Advanced Optical Imaging

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ESA–MOST China Dragon 4 Cooperation

2019 ADVANCED INTERNATIONAL TRAINING COURSE IN LAND REMOTE SENSING

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Source of materials

C. Cartalis, 2017, Optical remote sensing, Dragon 4 advanced land remote sensing course, Kunming.

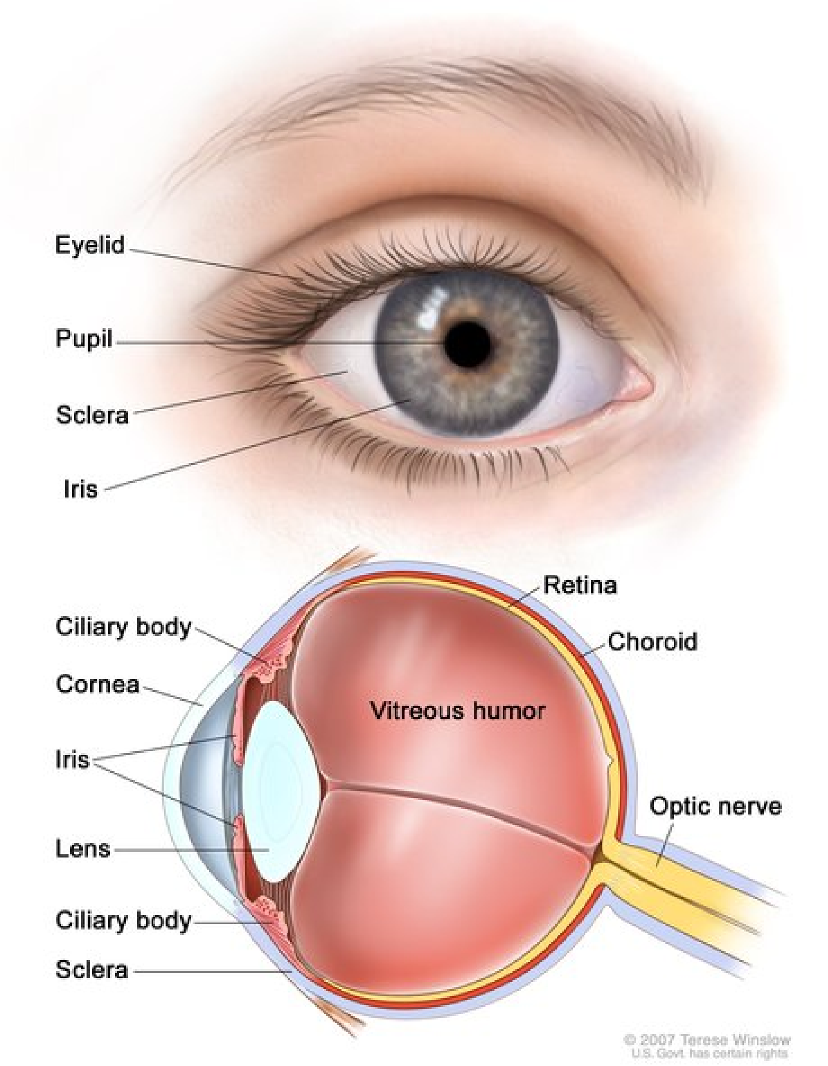
X. Ding, 2015, Hyperspectral Imaging, Dragon 4 advanced land remote sensing course, Tianjing.

Y.L. Desnos, 2015, ESA EO programmes, Dragon 4 advanced land remote sensing course, Tianjing.

Q. Liu, 2015, Advanced Optical High Resolution Imaging and Quantitative Inversion, Dragon 4 advanced land remote sensing course, Tianjing.

W. Verhoef, 2012, Multi-angular observations, EUFAR/EUROSPEC REFLEX advanced training course.

Contents

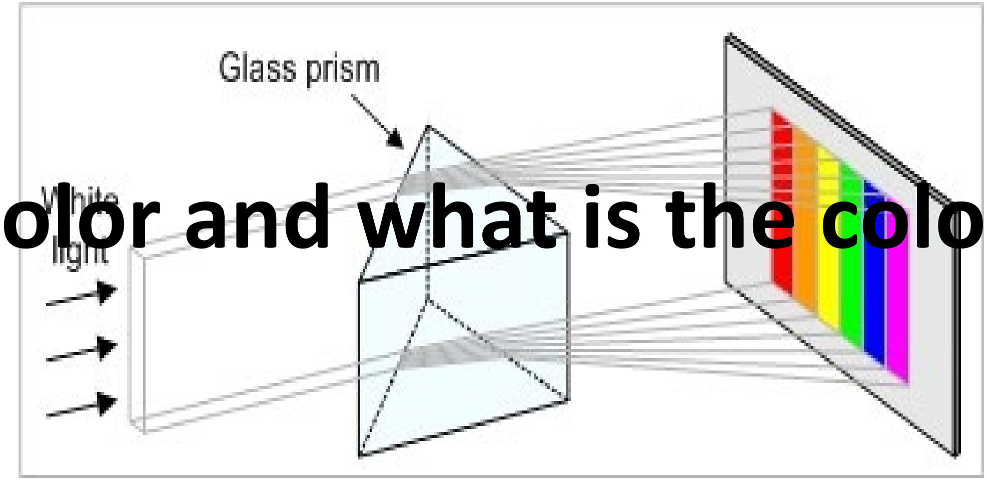


We receive more than 80% information from the outside world by seeing (vision)!

(to see is to receive lights in our eyes - (light rays entering the eye are transformed by the retina into electrical signals that are transmitted to the brain via the optic nerve – **light rays reflected or emitted from objects representing their properties (such as color, luminosity, shape, and size**)

What is imaging (seeing)?

We receive more than 80% information from the outside world by seeing (vision)!



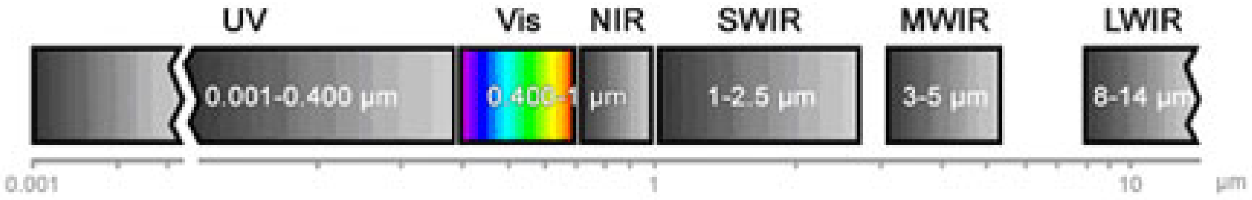
What is color and what is the color of light?

Isaac Newton reflected sunlight through a glass prism and discovered the "color spectral separation" and the white light is actually made of many colors in 1666.

Optical radiation wavelength range

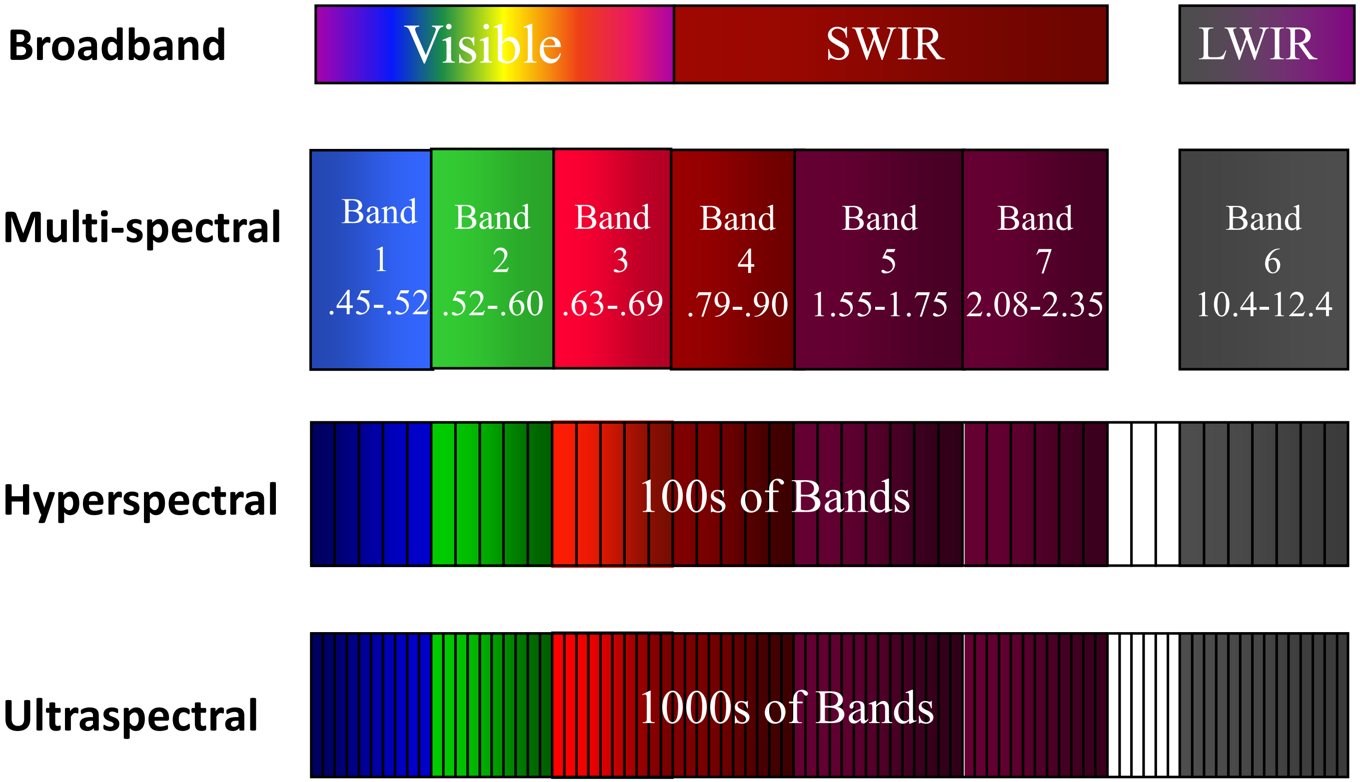
Color is the visible manifestation of light's wavelength

(Optical imaging usually refers to Vis/NIR/SWIR requency range)



		Atmospheric window not considered	Atmospheric window considered
UV	Ultraviolet	10~390nm	10~390nm
VIS	**Visible band**	**0.39~0.75µm**	**0.39~0.75µm**
NIR	**Near infrared**	**0.75~1.1µm**	**0.75~1.1µm**
SWIR	**Short wavelength infrared**	**1.1~3.0 µm**	**1.1~2.5 µm**
MWIR	Medium wavelength infrared	3.0~6.0 µm	3.0~5.0 µm
LWIR	Long wavelength infrared	6.0~25.0 µm	8.0~14.0 µm

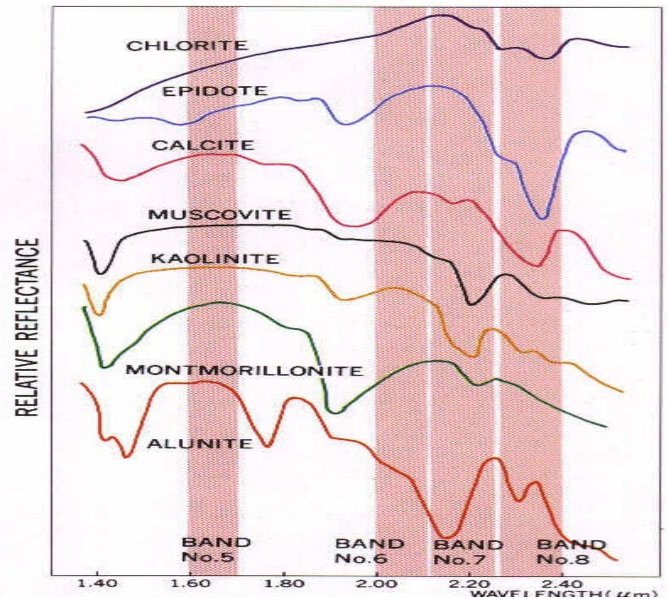
Classification of optical remote sensing



Panchromatic remote sensing

Single band (Black and White) image
Only geometric image without spectral information

