   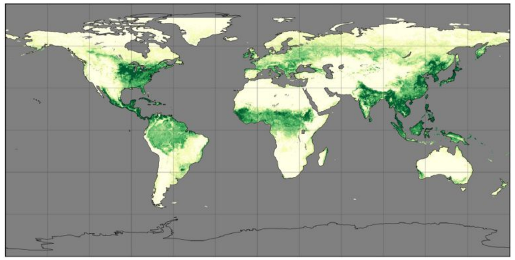

EARTH OBSERVATION – SATELLITES

AERO0025-1 SATELLITE ENGINEERING

Prof. François JONARD

September 28, 2022

LIÈGE université

General information

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- SPHERES Research Unit
- Faculty of Sciences

LIÈGE université
Geomatics

Introduction

Earth Observation - Remote Sensing

Acquisition of information about an object without being in physical contact with it

Information is acquired by detecting and measuring changes/perturbations imposed by an object on the surrounding field, be it an electromagnetic, acoustic, or potential field

⇨ e.g., emission, absorption, scattering of electromagnetic waves;
magnetic or gravitational perturbations; reflection of acoustic waves

- The term “remote sensing” is commonly used in connection with electromagnetic techniques of information acquisition

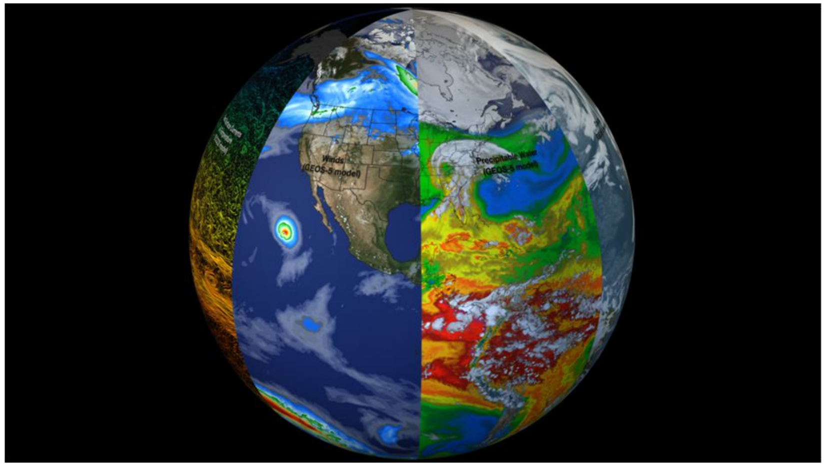
- Remote sensing is one of the most important data sources for geosciences studies and applications

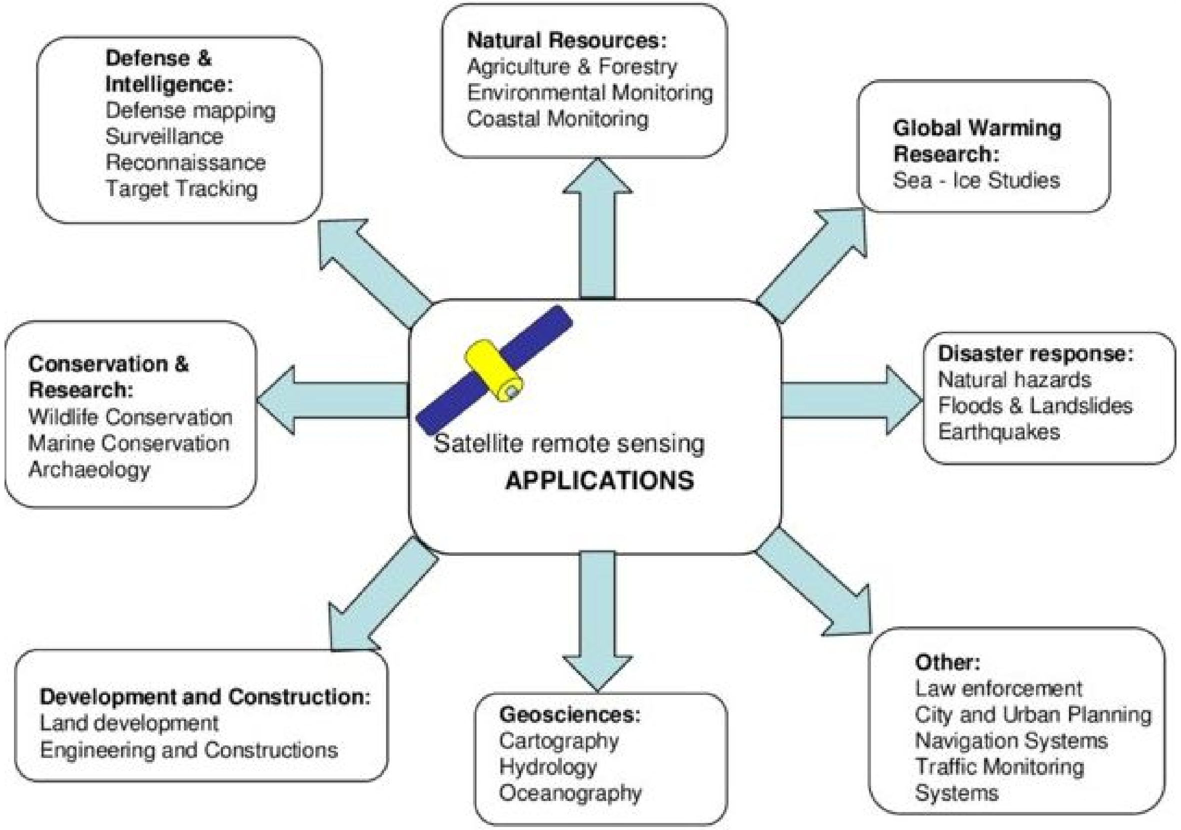
NASA Earth Science Data: https://earthdata.nasa.gov/

ESA Earth Online Data: https://earth.esa.int/web/guest/data-access

Introduction

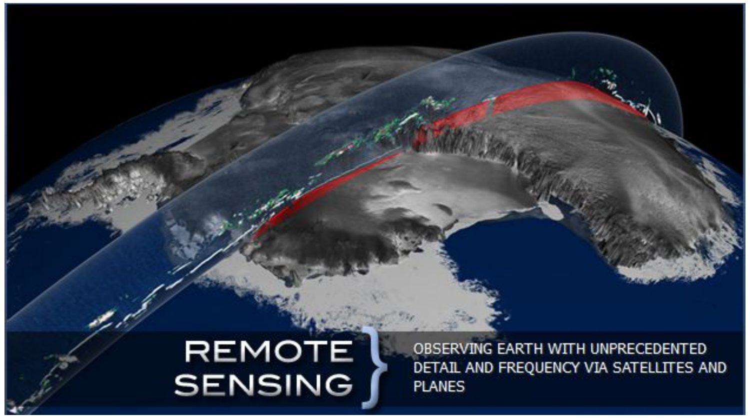
Some Applications





Introduction

Satellite Remote Sensing



Provide information which can be **Global, Repetitive, and Long term**

- The rapid wide coverage capability of satellite platforms allows monitoring of rapidly changing phenomena, particularly in the atmosphere
- The long duration and repetitive capability allows the observation of seasonal, annual, and longer-term changes such as polar ice cover, desert expansion, solid surface motion, and subsidence and tropical deforestation
- The wide-scale synoptic coverage allows the observation and study of regional and continental scale features such as plate boundaries and mountain chains

Provide information about global patterns and dynamics of:

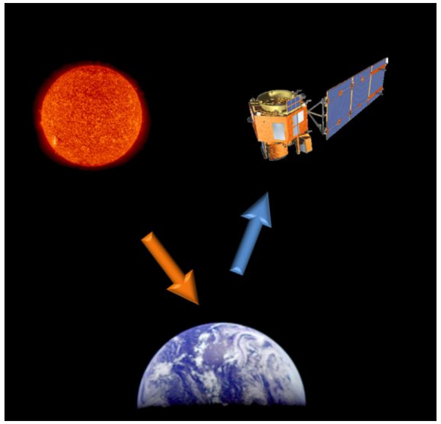
Atmosphere:
- Cloud cover
- Winds
- Temperature and pressure
- Chemical composition

Earth's surface:
- Vegetation cover
- Geomorphology
- Polar caps
- Oceans surface temperature

Introduction

Active and Passive techniques

To properly record the energy reflected or emitted from a given surface or target, a **sensor** must be installed on a **platform** distant from the surface or target being observed.



