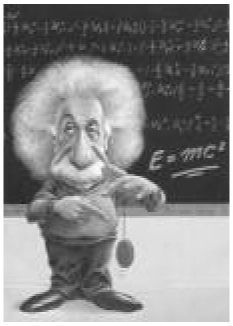


In 1921, contrary to popular belief, Einstein did not win his Noble Prize in Physics for his work on relativity, but rather for a little experiment called the 'photoelectric effect'.

FOR 504 Advanced Methods in Remote Sensing

What you should Know of Remote Sensing: Lectures 2 and 3

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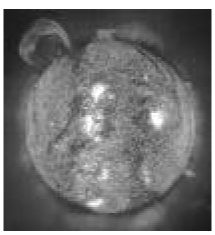
Electromagnetic energy is generated by several mechanisms, including changes in the energy levels of electrons, decay of radioactive substances, and the thermal motion of atoms and molecules.



Nuclear reactions within the sun produce a full spectrum of electromagnetic radiation.

---

## Wave Model of Electromagnetic Radiation

The question of what light is made of has been asked by people for centuries.

In the 1600s: Isaac Newton thought light = particles

This view of what light is changed in 1860 when James Clerk Maxwell presented his 'Electromagnetic Theory' of light.

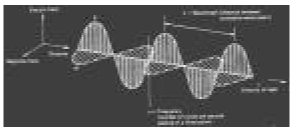
## Wave Model of Electromagnetic Radiation

The theory is described by Maxwell's Equations, which demonstrated that:

A) Time-varying magnetic field → Electric Field

B) Time-varying Electric field → Magnetic Field

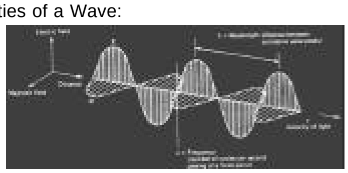
When Either field changes with time the other is produced. This causes an 'electromagnetic disturbance' that travels through space and has the properties of a wave:



As Electromagnetic waves radiate away from a source they are often described as Electromagnetic Radiation

---

Properties of a Wave:



**Wavelength** (λ) is the distance from one wave crest to the next. Typically expressed in nanometers or micrometers.

**Frequency** (ν) is the number of crests passing a fixed point in a given period. Typically expressed in hertz.

**Amplitude** is the height of each peak. Typically expressed in Watts/ meter$^2$ / μmeter.

$c = ln$      ***c = speed of light***

---

Properties of a Wave:

Reflection and Refraction (*also interference and diffraction*):

http://www.phy.ntnu.edu.tw/java/propagation/propagation.html

Refraction is the bending of light rays at the contact between two media that transmit light.

Index of refraction ($n$): ratio between the velocity of light in a vacuum (c) to its velocity in the medium ($c_n$):

$$n = c / c_n$$

Snell's law: as light passes into denser media it is deflected towards the surface normal (line perpendicular to the surface).

$$n \sin q' = n' \sin q'$$

where $n$ and $n'$ are the indices of refraction of the two media

Electromagnetic Disturbances:

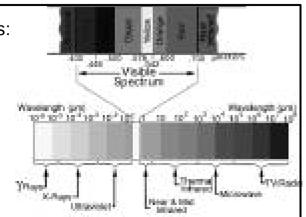
Radio Waves

Television

Light

X-rays

Electromagnetic Spectrum:




UV - .3-.38 µm
Visible - .38-.72 µm
IR
Near - .72-1.3 µm
Mid - 1.3-3 µm (SWIR)
Far - 7.0-1,000 µm (Thermal)
Microwave 1mm-30cm
Radio >30cm

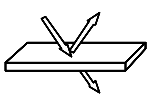
optical spectrum - .3-15 µm - wavelengths that can be reflected and refracted with lenses and mirrors

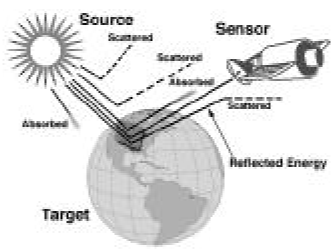
reflective spectrum - .38-3 µm - wavelengths used directly for passive remote sensing

A wavelength or frequency interval in the EMR is commonly referred to as a band, channel, or region

Fates of Incident radiation from the Sun or another source:

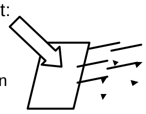
- Reflected
- Transmitted
- Absorbed






## The Particle Model of Light:

The photoelectric effect:



Electrons

Light shining on clean sodium metal in a vacuum

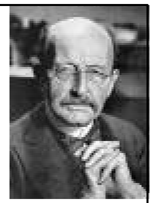
The problems with this result if light is a wave:

The electrons were emitted immediately (i.e. no time lag)

Increasing the intensity of the light INCREASED the number of electrons emitted but NOT their energy

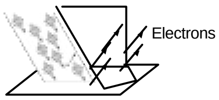
Red Light does not cause any electrons to be emitted

## The Contribution of Max Planck:



The Particle (Quantum) Description:

Light consists of bundles of energy called photons




Experimental Results:

Energy Emitted Electrons was proportional to frequency of incident light

The electron energy did not depend on the energy of the incident light

Planck's Hypothesis:

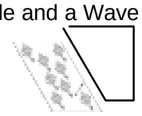
'Light can only exist in discrete bundles with energy given by:

$E = hv$

Where, h = Planck's constant = 6.626 E-34'

## Light as Both a Particle and a Wave

Wave Particle Duality



| Properties of EM Radiation | Can be Explained by: Wave | Particle |
|---|---|---|
| Reflection | Yes | Yes |
| Refraction | Yes | Yes |
| Interference | Yes | No |
| Diffraction | Yes | No |
| Polarization | Yes | No |
| Photoelectric Effect | No | Yes |

## Summary: EM Radiation Laws

EM radiation simultaneously displays behavior associated with both discrete and continuous phenomena.

"quanta vs wave"

EM radiation is absorbed and emitted in discrete units called *photons* or *quanta.* (photoelectric effect)

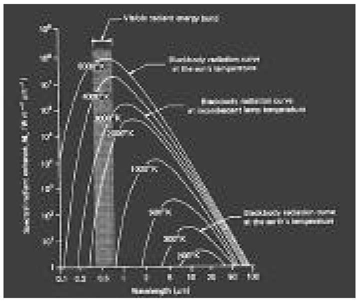
$$Q = h\nu$$

where $Q$ = energy of a quantum (Joules), $h$ = Planck's constant

$$Q = hc/\lambda$$

..the longer the wavelength, the lower the quantum energy – pixel size/sensor design, sun is a plasma generating full spectrum

The Quantity of Energy Radiated by the sun



A blackbody is a hypothetical source of energy that absorbs all incident radiation (without reflection) and emits this radiation with perfect efficiency. Varies with temperature.

The Quantity of Energy Radiated by the sun

Atoms of a particular Temperature move about in random directions (Brownian Motion).

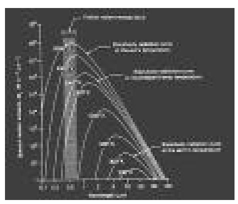
http://www.phy.ntnu.edu.tw/java/gas2D/gas2D.html

Now and again, the electrons are forced into 'higher energy levels' and this results in the emission of a photon.

http://www.phys.hawaii.edu/~teb/optics/java/atomphoton/

http://members.aol.com/WSRNet/tut/ut4.htm

The distribution of the energy emitted by these photons (at a particular Temperature) is shown by the Planck function.



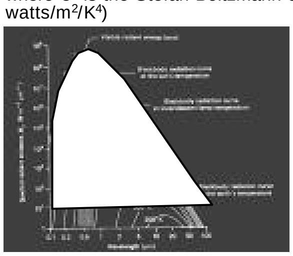
**Measuring the Total Energy Emitted by a Blackbody:**

**Stefan-Boltzmann law:**

Relationship between total emitted radiation ($M_{\lambda}$) and temperature ($T$ - abs. Temp., K)

$$M_{\lambda} = s\ T^4$$

where $s$ is the Stefan-Boltzmann constant (5.67 x $10^{-8}$ watts/$m^2$/$K^4$)



Total Energy Emitted:

Area under 'Planck Function' Curve

**Determining the dominant Wavelength of light emitted by the sun?**

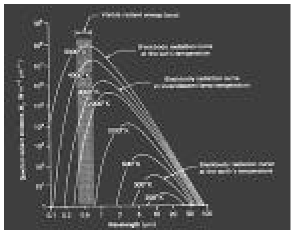
***Wien's displacement law*****:** defines the relationship between the peak (max) wavelength of radiation emitted and the temperature of the object:

$$\lambda_{(max)} = k \;/\; T = 2{,}897.8 \;/\; T$$

*where k is a constant, and* $\lambda$ *is the wavelength of maximum radiance*

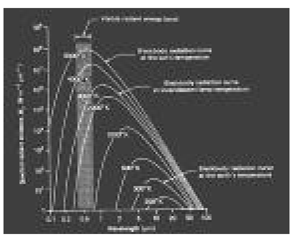
For the Sun = 480 nm

This is UV-Blue



***Kirchhoff's law*****:** **emissivity** ($\varepsilon$) is the ratio between the emittance of a given object ($M$) and that of a blackbody at the same temperature ($M_b$):

$$\varepsilon = M \;/\; M_b$$



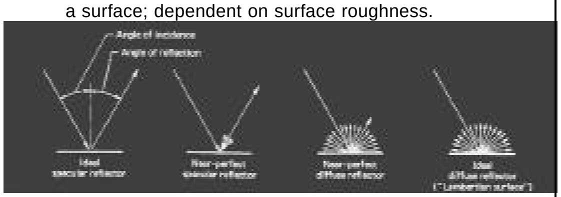
Practical significance of the wave & particle theories to remote sensing?