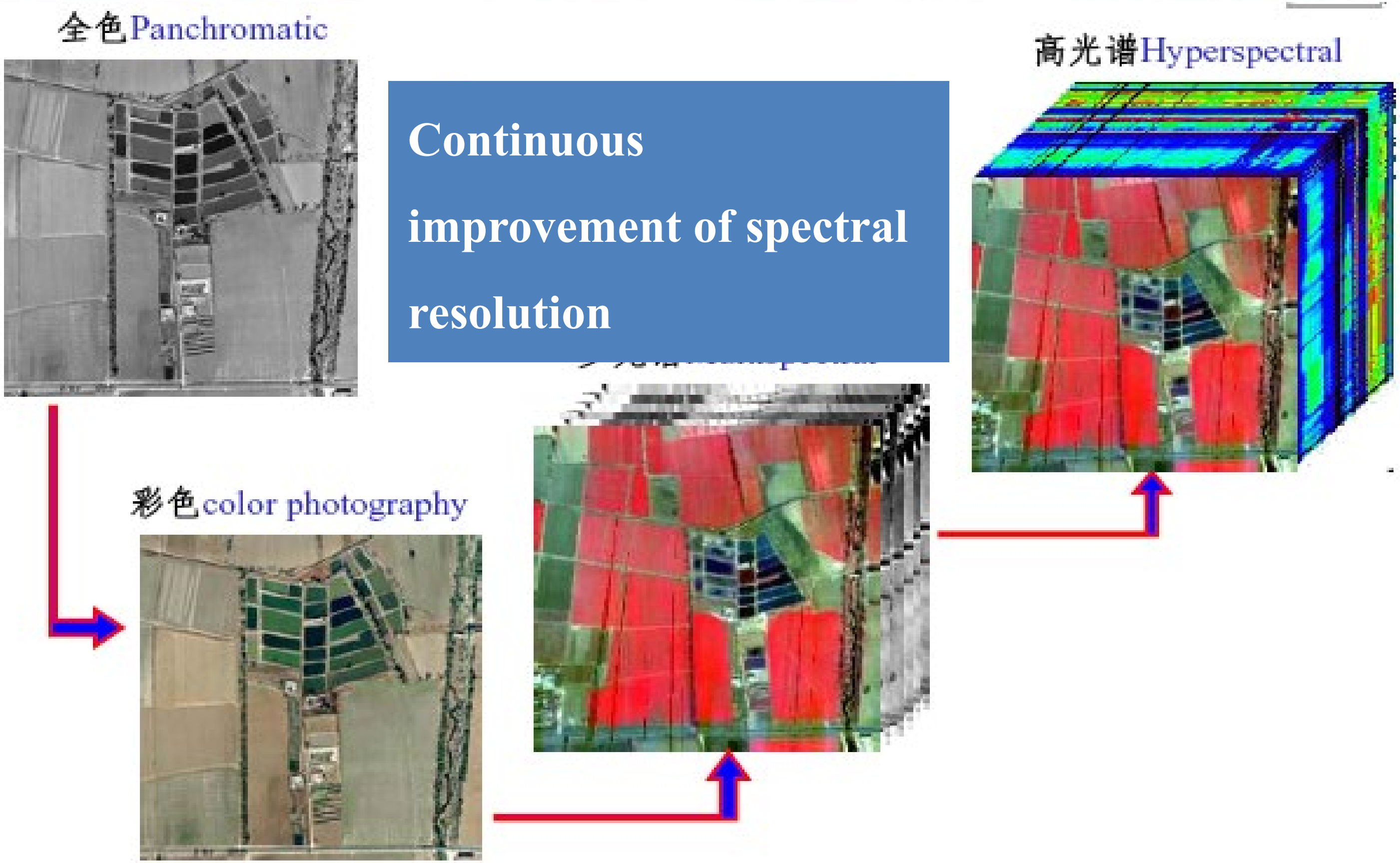
Conventional Spectral Measurement



Relative Reflectance

Only measure object's spectral information - without imaging

Development path of optical remote sensing



Continuous improvement of spectral resolution

Terminology of radiant energy

Energy from the Earth Atmosphere

over time is

Flux

which strikes the detector area

Irradiance

at a given wavelength interval

Monochromatic Irradiance

over a solid angle on the Earth

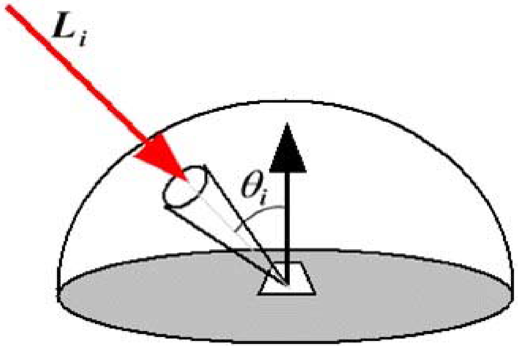
Radiance observed by satellite radiometer

is described by

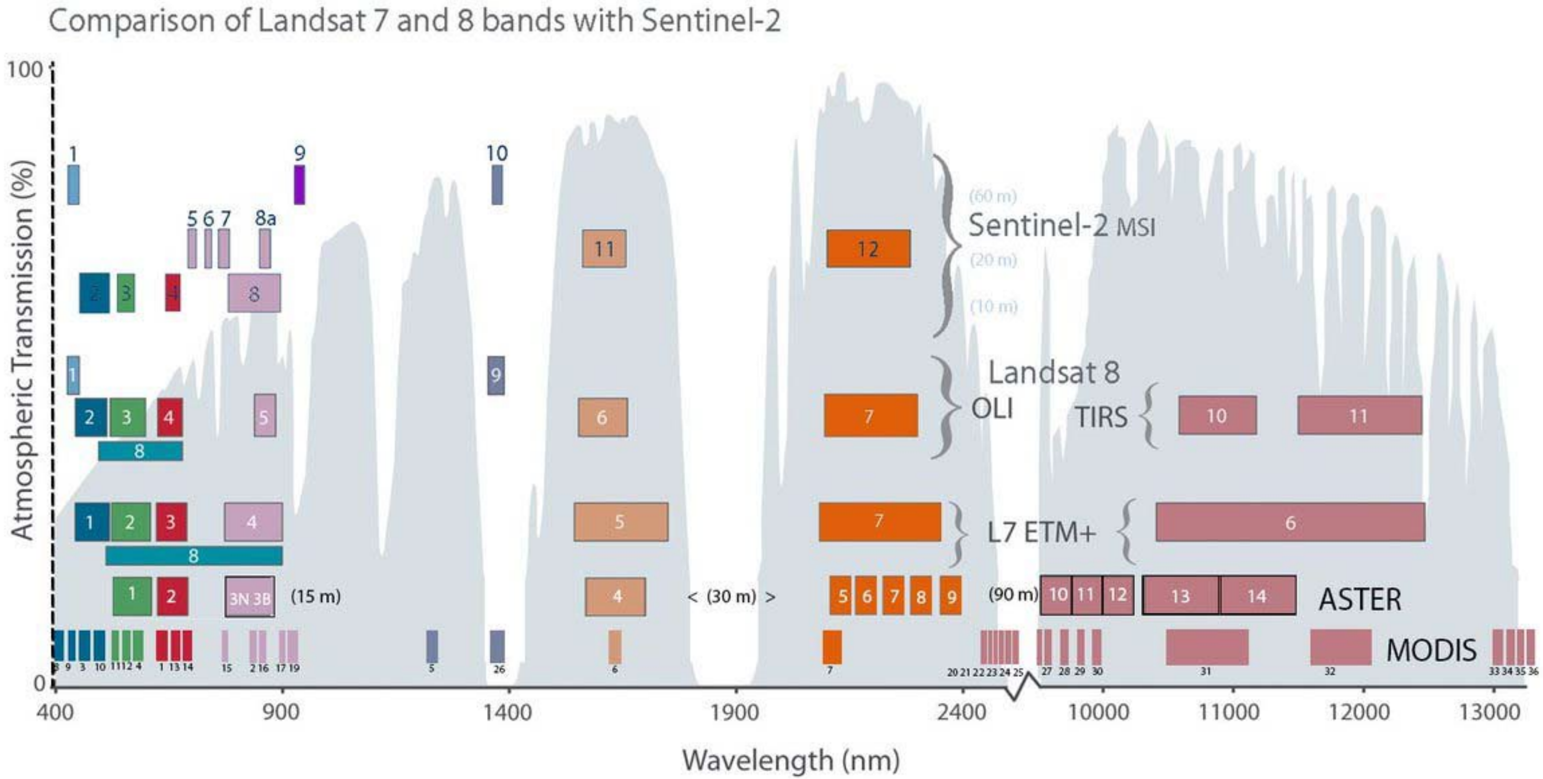
The Planck function

can be inverted to

Brightness temperature



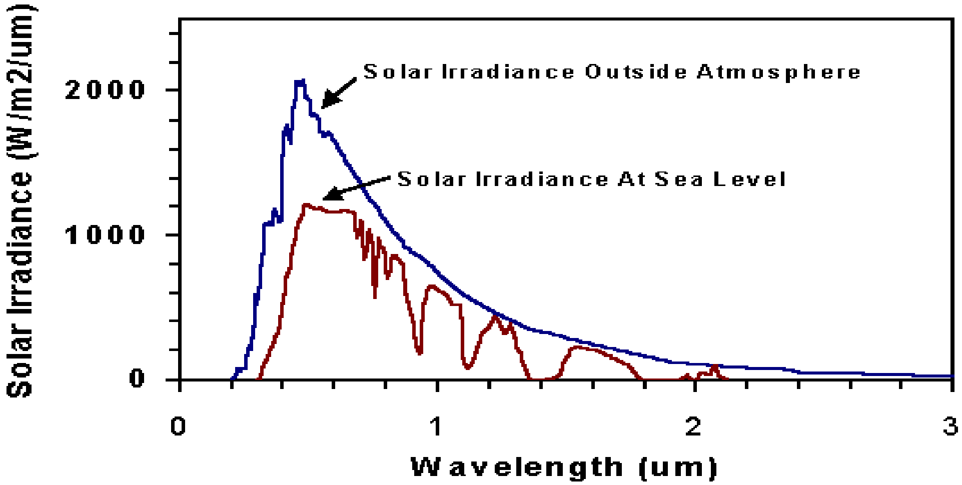
Spectral bands (wavelength) of some sensors

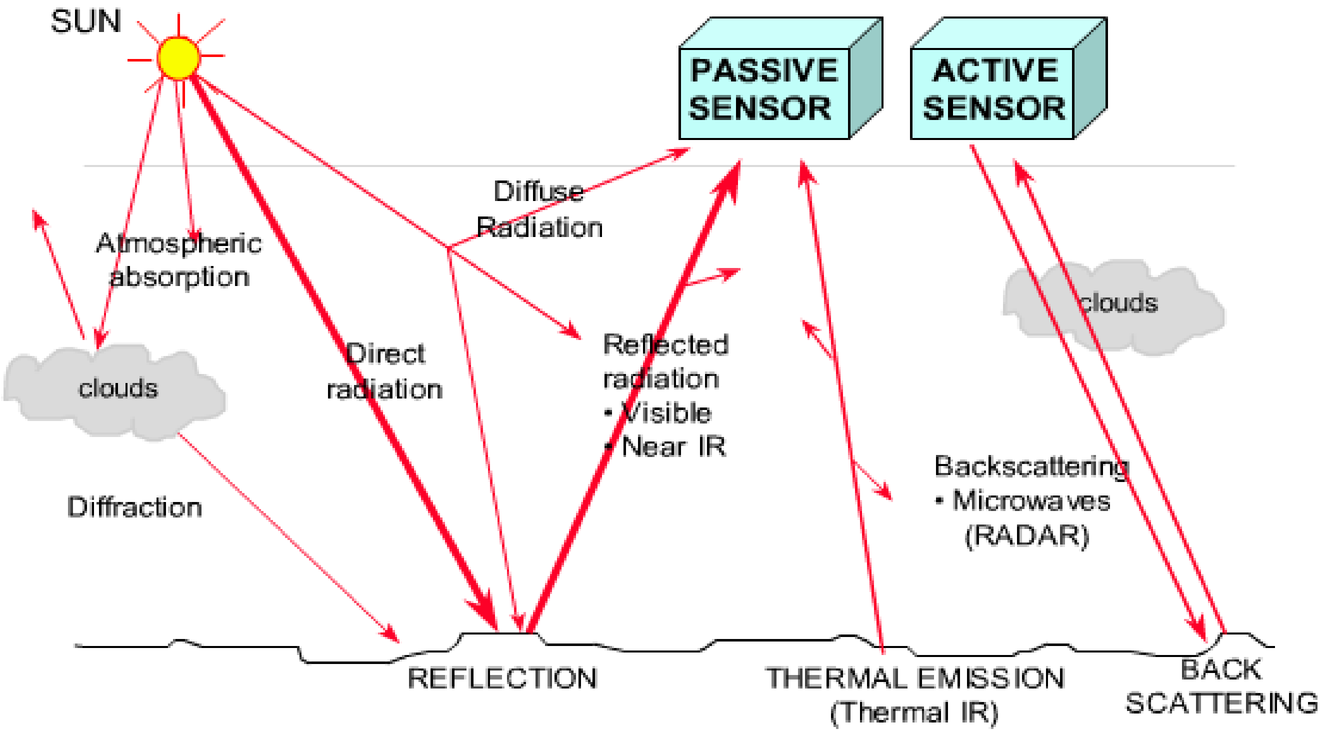


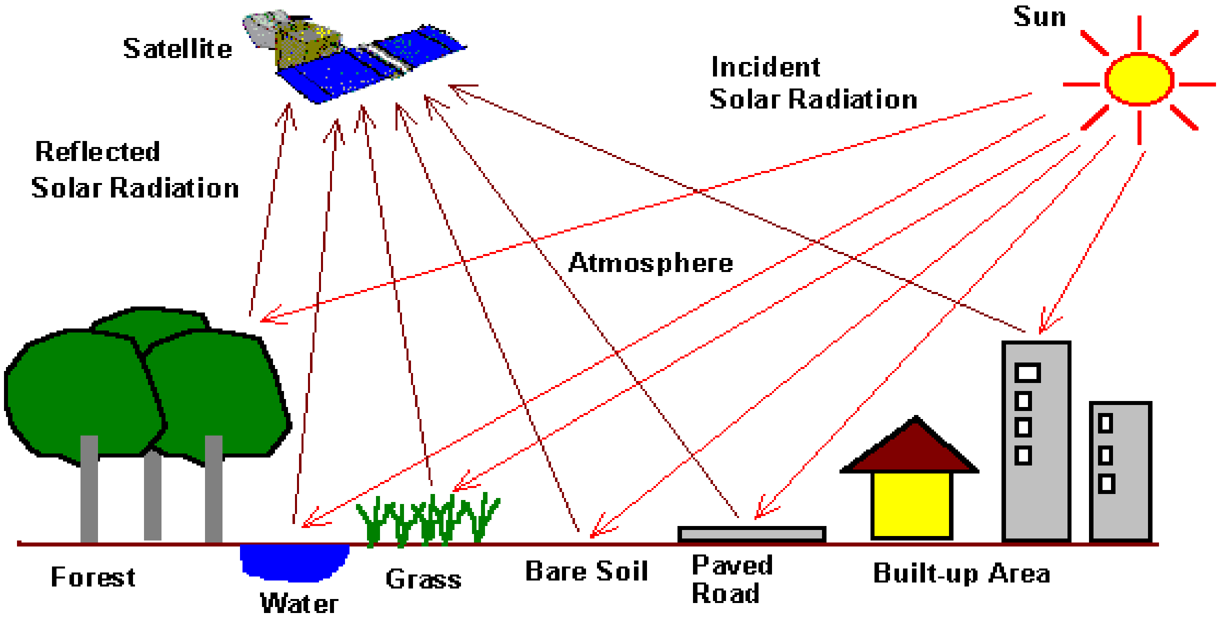
Solar Irradiation

Optical remote sensing utilizes the solar illumination. The solar irradiation spectrum above the atmosphere can be modeled by a black body radiation spectrum having a source temperature of 5900 K.