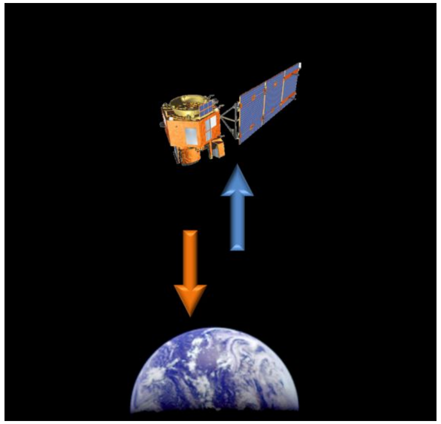
Passive sensor

Passive techniques: The sensor operates based on external illumination (Sun) or receive the spontaneous thermal self-emission. Low power requirements.

e.g., photographic sensor (without flash), multi/hyperspectral sensors, radiometer

Active techniques: The sensor provides its own source of electromagnetic energy; the information of interest is obtained from reflected or scattered waves. High power requirements.

e.g., laser (LiDAR), radar (SAR)



Active sensor

www.nasa.gov

Introduction

Remote Sensing Data/Sensors - Types and Classes

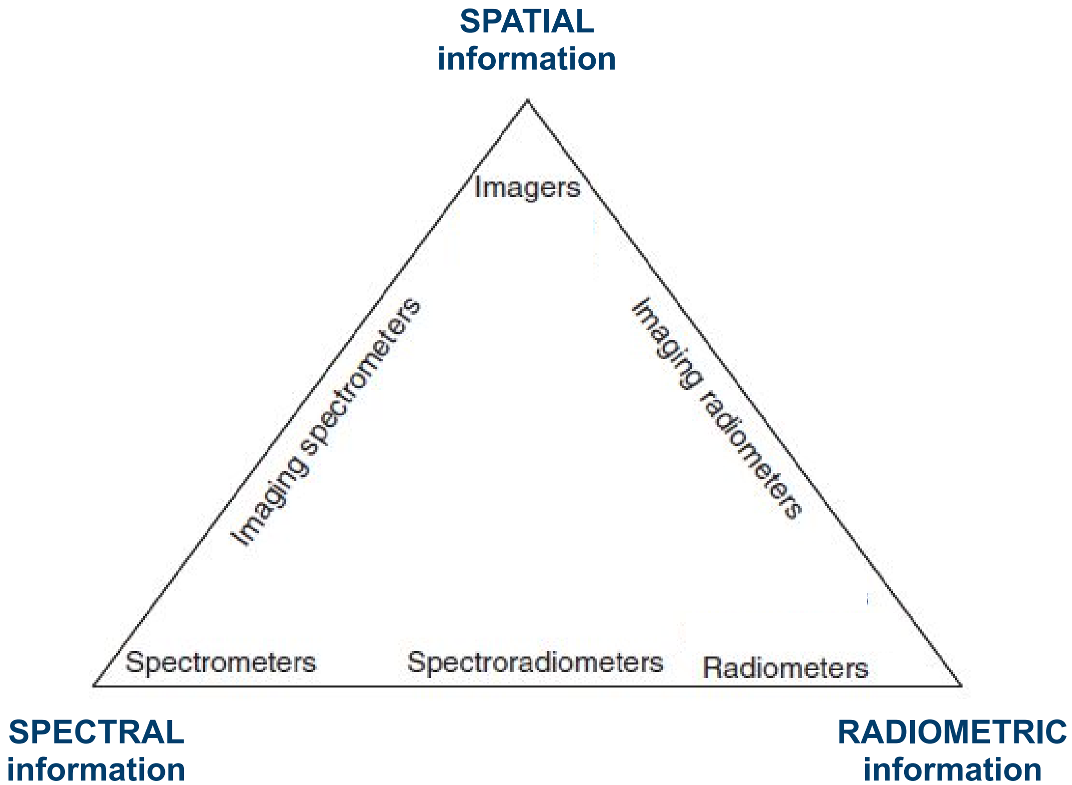


Diagram illustrating the different types of information and the type of sensor used to acquire this information

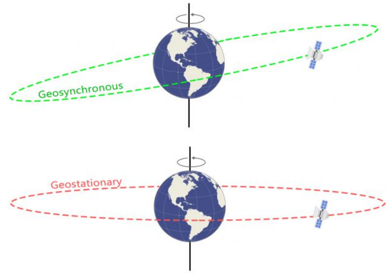
- Spectral information is acquired with a spectrometer
- 2D surface spatial information is acquired with an imager such as a camera
- An imaging spectrometer also acquires for each pixel in the image the spectral information

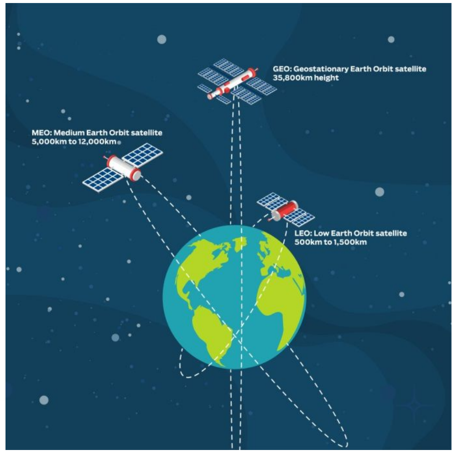
More info: AERO0024-1 Astrodynamics (Prof. G. Kerschen)

Introduction

Orbits of Earth Observation Satellites

$$T = \frac{2\pi R}{v} = 2\pi R \sqrt{\frac{R}{g\, R_T^2}}$$





○ Geosynchronous orbit

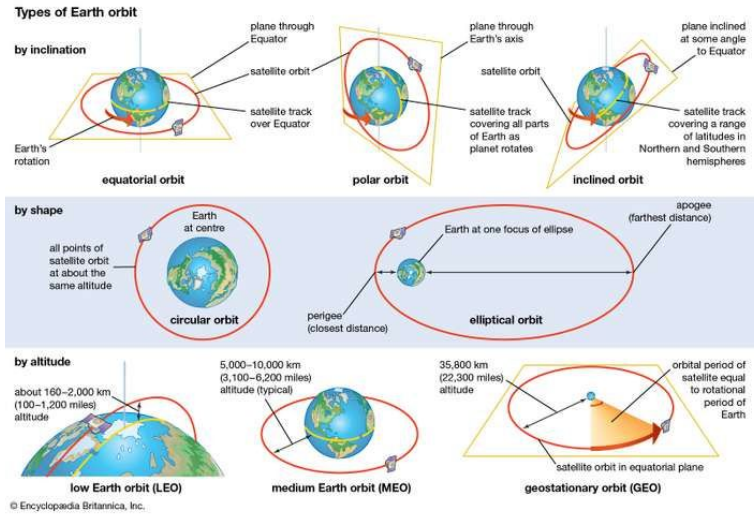
Earth-centered orbit with an orbital period that matches Earth's rotation.
A circular geosynchronous orbit has a constant altitude of 35786 km.
Allows continuous observation of a specific region.
Geostationary orbit if the inclination = 0 (on the same plane as the equator).
E.g., communication and meteorological satellites (Meteosat, MSG, GOES)

○ Polar or near-polar orbit

One of the most frequent orbit types for Earth observation satellites.
Much lower altitude (500 - 1500 km); orbits with inclination angles between 80 and 100 degrees. Allows observing the entire globe with relatively frequent revisits.

Sun-synchronous (heliosynchronous) orbit

$\Rightarrow$ constant orientation of the orbital plane with respect to the Sun.
$\Rightarrow$ Same zone viewed at same local time (allows to observe the same region under similar illumination conditions).
E.g., SPOT, IKONOS, Landsat



Introduction

Sensor Resolutions

- Spectral resolution (and spectral range)

The ability of a sensor to distinguish between electromagnetic radiation of different frequencies

- Radiometric resolution

The ability of a sensor to recognize small differences in the intensity of received electromagnetic energy

- Temporal resolution

Time resolution is a function of the frequency at which the same area is observed by a sensor

- Spatial resolution (and spatial extend)

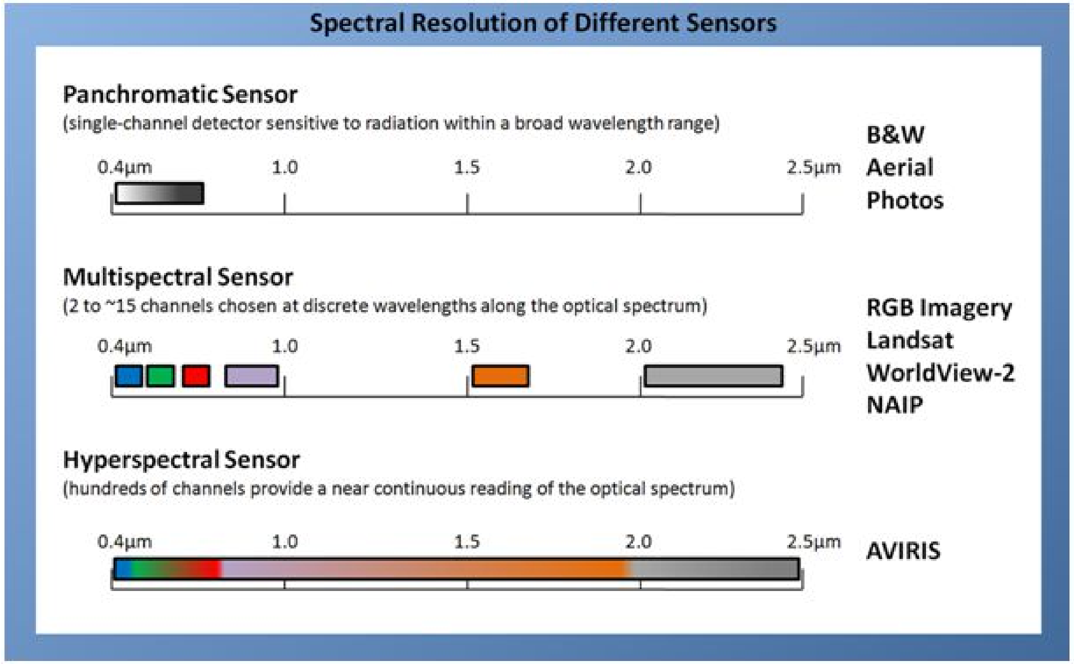
The spatial resolution is a function of the size of the smallest feature that can be detected on the observed surface