- Wavelengths may be split into component bands or channels for sensing and visualization
- Particles/photons build up the electrical charge at a sensor→ measure brightness

http://fireangel.planet-faa.de/galerie/Mirror%20of%20the%20Light.jpg

Part 2: Interactions of Light

**Reflection** occurs when light is redirected as it strikes a surface; dependent on surface roughness.




specular reflection: surface is smooth relative to $\lambda$

diffuse (Lambertian) reflection: surface is rough relative to $\lambda$ and energy is scattered ~equally in all directions

bidirectional reflectance distribution function: quantifies reflection characteristics of surfaces based on azimuth and elevation of source and the sensor

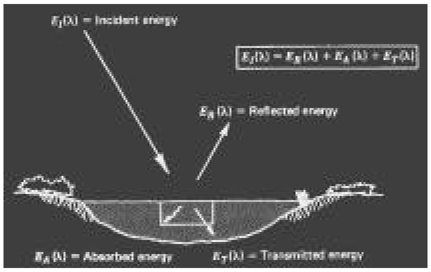
## Radiation Interacting with a surface:

Several measures have been developed that allow us to carefully measure the amount of radiant flux incident and exiting a surface.

These include:

- The Radiation Budget Equation
- Hemispherical reflectance, transmittance, and absorption
- Radiant Flux at the surface per unit Area:
  - *Irradiance*
  - *Radiant Exitance*
- Radiance

## The Radiation Budget Equation




Dependent on: nature of the surface; λ of the energy; and the angle of illumination

*Radiation budget equation:*

$$\phi_{i_\lambda} = r_\lambda + \tau_\lambda + \alpha_\lambda$$

$\phi_{i_\lambda} =$ total amount of radiant flux in specific wavelengths incident to the terrain

$r_\lambda =$ amount of energy reflected from the terrain

$\tau_\lambda =$ amount of radiant energy transmitted through the surface

$\alpha_\lambda =$ amount of energy absorbed by the terrain

## Hemispherical Reflectance

Hemispherical reflectance ($r_\lambda$) is defined as the ratio of the radiant flux reflected from the surface to the radiant flux incident on the surface.

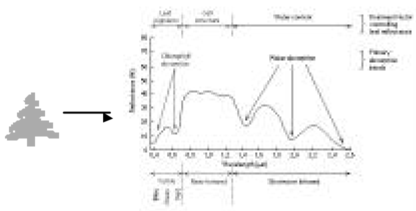
$$r_\lambda = \frac{\Phi_{\text{reflected}}}{\Phi_{i_\lambda}} \qquad \tau_\lambda = \frac{\Phi_{\text{transmitted}}}{\Phi_{i_\lambda}}$$

Hemispherical transmittance ($t_\lambda$) is defined as the ratio of the radiant flux transmitted from the surface to the radiant flux incident on the surface AND Hemispherical absorptance ($a_\lambda$) is defined as the ratio of the radiant flux absorbed into the surface to the radiant flux incident on the surface.

$$\alpha_\lambda = \frac{\Phi_{\text{absorbed}}}{\Phi_{i_\lambda}} = 1 - (r_\lambda + t_\lambda)$$

## Production of % Reflectance

$$\text{Hemispherical Reflectance Percentage} = \frac{\Phi_{reflected}}{\Phi\, i_{\lambda}} \times 100 = p\, r_{\lambda}$$



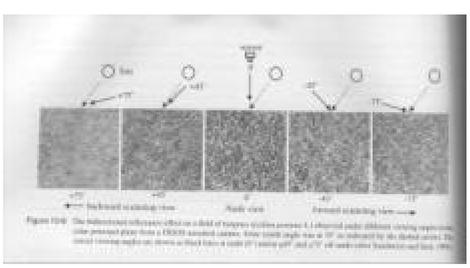
These measures of reflectance assume that the quantity of radiant flux reflected toward the sensor are the same no matter what the sun-angle is or the view geometry of the sensor.

**Most Remote Sensing research accepts this assumption**

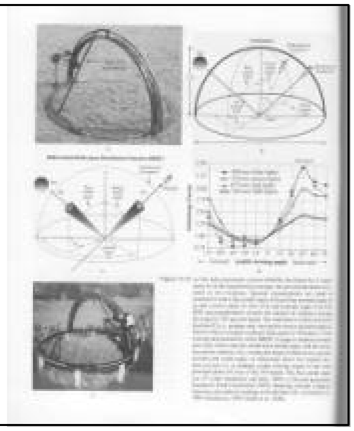
Radiant flux leaving a vegetation canopy IS altered by:

- Geometry of light source (i.e. the sun) and the sensor
- The shape and structure of the vegetation canopy
- The leaf area and leaf-angle-distribution
- The Texture, color, and moisture of the soil

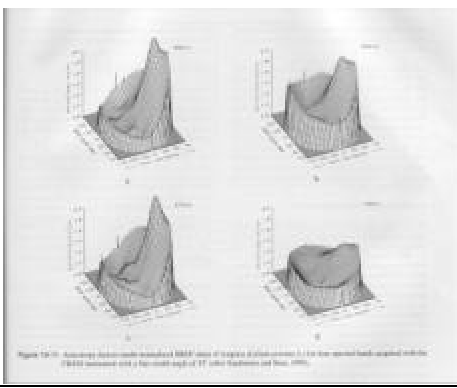
To account for these variations the Bi-direction Reflectance Function (BRDF) is used. It is defined as the ratio of radiance (reflected in one direction) divided by Sun's incident irradiance:



The Goniometer:



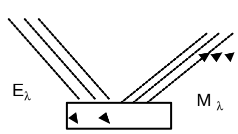
Example BRDF data of ryegrass for 4 spectral bands



Radiant Flux at the surface per unit Area:

Irradiance ($E_\lambda$) is the incoming radiant flux / unit area (W/m²)

Radiant Exitance ($M_\lambda$) is the rate of outgoing radiation or emittance / unit area (W/m²)



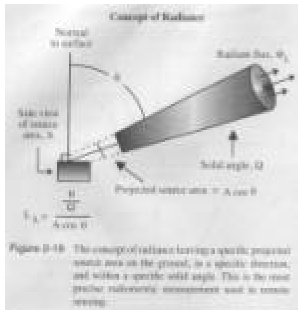
Target and Path Radiance:

Radiance is the most precise remote sensing radiometric measurement

Radiance ($L_\lambda$) is the radiant flux per unit solid angle leaving an extended source area in that direction.

Units of radiance are Watts per meter squared per steradian ($W/m^2/sr$)

Does not account for radiation interacting with the atmosphere on the path between the ground and sensor



Target and Path Radiance:

Additional Sources of radiant flux entering the sensor:

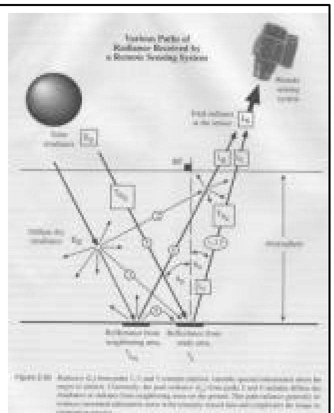
1: Some of the incident radiation may be absorbed by the atmosphere

2: diffuse sky irradiance that never reaches the ground but may scatter into the sensor

3: Atmospheric scattering

4: Radiation reflected or scattered from nearby terrain

5: Radiation reflected or scattered from nearby terrain onto the study area

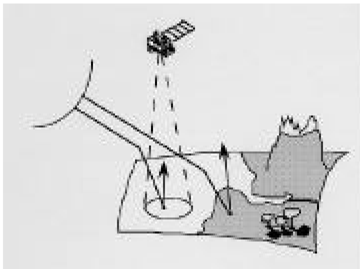


**The 'Missing Energy' 1**

A fraction of the photons do not reach the target and therefore contain no useful information.

Source: Klein (2004) Texas A&M University

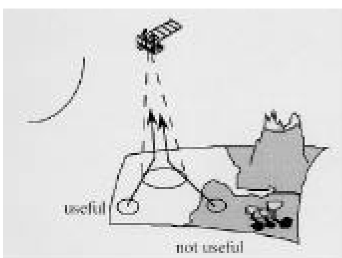
## The 'Missing Energy' 2



A fraction of the photons scatter in the atmosphere and arrive at other surfaces as diffuse radiation.

Source: Klein (2004)
Texas A&M University

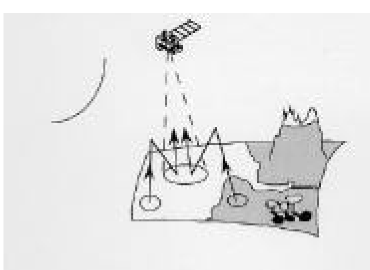
## The 'Missing Energy' 3




A fraction of the photons reaching the sensor have been scattered from other targets.

Source: Klein (2004)
Texas A&M University

## The 'Missing Energy' 4



A fraction of the photons traveling through the atmosphere from the target to the sensor are backscattered back onto the target.

Source: Klein (2004)
Texas A&M University

## Refraction is the bending of light rays at the contact between two media that transmit light.

Index of refraction ($n$): ratio between the velocity of light in a vacuum (c) to its velocity in the medium ($c_n$):

$$n = c / c_n$$

Snell's law: as light passes into denser media it is deflected towards the surface normal (line perpendicular to the surface).

$$n \sin q' = n' \sin q'$$

where $n$ and $n'$ are the indices of refraction of the two media

**Scattering** is the redirection of EM energy by particles suspended in the atmosphere or by large molecules of atmospheric gases. Dependent on: size of particles; abundance; λ; depth of atm

1. Rayleigh scattering: atm particles have diameters small relative to λ, and λ dependent - blue sky effect
2. Mie scattering: atm particles ~= to the λ of the scattered EM radiation, λ dependent, (smoke, dust)
3. Nonselective scattering: atm particles much larger than the λ of the scattered radiation, not λ dependent so all visible λ's are scattered equally - clouds

contrast, short λ's normally filtered out

components of observed brightness - shadows

**Absorption** of EM radiation occurs when the atmosphere prevents, or strongly attenuates, transmission of radiation or its energy through the atmosphere. Energy absorbed is re-radiated at longer λ's.

