – measuring temperature

Satellites *vs*. other platforms

- Satellites are only one of several remote-sensing platforms; these include aircraft, auvs, helicopters, ships, trucks, rooftops, submarines, uavs, people…….
- The physics of the measurements are the same
  - electromagnetic or acoustic waves
  - this is very constraining: what can we measure?

What can be measured from space?

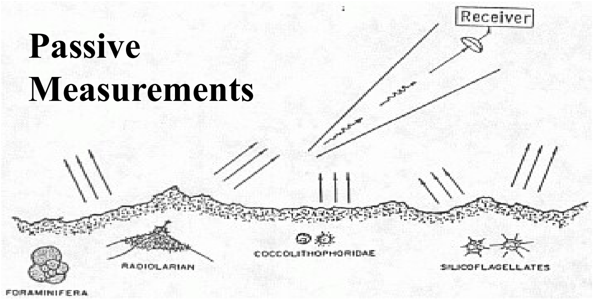
Only 5 things (related to remote sensing) can be measured from space:

- Amount of reflected sunlight
- Amount of emitted heat
- Surface roughness
- Distance between the sensor and the target (time of flight)
- Doppler shift in a reflected pulse (radar, lidar)

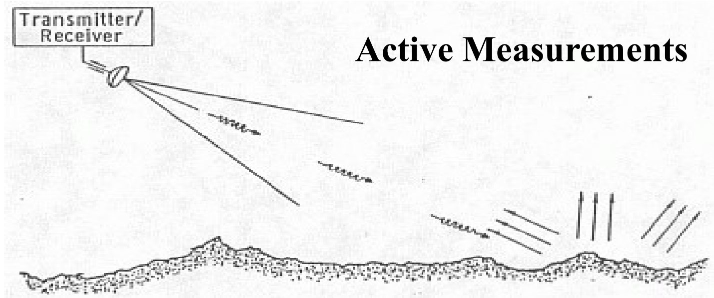
Passive & Active

- Passive remote sensing uses natural emission or natural illumination to study physical phenomena.
- Active remote sensing uses a transmitted beam of electromagnetic energy to illuminate the target area, and measures the backscattered energy.

Passive and Active Sensors



Naturally occurring EMR emitted by sea surface, radiation emitted by atmosphere, reflection at the sea surface of downward atmospheric and solar emission.



Backscatter of EMR transmitted toward sea surface from a space borne instrument.

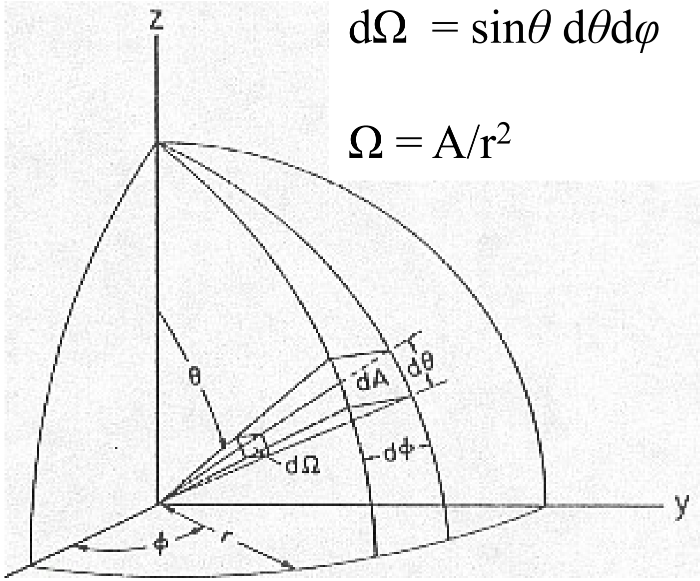
Some definitions

- Power: The time rate of flow of radiant energy [$W = Js^{-1}$]
- Flux: Time rate of flow of energy; the radiant power in a beam [W]
- Flux Density: Flux crossing a unit area normal to the beam [Wm^{-2}]
- Irradiance: Flux incident per unit area of a surface. Also called radiant flux density [Wm^{-2}]
- Spectral irradiance: Irradiance per unit spectral interval at a given wavelength, wavenumber or frequency unit range [$Wm^{-2}\,\mu m^{-1}$; $Wm^{-2}\,(cm^{-1})^{-1}$; $Wm^{-2}\,(s^{-1})^{-1}$]

  (Wavenumber – the number of wavelengths in a cm)
- Radiance: Radiant power per unit source area per unit solid angle [$Wm^{-2}\,st^{-1}$]
- Spectral radiance: Radiance per unit spectral interval at a given wavelength, wavenumber or frequency, expressed in watts per steradian per unit area per spectral interval. [$Wm^{-2}\,st^{-1}\mu m^{-1}$; $Wm^{-2}\,st^{-1}(cm^{-1})^{-1}$; $Wm^{-2}\,st^{-1}(s^{-1})^{-1}$]