… but there is a trade-off between these different resolutions

Introduction

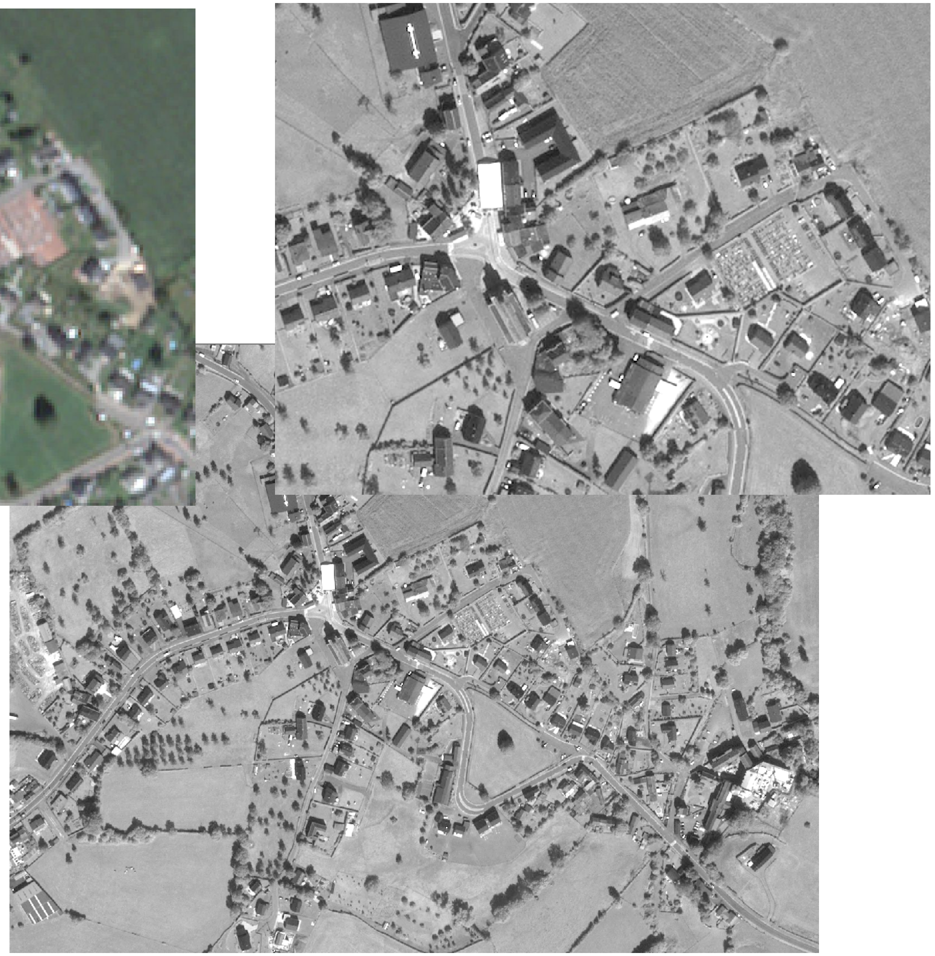
Spectral Resolution

- Panchromatic Sensor
- Multispectral Sensor
- Hyperspectral Sensor



Spectral Resolution

Multispectral image(Pleiades – 2 m)



Panchromatic image(Pleiades – 50 cm)

Introduction

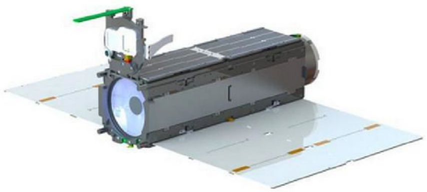
Spatial and Temporal Resolution

- VHR Sensor (very high resolution)
  < 1m
- HR Sensor (high resolution)
  1-10 m
- MR Sensor (medium resolution)
  10-50 m
- LR Sensor (low resolution)
  > 50 m

Trends in commercial imagery - Resolution versus revisit, two strategies (Denis et al., Acta Astronautica, 2017)

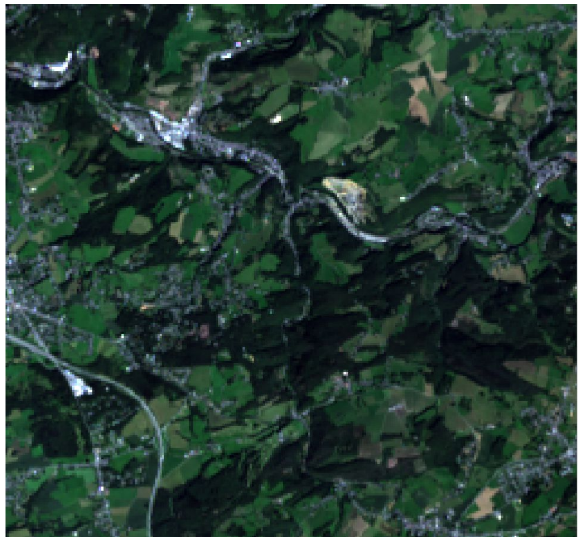
Sart-Tilman - 2019 - Echelle 1:30000

Introduction



Planet Doves - 3 m / 1 jours

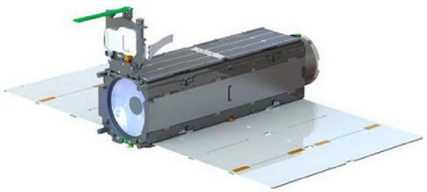
Sentinel 2 - 10 m / 5 jours



Landsat 8 - 30 m / 16 jours

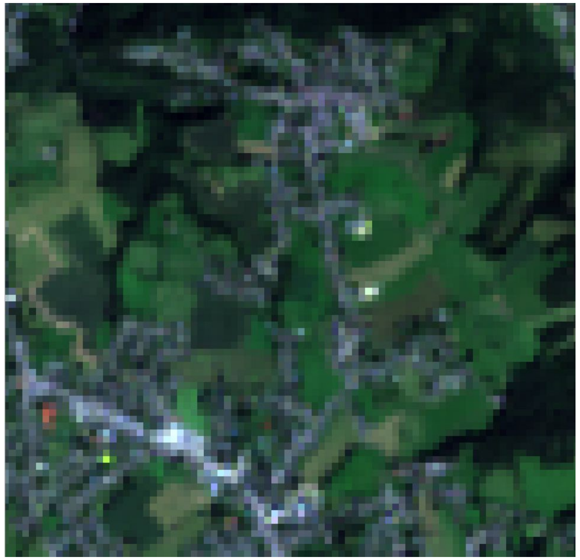
Sart-Tilman - 2019 - Echelle 1:10000

Introduction



Planet Doves - 3 m / 1 jours

Sentinel 2 - 10 m / 5 jours



Landsat 8 - 30 m / 16 jours

Introduction

Remote sensing - Brief history


"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

SOVIET FIRES EARTH SATELLITE INTO SPACE;
IT IS CIRCLING THE GLOBE AT 18,000 M. P. H.;
SPHERE TRACKED IN 4 CROSSINGS OVER U. S.

HOFFA IS ELECTED TEAMSTERS HEAD; WARNS OF BATTLE

COURSE RECORDED

Navy Picks Up Radio Signals—4 Report Sighting Device

560 MILES HIGH

Visible With Simple Binoculars, Moscow Statement Says

Device Is 8 Times Heavier Than One Planned by U.S.

Sputnik 1 (4 October 1957)
First spacecraft placed in orbit around the Earth

*Beginning of the **Space Age***

There has been great progress in spaceborne remote sensing over the last decades

Up until 1946, remote sensing data were mainly acquired from airplanes or balloons

- **1957** First man-made object placed into orbit: Sputnik 1 – Soviet Space Program (dual-frequency radio transmission over a 21-day period)
- **1959** First Earth image from space: Explorer 6 – NASA (small, spheroidal satellite designed to study trapped radiation in the upper atmosphere)
- **1960** Systematic orbital observations of the Earth began with the launch of NASA TIROS-1 (Television and InfraRed Observation Satellite), the first satellite for global weather observation, using a low-resolution imaging system.
- **1961** Orbital color photography was acquired by an automatic camera in the unmanned MA-4 Mercury spacecraft. This was followed by photography acquired during the Mercury, Gemini, Apollo, and Skylab missions.
- **1969** On Apollo 9, the first multispectral images were acquired to assess their use for Earth resources observation.
- **1972** Launch of the first Earth Resources Technology Satellite (ERTS-1, later renamed Landsat-1), one of the major milestones in the field of Earth remote sensing. ERTS-1 was followed by a series of Landsat missions.

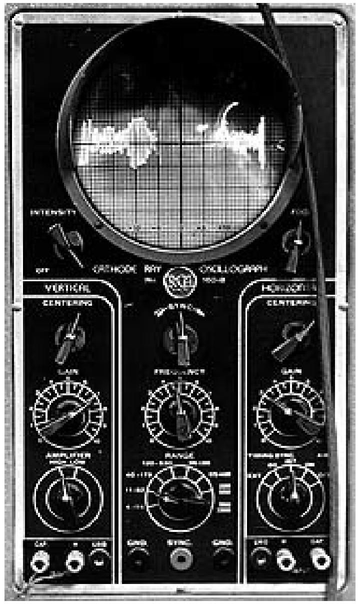
Space Race
between the Soviet Union and the United States following World War II

1972-2022
50 Years of NASA Landsat!

Introduction

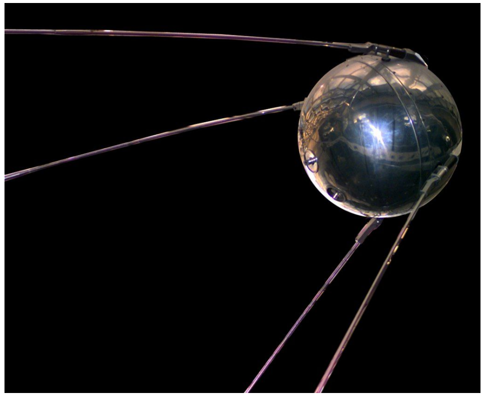
Remote sensing - Brief history

4 October 1957: A breakthrough



Bip-Bip...

