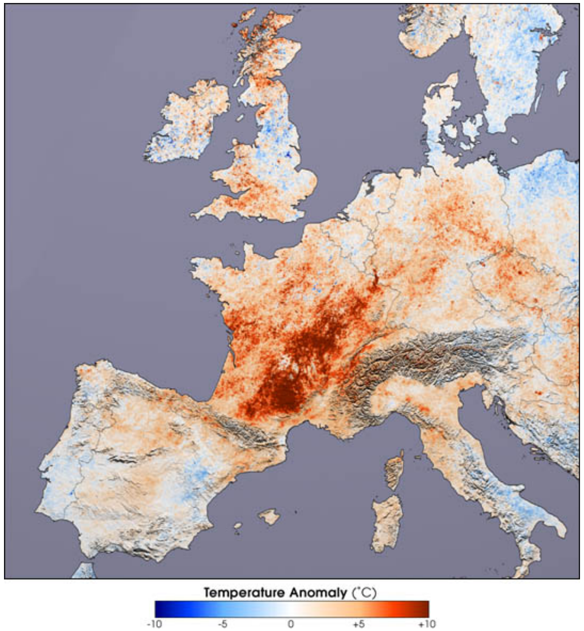
SECOND YEAR: 2604
REMOTE SENSING

PASSIVE REMOTE SENSING OF THE LAND SURFACE

PROF. HARTMUT BOESCH

Contact: ***hartmut.boesch@le.ac.uk***

Earth Observation Science, Dept. of Physics and Astronomy, University of Leicester, U.K.



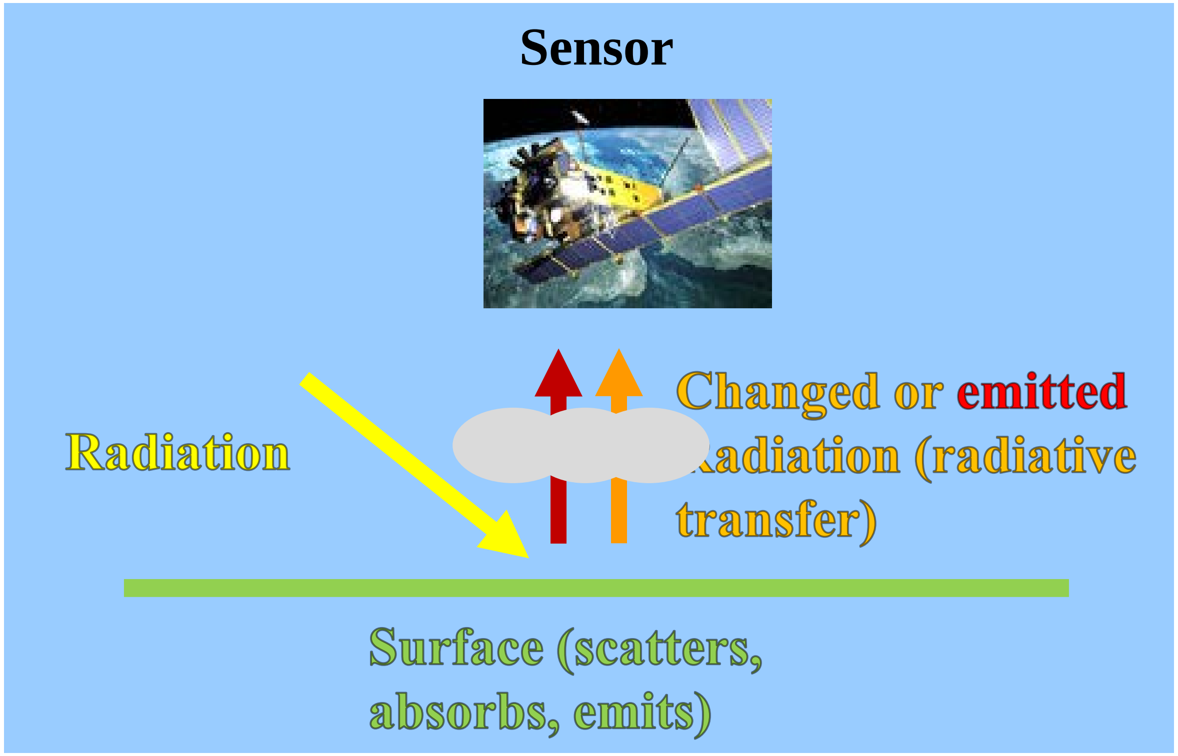
PROPERTIES OF LAND SURFACES

Compared to <u>sea surface</u>, land surface:

- **has emissivity and reflectance properties which are much more complicated functions of *surface type, wavelength, temperature* and *viewing angle***
- **is much more structured (heterogeneous) on *sub-km* scales e.g. cities, fields in the UK.**
- **can have strong temperature variations on sub-km scales (fires are an extreme example).**
- **has surface properties which are more difficult to deduce even from multi-wavelength spectral data**

  [In the IR, the large difference between land and air surface temperature near surface causes inaccuracies in properly accounting for the atmospheric component to the signal]

A fundamental problem for remote sensing of the surface



- Interaction of E/M radiation with surface will change radiation in in specific way depending on surface properties which can be observed with satellite sensort
- BUT there is one fundamental problem:

  The atmosphere is between surface and satellite which will further alter E/M radiation

Thermal Emission

Spectral directional emittance is given by emitted (upwelling) radiance compared to black body emission of surface

$$\varepsilon_s(\lambda, \varphi) = I^+(\lambda, \varphi) / B(\lambda, T_s)$$

In general ε depends on direction of emission, the surface temperature (particularly in the microwave), and wavelength of the radiation.

A surface for which ε is unity for all directions and frequencies is a blackbody.

A hypothetical surface for which ε = constant<1 for all wavelength is a *graybody*.

Absorption

Let a surface be illuminated by a downward intensity I. Then a certain amount of this energy will be absorbed by the surface. We define the spectral directional absorptance as:

$$\alpha_s(\lambda, \varphi) = I_a^-(\lambda, \varphi) \,/\, I_0^-(\lambda, \varphi)$$

Note: Definition of absorptance is the same as for transmittance

$$\mathcal{T}(\lambda) = I_t(\lambda) \,/\, I_0(\lambda)$$

Kirchhoff law: $\alpha(\lambda)=\varepsilon(\lambda)$

-> a good absorber is also a good emitter, and vice-versa

Absorption, Reflection, Transmission

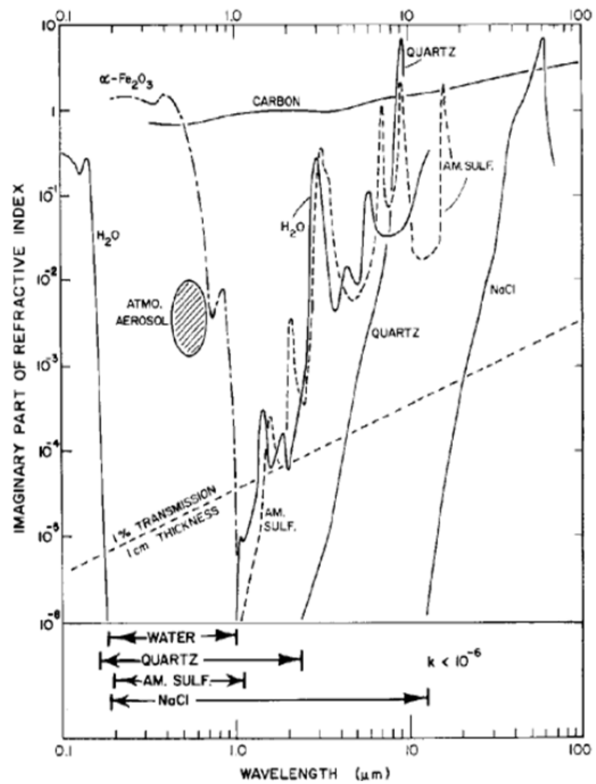
In general, all incoming energy is either absorbed or reflected (integrated over all directions) or transmitted by surface:

$$R_s(\lambda) + \alpha_s(\lambda) + \mathcal{T}_s(\lambda) = 1$$

Opaque surface: All incoming energy is either absorbed or reflected

$$R_s(\lambda) + \alpha_s(\lambda) = 1$$

With Kirchhoff law: $\varepsilon_s(\lambda) = 1 - R_s(\lambda)$



$R_s(\lambda)$, $\alpha_s(\lambda)$, $\mathcal{T}_s(\lambda)$ are primarily governed by the refractive index of the material of the surface.
Note n is a complex number ñ = n + ik (imaginary part determines absorption)

Recap: Thermal IR Remote Sensing Sensing

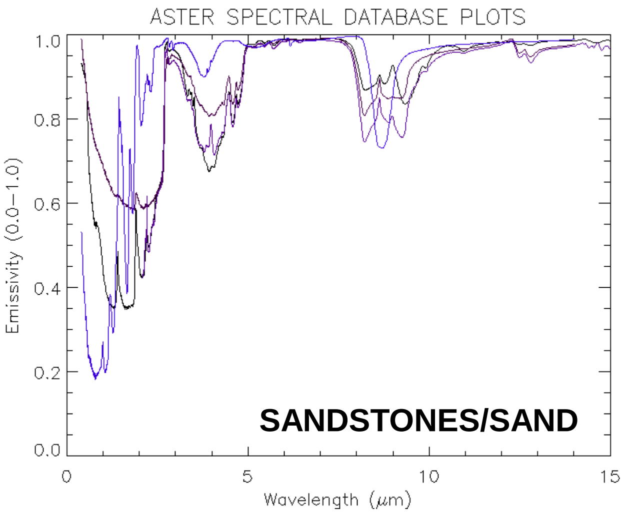
Single gas layer model:

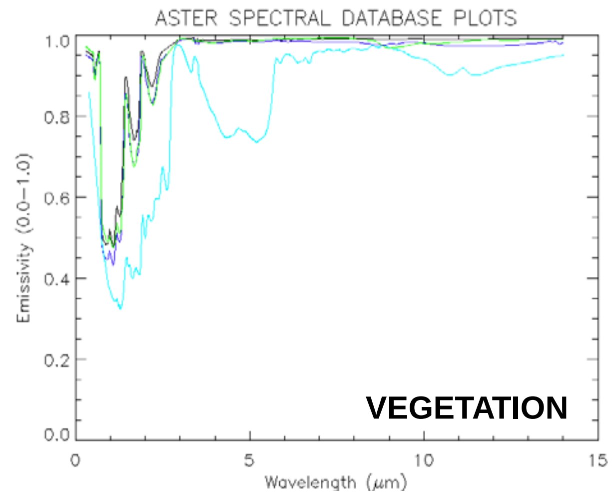
$$I(\lambda) = \varepsilon_s(\lambda) \times B(\lambda,T_s) \times \mathcal{T}_g(\lambda) + (1- \mathcal{T}_g(\lambda)) \times B(\lambda,T_g)$$