3 principle absorbers

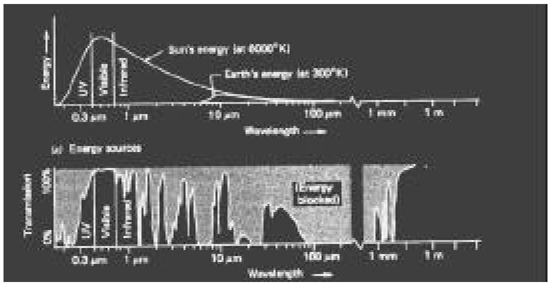
Ozone, $O_3$: absorbs high energy, short λ radiation (~ less than .24 µm) harmful to plants & animals, ~ uniform in the high atmosphere (stratosphere), .1-.2 ppm

Carbon Dioxide, $CO_2$: absorbs mid and far IR, ~ uniform in the lower atmosphere, .03% dry volume

Water Vapor, $H_2O$: absorbs mid and far (thermal) IR, highly variable lower atmosphere, 0-3% by volume

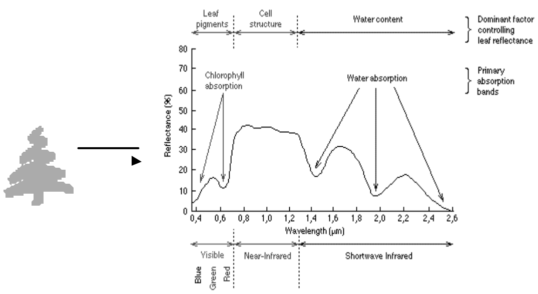
Notice that CO2 and H2O are greenhouse gases…

Planck's Function Deciphers the Greenhouse Effect…




Atmospheric windows: λ ranges where the atmosphere transmits EM energy

## Part 3 – The Remote Sensing of Vegetation

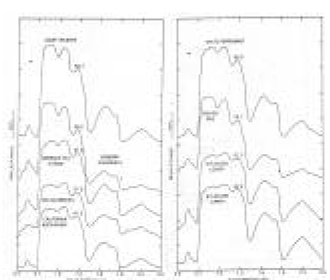



### Examples of Green Vegetation Spectrums

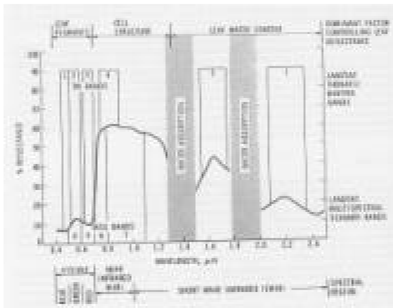
**Source: Elvidge (1990): Reflectance spectra of green leaves (and green stems).**

**The spectra are displaced vertically to to avoid overlap.**

**The percent reflectance at 1.3 µm is provided for each spectrum.**



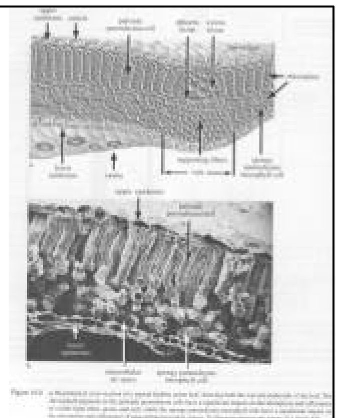
## Summary Dissection Diagram



Source: Goetz (1992)

Factors controlling leaf reflectance:

Pigments, leaf structure and water content: wavelength specific impacts



## The Visible Region: 0.4 - 0.7 μm

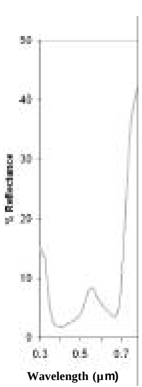
This region is governed by the absorption of the incoming EM radiation by pigments:

(e.g. chlorophyll absorbs 70-90% of the EM radiation at 0.45 *(green)* and 0.67 *(red)* μm – i.e. healthy veg. appears 'green' )

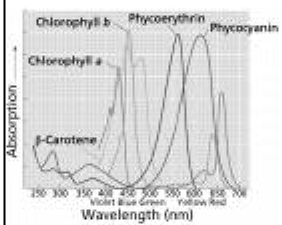
Vegetation with low chlorophyll concentrations (e.g. lettuce) can have red and green reflectance values up to 30% higher (Reeves et al. 1975)

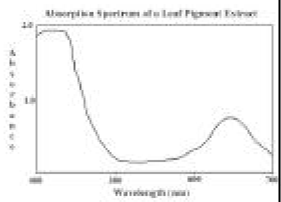
However, low chlorophyll vegetation can also have absorption features due to other pigments like:

- carotene and anthocyanin (which make vegetation look orange and red)
- xanthophyll (which make vegetation look yellow)