For more definitions, see http://www.photonics.com/edu/Dictionary.aspx

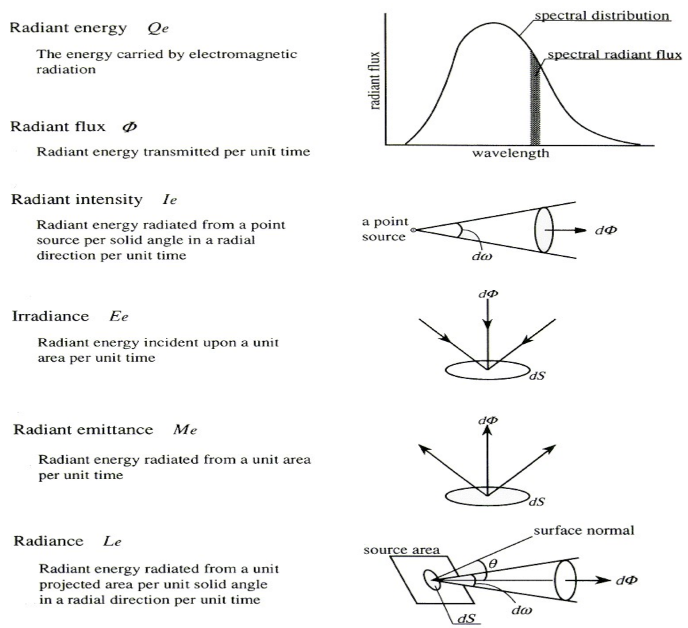
Solid Angle



$$d\Omega = \sin\theta \, d\theta d\varphi$$

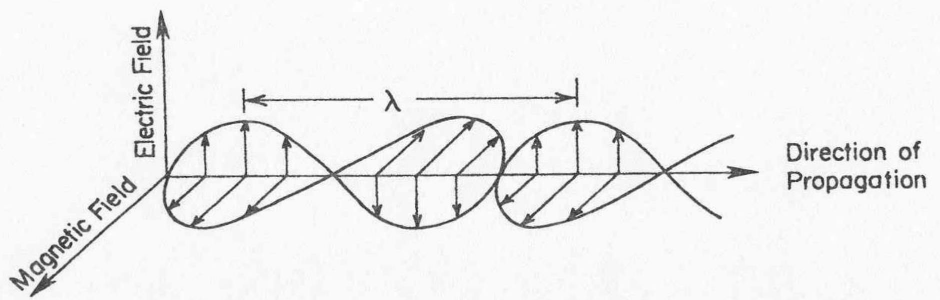
$$\Omega = A/r^2$$

Definitions with diagrams



NB – there is not a consistent use of symbols (with a few exceptions).

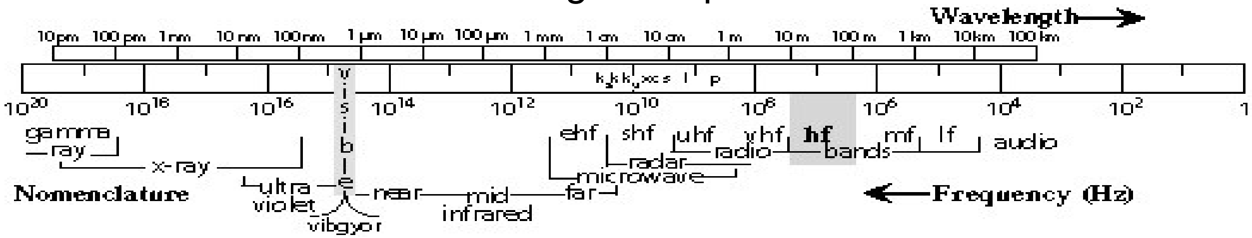
Electromagnetic waves

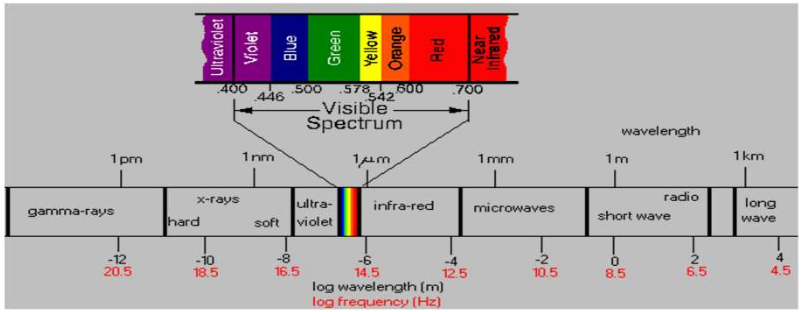


Schematic representation of electromagnetic waves.