After passing through the atmosphere, the solar irradiation spectrum at the ground is modulated by the **atmospheric absorption windows.** Significant energy remains only within the wavelength range from about 0.25 to 3 μm.




SUN
PASSIVE SENSOR
ACTIVE SENSOR
Diffuse Radiation
Atmospheric absorption
clouds
Direct radiation
Reflected radiation
• Visible
• Near IR
clouds
Backscattering
• Microwaves (RADAR)
Diffraction
REFLECTION
THERMAL EMISSION (Thermal IR)
BACK SCATTERING



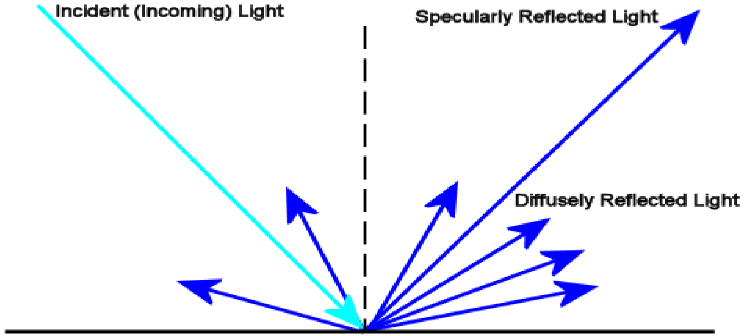
Optical remote sensing makes use of visible, near infrared and short-wave infrared sensors to form images of the earth's surface by detecting the solar radiation reflected from targets on the ground.

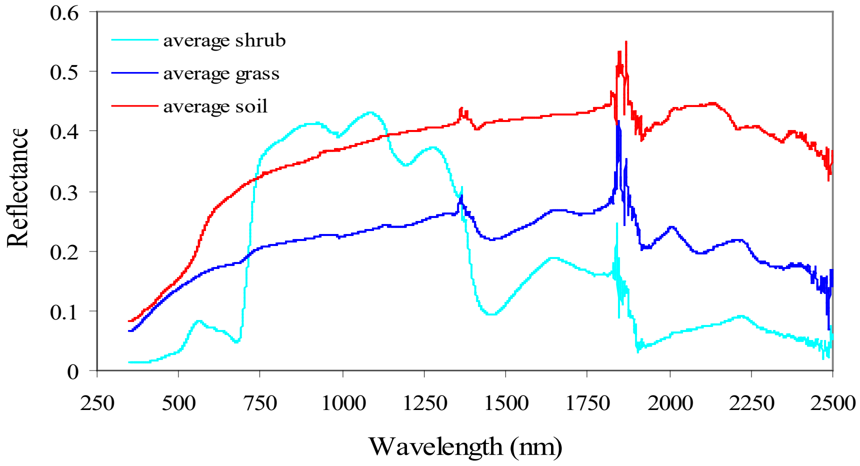
Spectral reflectivity and albedo

Spectral reflectivity is the percentage of radiation reflected by the object in a wavelength or spectral bands

Albedo is ratio of the amount of radiation reflected by a surface to the amount of incident radiation on the surface.

Albedo is reflectance integrated over the upper hemisphere (and over the optical wavelengths).

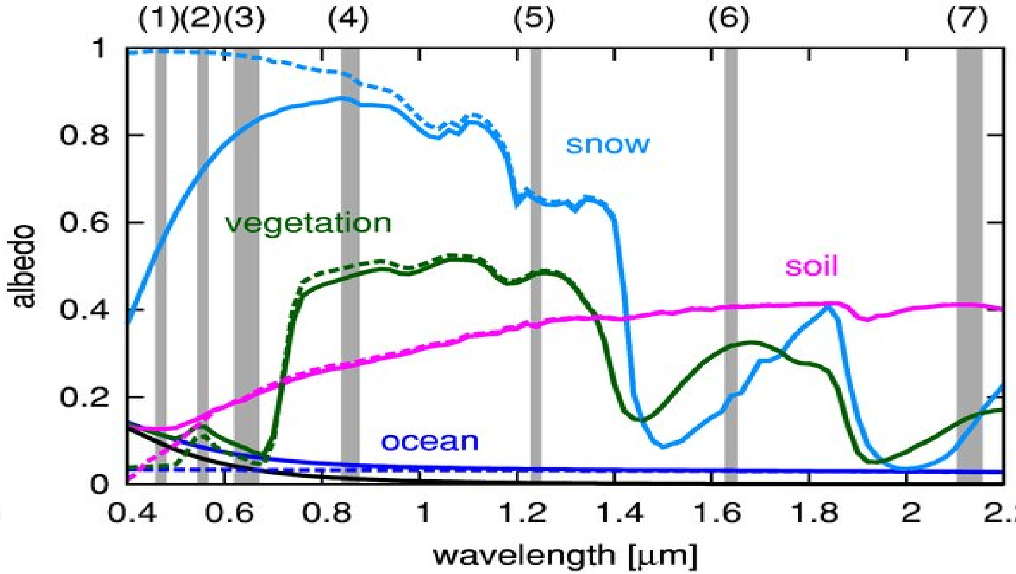




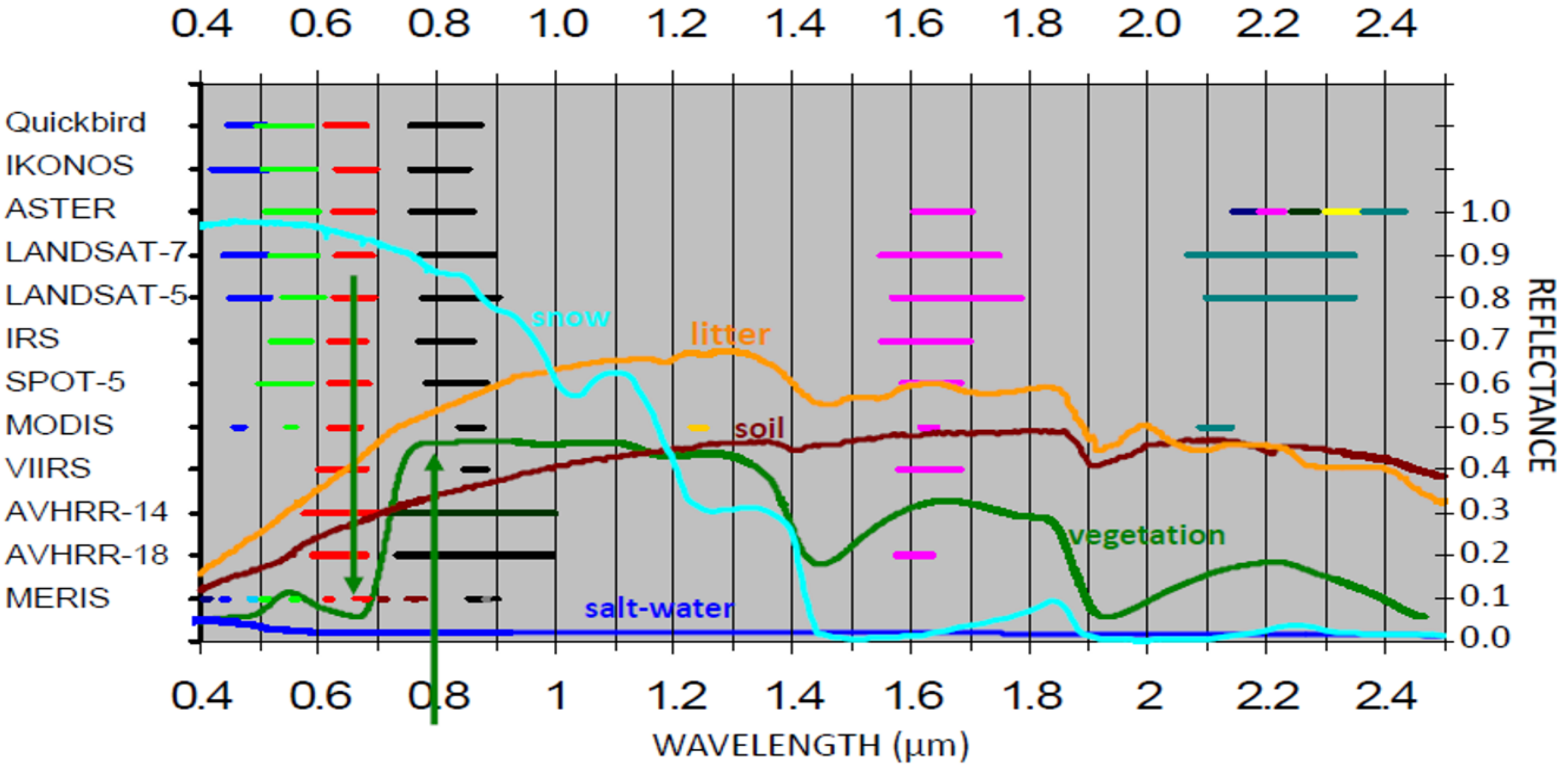
Reflectance spectrum

<u>Different materials reflect and absorb differently at different wavelengths</u>.

The reflectance spectrum of a material serves as a unique signature for the material. In principle, a material can be identified from its spectral reflectance signature if the sensing system has sufficient **spectral resolution** to distinguish its spectrum from those of other materials.



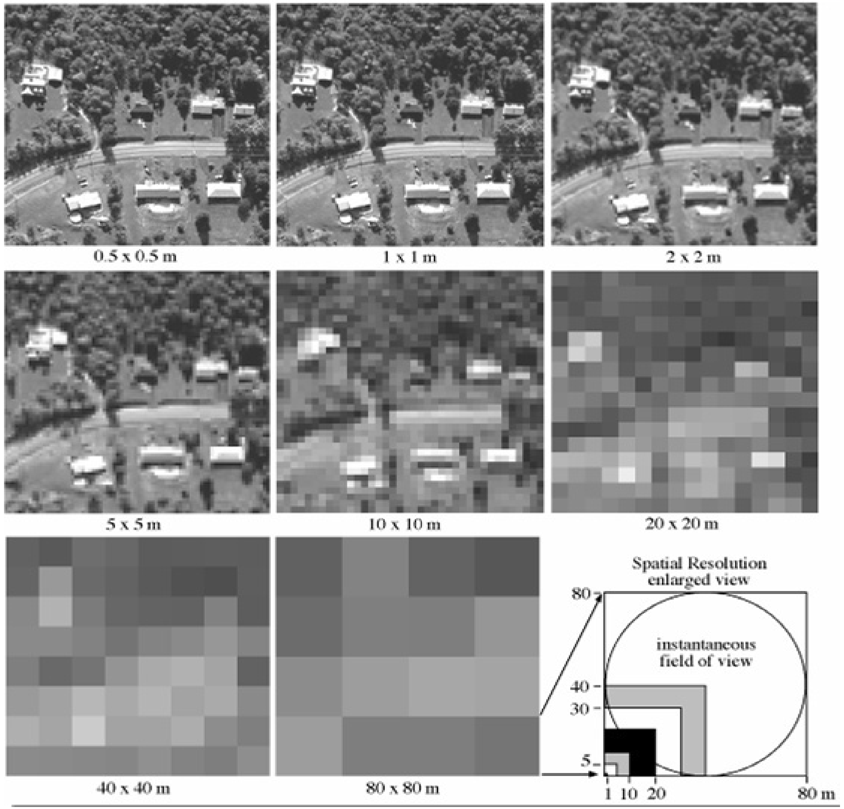
Some available optical sensors



Imaging aspects

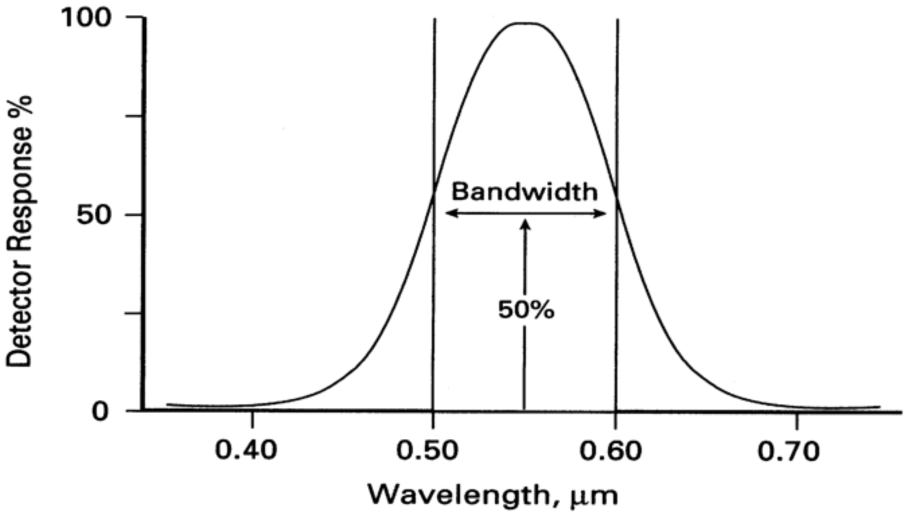
- Satellite Sensor
  - Spatial resolution
    - what size can we resolve
  - Spectral resolution
    - what wavelengths do we use
  - Temporal resolution
    - how often do we observe
  - Radiometric resolution
    - degree of detail observed

Different Spatial Resolution



Spectral resolution

Full width at half maximum (FWHM) is used to express detector function, given by the difference between the two extreme values of the independent variable at which the dependent variable is equal to **half** of its **maximum** value.