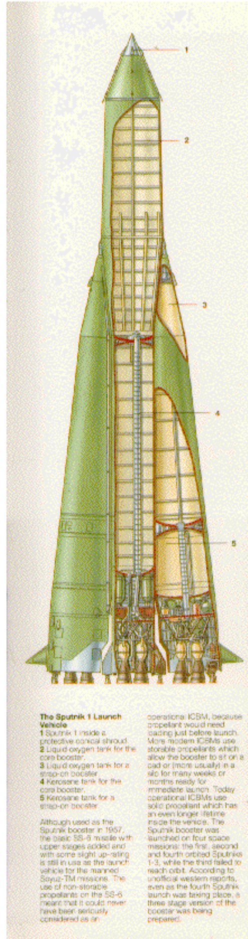
Sputnik 1



Mass: 84 kg
Perigee: 227 km
Apogee: 945 km
Inclination : 65.0 deg

The R-7 rocket

Total Mass: 265,500 kg
Liftoff Thrust: 396,298 kgf
Core Diameter: 3.0 m
Total Length: 28.0 m



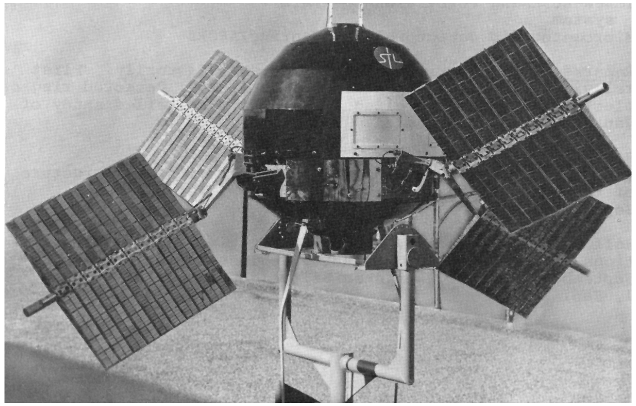
Introduction

Remote sensing - Brief history

14 August 1959: First photos of Earth from a satellite

Thor-Able
7 August 1959 - Cape Canaveral (FL)

NASA Explorer-6 satellite



65-kg
Highly-elliptical orbit (237-41900 km)
Study of trapped radiations
Imaging system : a crude photocell scanner
Image transmission required 40 hrs!

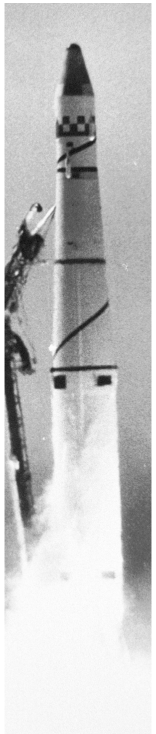
The first image taken by Explorer 6 shows a sunlit area of the Central Pacific Ocean and its cloud cover. The photo was taken when the satellite was about 27,000 km (17,000 mi) above the surface of the Earth on 14 August 1959. At the time, the satellite was crossing Mexico.

Introduction

Remote sensing - Brief history

Reconnaissance (intelligence) satellite for military applications

28 February 1959
Discoverer-1 (CIA)
CORONA program
Thor-Agena A rocket
Vandenberg Air Force Base (CA)



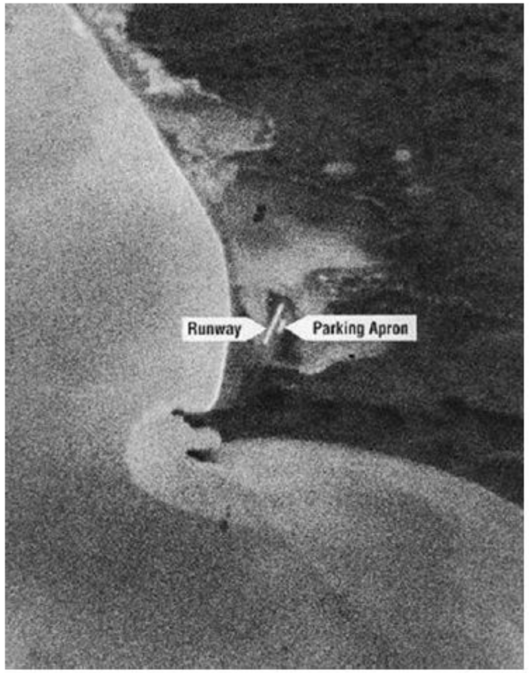
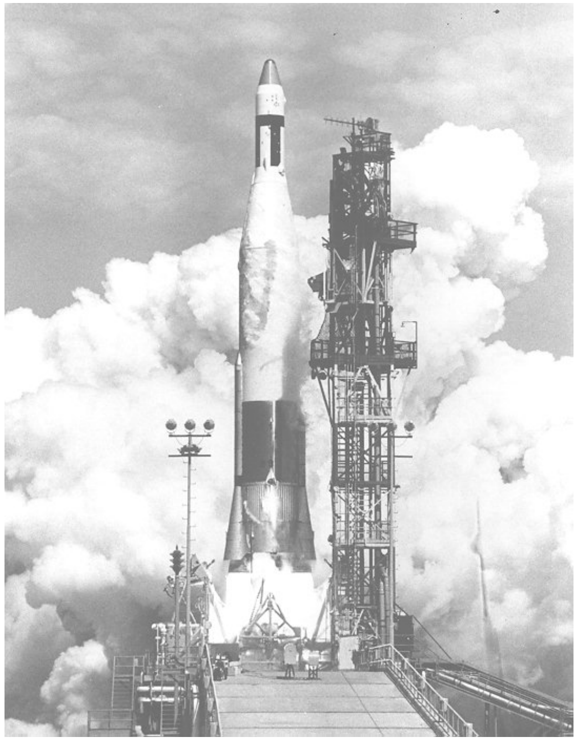


Photo of a Soviet air base at Mys Shmidta, Siberia, taken in August 1960 by a camera onboard the CORONA satellite *Discoverer-14*. Image courtesy of the U. S. National Reconnaissance Office

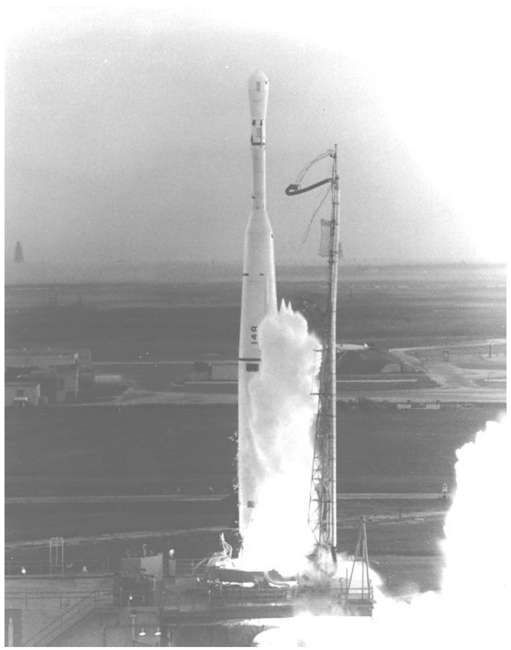
26 February 1960
SAMOS-1 (USAF)
SAMOS-E program
Atlas-Agena rocket
Vandenberg Air Force Base (CA)