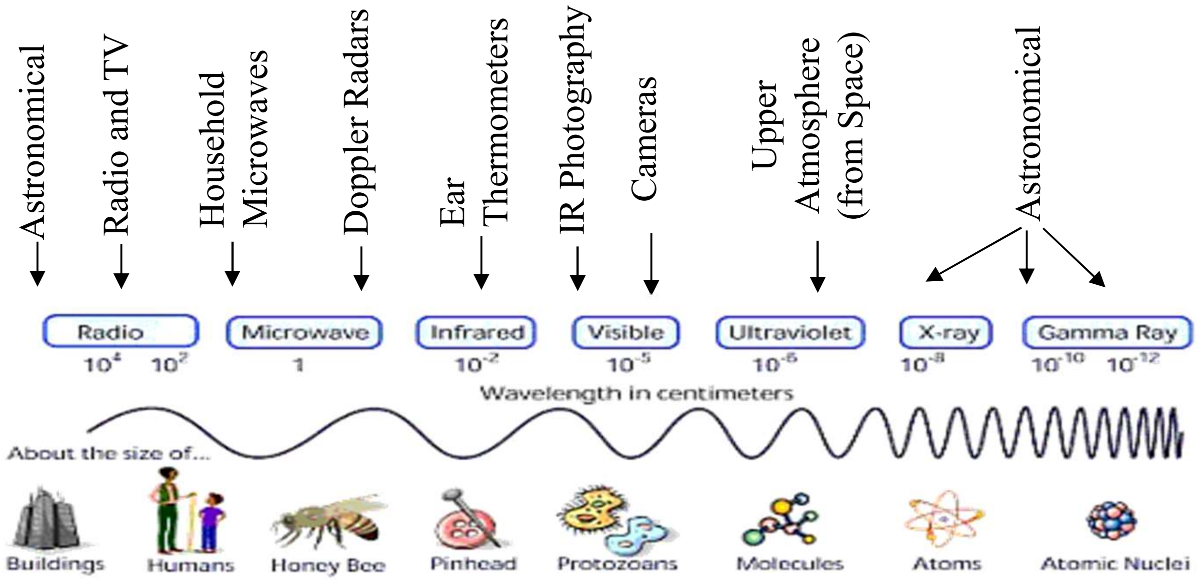
The Electromagnetic Spectrum

The energy of quanta (photons) ranging from gamma rays to radio waves in the electromagnetic spectrum.