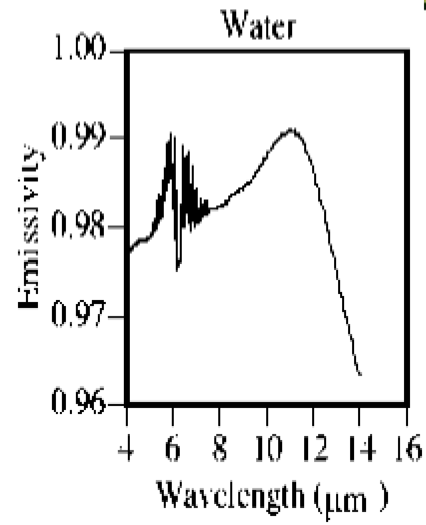
Surface terms

- **Temperature and properties of surface can be measured from $B(\lambda,T_s)$ and $\varepsilon_s(\lambda)$ (but usually not both at same time)**
- **Atmospheric term contributes to signal (but become smaller for $\mathcal{T}_g(\lambda) \to 1$)**
- **Main difficulties**
  - **Scene and atmosphere over land are more heterogeneous than for oceans (ie. variable T_s and ε_s)**
  - **bi-directional dependence of thermal emissivity makes it more difficult to apply atmospheric correction**
  - **Atmospheric correction needs to be applied. Larger source of error than over oceans but same method as for oceans are used.**

INFRA-RED SURFACE EMISSIVITY







- Emissivity is critical parameter for land remote sensing in IR
- Sandstone/sand has distinct absorption feature at 4 mm and 8 to 9.5 μm
- Vegetation close to blackbody throughout infra-red with feature at 5 mm
- Near blackbody elsewhere in the IR
- Far from black-body in the near infra-red (1 to 3 μm particularly).
- In comparisons: water almost constant and close to 1

EXAMPLES

Assume surface pixel has non-uniform emissivity at 12 μm.

Half the pixel has emissivity of 0.5, a quarter has emissivity of 0.8 and quarter of 1.0.

Calculate the signal that would be seen at the top of the atmosphere (TOA) if the temperature of the pixel is uniform at 290 K and the atmosphere has a transmission of unity across the pixel. Assume R_s term can be neglected.

Surface of emissivity, $\varepsilon(\lambda)$, and temperature, Ts:

$$I(\lambda) = \varepsilon_s(\lambda) \times B(\lambda, Ts) \times \mathcal{T}_g(\lambda) + (1 - \mathcal{T}_g(\lambda)) \times B(\lambda, Tg)$$

So at 12 μm ($\mathcal{T} = 1$),

$$I(\lambda) = 0.5 \times (0.5 \times B(290)) + 0.25 \times (0.8 \times B(290)) + 0.25 \times (1.0 \times B(290))$$

$$= 0.25\, B(290) + 0.2\, B(290) + 0.25\, B(290) = 0.7\, B(290).$$

If the pixel was uniform with an emissivity of 1.0: Answer: B(290)

If the pixel was uniform with an emissivity of 0.5: Answer: 0.5 x B(290)

Clearly, the non-uniformity of the emissivity matters.

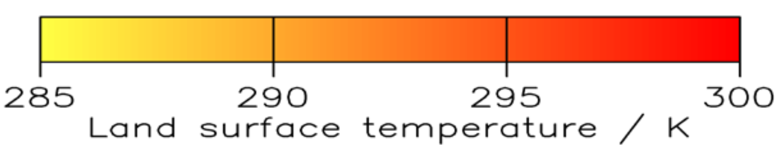
What would happen if each fraction of the pixel had different temperatures ?

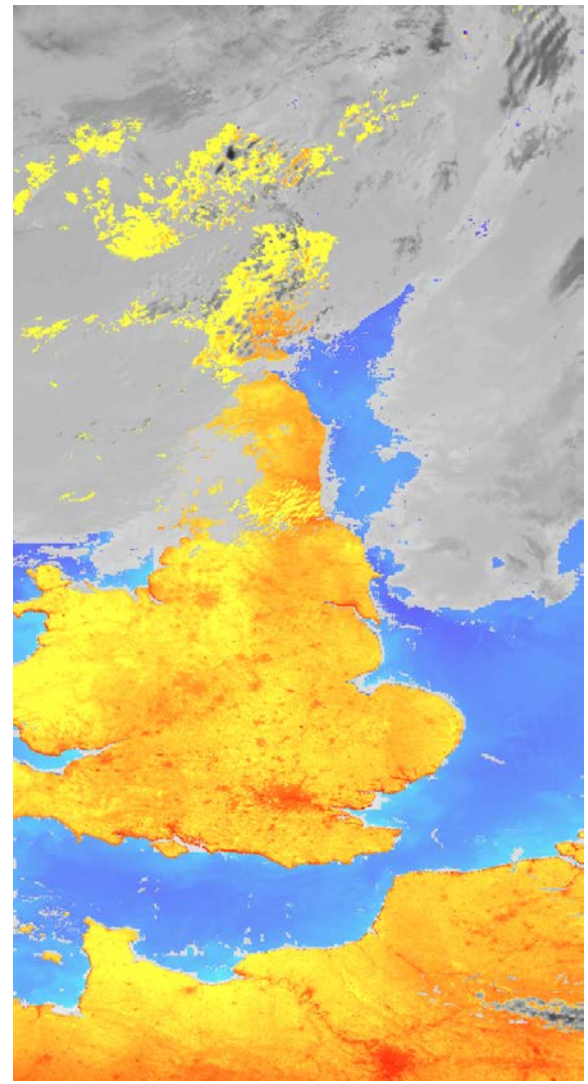
LAND SURFACE TEMPERATURE FROM AATSR (U.K.)

- **Land surface temperature (LST) is key parameter in physics of land surface processes, surface-atmosphere interactions and energy fluxes between atmosphere and surface**

- **LST is required for a wide variety of scientific studies ranging from climatology to hydrology to ecology and biogeology**

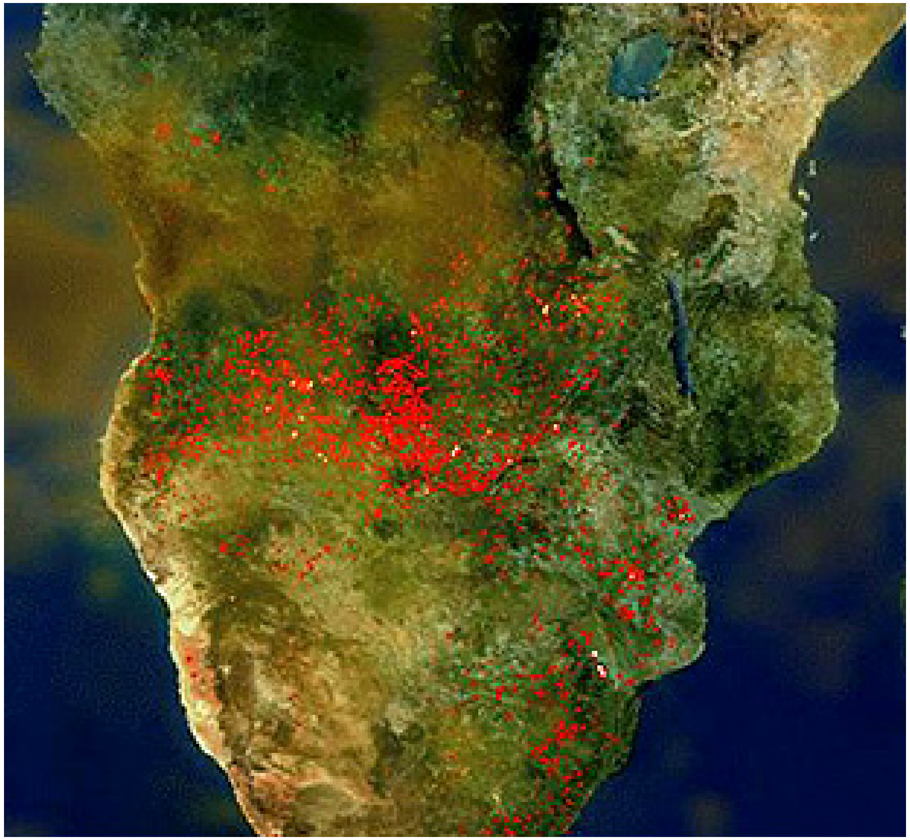
- **LST is retrieved from $B(T_s, \lambda)$ assuming emissivity $\varepsilon(\lambda)$ from land type climatology and using atmospheric correction**