Spectral resolution, or bandwidth, of a detector, FWHM=0.10 μm

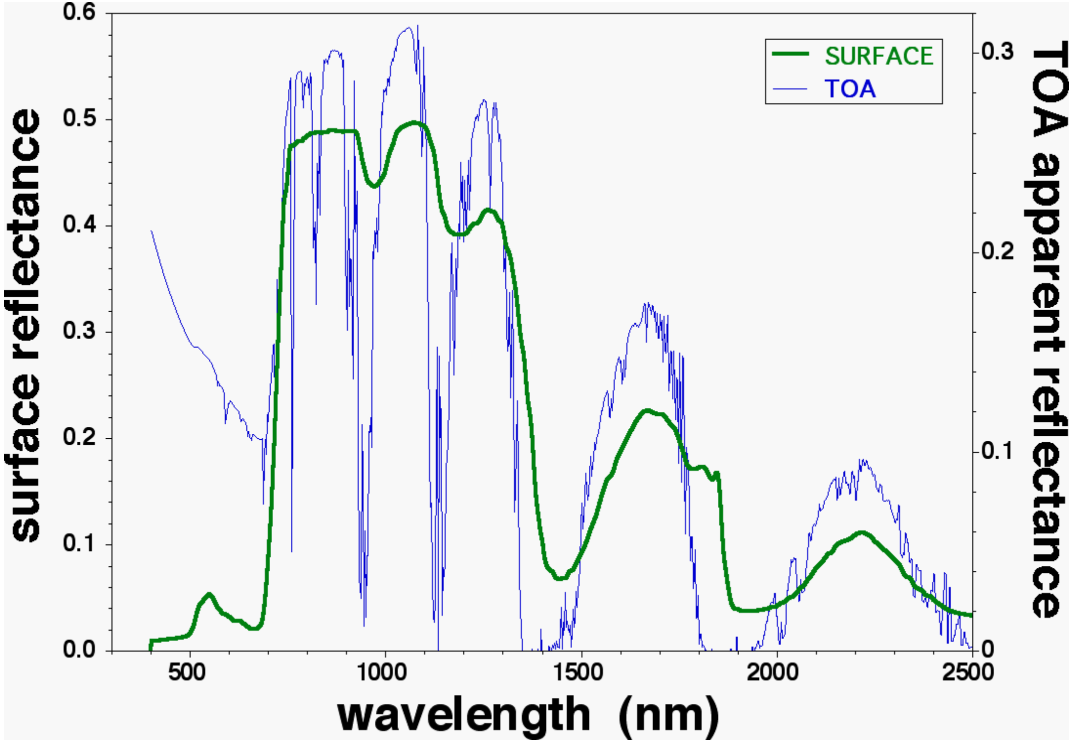
2-bit range
0 → 4

6-bit range
0 → 63

8-bit range
0 → 255

10-bit range
0 → 1023

FROM SATELLITE IMAGE TO IMAGE INFORMATION


surface reflectance
TOA apparent reflectance
wavelength (nm)
SURFACE
TOA
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.1
0.2
0.3
500
1000
1500
2000
2500

ATMOSPHERIC CORRECTION

From the sun to the Earth and then to the sensor, electromagnetic energy passes through the atmosphere twice.

Absorption reduces the intensity with a haziness effect. Scattering redirects EM energy in the atmosphere causing an adjacency effect where neighboring pixels are shared.

These two processes affect the quality of an image and are reasons for atmospheric correction.

Atmospheric correction removes the scattering and absorption effects from the atmosphere to obtain the surface reflectance (surface properties).

Atmospheric Correction Steps

DN (raw value from the sensor)

Convert DNs to radiance based on the rescaling factors provided in the metadata file

At-sensor radiance

Requires additional information: Earth-sun distance, solar zenith angle, exoatmospheric irradiance, often found in metadata

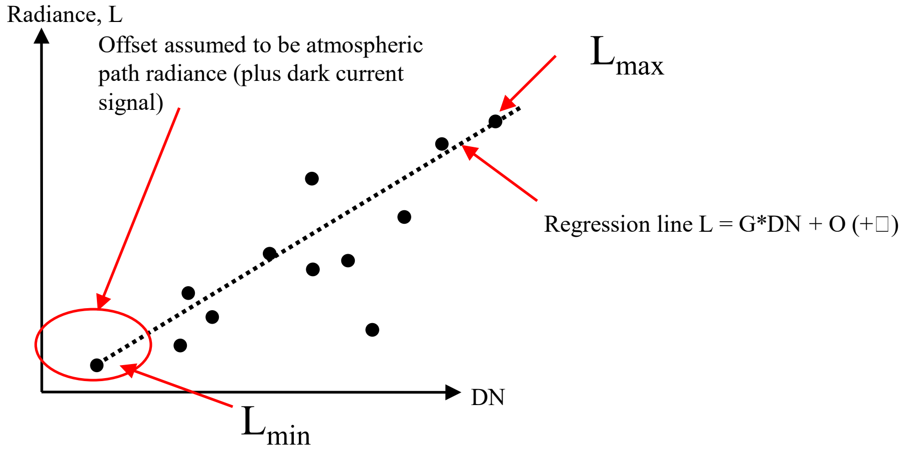
Top of the Atmosphere (TOA)

Requires knowledge of atmospheric conditions and aerosol properties at the time the image was acquired

Surface Reflectance

Simple methods

- e.g. empirical line correction (ELC) method
- Use target of "known", low and high reflectance targets in one channel e.g. dense dark vegetation & snow
- Assuming linear detector response, radiance L = gain * DN + offset
- e.g. $L = DN(L_{max} - L_{min})/255 + L_{min}$



Atmospheric Correction

$$L_{tot} = \frac{\rho E T}{\pi} + L_p$$

$$\rho = \frac{\left(L_{tot} - L_p\right)\cdot \pi}{ET}$$

L_{tot} = radiance measured by the sensor

ρ = reflectance of the target

E = irradiance on the target

T = transmissivity of the atmosphere

L_p = path radiance (radiance due to the atmosphere)

Atmospheric RTMs

simulate the radiative transfer interactions of light scattering and absorption in the atmosphere.
Used for the atmospheric correction of airborne/satellite data and allow retrieving atmospheric composition.

Some RTMs:

- MODTRAN (MODerate resolution atmospheric TRANsmission)
- 6S (Second Simulation of the Satellite Signal in the Solar Spectrum)
- OPAC (Optical Properties of Aerosols and Clouds)

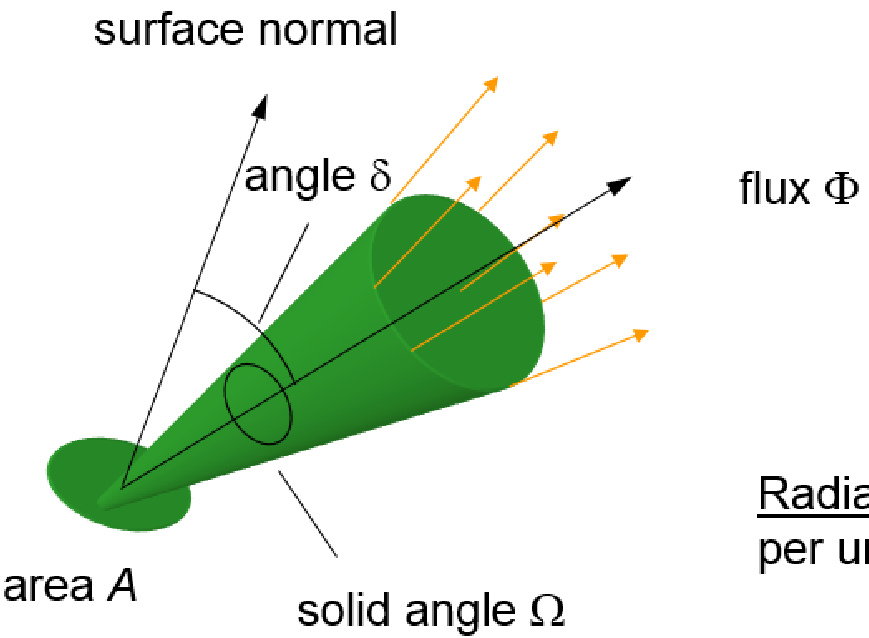
https://artmotoolbox.com/radiative-transfer-models.html

Land radiative transfer modeling

Radiative transfer modeling

- Some radiative transfer basics
- 4-stream modelling
- Particular models: SAIL, SLC, 4SAIL, SCOPE

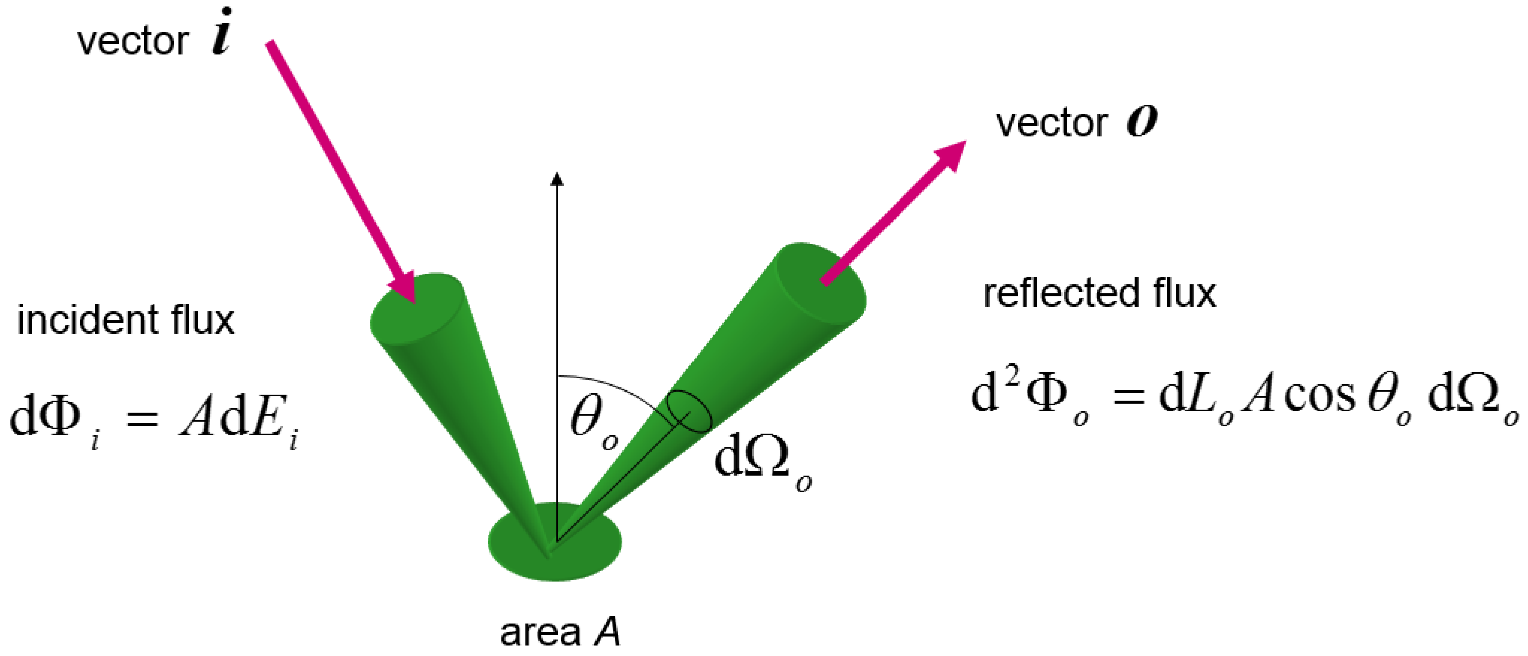
Flux from a surface in a given direction



Radiance = flux per unit projected area and per unit solid angle

$$L = \frac{\Phi}{A \cos \delta \, \Omega}$$, unit = W / m² sr, differential form $$L = \frac{d^2\Phi}{dA \cos \delta \, d\Omega}$$

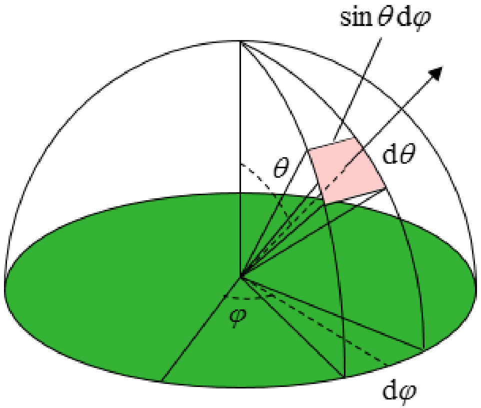
Bi-directional reflection



Bi-directional reflectance distribution function BRDF, from $dL_o = \rho' dE_i$

Unit of BRDF (ρ') = sr $^{-1}$

Hemispherical integral



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

$$\int_{2\pi} \cos\theta \, d\Omega = \int_0^{2\pi} \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta \, d\varphi = 2\pi \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = 2\pi \times \tfrac{1}{2} \sin^2\theta \Big|_0^1 = \pi$$

Irradiance from a uniform sky (L_{sky} = constant): $E_i = \pi L_{sky}$

Perfect (white) Lambertian reflector:

- radiance is constant (independent of viewing angle); this implies a constant BRDF (ρ')

- total (hemispherical) reflected flux = incident flux

Total reflected flux for Lambertian surface:

$$\mathrm{d}\Phi_o = \int_{2\pi} \rho' \,\mathrm{d}E_i A \cos\theta_o \,\mathrm{d}\Omega_o = \pi\rho' \,\mathrm{d}\Phi_i$$

so this implies that $\rho' = \pi^{-1}$ for perfect Lambertian surface

By convention, we write $\mu = \cos\theta$, $\mu_o = \cos\theta_o$, etc.