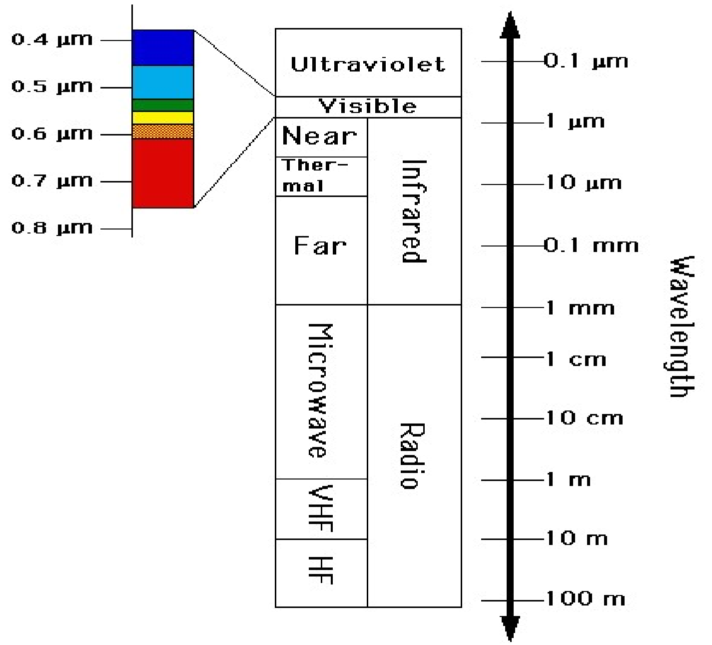


The Electromagnetic Spectrum



http://imagers.gsfc.nasa.gov/

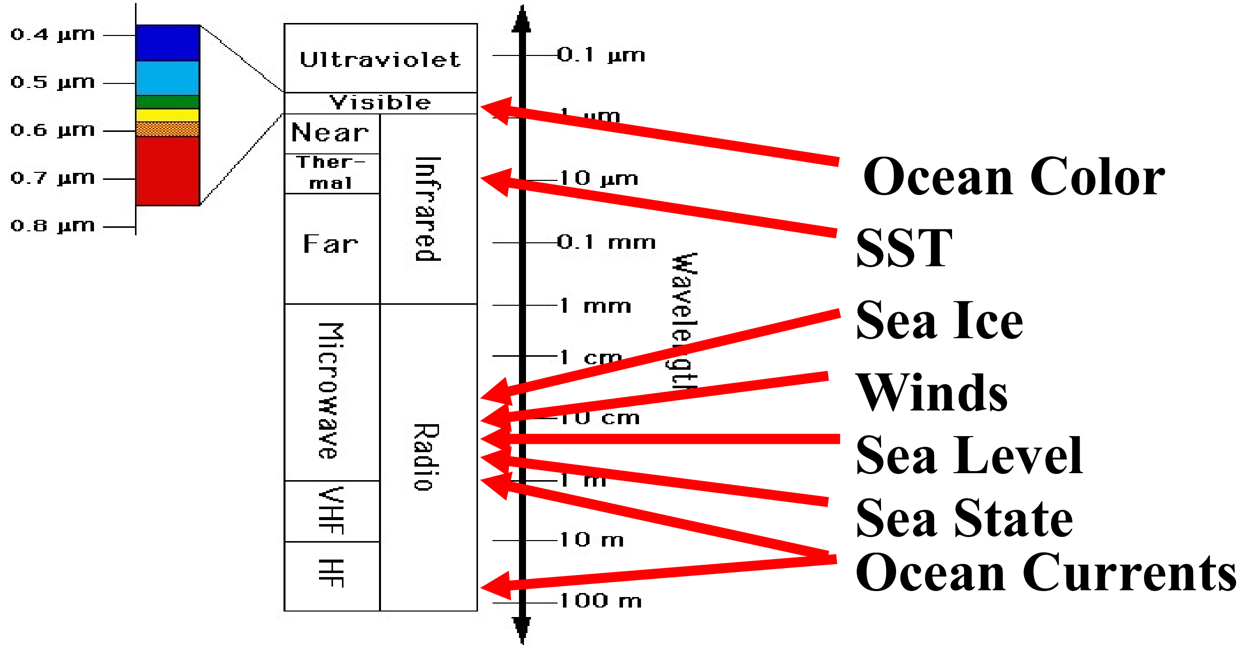
The Electromagnetic Spectrum



Short Wavelength
High Frequency
High Energy

Long Wavelength
Low Frequency
Low Energy

Oceanographic Applications



Theory of Electromagnetic Waves

The physical theory is 'classical' i.e. pre-Quantum Theory. While it can successfully explain many phenomena, it cannot, for example, explain the spectrum of radiant emitted energy – for this we need Planck's equation, based on quantum theory.

Planck’s Function

In searching for a theoretical derivation of blackbody radiation, Planck made the revolutionary assumption that an oscillating atom in the wall of a cavity can exchange energy with the radiation field inside a cavity only in discrete bundles called *quanta* given by $\Delta E = h\nu$, where h is known as *Planck’s constant*.

With this assumption, he showed that the radiance being emitted by a blackbody is given by

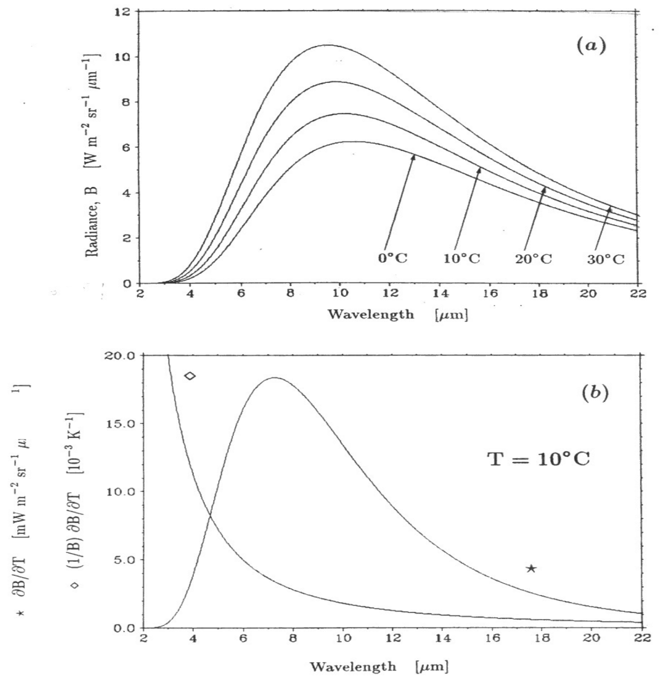
$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp\left(\dfrac{hc}{\lambda kT}\right) - 1}, \qquad (3.7)$$

where k is Boltzmann’s constant, and T is the absolute temperature.

This is the *Planck function*; it earned him the Nobel Prize in 1918. The Planck function is more conveniently written as

$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp\left(\dfrac{c_2}{\lambda T}\right) - 1}, \qquad (3.8)$$

where c_1 and c_2 are the first and second radiation constants.



Rayleigh-Jeans Approximation

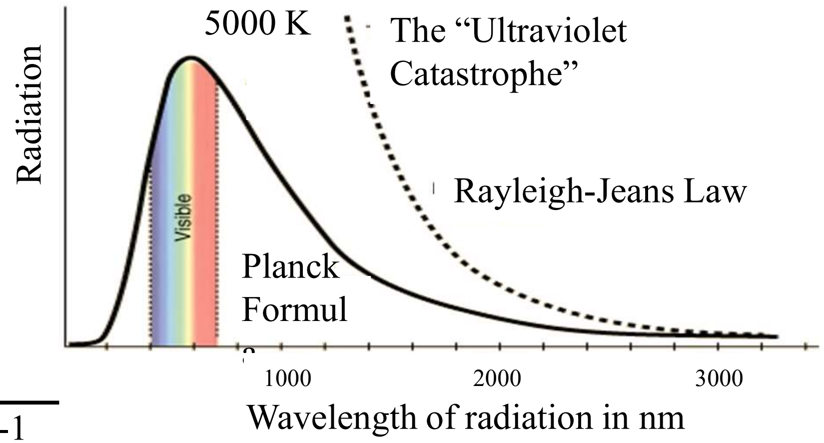
Rayleigh-Jeans Law corresponds to the Planck Law in the case of small frequencies, in which case $h\nu/(kT) << 1$ allows the approximation