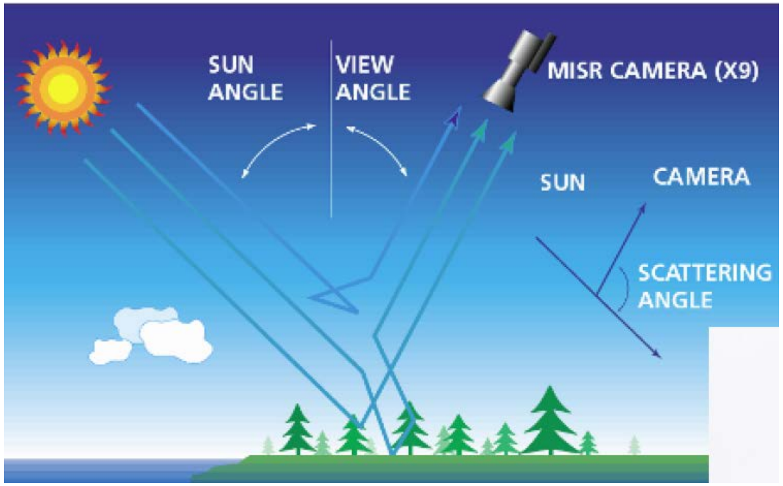
BIOMASS BURNING FIRES AND AEROSOLS

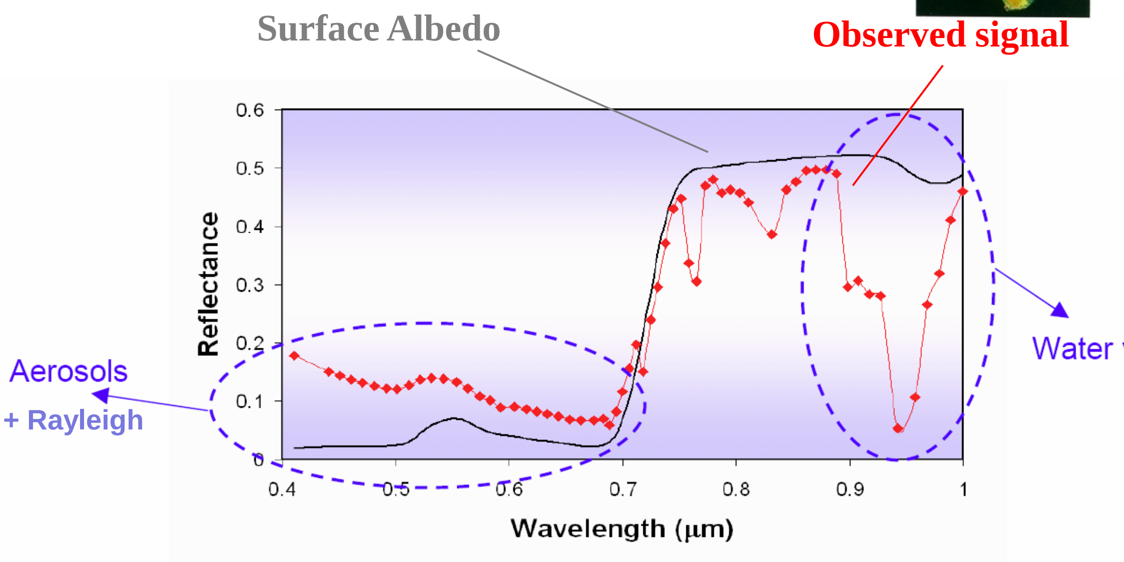
TOMS AEROSOL,AVHRR FIRES,SEPT,2000



- Fires can be detected at infra-red window channels but 3-4 μm is particularly good because fires are hot (Wien law).
- Often fire detection is limited simply to saturation of channel signals (Stefan Boltzmann law: $I \sim T^4$)

VISIBLE/NEAR-IR Land Sensing

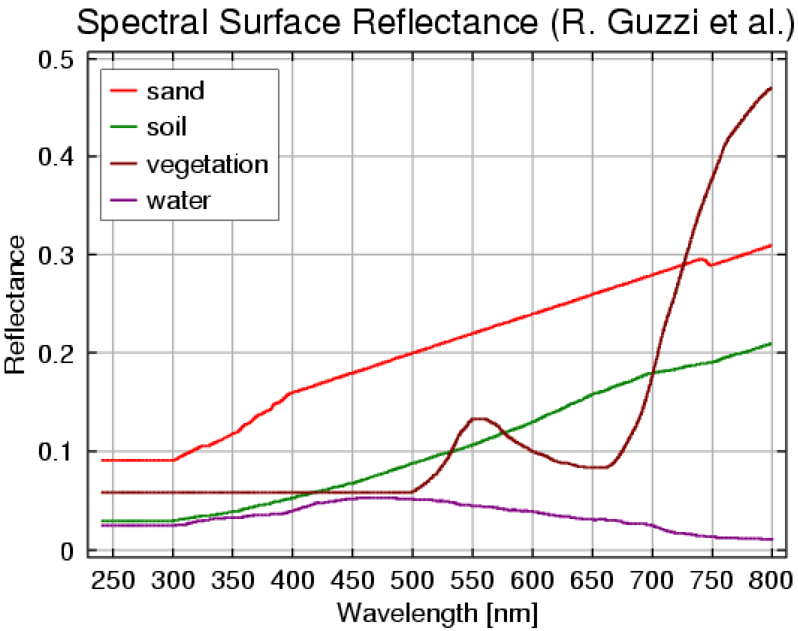




- **High atmospheric transparency and high signal levels (sunlight)**
- **Reflectance of light by surface with specific signature will be observed in visible/near-IR**
- **But, signal related to surface will be strongly modified by interaction with atmosphere**
  - **Scattering by aerosol and molecules will induce highly variable changes broad-band signal levels**
  - **Also, as in IR Clouds can complete mask the surface signal and absorption by molecules will result in high-frequency variations**
  - **Note: Strong, saturated absorption bands can be rel. broad (e.g. H_2O)**

Reflection on Land Surfaces

- Photons can be absorbed and/or reflected by the Earth surface
- Albedo is fraction of incoming solar radiation (energy) reflected by a surface, integrated over whole viewing directions (often referred as flux albedo)
- Wavelength-dependence of albedo depends on surface characteristics (and provides information about surface)
- Often assumed is Lambert surface where reflected intensity does not depend on viewing angle
- In reality, surface reflectance has directional component



Surface reflection: the BRDF

Consider downward-moving angular beam with intensity I^-_v within solid angle dΩ'

Then incident energy flux on flat surface: $I^-_v \cos\theta' \, d\Omega'$

Let dI^+_v be intensity reflected in direction ξ and solid angle dΩ

Bidirectional reflectance distribution function BRDF gives ratio of reflected intensity to energy flux in incident beam

$$\rho_\nu(\xi, -\xi') = \frac{dI^+_{r,\upsilon}(\xi)}{\cos\theta' \, I^-_\upsilon(-\xi') \, d\Omega'}$$

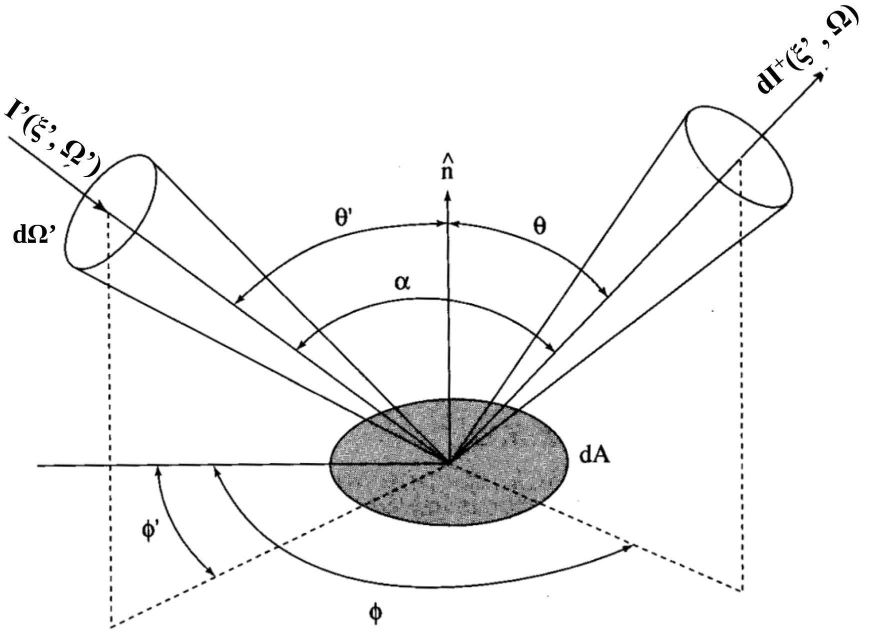


Figure 5.1 Geometry and symbols for the definition of the BRDF. The angle α is the backscattering angle.

BRDF – Lambertian Reflectance

Total reflected intensity if given by integral over all incoming directions Ω' (over hemisphere)

$$I^{+}_{r,\upsilon}(\xi) = \int_{-} \rho_{\nu}\left(\xi,-\xi'\right)\cos\theta'\, I^{-}_{\upsilon}(-\xi')\, d\Omega'$$

Assume Lambertian reflectance (independent of ξ and ξ')

$$\rho^{L}_{\nu} = \rho_{\nu}\left(\xi,-\xi'\right)$$

Then

$$I^{+}_{r,\upsilon} = \rho^{L}_{\nu} \int_{-} \cos\theta'\, I^{-}_{\upsilon}(-\xi')\, d\Omega' = \rho^{L}_{\nu} F^{-}_{\nu}$$

F^{-} is hemispherical downward flux (lecture 2):

$$F^{-} = \int_{-} I \;\cos\theta\, d\Omega$$

Note:

$$\rho^{L}_{\nu,\max} = 1/\pi$$

(no absorption, all incoming light is reflected)

See isotropic radiance distribution (lecture 2): F = π I

Collimated Incidence - Lambertian Surface

If incident light is collimated (direct sunlight)

$$I_{\upsilon}^{-}(\xi') = F_{\nu}^{s}\,\delta(\xi' - \xi_0)$$

and $$I_{r,\upsilon}^{+} = \rho_{\nu}^{L} \int_{-} \cos\theta' \, I_{\upsilon}^{-}(-\xi')\, d\Omega'$$

Reflected intensity is then given by

$$I_{r,\upsilon}^{+} = \rho_{\nu}^{L} F_{\nu}^{-} = \rho_{\nu}^{L} F_{\nu}^{s} \cos\theta_0$$

F^{s} **: Solar flux (in direction to Sun)**

Delta function δ

$$\delta(x) = \begin{cases} +\infty & x = 0 \\ 0 & x \neq 0 \end{cases}$$

$$\int \delta(x)\, dx = 1$$

$\delta(\xi' - \xi_0)$ **has units of 1/sr**

Reflected intensity is proportional to cosine of incoming (collimated) beam

Reflectance from Satellites

For satellite observations we use following nomenclature to describe the reflectance

Measured by satellite

$$R_\lambda(\theta_i,\phi_i,\theta_o,\phi_o) = \pi\rho(\xi,-\xi') = \frac{\pi I_\lambda^+(\theta_i,\phi_i)}{\cos\theta_0\, F_\lambda^s(\theta_i,\phi_i)}$$

- λ **is wavelength**
- θ_I **and** ϕ_i, **represent the incoming light direction in spherical coordinates**
- θ_o **and** ϕ_o **represent the outgoing reflected direction in spherical coordinates**
- **Note: this is sometimes also called BRDF**

For a Lambertian surface:

Reflected light is isotropic: $\pi I^+ = F^+$

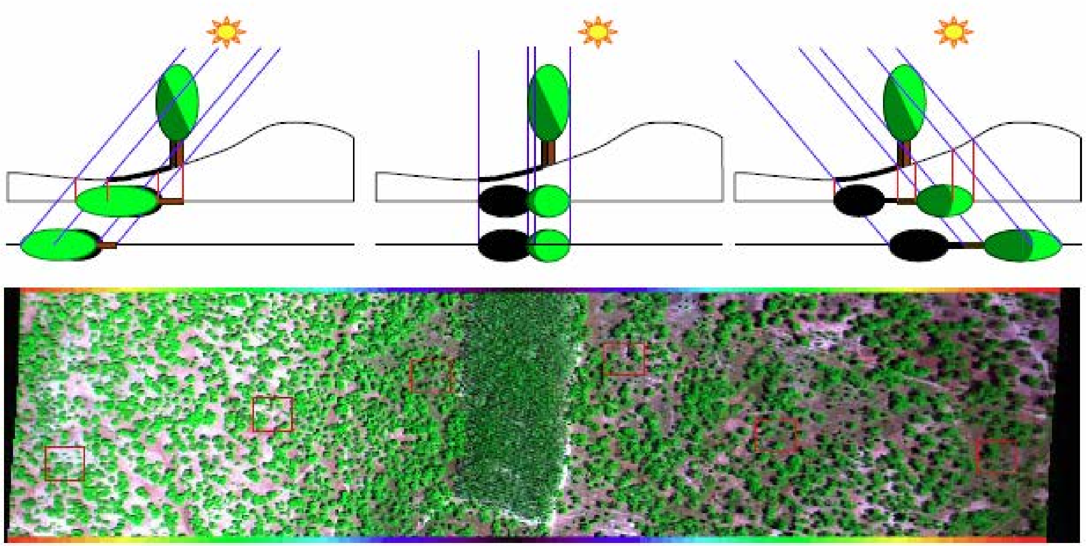
thus $R = F^+/(\cos\theta_o\, F^s) = F^+/F^-$ **R is the (flux) albedo**

For Lambertian surfaces: $0 \le R \le 1$

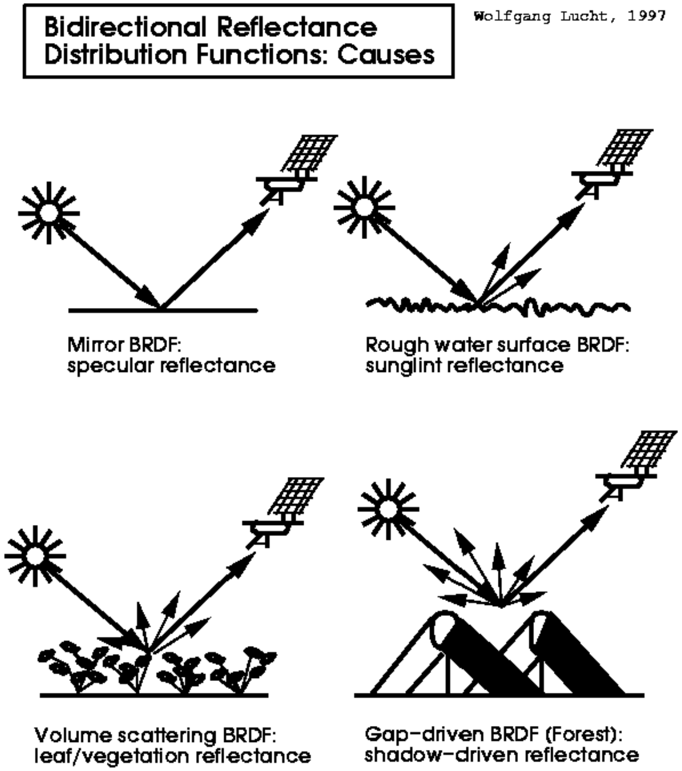
R can be >1 for some directions for non-Lambertian surfaces, but albedo is still ≤ 1 **(energy conservation)**

ANGULAR EFFECT OF SURFACE REFLECTANCE

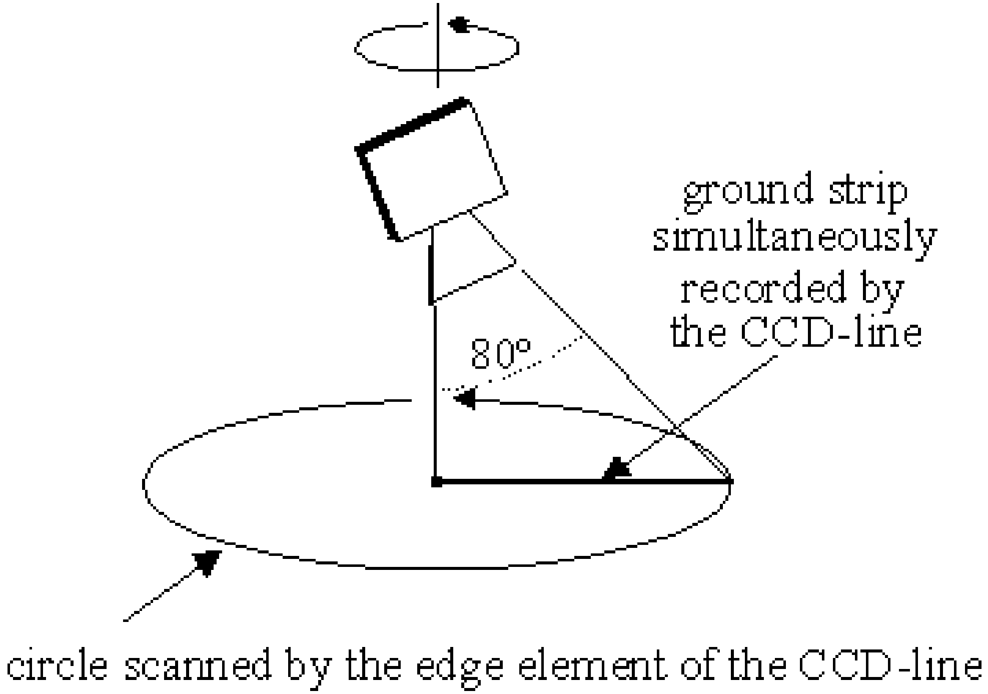
- For structured surfaces we observe shadow effects and scattering effects inside the volume (e.g. inside tree canopy)
- Reflectance of surface depends on sun position, viewing angle and surface structure (and type)
- Space-based and aircraft will be strongly impacted by angular effect