Introduction

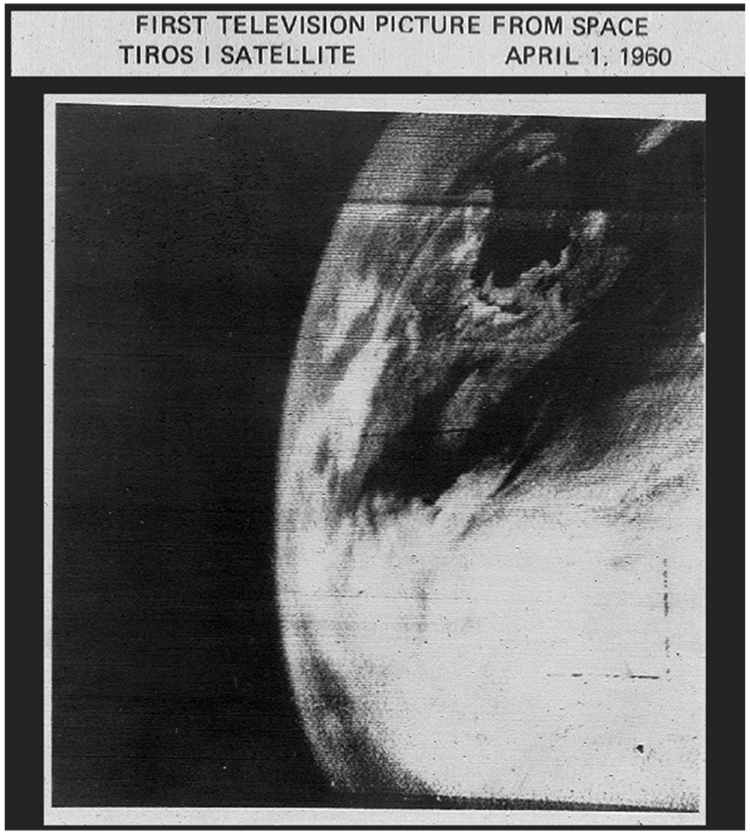
Remote sensing - Brief history

1 April 1960: First satellite for global weather observation



1 April 1960 - Cape Canaveral (FL)

NASA TIROS-1

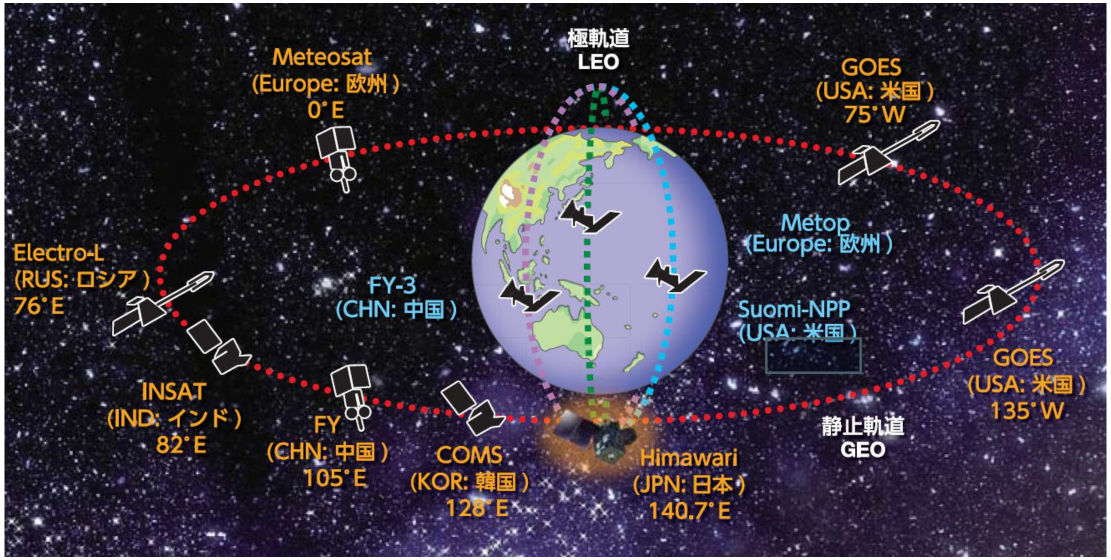


Introduction

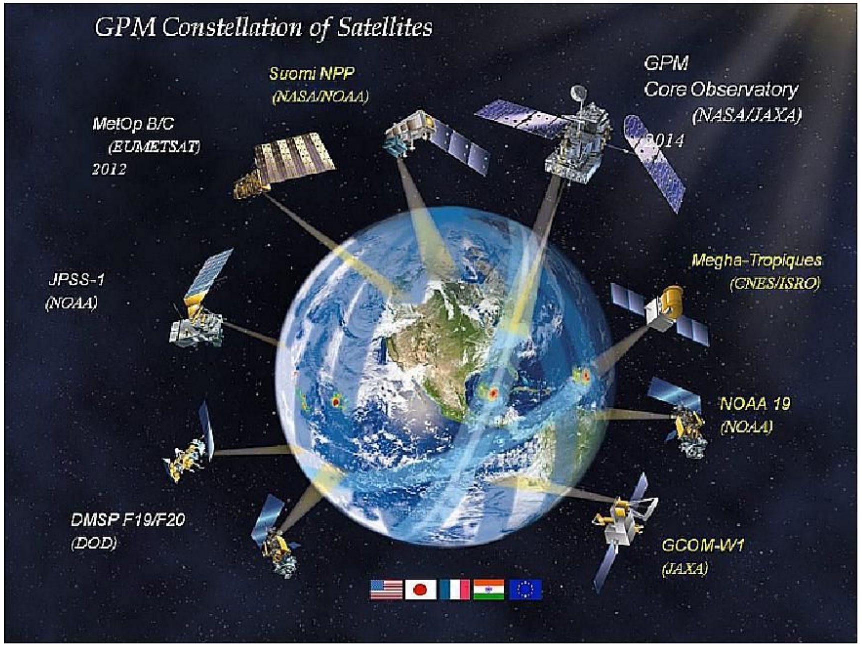
Remote sensing - Brief history

Meteorology: Two types of orbits

Geosynchronous Earth Orbit (GEO) Meteorological satellites



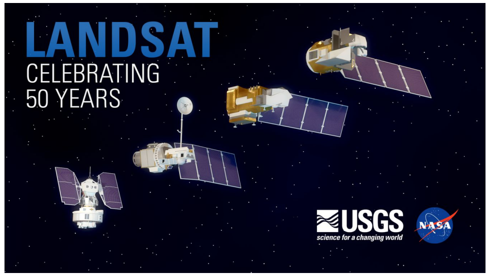
Low-Earth Orbiting (LEO) Meteorological satellites



Introduction

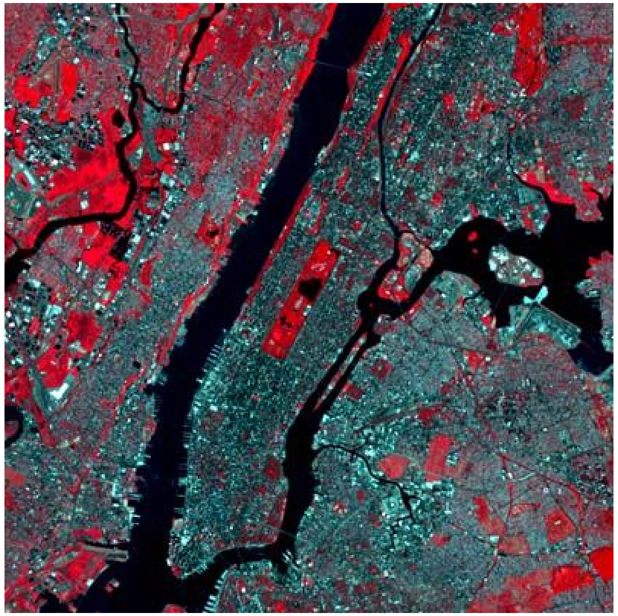
Remote sensing - Brief history

Earth resources: 50 Years of Global Observations



VIS 0.45 - 0.69 µm

VIS/NIR 0.52 - 0.90 µm



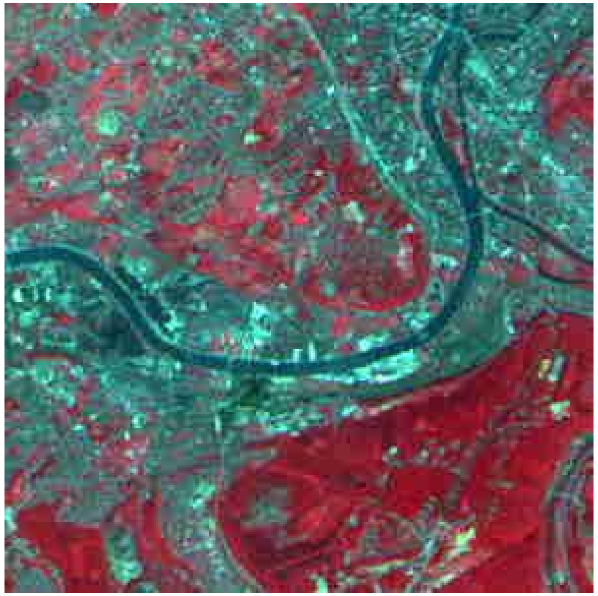
LANDSAT TM
Manhattan (30 m)

Introduction

Remote sensing - Brief history

Earth resources: 50 Years of Global Observations

Liège
SPOT XS (20 m)

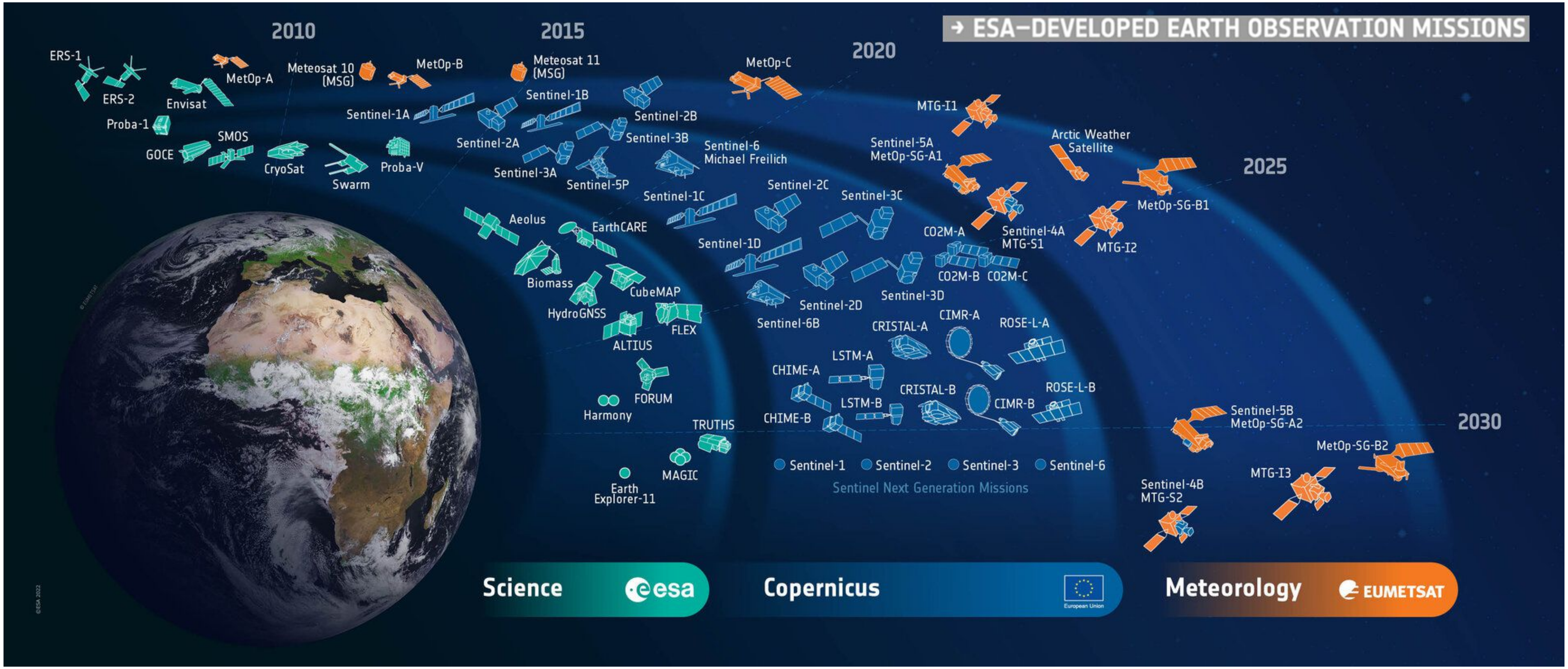


Liège
IKONOS XS (4 m)