$e^{h\nu/(kT)} \approx 1 + h\nu/(kT) + \ldots.$

Putting this into the Planck law gives

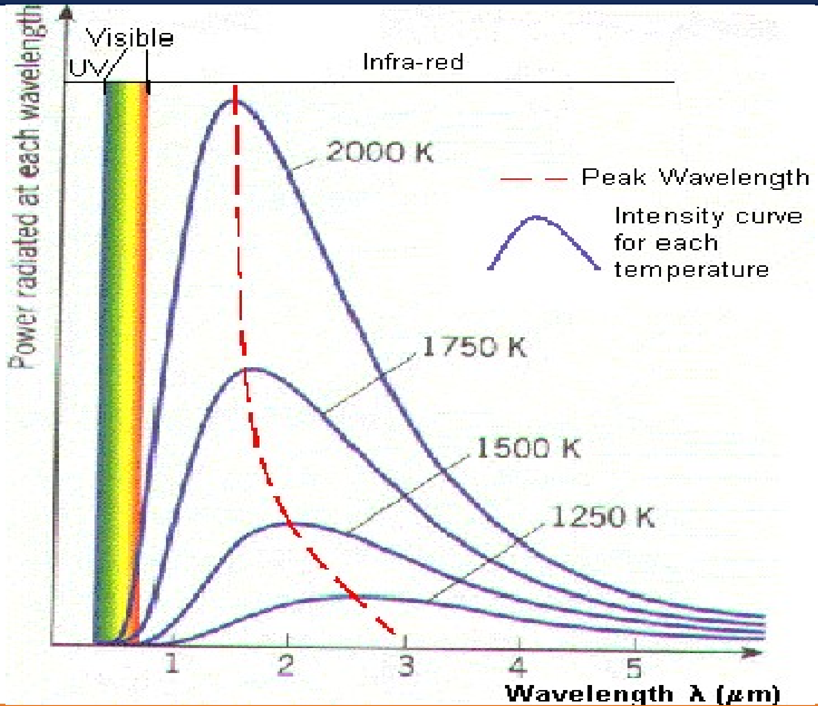
$$R_\nu(T) \approx \frac{2\nu^3 h}{c^2} \frac{1}{(1+h\nu/(kT)+\ldots) - 1}$$

$$= 2\nu^2 kT/c^2$$



See http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html

Temperature dependence of the Planck Function



Wien's Displacement Law:

$$\lambda_{max} = b/T$$

λ_{max}, is the wavelength of peak spectral emission.

T is the temperature of the blackbody in kelvin (K)

b is Wien's displacement constant

$= 2.897 \times 10^{-3}$ m K

Non-Black Bodies

Nonblackbodies

Since real material is not perfectly black, a way must be devised to quantify how closely it approximates a blackbody. The *emittance* of a body is defined as

$$\varepsilon_\lambda \equiv \frac{\text{emitted radiation at } \lambda}{B_\lambda(T)}.$$

Emittance can be a function of temperature and viewing geometry as well as wavelength. For a blackbody, ε_λ is identically one.

Kirchhoff's Law

Three related quantities describe the fate of radiation incident on a body:

$$\alpha_\lambda = \text{absorptance} \equiv \frac{\text{absorbed radiation at } \lambda}{\text{incident radiation at } \lambda},$$

$$\rho_\lambda = \text{reflectance} \equiv \frac{\text{reflected radiation at } \lambda}{\text{incident radiation at } \lambda},$$

$$\tau_\lambda = \text{transmittance} \equiv \frac{\text{transmitted radiation at } \lambda}{\text{incident radiation at } \lambda}.$$

Because these three processes are the only possibilities for the incident radiation, by energy conservation, each quantity must be between zero and one, and

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda \equiv 1.$$

Kirchhoff discovered that a body is exactly as good an absorber as it is an emitter. This is summarized in *Kirchhoff's law:*

$$\alpha_\lambda \equiv \varepsilon_\lambda.$$

This law applies only to material that is in *local thermodynamic equilibrium*, which means that it can be characterized by a single thermodynamic temperature. This is a good assumption below about 100 km in the Earth's atmosphere. Above 100 km, collisions between molecules are rare enough that different chemical species can have different thermodynamic temperatures. For most satellite meteorology applications, however, the Earth's atmosphere can be considered to be in local thermodynamic equilibrium.

Stefan-Boltzmann's Law

By integrating Planck's Function over all wavelengths (or frequencies or wavenumbers), the total energy radiated per unit surface area of a black body in unit time (known variously as the black-body emittance, energy flux density, radiant flux, or the emissive power), *Q*, is directly proportional to the fourth power of the black body's thermodynamic temperature T (also called absolute temperature):