Special cases of directional reflectance factors

1. Bi-directional reflectance factor (BRF) = directional reflectance factor for specular (solar) incidence, symbol r_{so}

2. Hemispherical-directional reflectance factor (HDRF) = directional reflectance for diffuse incident flux, symbol r_{do}

Relations with BRDF:

$$r_{so}(\boldsymbol{s},\boldsymbol{o}) = \pi\rho'(\boldsymbol{s},\boldsymbol{o}) \qquad r_{do}(\boldsymbol{o}) = \int_{2\pi} \rho'(\boldsymbol{i},\boldsymbol{o})\mu_i \mathrm{d}\Omega_i$$

Special cases of hemispherical reflectance factors

1. Directional-hemispherical reflectance factor (DHRF) = hemispherical reflectance for specular (solar) incidence, sometimes called “black sky albedo”, symbol r_{sd}

2. Bi-hemispherical reflectance factor (BHRF) = hemispherical reflectance for diffuse incident flux, sometimes called “white sky albedo”, symbol r_{dd}

Relations with BRDF:

$$r_{sd}(\boldsymbol{s}) = \int_{2\pi} \rho'(\boldsymbol{s},\boldsymbol{o})\mu_o \mathrm{d}\Omega_o \qquad r_{dd} = \pi^{-1} \int_{2\pi}\int_{2\pi} \rho'(\boldsymbol{i},\boldsymbol{o})\mu_i \mathrm{d}\Omega_i \mu_o \mathrm{d}\Omega_o$$

Four-stream approximations of surface reflectance

- assume that fluxes are either specular or perfectly diffuse (uniform by hemisphere)

$$r_o = \frac{r_{so} E_{\mathrm{sun}} + r_{do} E_{\mathrm{sky}}}{E_{\mathrm{sun}} + E_{\mathrm{sky}}}$$

directional reflectance factor DRF

$$r_d = \frac{r_{sd} E_{\mathrm{sun}} + r_{dd} E_{\mathrm{sky}}}{E_{\mathrm{sun}} + E_{\mathrm{sky}}}$$

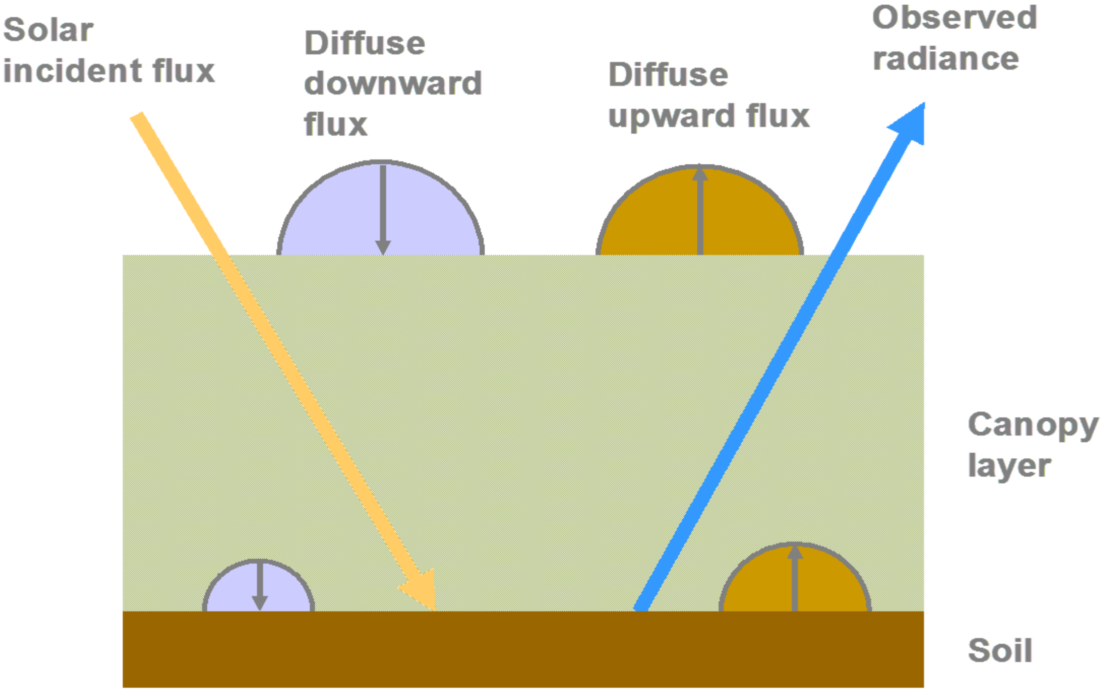
hemispherical reflectance factor HRF
(spectral albedo)

SAIL model

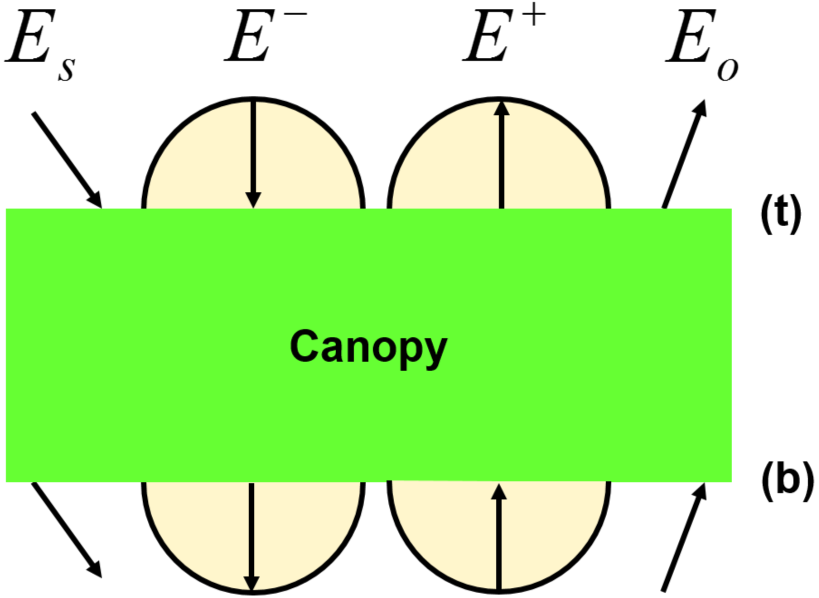
- scattering from arbitrarily inclined leaves
- canopy reflectance model (1981)
- refinement of Suits model (H and V leaves)
- solved by boundary condition method
- parameters $\rho, \tau, r_s, \mathrm{LAI}, \mathrm{LIDF}, \theta_s, \theta_o, \psi, f_{\mathrm{sky}}$

Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote sensing of environment*, *16*(2), 125-141.

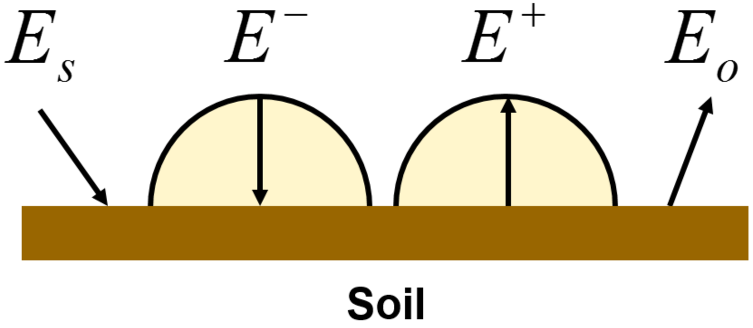
4-STREAM RADIATIVE TRANSFER



Adding canopy and soil



Adding mechanism



$$E_s(\mathrm{b}) = \tau_{ss} E_s(\mathrm{t})$$

$$E^-(\mathrm{b}) = \tau_{sd} E_s(\mathrm{t}) + \tau_{dd} E^-(\mathrm{t}) + \rho_{dd} E^+(\mathrm{b})$$

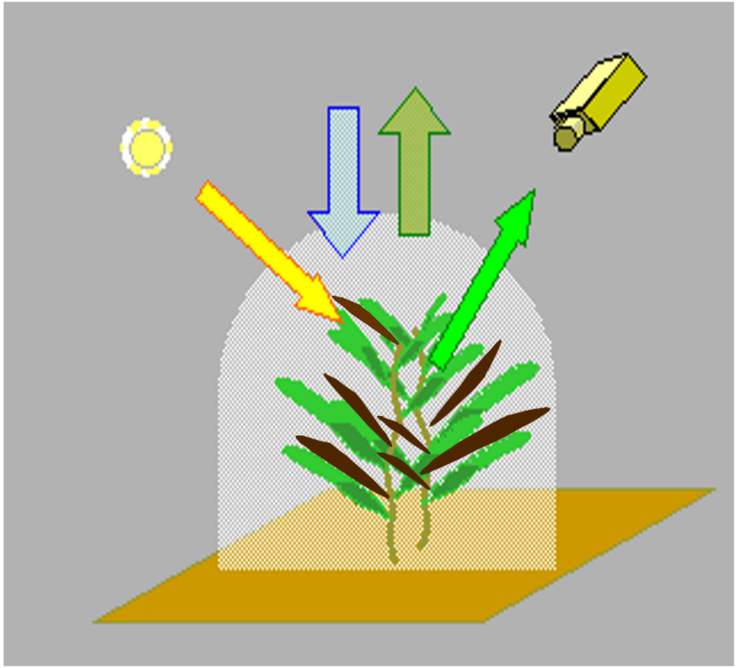
$$E^+(\mathrm{t}) = \rho_{sd} E_s(\mathrm{t}) + \rho_{dd} E^-(\mathrm{t}) + \tau_{dd} E^+(\mathrm{b})$$

$$E_o(\mathrm{t}) = \rho_{so} E_s(\mathrm{t}) + \rho_{do} E^-(\mathrm{t}) + \tau_{do} E^+(\mathrm{b}) + \tau_{oo} E_o(\mathrm{b})$$

$$E^+(\mathrm{b}) = r_{sd} E_s(\mathrm{b}) + r_{dd} E^-(\mathrm{b})$$

$$E_o(\mathrm{b}) = r_{so} E_s(\mathrm{b}) + r_{do} E^-(\mathrm{b})$$

SOIL-LEAF-CANOPY MODEL (SLC)