Louvre Museum (Paris)
Pleiades-1A (50 cm)

Introduction

Earth Observation in Europe



Introduction

Earth Observation in Europe - ESA's Earth Explorer missions

Introduction

Earth Observation in Europe – Copernicus Services

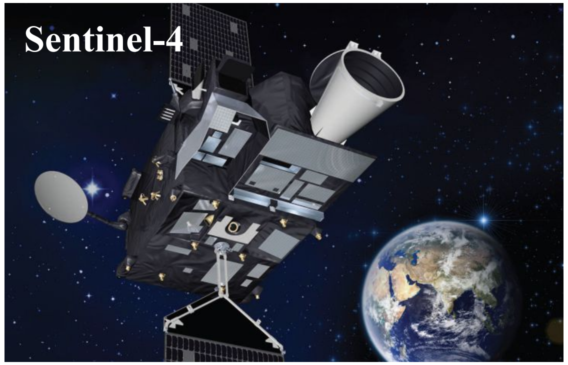
https://www.copernicus.eu/en/copernicus-services

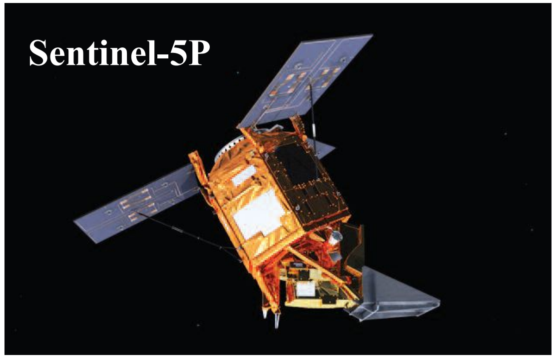
Europe's eyes on Earth

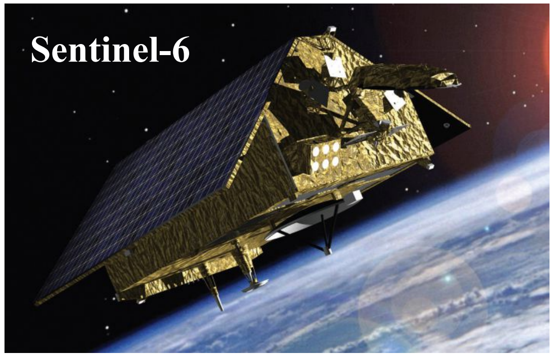
Looking at our planet and its environment for the benefit of Europe's citizens

Sentinels – Most comprehensive EO system worldwide for environmental monitoring

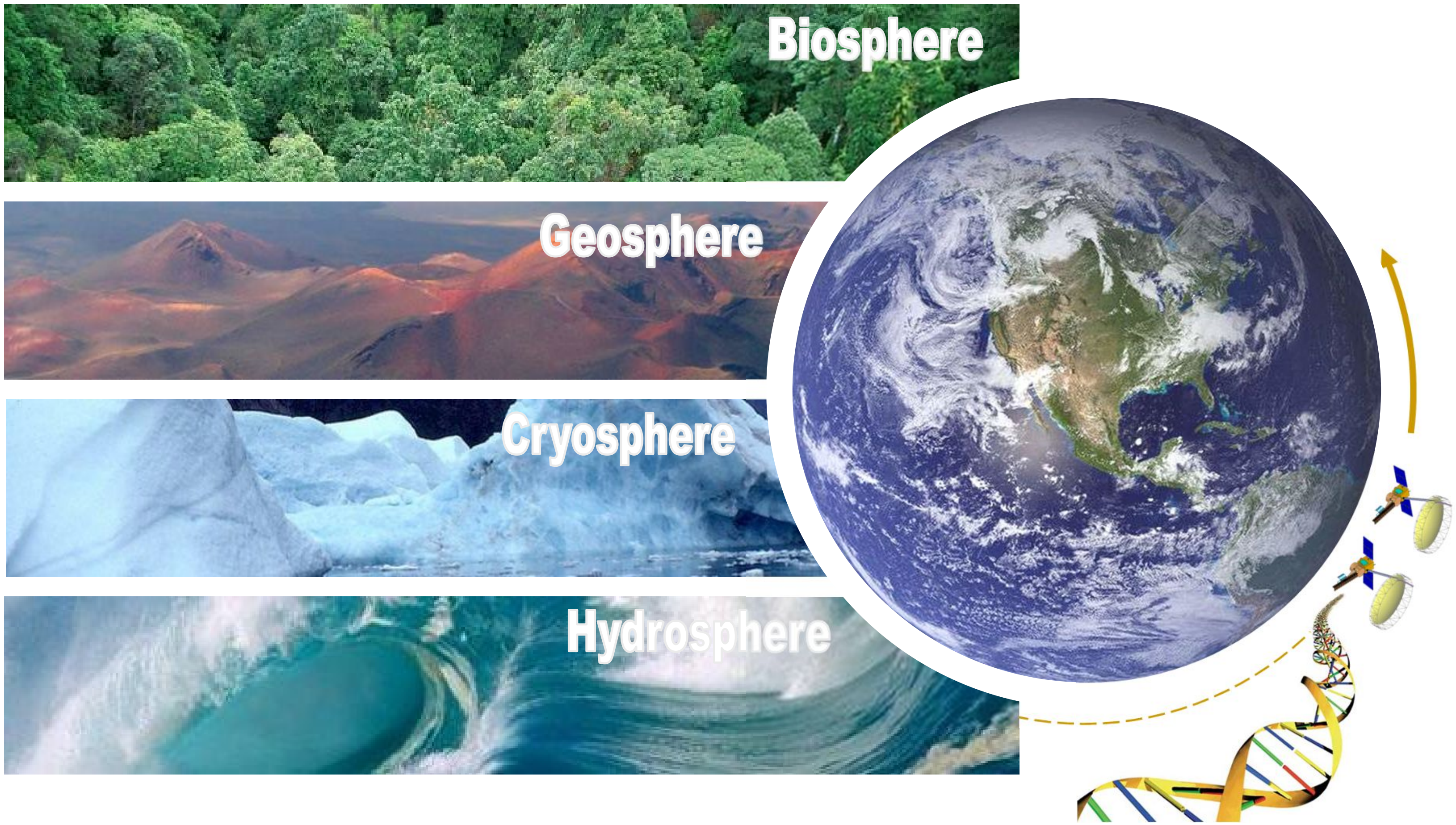
- Data available free-of-charge
  Copernicus Open Access Hub
  https://scihub.copernicus.eu/
- Business displaced to applications and services
- Continuous data flow
- Gigantic data volume to be processed, distributed, archived
- User ground-segment concept drastically changed
- Big data paradigm