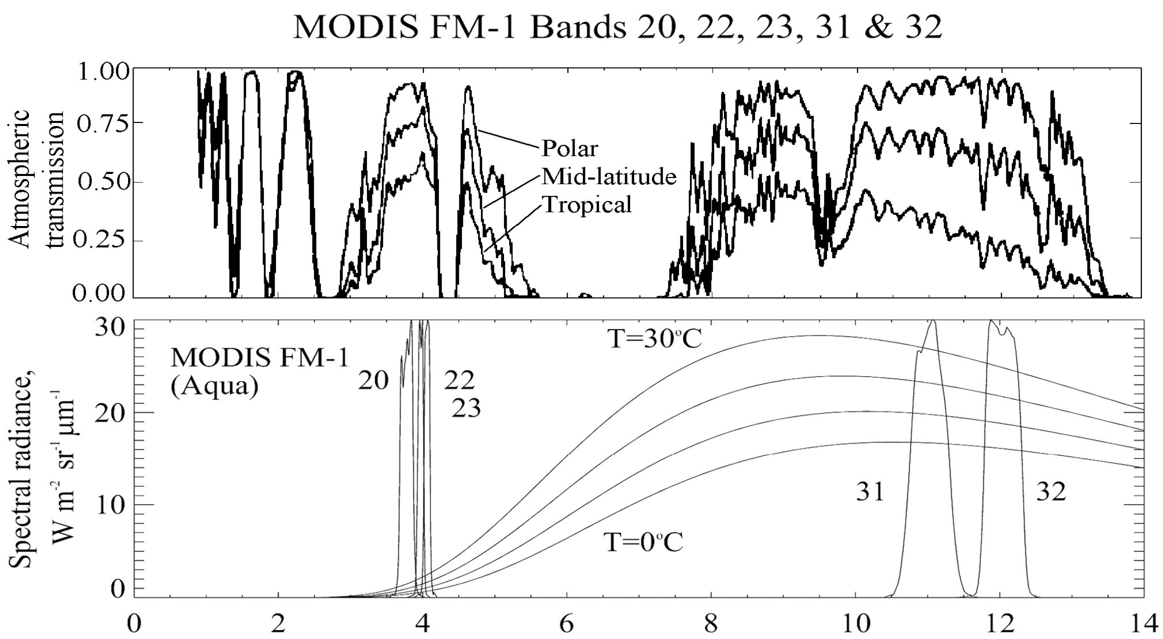
$$Q = \varepsilon \sigma T^4$$

$$\sigma = (2\pi^5 k^4) / (15 c^2 h^3) = 5.6704\ 10^{-8}\ \mathrm{J s^{-1} m^{-2} K^{-4}}$$

A measurement of the radiant energy flux at all wavelengths, and a knowledge of the emissivity, can lead to a remote measurement of temperature.

Emitted heat

- Typical sensors –
  - AVHRR, MODIS, VIIRS, (A)ATSR, SSM/I, TMI, AMSR-E, AMSR2
- Typical variables –
  - Ocean temperature
  - Cloud top temperature
  - Ice cover
  - Wind speed
  - Atmospheric water vapor content
  - Atmospheric temperature and humidity profiles
  - Land surface cover, vegetation



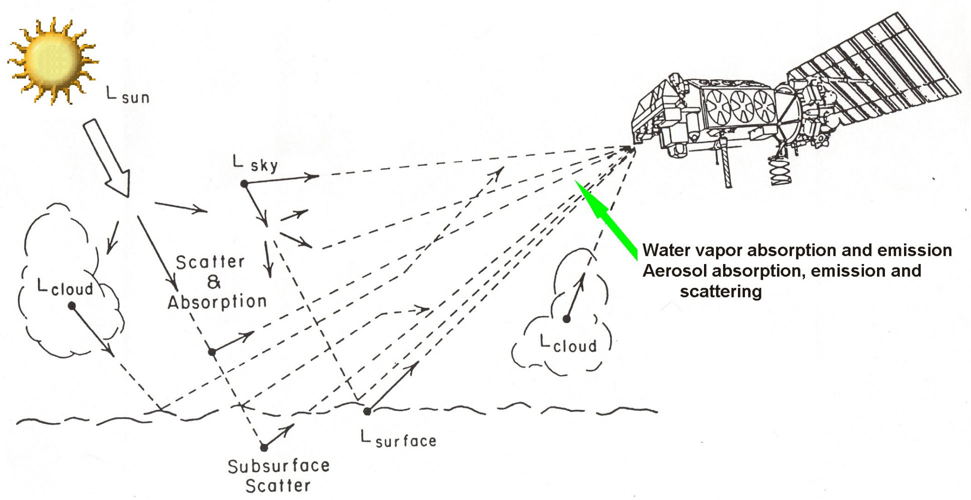
Spectral dependence of the atmospheric transmission for wavelengths of electro-magnetic radiation from about 1 to 14 µm, for three characteristic atmospheres (above), and (below) the black-body emission for temperatures of 0, 10, 20 and 30°C, and the relative spectral response functions of the bands MODIS (Flight Model 1) on *Aqua* used to derive SST.

What can happen to a beam of radiation as it passes through the atmosphere ?