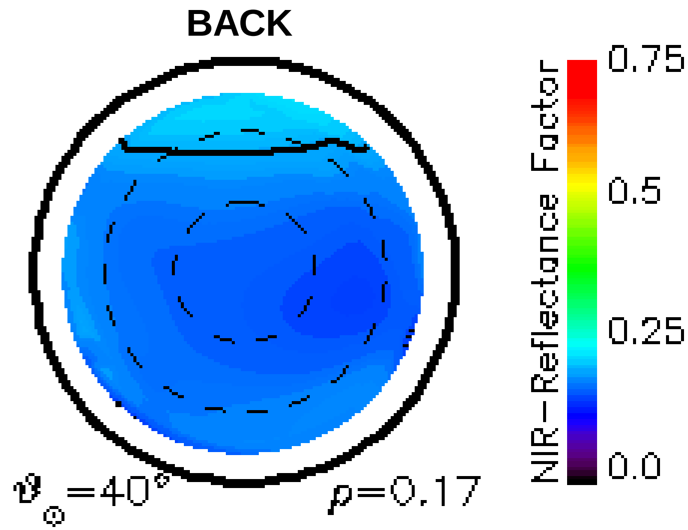
Backwards Forwards



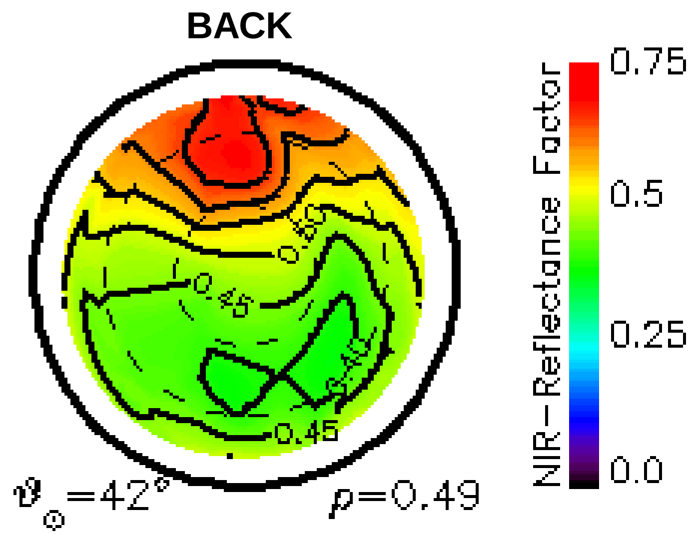
Measuring the BRDF



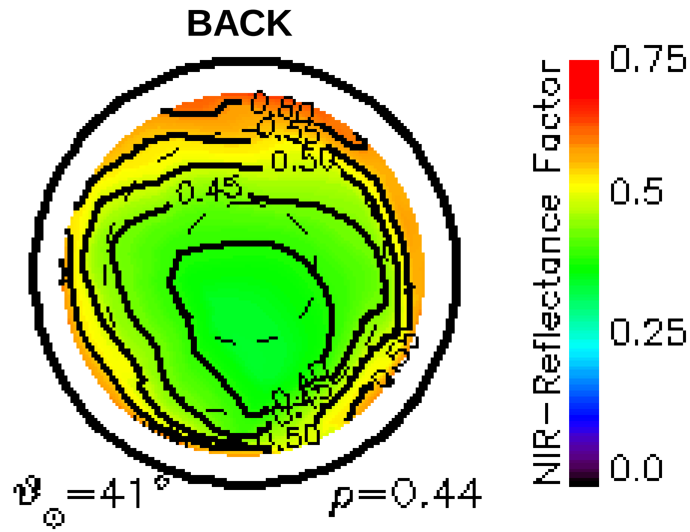
Example: Asphalt BRDF



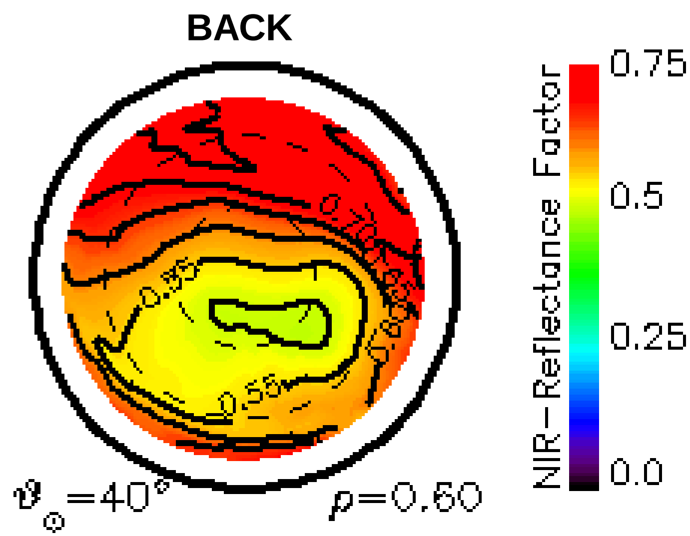
Example: Broccoli BRDF



Example: barley seed BRDF

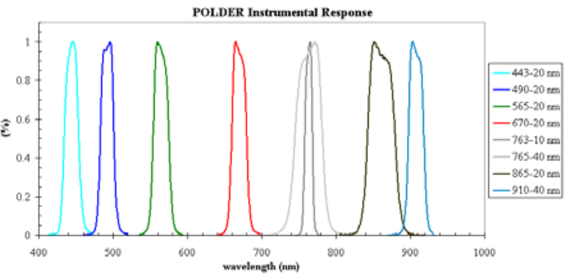


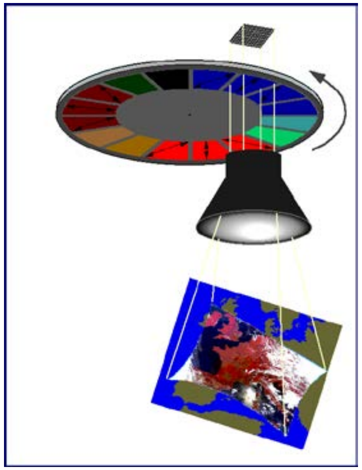
Example: Rye Gras BRDF



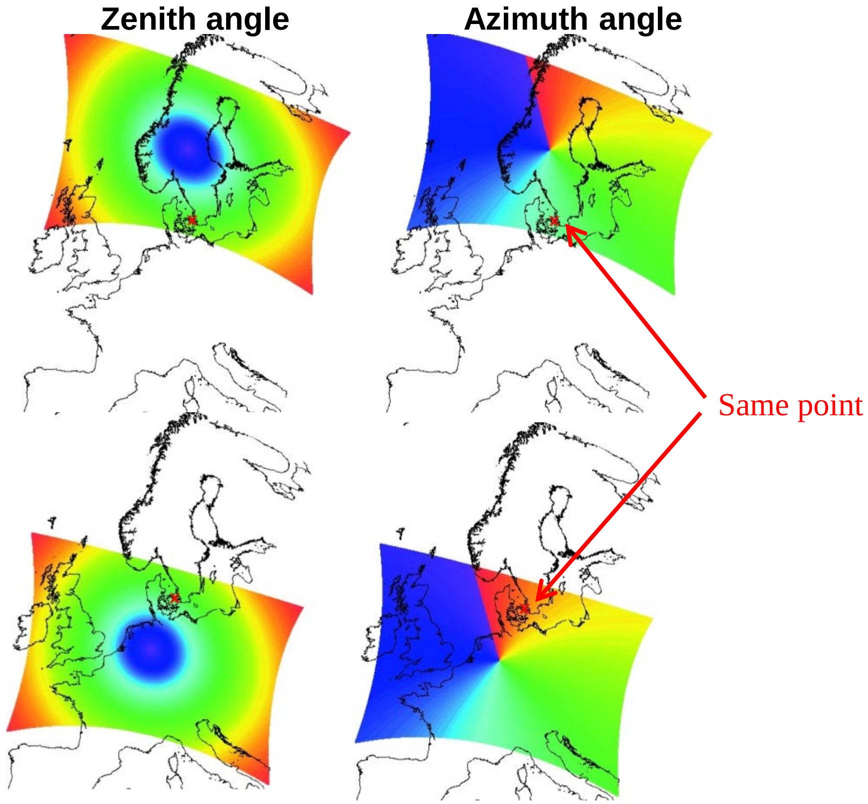
BRDF Observations from Space: The POLarization and Directionality of the Earth's Reflectances Instrument

- POLDER has been build by French Space Agency and launched in 2002 on Japanese ADEOS platform (Successor Parasol launched in 2004)
- POLDER is wide field of view imaging radiometer that has provided measurements of spectral, directional and polarized characteristics of reflected solar radiation





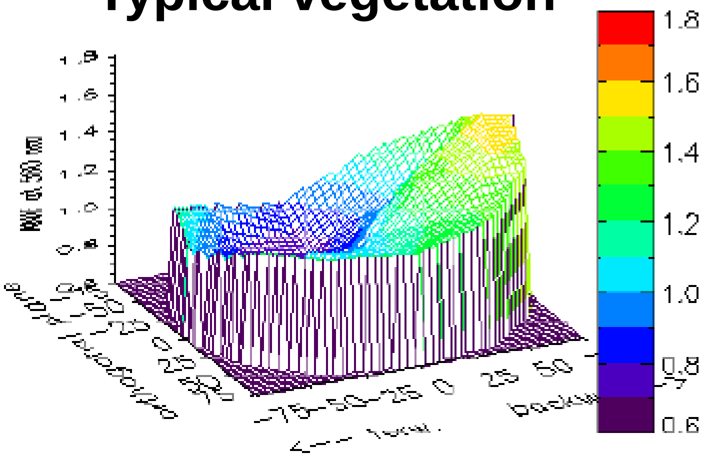
POLDER instrument is a camera composed of a two-dimensional CCD detector array, wide field of view optics and rotating wheel carrying spectral and polarized filters

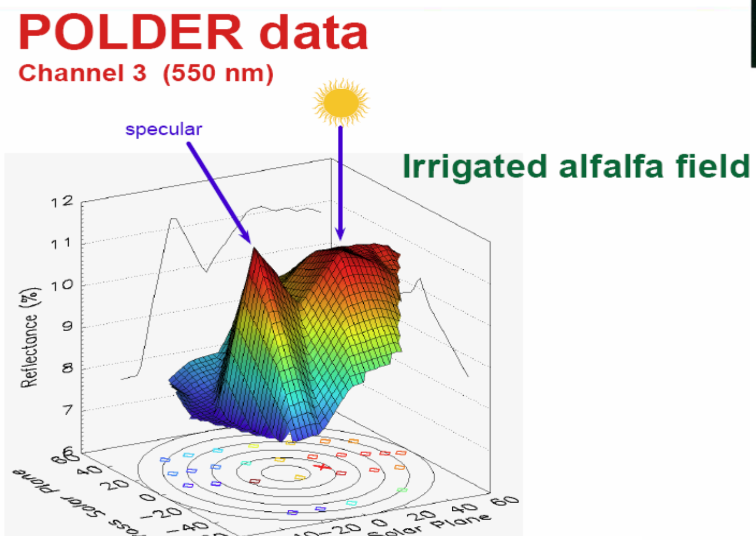


At a given location, solar angle remains nearly constant whereas viewing angle and the azimuth change rapidly

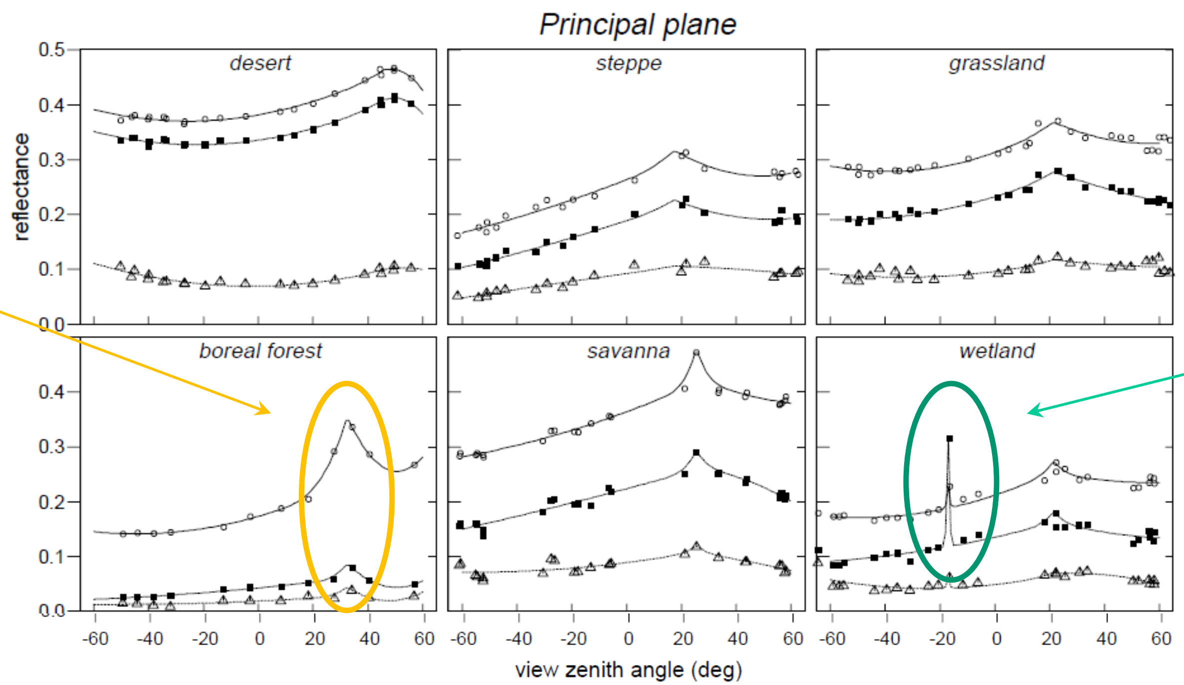
BRDF as observed from Space

Typical vegetation





‘hot spot’: viewing direction coincides with solar direction



Specular (Fresnel) reflection on water

BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION BRDF - SUMMARY

- **Bi-directional reflectance distribution function** (BRDF) expresses dependence of E/M radiation observed by a sensor on viewing angle of sensor
- For visible radiation, BRDF depends on **angle of incidence of light and viewing angle of sensor**
- Radiation field directed to space is **anisotropic**
- Effects are **mainly for land** but sun glint on oceans is important, too
- Rock surfaces are simplest surfaces and vegetation is one of the most complicated due to its canopy.
- A "hot spot" is often observed for vegetation corresponding to increased reflectance of the vegetation in direction of illuminating radiation

Interaction of light with soil-vegetation

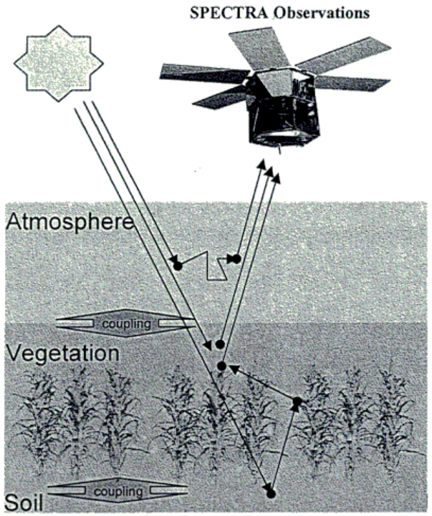


Figure 4.1: Schematic of the interactions of the radiation with the soil-vegetation-atmosphere, showing the coupling between the radiative transfers of each of these components.