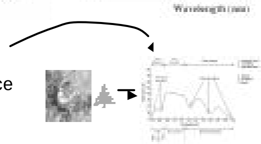


## Pigments: chlorophyll, carotenes, xanthophyll, anthocyanin



Influence visible light absorptance/reflectance



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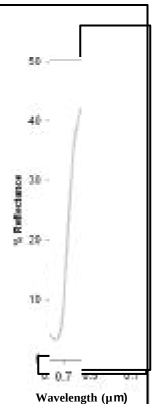
### The Red Edge 0.7 - 0.8 µm

This region is governed by the internal structure of the vegetation:

- In most vegetation, the 'spongy' mesophyll layer scatters EM in the NIR.
- The NIR reflectance increases with the number of leaf layers (up to 8) due to multiple scattering (Reeves et al 1975).

The sharp contrast between the absorption of EM radiation due to chlorophyll at red wavelengths and the reflection of EM radiation due to mesophyll at NIR wavelengths is the basis for several vegetation indices

- e.g. NDVI exploits this contrast.

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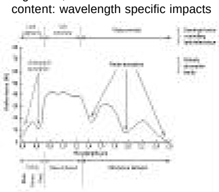
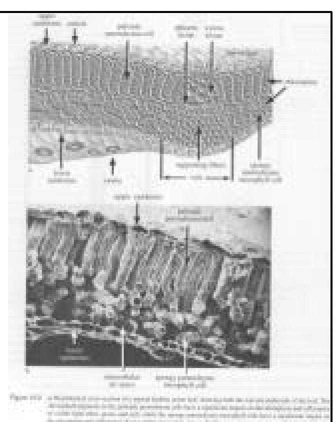
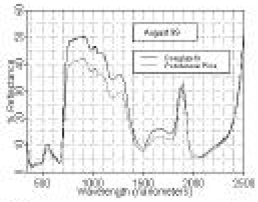
## Factors controlling leaf reflectance:

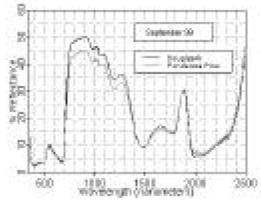
Pigments, leaf structure and water content: wavelength specific impacts

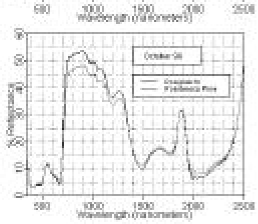


**Atmosphere water absorption centers: 1.45, 1.94, 2.7**





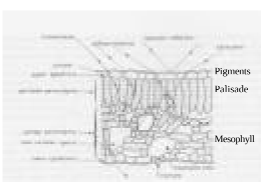

Water content: Mid IR

Usually see strong relationship between foliar water content and Mid-IR reflectance changes.

**The NIR Plateau: 0.8 - 1.3 µm**

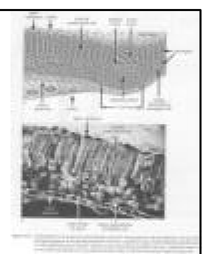
This region is governed by the reflection of the EM radiation by the mesophyll layer coupled with the absorption of the incoming EM radiation by water:

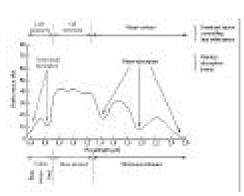
- The dips in the NIR plateau are due to water within the leaves.




**The Structure of a Leaf (source Guyot et al 1992):**


NIR: spongy mesophyll reflects large amounts of energy

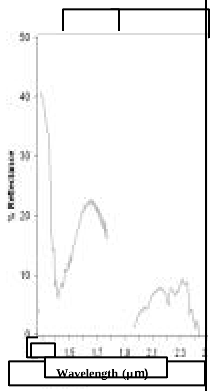




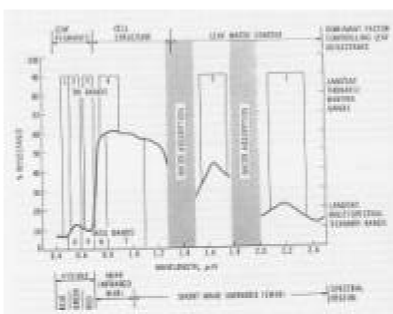
## The MIR 'Tail Off': 1.3 - 2.5 µm

This region is governed by the absorption of the incoming EM radiation by water and the thickness of the vegetation leaves

The water absorption feature at 1.45 µm masks other plant absorption features such as that of lignin and cellulose.




## Summary Dissection Diagram



Source: Goetz (1992)

## Variations in Vegetation Spectra

The spectral reflectance of vegetation is influenced by several key factors, which include:

i. Leaf Maturation
ii. Sun and Shade Leaves
iii. Leaf Senescence
iv. Vegetation Water Content
v. Disease

## Leaf Maturation

In general, as a leaf ages the mesophyll layer increases in thickness.

Young leaves have compact mesophyll layers and are filled with small protoplasmic cells.

Old leaves are filled with loosely packed large vacuolated cells in the mesophyll. Older leaves are more 'spongy' and larger.