Dry soil reflectance spectrum
Soil moisture SM
Soil BRDF Parameters (b, c, B0, h)

soil

Chlorophyll Cab
Water Cw
Dry matter Cdm
Senescent material Cs
Mesophyll structure N

green
leaves
brown

Leaf Area Index LAI
LIDF leaf slope parameter a
LIDF bimodality parameter b
Hot spot parameter hot
Fraction brown leaf area fB
Layer dissociation factor D
Crown coverage Cv
Tree shape factor zeta

canopy

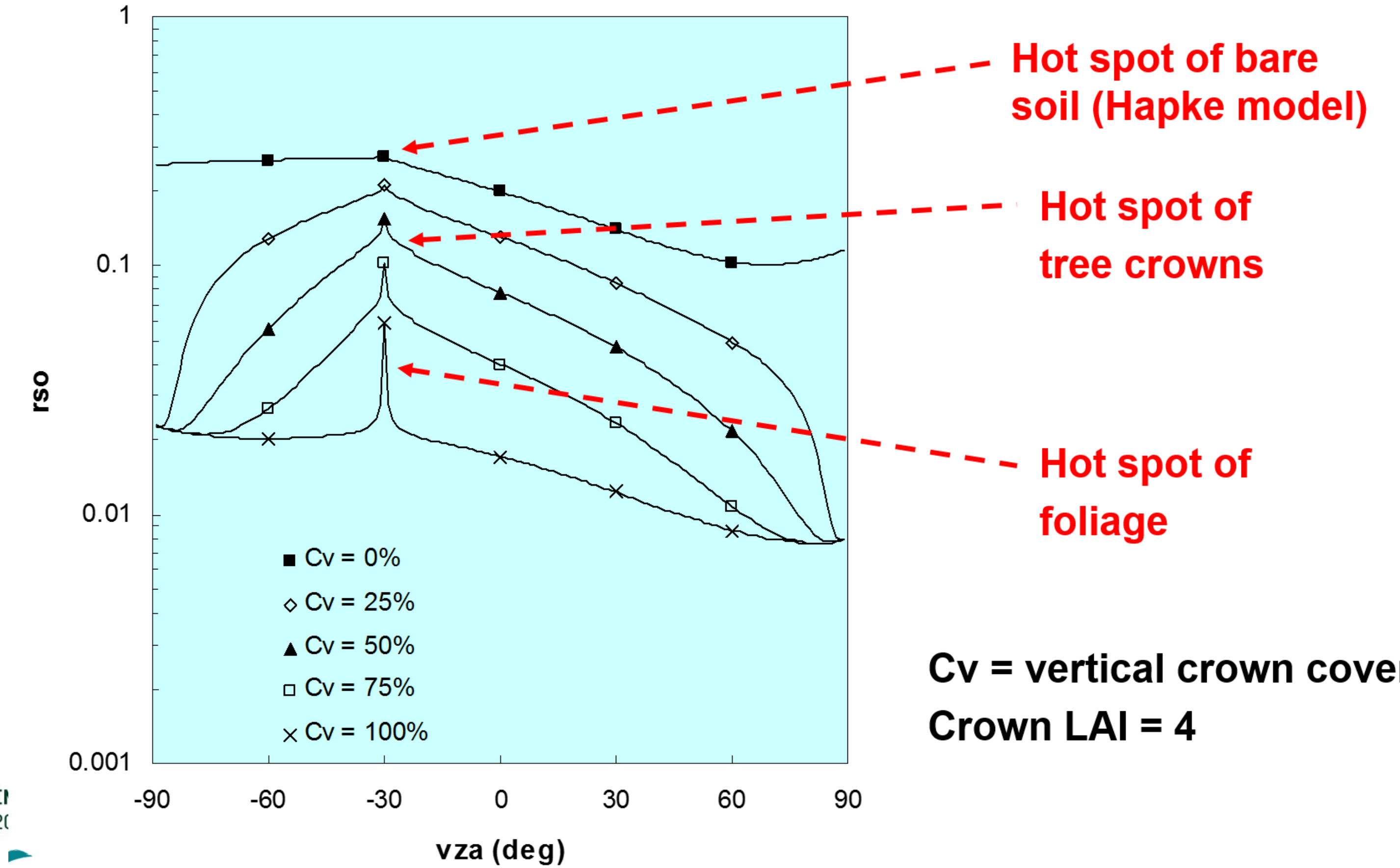
Fluxes considered

1. Direct solar flux
2. Diffuse downward flux
3. Diffuse upward flux
4. Direct observed flux (radiance)

Solar zenith angle sza
Viewing zenith angle vza
Relative azimuth angle raa

sun-observer
geometry

BRDFs in the principal plane simulated with SLC (3 hot spots)



Cv = vertical crown cover %

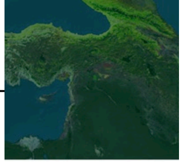
Crown LAI = 4

4SAIL MODEL

- Modernized version of SAIL
- Speed-optimized
- Numerically robust
- Single homogeneous layer of leaves
- Supports thermal infrared applications
- Directional emissivity and brightness temperature
- Differentiation of leaves and soil in the sun and the shade

Verhoef, W., Jia, L., Xiao, Q., & Su, Z. (2007). Unified optical-thermal four-stream radiative transfer theory for homogeneous vegetation canopies. *IEEE Transactions on Geoscience and Remote Sensing*, *45*(6), 1808-1822.

4SAIL MODEL



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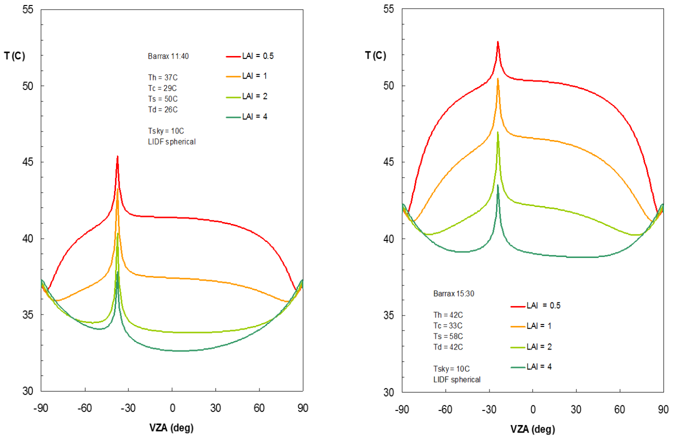
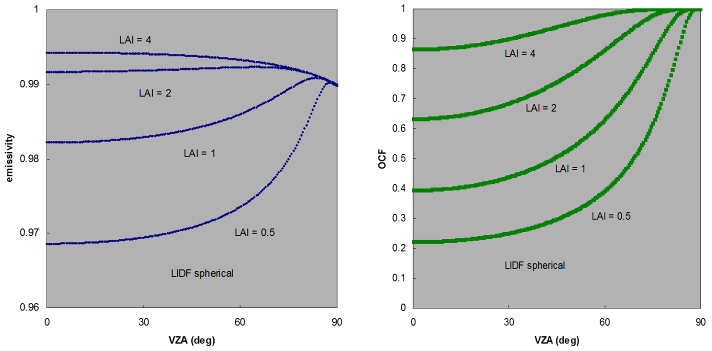
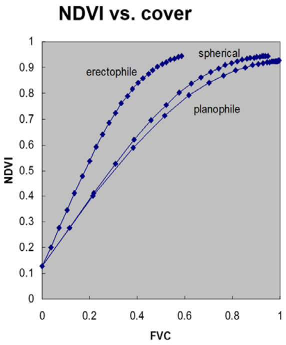
SIMULATED BRIGHTNESS TEMPERATURE ANGULAR PROFILES IN THE PRINCIPAL PLANE

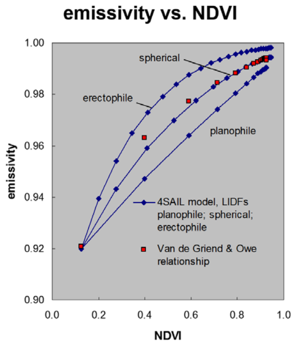


DIRECTIONAL EMISSIVITY AND OBSERVED COVER FRACTION (OCF) VS. VIEWING ZENITH ANGLE

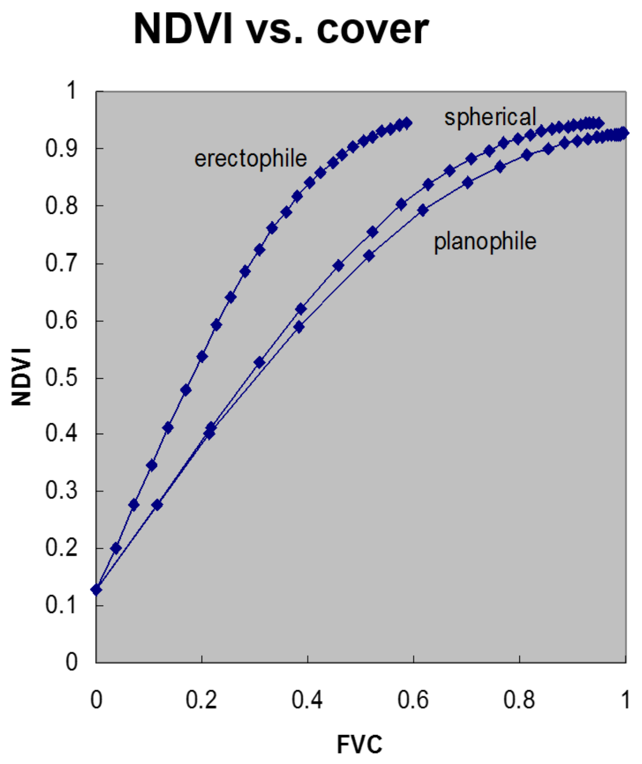


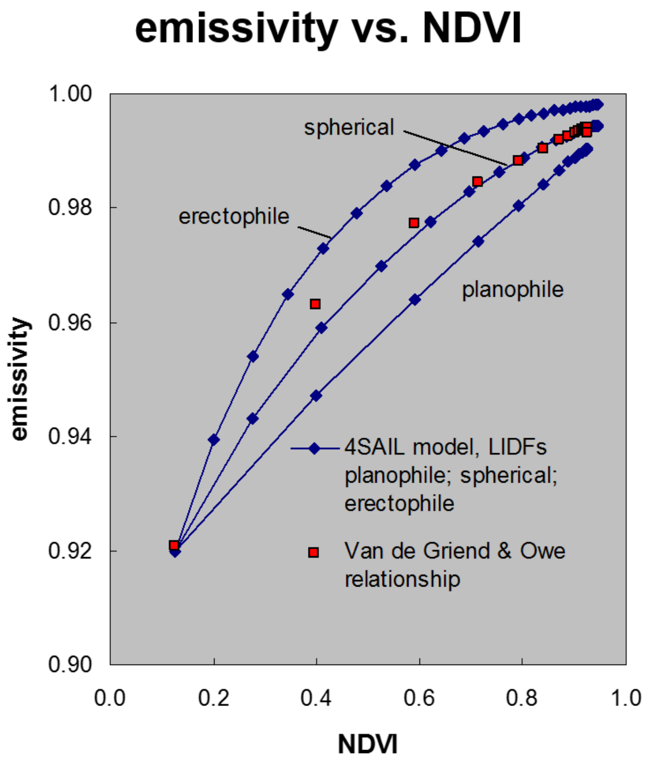
RELATIONS WITH NDVI





RELATIONS WITH NDVI



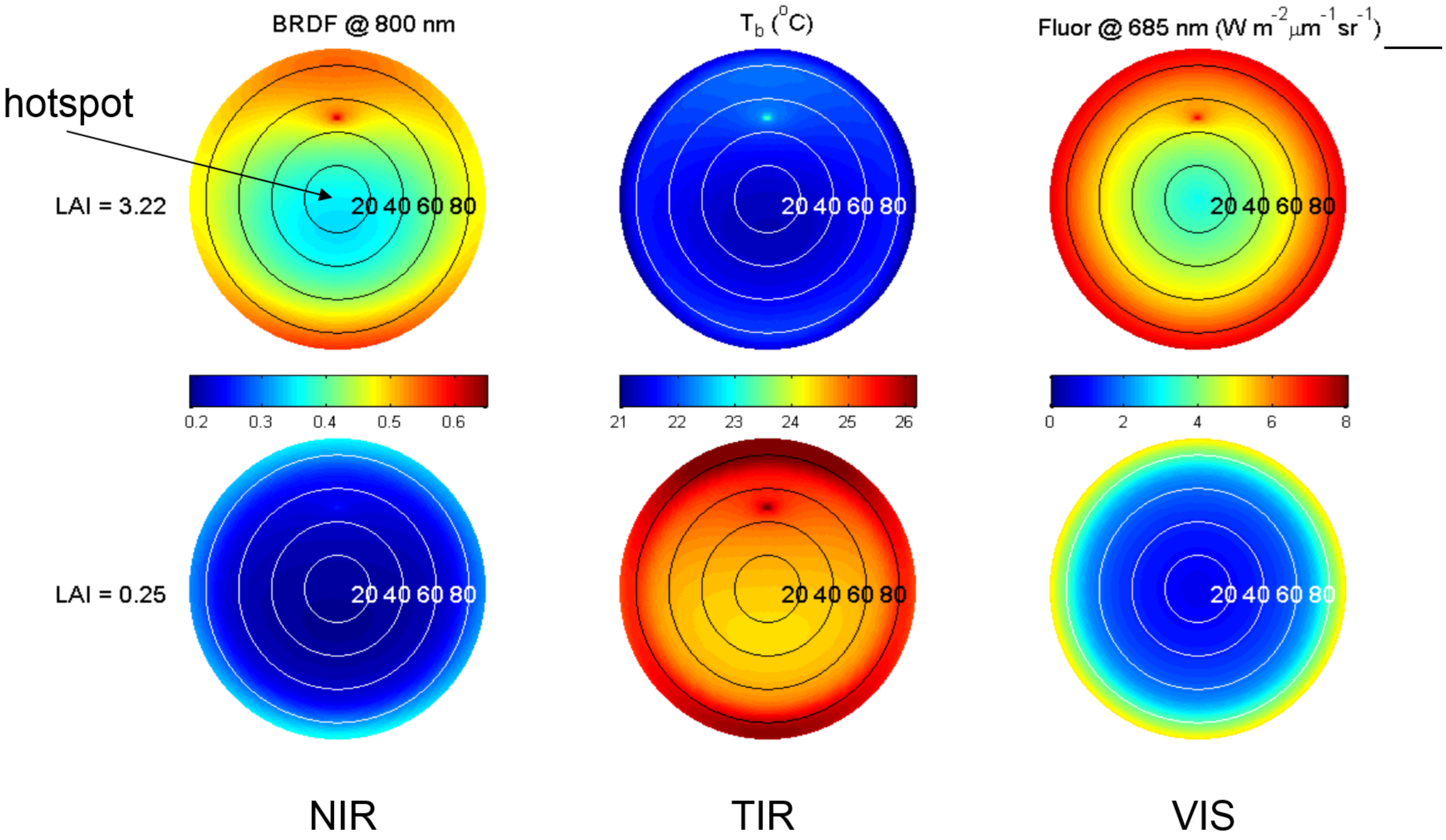


SCOPE MODEL

- Soil-Canopy spectral Observations, Photosynthesis and Energy balance model
- Numerical model uses the energy balance at leaf level as a function of its orientation and depth
- Output: leaf temperatures, fluorescence, photosynthesis, and directional observed radiances
- Available in Matlab code

Tol, C., Verhoef, W., Timmermans, J., Verhoef, A., & Su, Z. (2009). An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy balance. *Biogeosciences*, *6*(12), 3109-3129.