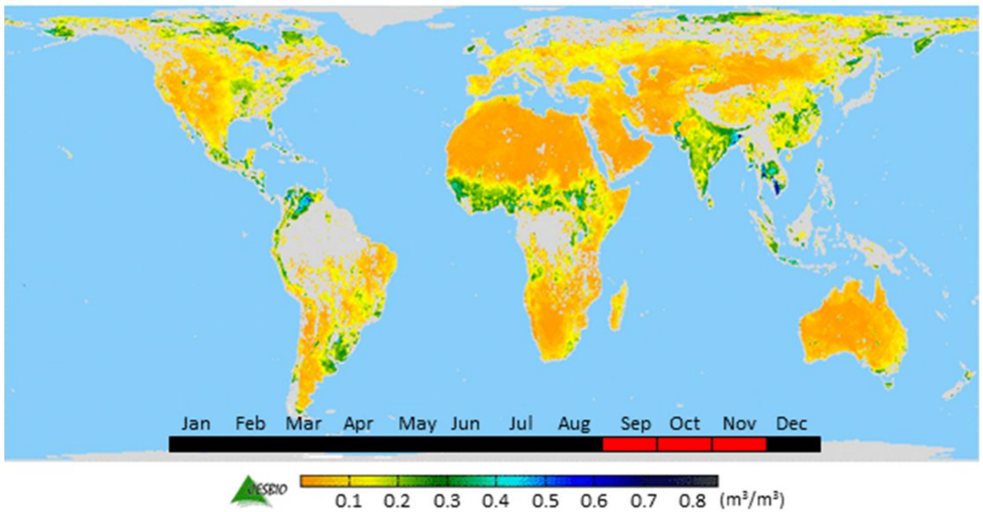
Remote sensing applications



Introduction

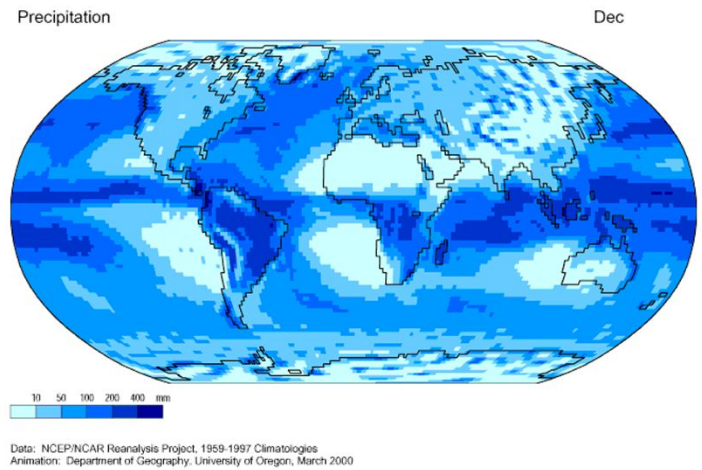
EO in Hydrology

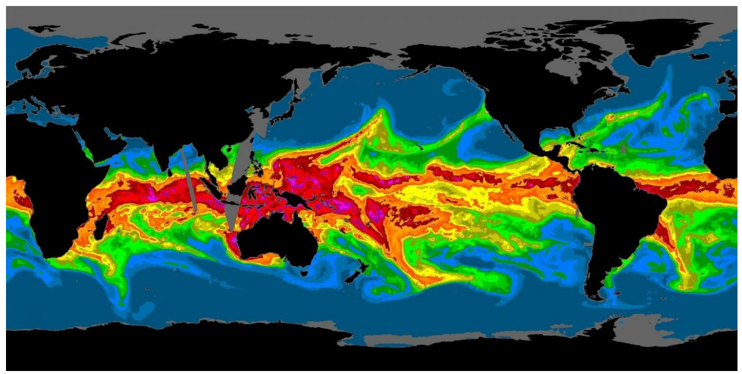
Monitoring hydrological variables from satellite remote sensing



Seasonal soil moisture from the L-band microwave radiometer onboard ESA's SMOS satellite

Satellite Earth observation has played an undeniable role in observing, understanding, and predicting the **global water cycle**!

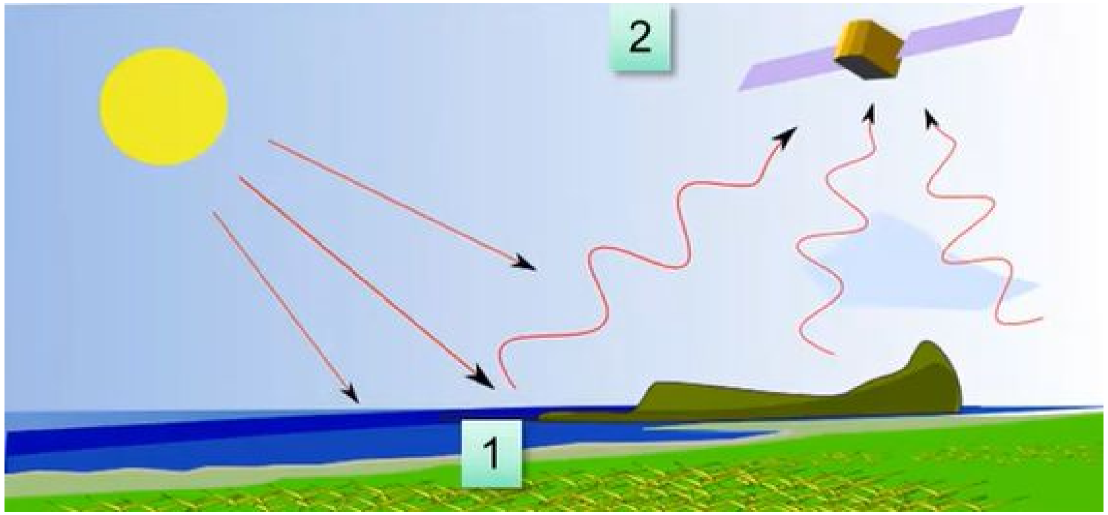




Microwave Image of Integrated Water Vapour Products from MODIS

Introduction

Remote Sensing fundamental requirements



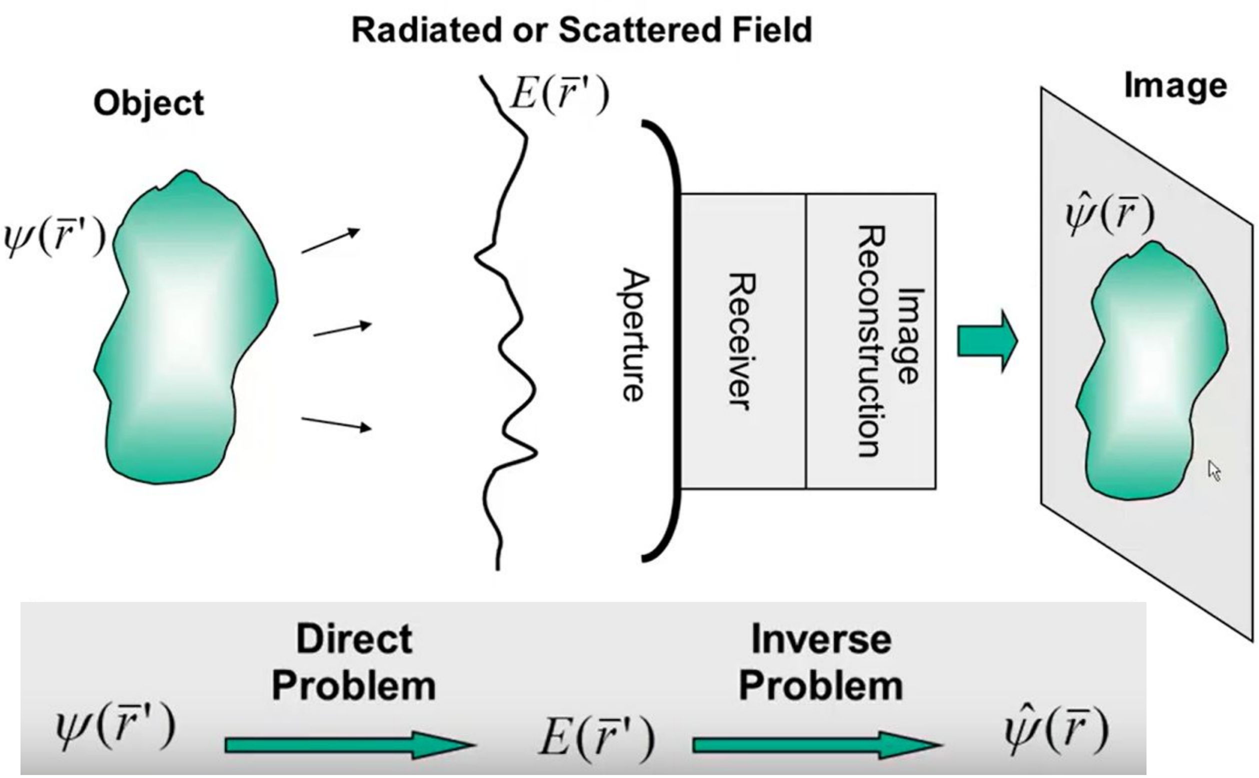
[1] Obtaining information (sensing): based on Wave–Matter interactions

[2] Information must travel from the scene to the (remote) sensor

Electromagnetic radiation is able to sense physical properties of materials and propagates efficiently through space