ATMOSPHERIC CORRECTION – VISIBLE/NEAR-IR

Atmospheric correction: Removal of atmospheric effects (scattering, absorption, emission) from measured sensor radiance, leading to the derivation of surface reflectance images

Methods (VISIBLE/NEAR-IR): Reflection measured by satellite (see lecture 6):

$$R(AOD,\Omega) = \boxed{R_{atm}(AOD,\Omega)} + \boxed{\frac{A_g \mathcal{T}_{down}(AOD,\Omega)\mathcal{T}_{up}(AOD,\Omega)}{1 - A_g r_{atm}(AOD,\Omega)}}$$

Pure atmosphere term

Multiple scattering + surface

T, R: atmospheric Transmission and Reflectance
A_g: surface reflectance
r: spherical albedo of atmosphere

Atmospheric correction possible by solving radiative transfer equation to calculate atmospheric correction. Requires knowledge about atmospheric parameters (aerosols, absorbers etc.)

Simple atmospheric correction possible by assuming

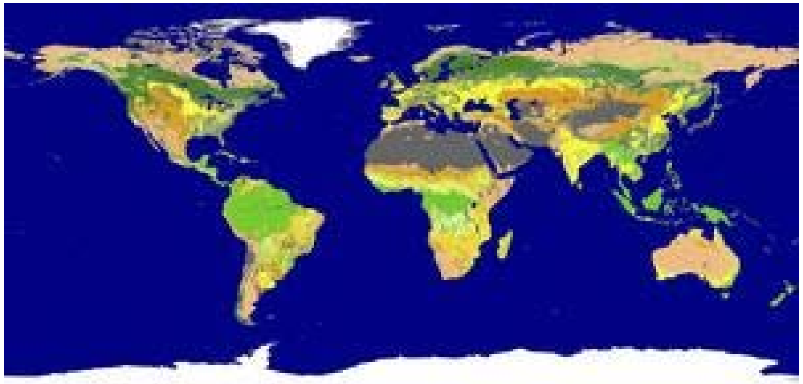
- Multiple viewing angles: Lambertian surface *A* is constant for multiple views
- Multiple wavelength: Scattering is constant (or change with λ is known)
- Observations of adjacent scenes: (spatial homogeneity of surface)
- Use other observations/models for atmospheric parameters

VEGETATION PROPERTIES

Satellite provide globally key parameters to characterize vegetation and their productivity:

- Biome type and dynamics: classification of different vegetation types and their temporal change (e.g. due to climate change)
- Biophysical variables: Leaf area index LAI and Fraction of Photosynthetically Active Radiation absorbed by vegetation fPAR
- Vegetation indices: NDVI, EVI etc.

MODIS Land Cover Map



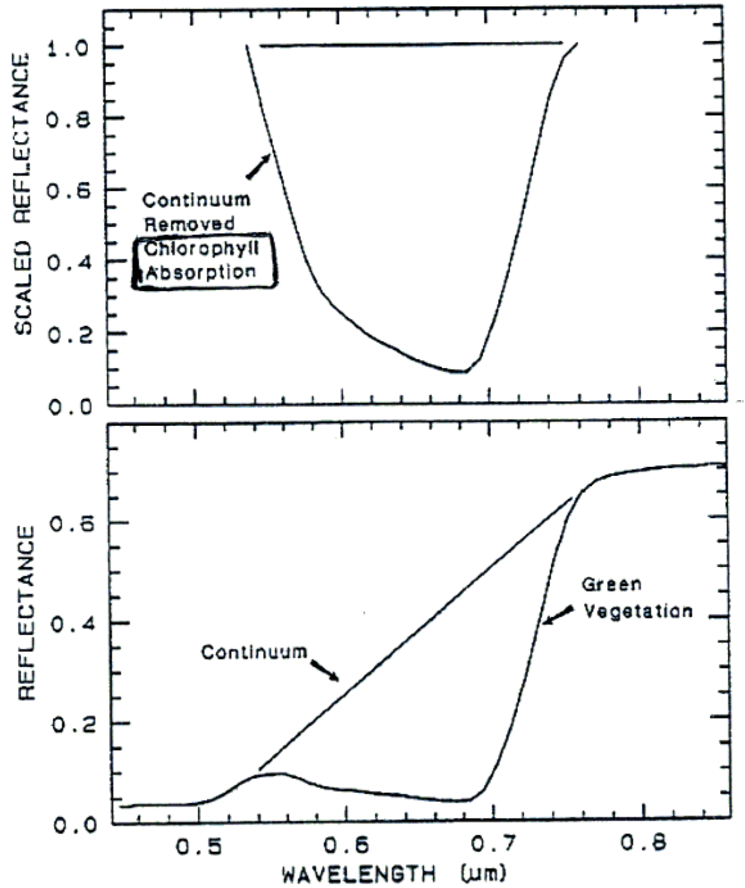
IGBP Classification in 11 natural vegetation classes, 3 developed and mosaicked land classes, and three non-vegetated land classes.

LC Type-1 (IGBP)	
Class	Color
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
254	
255	

VEGETATION SPECTRA

For vegetation, three main compounds causing spectral variation in near infra-red/visible regions are:

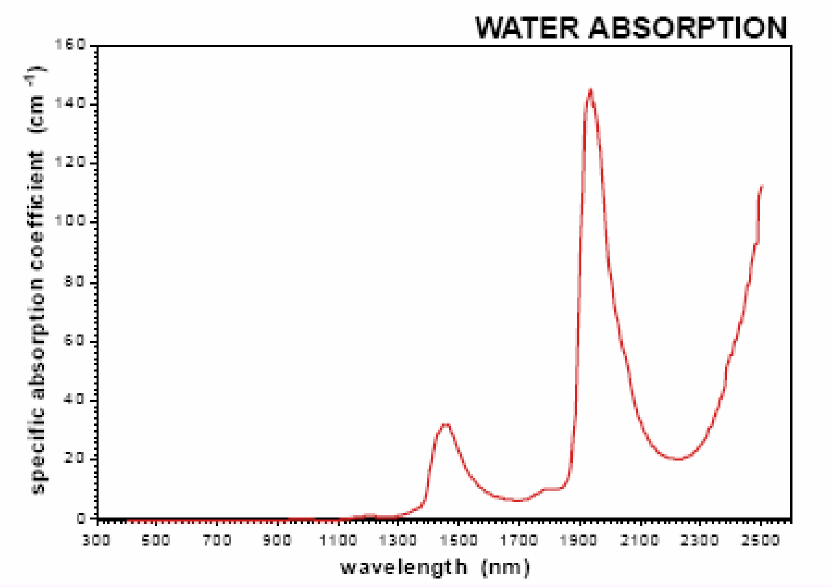
- **Chlorophyll which absorbs in visible domain (below 800nm).**



VEGETATION SPECTRA

For vegetation, three main compounds causing spectral variation in near infra-red/visible regions are:

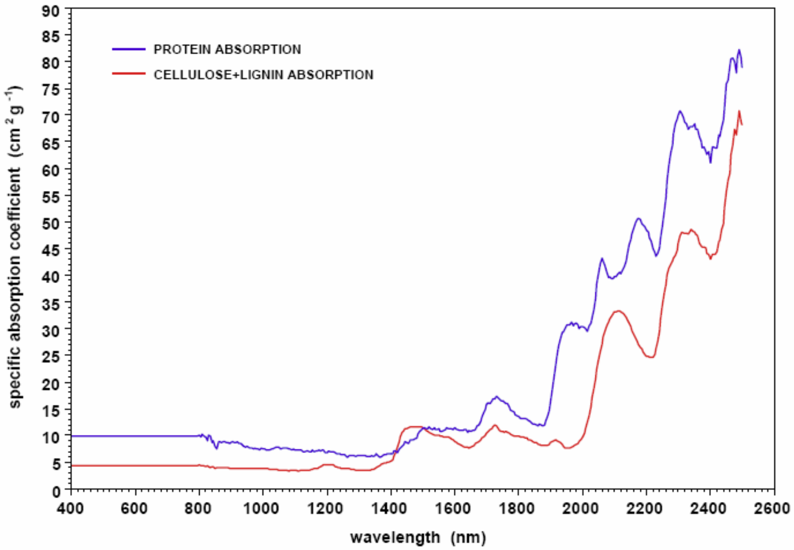
- **Chlorophyll which absorbs in visible domain (below 800nm).**
- **Plant-water which absorbs mostly in near to middle IR spectral range**



VEGETATION SPECTRA

For vegetation, three main compounds causing spectral variation in near infra-red/visible regions are:

- **Chlorophyll which absorbs in visible domain (below 800nm).**
- **Plant-water which absorbs mostly in near to middle IR spectral range**
- **Biochemicals such as protein, lignin, cellulose, hemicellulose, that constitute most of leaf dry mass absorption in near and middle IR region**



NORMALISED DIFFERENCE VEGETATION INDEX (NDVI)

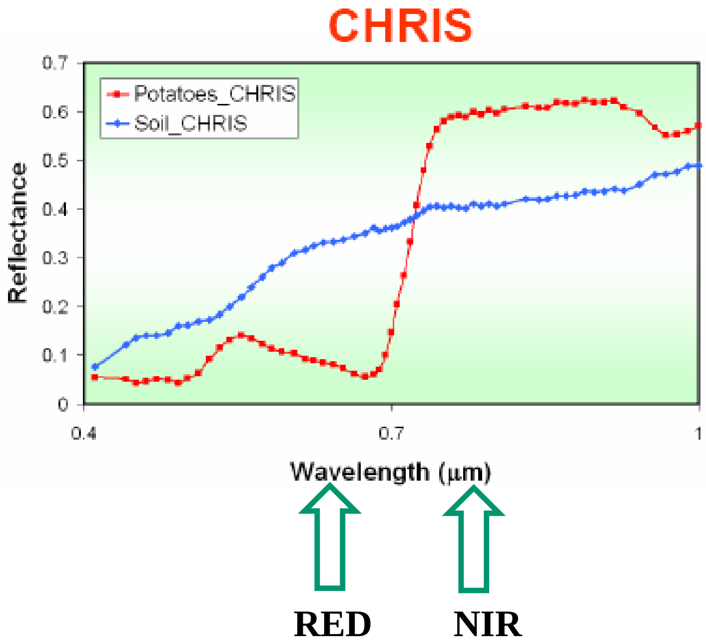
- From the satellite data alone, it is possible to define ***vegetation indices*** **based on sharp red edge induced by chlorophyll absorption.**
- **Normalised Difference Vegetation Index (NDVI) is common:**