Hemispheric directional plots from SCOPE model



Radiative transfer modeling

SCOPE - Simulation model for radiative transfer, photosynthesis and energy fluxes in vegetation and soil
https://github.com/Christiaanvandertol/SCOPE

Automated Radiative Transfer Models Operator (**ARTMO**)
Graphic User Interface (GUI)
https://artmotoolbox.com/

2SeaColor - Two-stream remote sensing model for water quality mapping:
https://github.com/suhybsalama/2SeaColor

Optical imaging and applications

- **Agriculture**: Gathering crop statistics and yield assessments
- **Urban**: Planning city-wide infrastructure improvements
- **Forests**: Checking de- or re-forested areas for treaty purposes
- **Biodiversity**: Understanding the habitats where wildlife exist
- **Health**: Tracking conditions associated disease spread
- **Water**: Evaluating water body extents for flood assessments
- **Disaster**: Making damage maps following major earthquakes
- **Cryosphere**: Mapping snow fields and glacier melting

Sentinel-2 in a nutshell

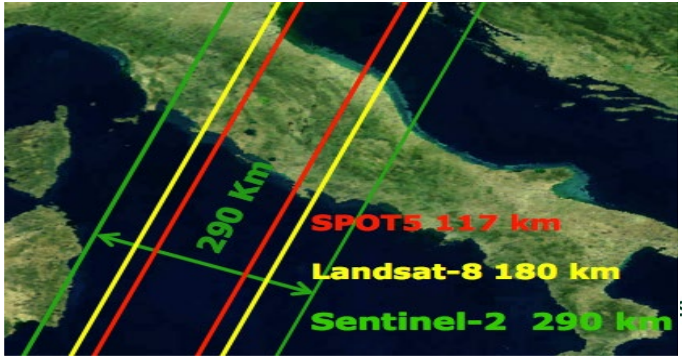
13 VIS/NIR/SWIR spectral bands: 3 bands in the red edge tailored to vegetation monitoring

Spatial resolution: 10m / 20m (60 m for atmosphere calibration)

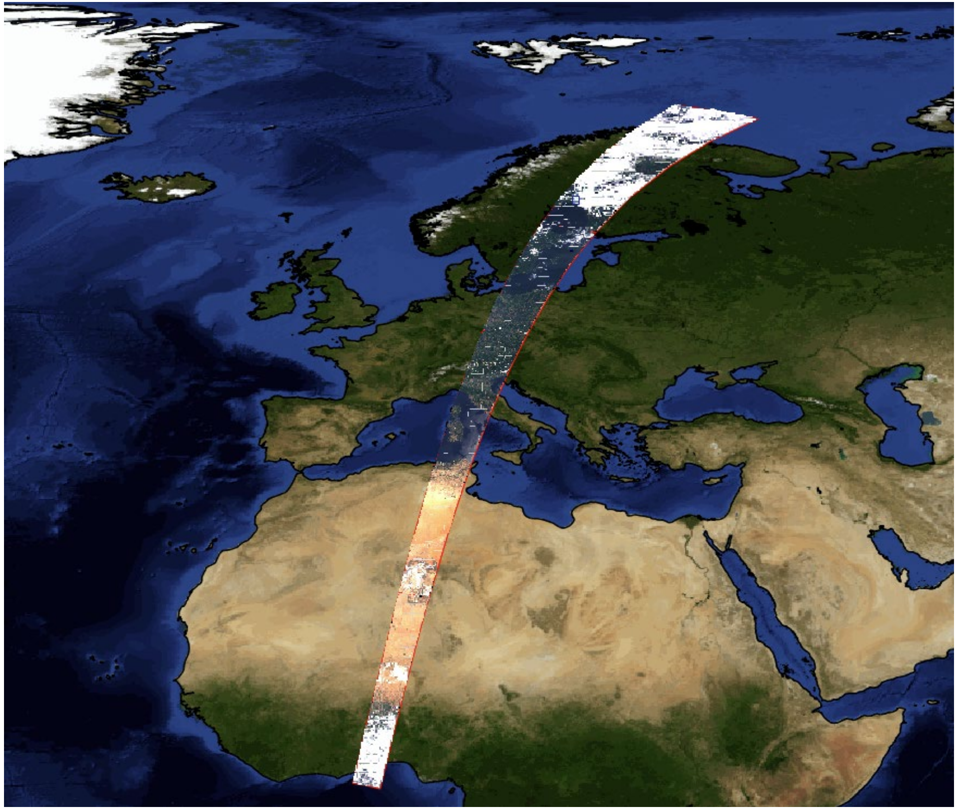
Swath: 290 km

2 spacecraft on same orbit, 180° apart: 5 days revisit at equator

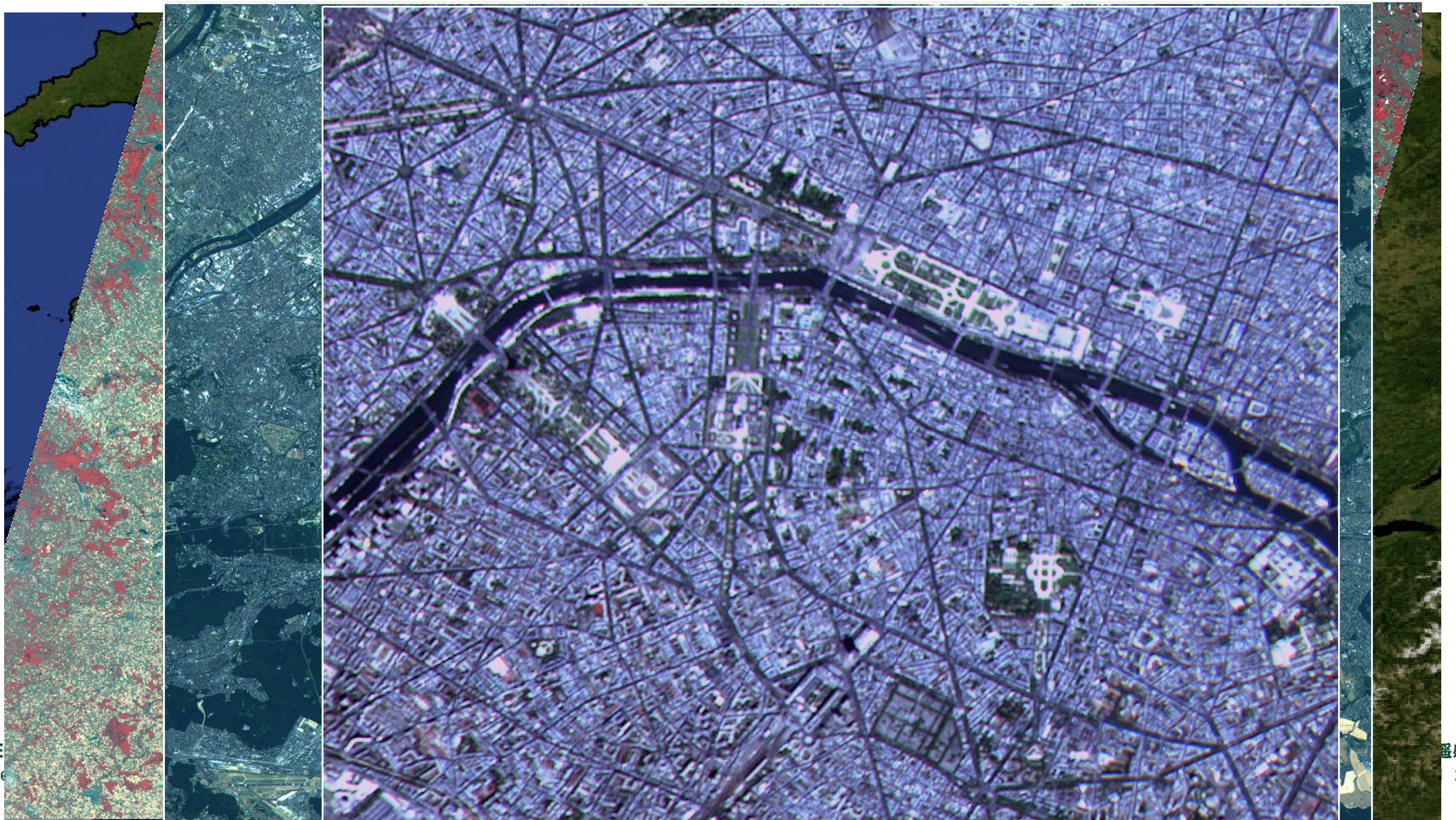
Systematic coverage between 84°N and 56°S



SENSING

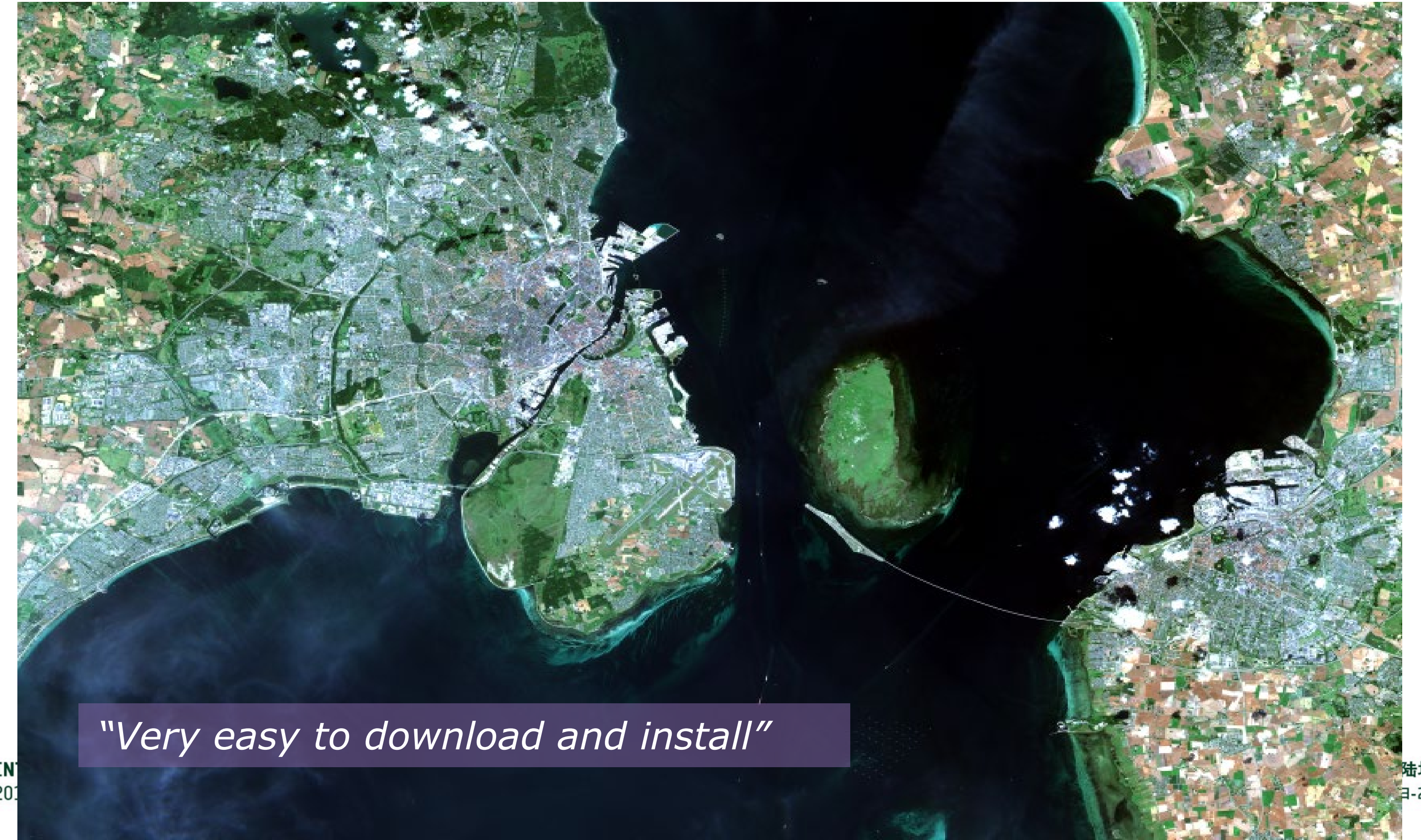


Paris!