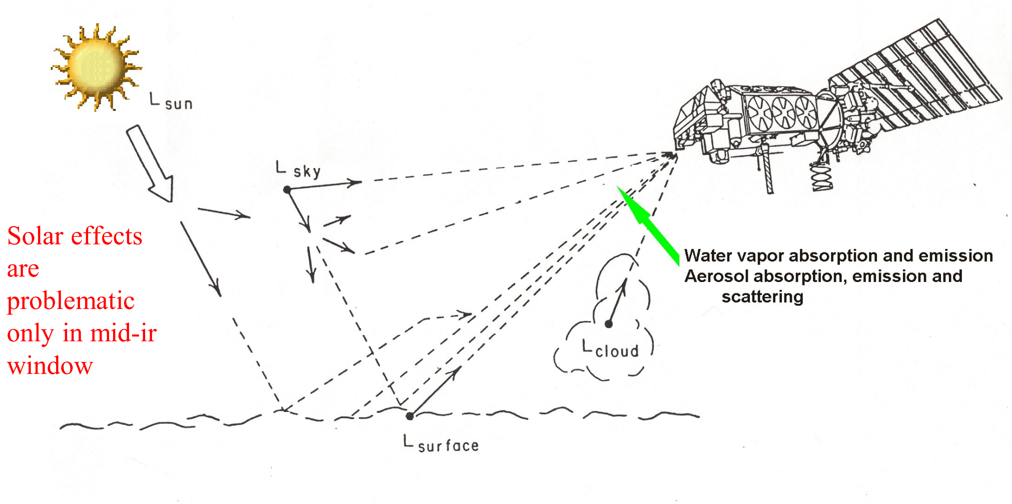
There are four processes that can alter the radiation as it passes through an elemental slab of the atmosphere:

- Radiation from the beam can be absorbed by the atmosphere
- Radiation can be scattered out of the beam into other directions
- Radiation can be emitted by the atmosphere
- Radiation can scattered into the beam from other directions

Atmospheric Effects



Atmospheric Effects - Infrared



Applications of infrared radiometry

- Infrared radiometry is used to measure temperature
  - in oceanography this is of the sea surface (SST)
  - in meteorology:
    - cloud-top temperature and. if temperature profile is known, cloud top height.
    - temperature profiles through the atmosphere can be derived (also humidity profiles, and trace gas concentrations)
  - for land studies land surface temperature (LST) and some information about land cover
- Measurements have to be well-calibrated, using on-board black-body targets.

Infrared radiometers

- Channels are selected where atmosphere is relatively transparent, for surface temperatures, and where there are spectral gradients in transmissivity for sounding.
- Reflected and scattered solar radiation is not important in thermal infrared window (10 - 12μm) but leads to contamination in the mid-ir window (3.5 - 4μm). Thermal measurements available night and day, mid-ir only during the night or when there is confidence in lack of sun-glitter contamination.
- Scattering may be of importance (currently neglected)
  - Rayleigh is not significant
  - Aerosols may be a problem
- Clouds (scattering and emission) $\Rightarrow$ discard data
- Even in atmospheric windows, atmospheric effects (absorption and emission) are very important for quantitative remote sensing. Water vapor is the main concern - very variable in time and space
- Inflight calibration is tractable, using one or two on-board black-body calibration targets.

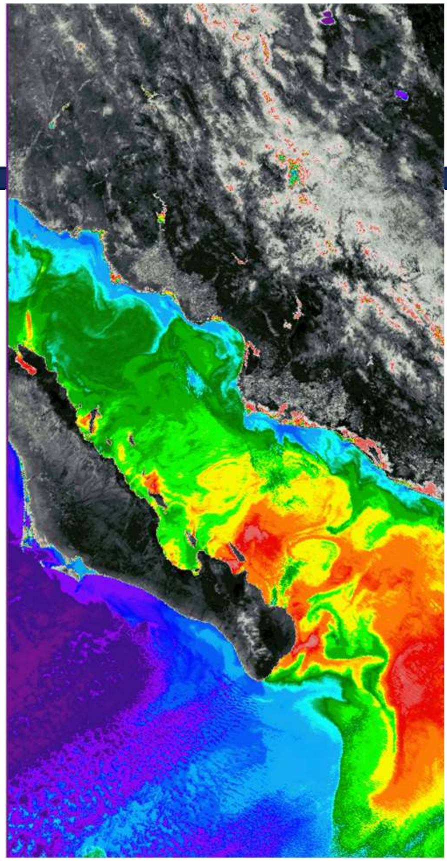
Radiometric sensitivity

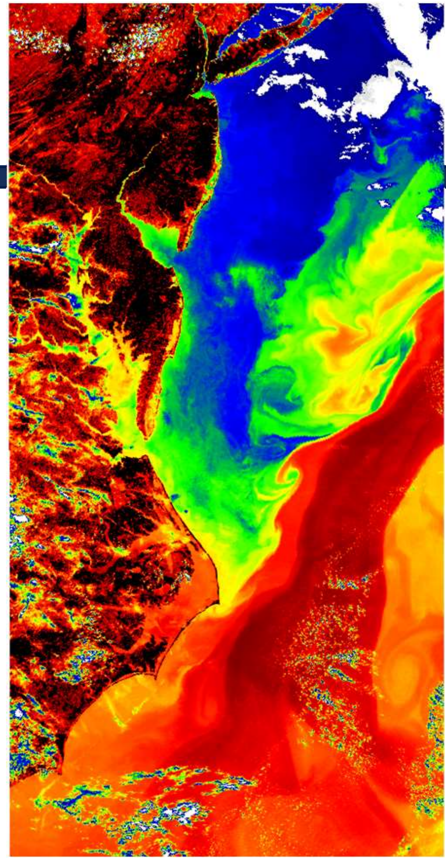
- At the wavelengths of 3.7 and 11 μm, where the atmosphere is relatively transparent, the shorter wavelength has a larger sensitivity to temperature change, but a much smaller signal.