  NDVI = (NIR – red)/(NIR + red)

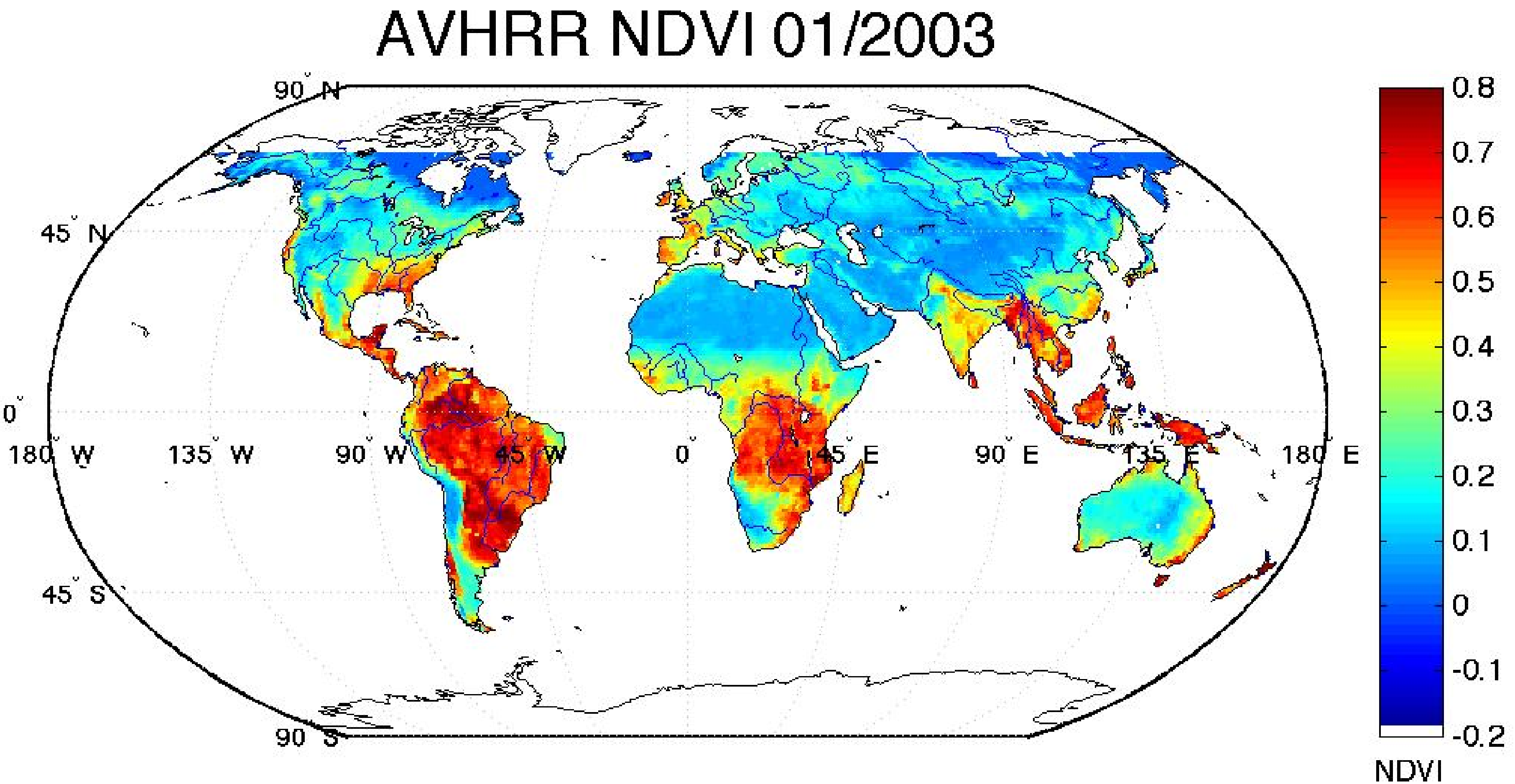
  NIR = near infra-red reflectances (> 750 nm)

  Red = reflectances in visible spectrum (600-700 nm)

- **Other common indices attempt to account for factors such as background soil contributions.**



NDVI VEGETATION INDEX (AVHRR)



COMPARISON OF PASSIVE LAND SENSORS

Classic systems which are useful for vegetation monitoring (NDVI) include LANDSAT, AVHRR and SPOT, as well as (A)ATSR.

	ATSR	AVHRR	LANDSAT TM
Red band	649-669 nm	580-680 nm	630-690 nm
Bandwidth	20 nm	100 nm	60 nm
Near IR band	855-875 nm	725-1100 nm	760-900 nm
Bandwidth	20 nm	375 nm	140 nm
Spatial resn.	1 x 1 km^2	1.16 x 1.16 km^2	30 x 30 m^2

- **Preference is for red band not to exceed 690 nm and for near IR band to start above 750 nm.**
- **AVHRR, designed for meteorological satellites, is slightly poorer in specification than ATSR-2 and LANDSAT.**
- **Note the spatial resolutions: case studies vs regional/global.**

CURRENT PASSIVE LAND INSTRUMENTS (EARTH)

Current sensors focus on a number of improvements including more dense spectral coverage (hyperspectral) and multi-angle viewing, because of the BRDF factor.

Hyperspectral

- **AATSR/ENVISAT [launched March 2002] has 7 bands between 0.55 μm and 12 μm (and 2 viewing angles)**
- **MODIS [launched December 1999] has 36 spectral bands between 0.405 μm and 14.385 μm**
- **MERIS/ENVISAT [launched March 2002] has 15 programmable spectral bands**
- **CHRIS-PROBA [launched October 2001] 19 bands at a spatial resolution of 18m, and 63 bands at 36m**

Multi-angle

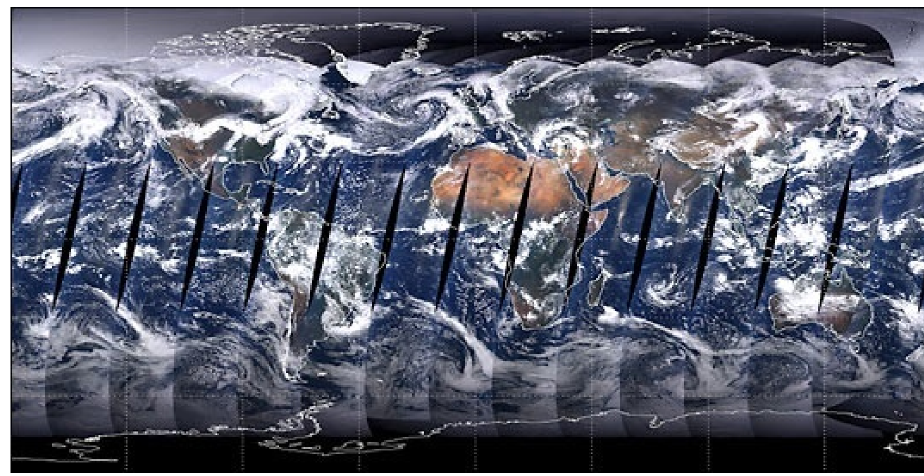
- **MISR/EOS-TERRA [launched December 1999] has 9 view angles (4 bands at 446, 558, 672 and 867nm)**
- **POLDER (launched 14/12/2002) and PARASOL (18/12/2004) – Multi-view with 9 bands**

EXAMPLE: Moderate Resolution Imaging Spectro-radiometer MODIS

MODIS is a key EO satellite:

- **On board AQUA (afternoon orbit) and TERRA (morning orbit)**
- **Wide-swath multi-wavelength imager, but no multi-view capability**
- **Global coverage every 1-2 days**
- **Spatial resolution between 250 – 1000 m**
- **Bands from UV to IR (day and night observations possible)**
- **Large number of land, ocean and atmosphere products**
- **Improved atmospheric correction for land products using the atmosphere products**

First complete day of MODIS observations



EXAMPLE: Moderate Resolution Imaging Spectro-radiometer MODIS

MODIS Bands

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud Boundaries	1	620-670	21.8	128
	2	841-876	24.7	201
Land/Cloud 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

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NEΔT(K)[4]
Surface/Cloud Temperature	20	3.660-3.840	0.45	0.05
	21	3.929-3.989	2.38	2.00
	22	3.929-3.989	0.67	0.07
	23	4.020-4.080	0.79	0.07
Atmospheric Temperature	24	4.433-4.498	0.17	0.25
	25	4.482-4.549	0.59	0.25
Cirrus Clouds	26	1.360-1.390	6.00	150[3]
Water Vapor	27	6.535-6.895	1.16	0.25
	28	7.175-7.475	2.18	0.25
	29	8.400-8.700	9.58	0.05
Ozone	30	9.580-9.880	3.69	0.25
Surface/Cloud Temperature	31	10.780-11.280	9.55	0.05
	32	11.770-12.270	8.94	0.05
Cloud Top Altitude	33	13.185-13.485	4.52	0.25
	34	13.485-13.785	3.76	0.25
	35	13.785-14.085	3.11	0.25
	36	14.085-14.385	2.08	0.35

<u>Main products:</u>

- ❒ Vegetation and land-surface cover, conditions, and productivity
  - ❖ Surface reflectance
  - ❖ Vegetation indices
  - ❖ Land cover
    - IGBP Land Cover Classification
    - Vegetation continuous fields and cover conversion
    - Net primary productivity, leaf area index, and fPAR
- ❒ Fire and thermal anomalies
- ❒ Snow and sea-ice cover
- ❒ Surface temperature
- ❒ Aerosol concentration and optical properties
- ❒ Cloud properties
- ❒ Atmospheric temperature and water vapor profiles.

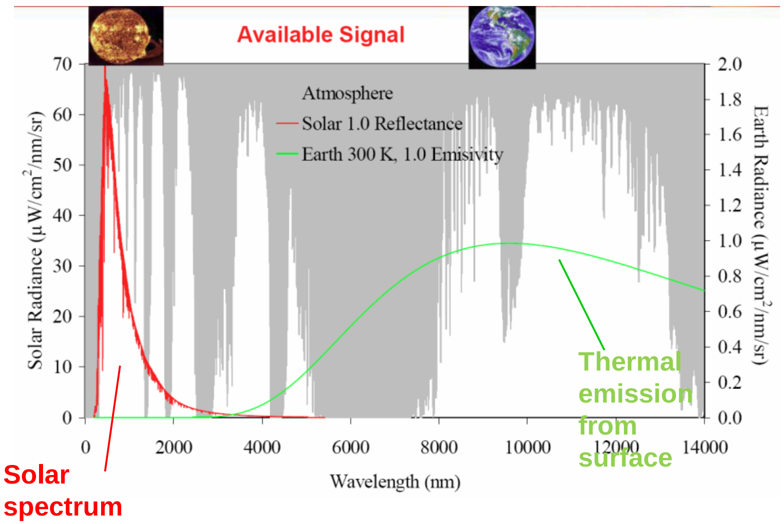
What do you need to know?