As the mesophyll layer reflects the NIR; older leaves are expected to reflect more NIR radiation than young leaves

## Examples of Ageing Leaves I

**Coffee**

**Ivy**

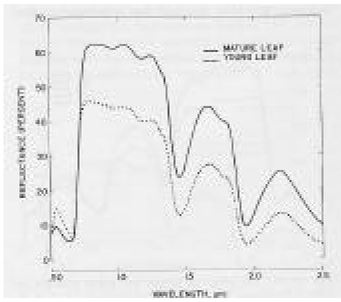
http://www. botgard.ucla.edu/html/ botanytextbooks/generalbotany/shootfeatures/generalstructure/leafcolor/variationsingreen.html

## Examples of Ageing Leaves II

*Podocarpus gracilior*

http://www. botgard.ucla.edu/html/ botanytextbooks/generalbotany/shootfeatures/generalstructure/leafcolor/variationsingreen.html

## The Spectral Changes of a Ageing Leaf




Source: Colwell (1983)

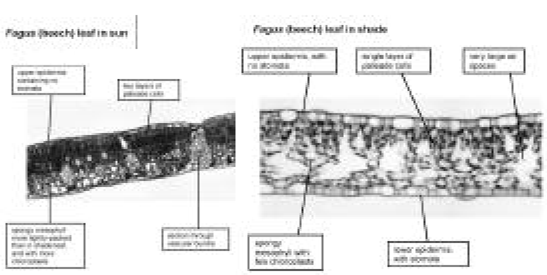
## Sun and Shade Leaves

In a tree canopy all leaves are not the same. Sun leaves develop in sunlight, whilst shade leaves develop in the shade.

These two leaf types can have radically different morphological, anatomical and biochemical characteristics and as such leaves in the same tree can exhibit markedly different spectra.

Sun leaves tend to be smaller and thicker than shade leaves. Sun leaves generally have a lower volume of air space, a larger palisade layer above the mesophyll, and a lower chlorophyll and pigment concentration.

## Schematic Diagram of Sun and Shade Leaves




Source: University of Cambridge

In same age leaves; the effective increase in the mesopyhyll layer in shade leaves would be expected to increase the reflection of NIR EM radiation.

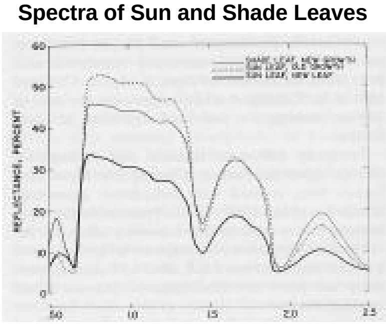
## Visual Example of Sun and Shade Leaves

**Sun Leaves** **Shade Leaves**

**Notice which direction the leaves are pointing**

**Source: SDSMT Remote Sensing and Ecology Lab**

## Spectra of Sun and Shade Leaves




Note that the old sun leaves have higher NIR reflection than the young shade leaves.

**Source: Colwell (1983)**

## Leaf Senescence

Leaf senescence is the deterioration or breakdown of a leaf as it nears the end of its functional life (Salisbury and Ross, 1969).

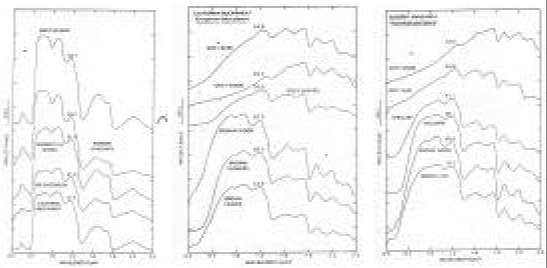
In deciduous trees, the leaves die, whilst the stems and roots survive. A range example is that of savanna grass, which senesce each year by moving nutrients from the leaves/stems to the roots.

As senescence proceeds, the concentration of chlorophyll, starch, protein, and ribonucleic acids (RNA) decrease.

The yellowing and browning of tree leaves during the fall is due to the loss of the green chlorophyll coupled with the emergence of carotene and anthocyanin absorption features.

## Leaf Senescence cont.

**Green Veg** **Senesced Vegetation**

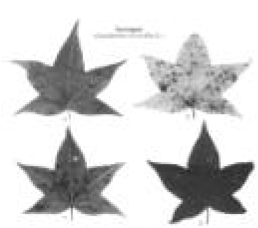


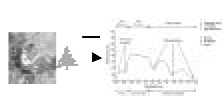
**Source: Elvidge (1990)**

## Visual Example of Senescence

The senescence of *Justicia brandegeana*. As the cholorphyll content decreases the pigment xanthophyll, which is yellow, becomes dominant.

http://www.botgard.ucla.edu/html/botanytextbooks/generalbotany/shootfeatures/generalstructure/leafcolor/variationsingreen.html