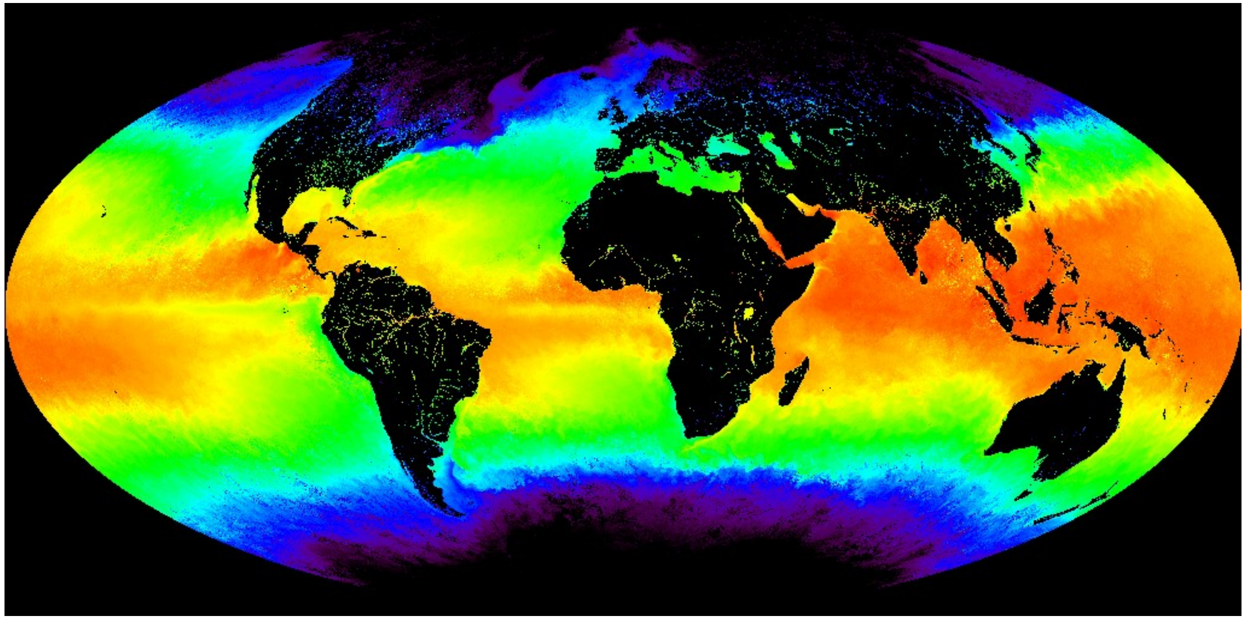
Wavelength	Temperature (T, K)	Radiance* (L)	1/L dL/dT (K^{-1})
3.7 μm	290.0	0.0003529	0.0463
3.7 μm	290.1	0.0003545	
11 μm	290.0	0.099627	0.0157
11 μm	290.1	0.099783	

* $Wm^{-2}\ sr^{-1}\ (cm^{-1})^{-1}$

- In reality spacecraft radiometers can be built to with sensitivity of between 1:100 to 1:1000, perhaps even better. To achieve this, the detectors must be cold (~80-105K) to reduce the noise generated by their own heat.







Signal to Noise Ratio

The power (P - the time rate of flow of radiant energy [$W = Js^{-1}$]) measured by a radiometer is:

$$P = A\,\delta\omega\,\delta\lambda\;L(\lambda)$$

Where A is the aperture of the instrument,

- $\delta\omega$ solid angle defined by the IFOV
- $\delta\lambda$ bandwidth
- $L(\lambda)$ Spectral radiance of the target

NEΔT is the 'noise equivalent temperature difference' which is the result of self-generated noise in the detector. [Since the detector measures radiance, the noise is in reality an NEΔL, and the conversion to NEΔT is temperature dependent, i.e. the NEΔT is higher for low target temperatures]

$$snr = A\,\delta\omega\,\delta\lambda\;L(\lambda)\,/\,NE\Delta L$$

To improve the snr requires increasing the terms of the numerator, or decreasing the denominator. A $\delta\omega$ $\delta\lambda$ are limited by the size/weight of the instrument, required ground and spectral resolutions, and $L(\lambda)$ by physics.

NEΔL limited by sensor technology, but is temperature dependent

Useful Texts

GC10.4.R4

Measuring the Oceans from Space: The principles and methods of satellite oceanography
Ian Robinson, 2004

An Introduction to Ocean Remote Sensing, Seelye Martin, 2004

Microwave Remote Sensing: Active and Passive (3 vols), Ulaby, F. T., R. K. Moore, and A.K. Fung, 1981-1986

Methods of satellite oceanography, Stewart, Robert H. 1985

Introduction to satellite oceanography, Maul, George A, 1985

Oceanographic applications of remote sensing, Ikeda, Motoyoshi and Frederic W. Dobson, 1995

Satellite meteorology: an introduction, Kidder, Stanley Q. and Thomas H. Vonder Haar, 1995

Atlas of satellite observations related to global change, R.J. Gurney, J.L. Foster, C.L. Parkinson, 1993

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