Sentinel 2

Copenhagen (Denmark) - Natural Colour (10m)



"Very easy to download and install"

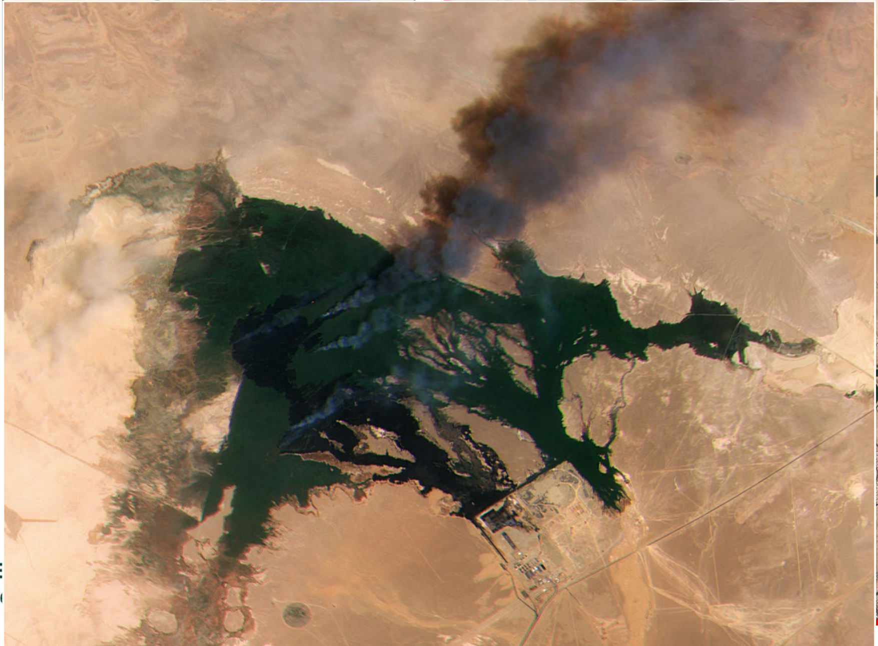
Sentinel 2

Nador (Morocco) - False Colour (10m)

Sentinel 2

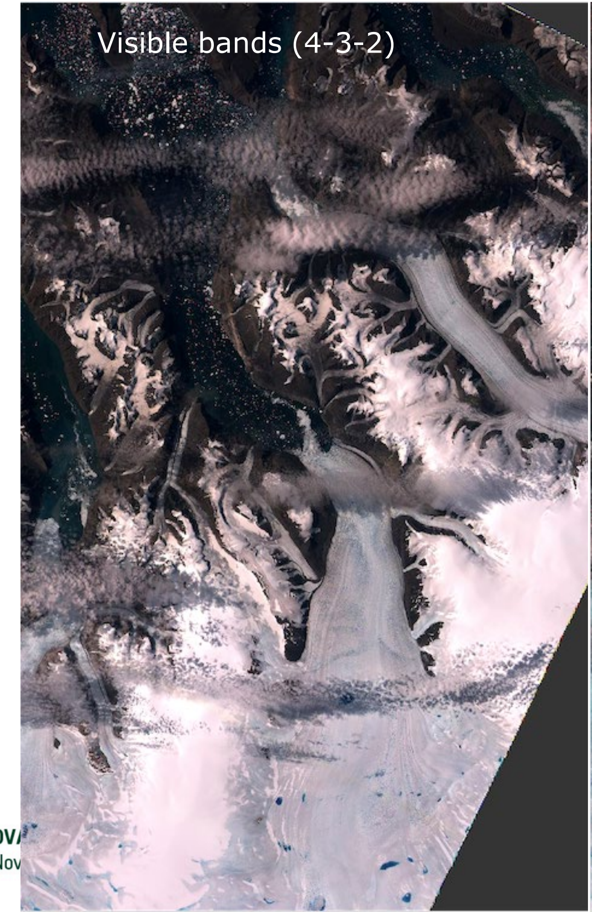
Pavia (Italy) - 'Red Edge' False Colour (20m)

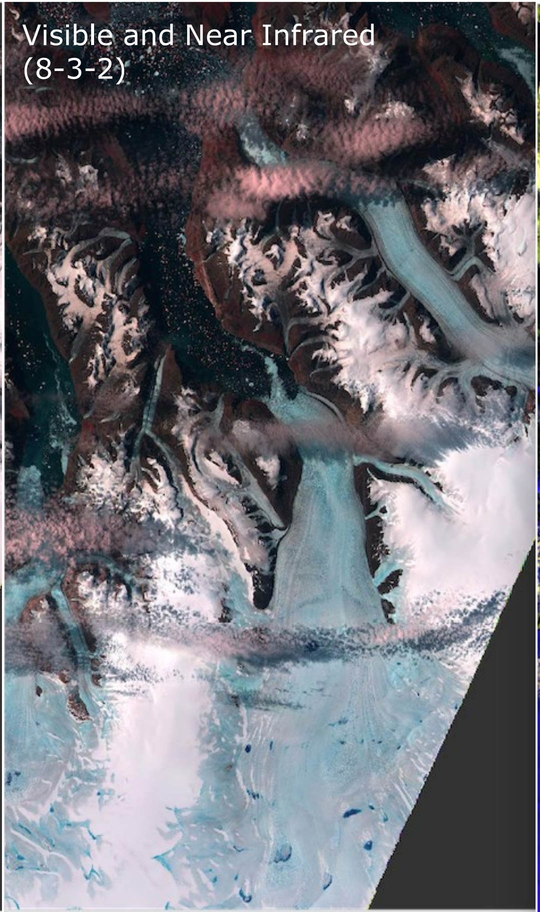
Irrigation and fires
in Tabuk, Saudi Arabia

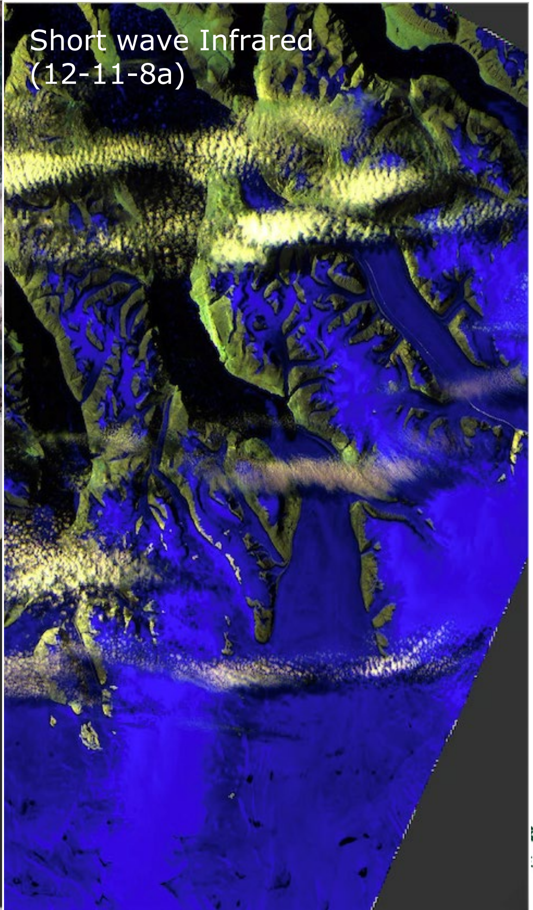


Urban Infrastructure and Motion in Venice/Italy

Greenland: Disko Bay
13 Spectral bands make the difference



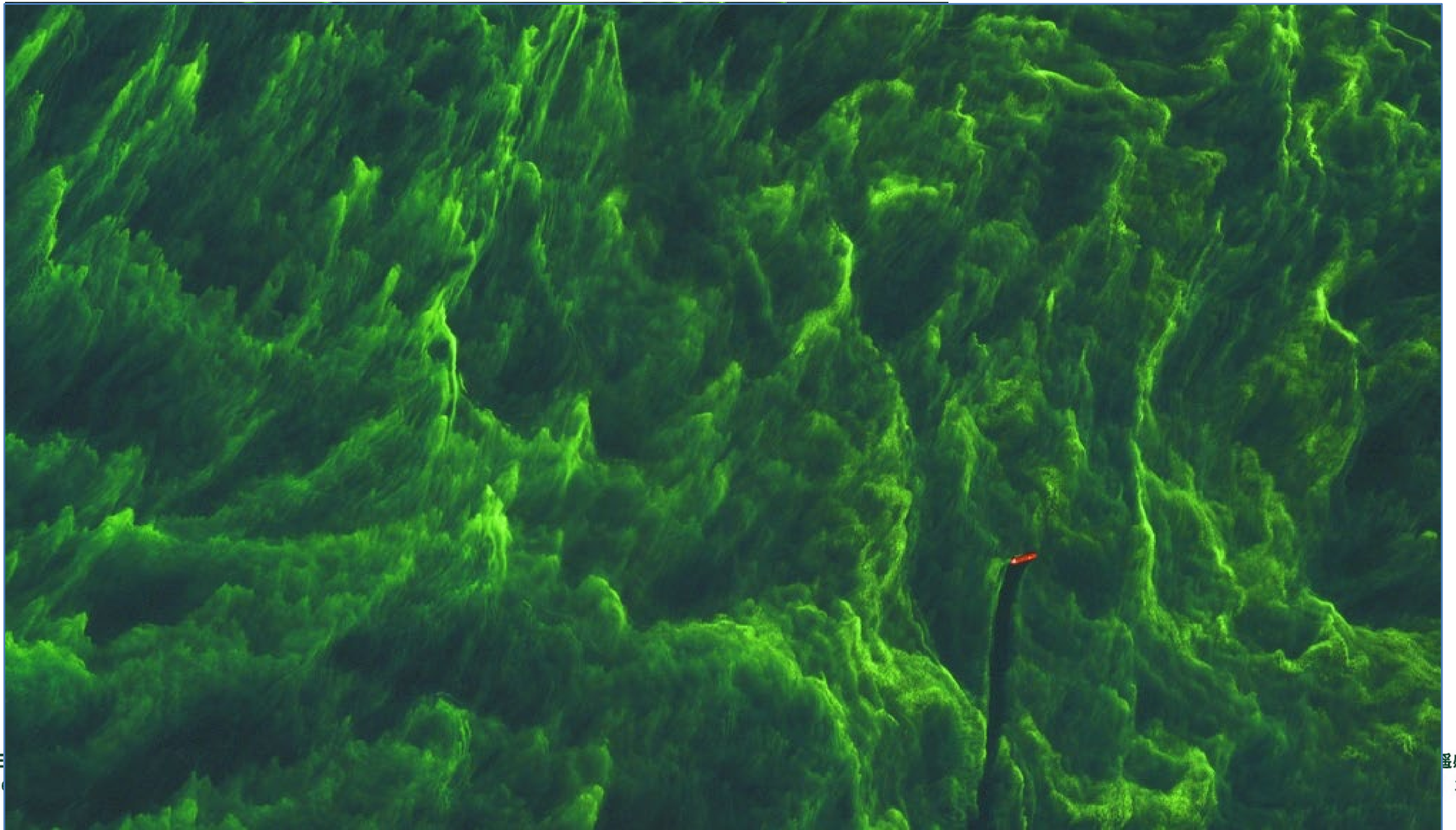


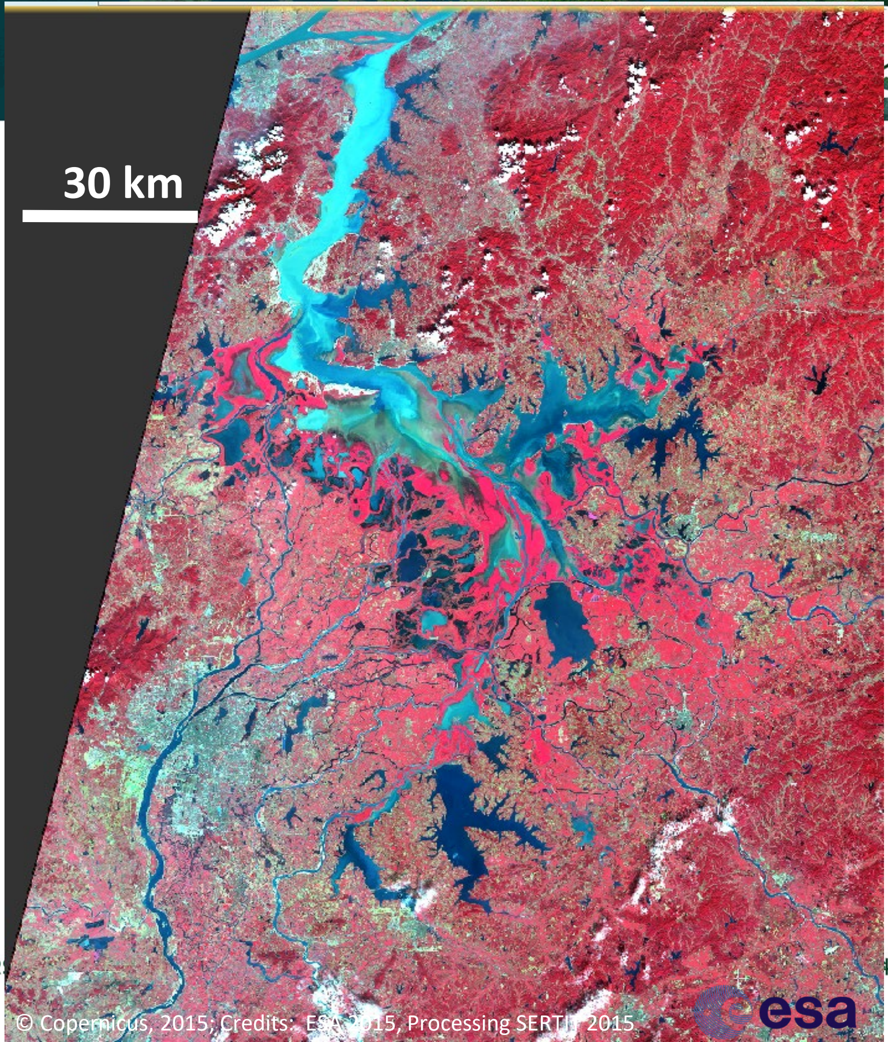


Sentinel-2 Western Greenland glaciers

Baja California: dry land vs irrigated land (NIR-VIS),
land discharge (red-edge) along a border

Stunning details: fronts and filaments of ocean biogeochemistry slashed open by shiptracks, wind blown structures…





Sentinel2

2015-10-20

10 m

15 km
Sentinel2
2015-10-20
10 m
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15 km
Sentinel2
2015-10-20
10 m
Thank you for your attention
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esa