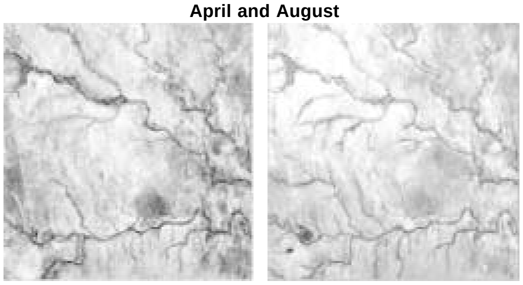


Use of spectral changes to understand plant stress

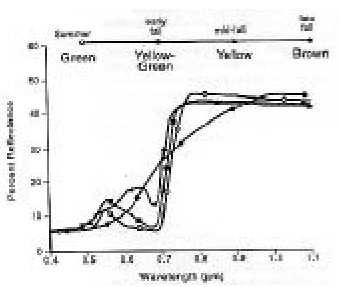
"Blue shift of the red edge"

## Remote Sensing Example of Senescence

**True Color Landsat Image of Rangeland in April and August**

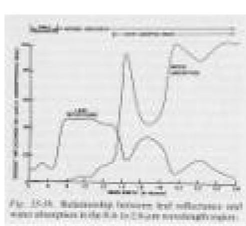


## Spectral Example of Senescence




## Vegetation Water Content

This feature in partly a function of age, as younger leaves generally have lower water contents due to the abundance of protoplasmic cells that do not exhibit high water storage capacities. Water content can also be a function of season or due to drought.



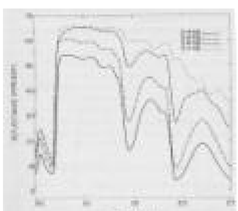
## Visual Example of Water Stress

Changes in the leaf water content also effect the VIS wavelengths though affecting the pigment concentrations – Namely chlorophyll. i.e. Providing water produces 'greener' leaves' limiting water produces 'browner-redder' leaves. Succulent plants have mesophylls that can hold more water than typical plants. As a result they absorb more water and have lower NIR reflectances.

## Spectral Example of Water Stress

This image shows the effect of progressive drying of leaves over a week on the spectra.

As water is being removed, absorption due to water decreases – causing a notable rise in NIR – MIR reflectances.



**Source: Colwell (1983)**

## Disease: Rust

**The Visual Effects of Rust on a Leaf**

*(Images Courtesy of J.Eitel)*

## Variations in Soil Spectra

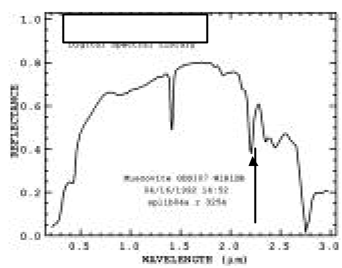
The spectral reflectance of soils is largely determined by five key factors:

i. mineral composition
ii. soil moisture
iii. organic matter content
iv. grain characteristics (size and shape)
v. soil texture

## Soil Spectra: Mineral Composition

Two examples of mineral composition effecting the spectra of soils are:

1. The presence of iron oxides, which produces higher red reflectances.
2. The presence of clay in the soil, which has a absorption features at 1.4 and 2.2 µm.



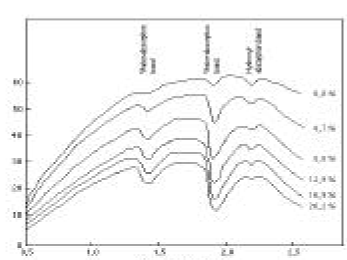

Source Clark *et al.* (2003): The spectral reflectance profile of Muscovite – note the clay hydroxyl absorption feature at 2.2 µm.

## Soil Spectra: Soil Moisture

The general effect of increasing soil moisture is to decrease soil reflectance across all wavelengths:

**Source: Bowers and Hanks (1965)**

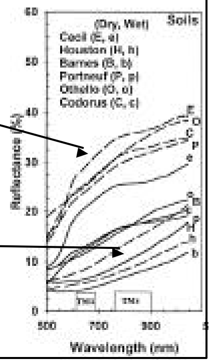
**Effect of increasing moisture content on the measured reflectance of silt-loam.**



## Soil Spectra: Organic Matter Content

• Soils that are poor in organic matter have convex spectral reflectance curves (between 0.5 and 1.3 μm)

• Soils that are rich in organic matter have concave spectral reflectance curves (between 0.5 and 1.3 μm)



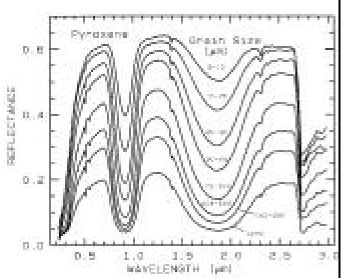

Source: Nagler *et al.* (2000)

## Soil Spectra: Grain Characteristics

An increase in grain size results in a corresponding decrease in measured reflectance:

This effect occurs because the larger grain sizes have a smaller surface area available for scattering compared to the volume available for internal absorption (lower A:V ratio).

Therefore as less scattering occurs than absorption the reflectance falls.




Source Clark *et al.* (2003): Reflectance Spectra of pyroxene with grain size.