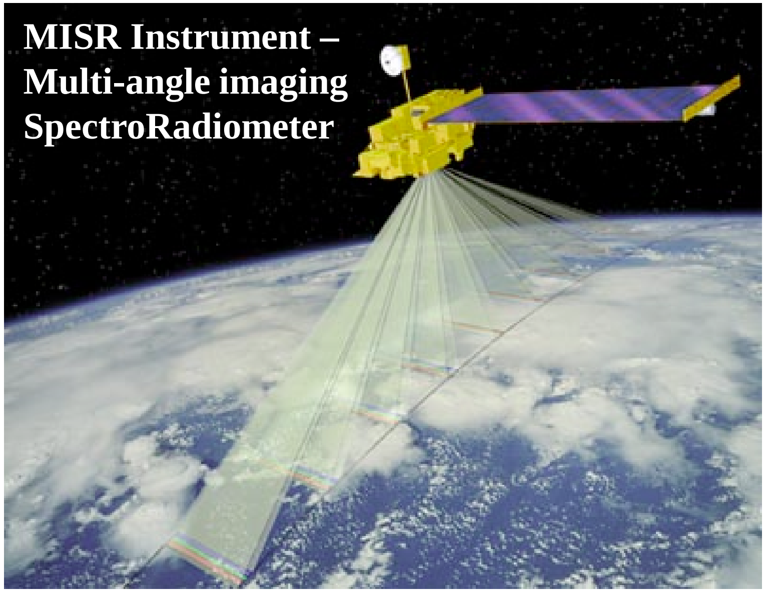
- Basic characteristics of surface effects:
  - Fresnel reflection
  - Reflectance, absorption and emission
  - BRDF
- Land radiative transfer – inhomogeneous (heterogeneous scenes)
- Main land parameters
- Main challenges of land remote sensing
- Basic ideas of atmospheric correction
- Retrieval of biophysical variables and vegetation index in visible/near-IR
- Typical instruments

OBSERVATIONS OF THE SURFACE

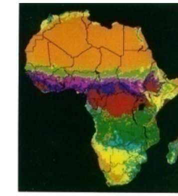
What should you consider when you design a satellite mission of land remote sensing?

- ❑ Sufficient light from a source (Sun, surface etc.)
- ❑ A spectral window (high atmospheric transmissivity $\mathcal{T}$)
- ❑ Observations at wavelength(s) which spectral signatures related to surface
- ❑ Nadir viewing with small ground pixel area:
    - To capture heterogeneity of land surface
    - To avoid cloud perturbation
- ❑ Optimally observations at more than one angle to characterize the directional reflectance/emission of surface
- ❑ Correction/Removal of atmospheric signals (multi-λ or multi-view)





EXAMPLES



Assume a land surface with emissivity of 0.8 and T_s=280 K and the atmosphere with T_g=250K

For which transmissivity at 12 micron do you get equal contributions from land and atmosphere?

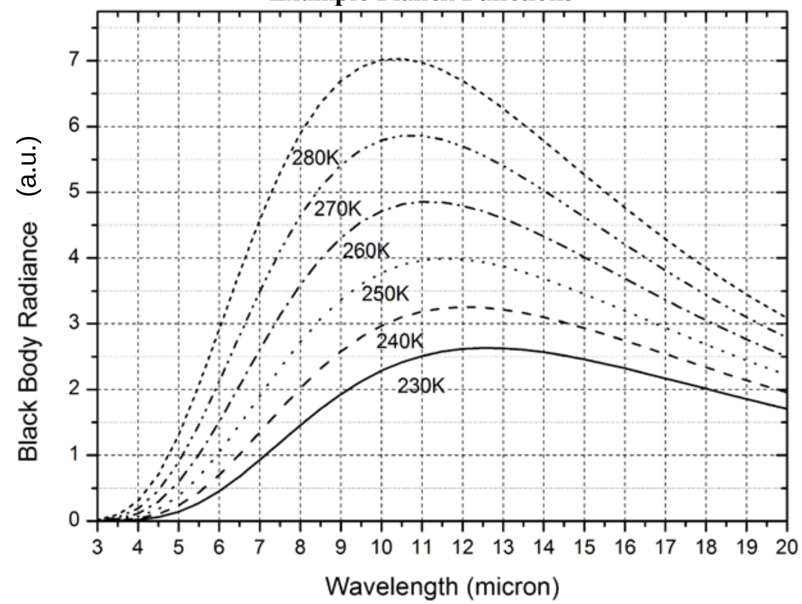
Surface contribution:

$$I_2 = \varepsilon_s(\lambda) \times B(\lambda, T_s) \times \mathcal{T}_g(\lambda)$$

Atmospheric contribution:

$$I_2 = (1 - \mathcal{T}_g(\lambda)) \times B(\lambda, T_g)$$

Example Planck Functions



Set $I_2 - I_1 = 0$

Then $0.8 \times B(280K) \times \mathcal{T} - B(250K) + \mathcal{T} B(250K) = 0$

and

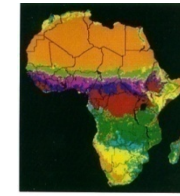
$$0.8 \times 7 \times \mathcal{T} - 4 + \mathcal{T} 4 = 0$$

$$9.6\, \mathcal{T} - 4 = 0$$

$$\mathcal{T} \sim 0.42$$

Higher T_s increase surface contribution !

LEAF AREA INDEX



- **Leaf Area Index** (LAI) gives the one-sided green leaf area per unit ground area
- LAI and FPAR (Fraction of Photosynthetically Active Radiation absorbed by vegetation) are **key biophysical variables** controlling exchange of energy and mass (e.g. water and CO_2) between surface and atmosphere that required for ecosystem models
- Usually LAI/FPAR are inferred from NDVI (but with low accuracy)

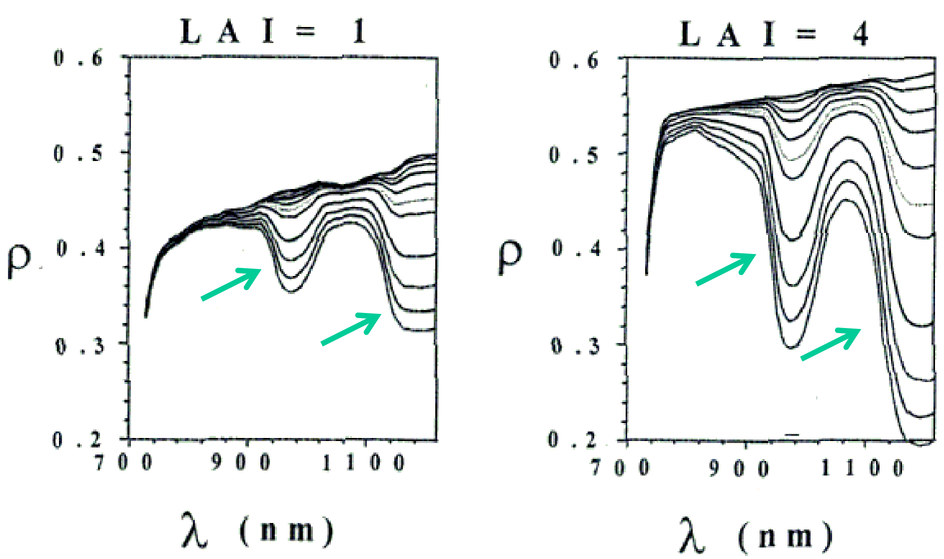


Figure 4.13: Changes in canopy reflectance as a function of leaf liquid water content, for two different LAI values. Changes are due to multiple scattering effects. These effects must be taken into account in estimating leaf water content from canopy spectra (Courtesy: J. Moreno).

- It is possible to retrieve LAI directly from spectrally resolved data from slope of absorption feature
- LAI is retrieved linked to some absorber component:
  - chlorophyll
  - water
  - dry matter

Specular Reflection

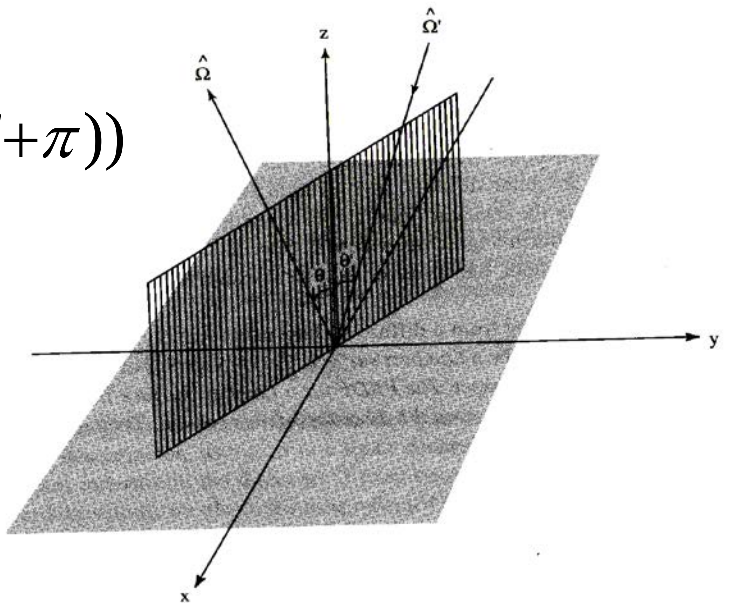
Mirror-like reflection: Reflected intensity is directed along the angle of reflection only [$\theta' = \theta$ and $\phi = \phi' + \pi$]

Opposite extreme to Lambert reflection

Smooth, untextured surfaces (calm water, clean smooth ice ..)

Reflected intensity:

$$I_\upsilon^+(\xi) = \rho_\upsilon^s(\theta) F_\nu^s \delta(\cos\theta - \cos\theta')\delta(\phi - (\phi' + \pi))$$



ρ^s depends on polarization!!
It can be derived directly from refractive index

Reflection from real surfaces has a Lambertian and a Fresnel component in its BRDF

See reflection and transmission of EM waves see Ch.11, Grant & Phillips