Introduction

The Imaging Process

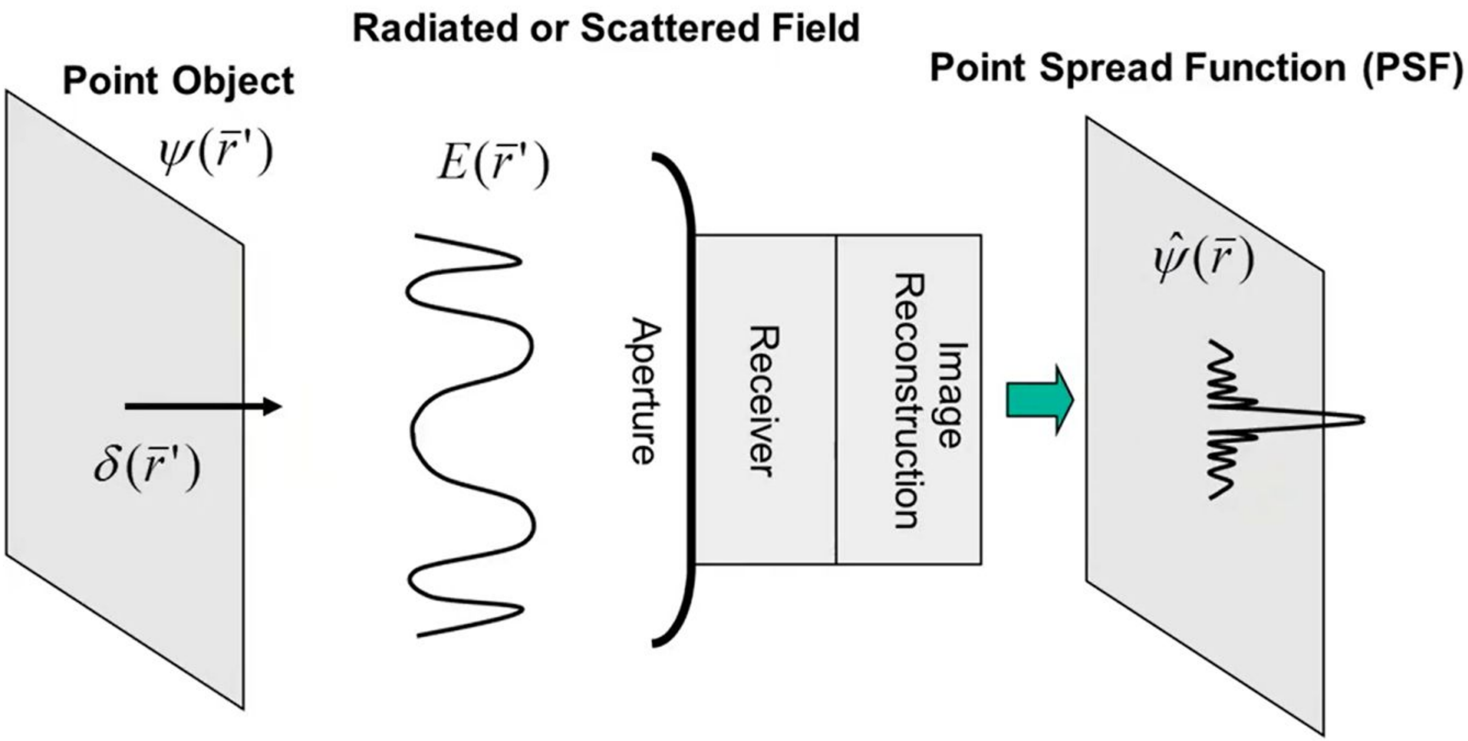


- The aim is to better design he instruments, improve the reconstruction algorithms and calibration procedures, …
  in order to obtain an image as close as possible to the original properties of the object.

- Scientists are working towards a better modelling of the direct problem, because if we know the direct problem well, we can reverse it to derive the original properties of the object.

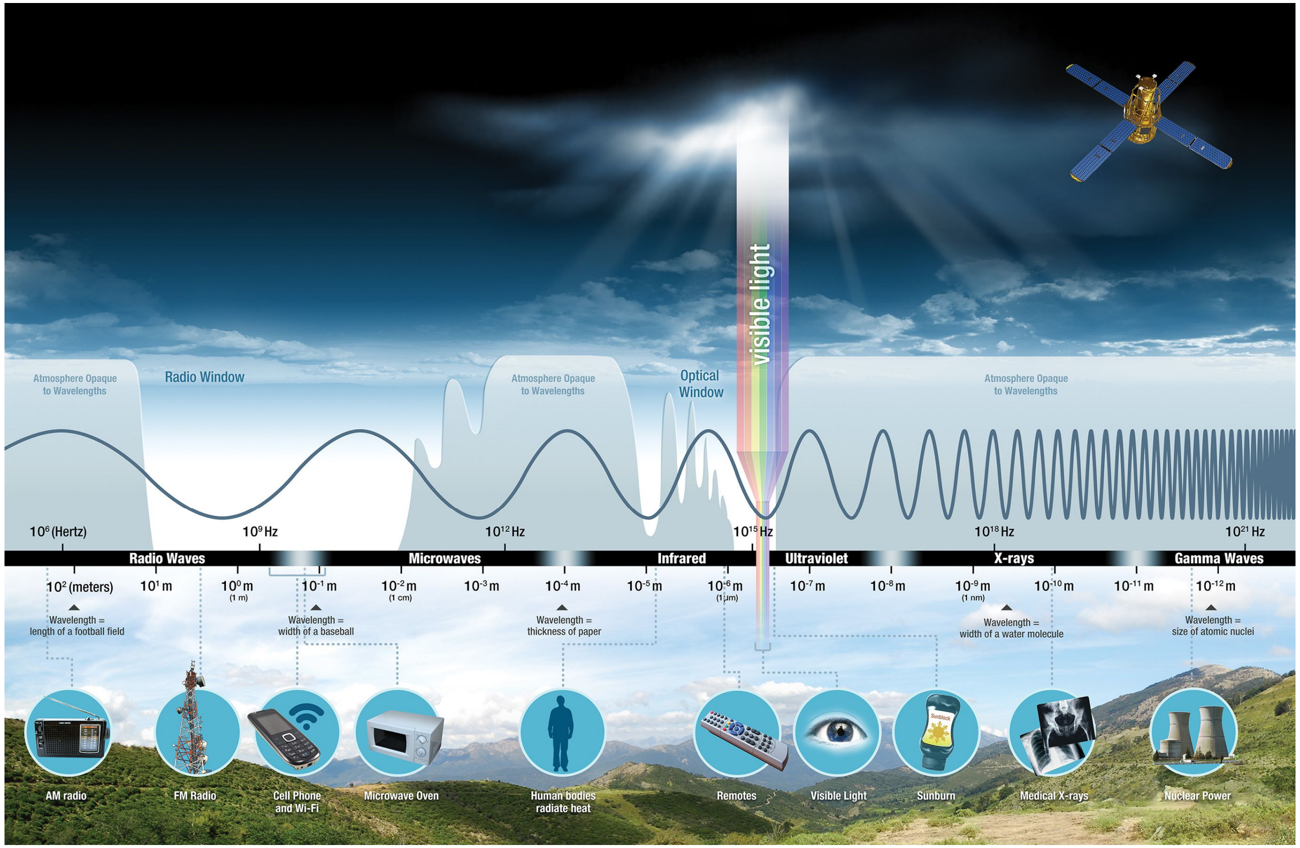
Introduction

Imaging Sensor Characteristics



Introduction

The electromagnetic (EM) radiation spectrum



Frequency (Hz)

Radiation Type

Wavelength (m)

Approximate Scale of Wavelength

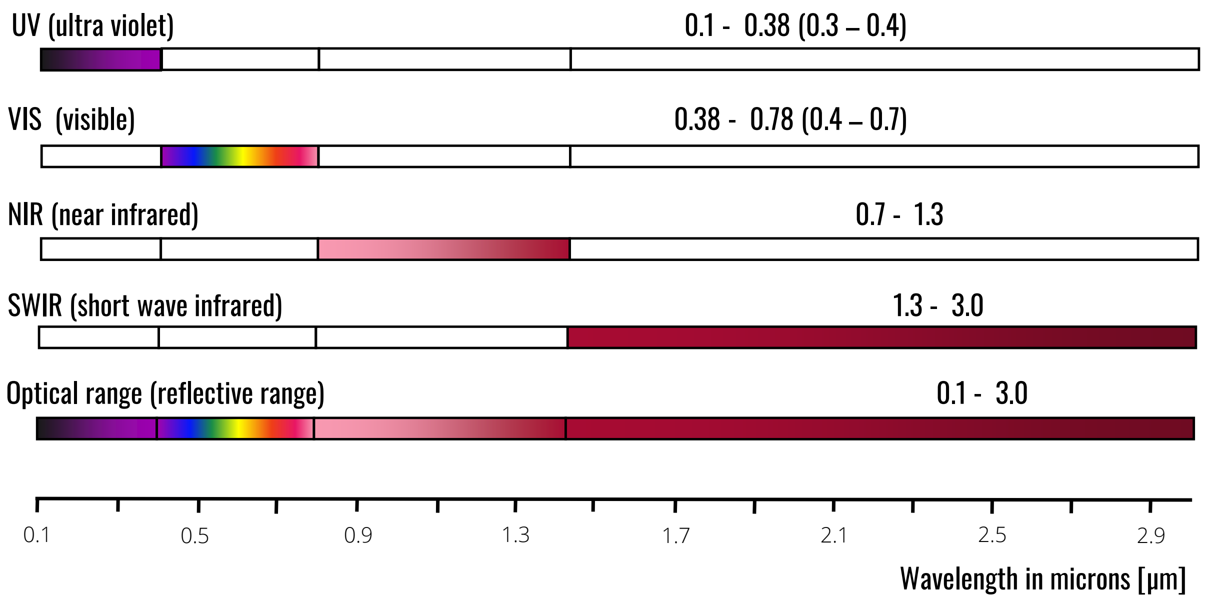
Remote sensing sensors are able to detect energy emitted or reflected by surface features within certain parts of the electromagnetic spectrum

- ❑ Optical remote sensing (visible -> 400–750 nm and near-infrared -> 750–3000 nm)
- ❑ Thermal remote sensing (thermal infrared -> 3000 nm-15000 nm)
- ❑ Microwave remote sensing (1 mm–1 m)

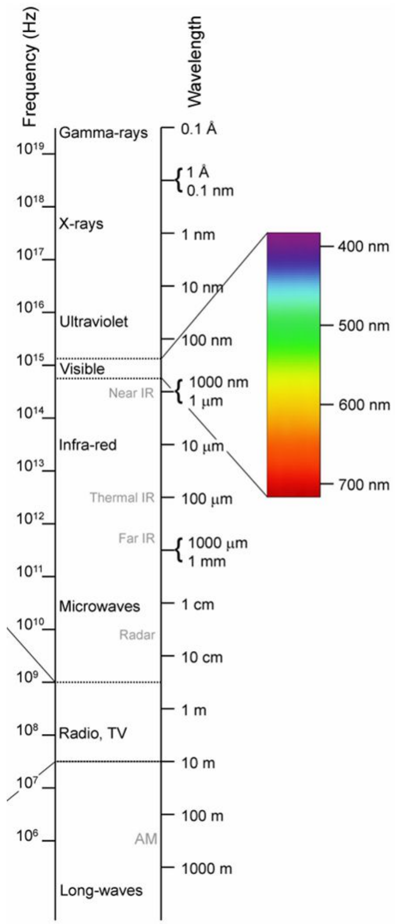
Visible and Near Infrared Remote Sensing

Visible and Near IR remote sensing

Wavebands and terminology

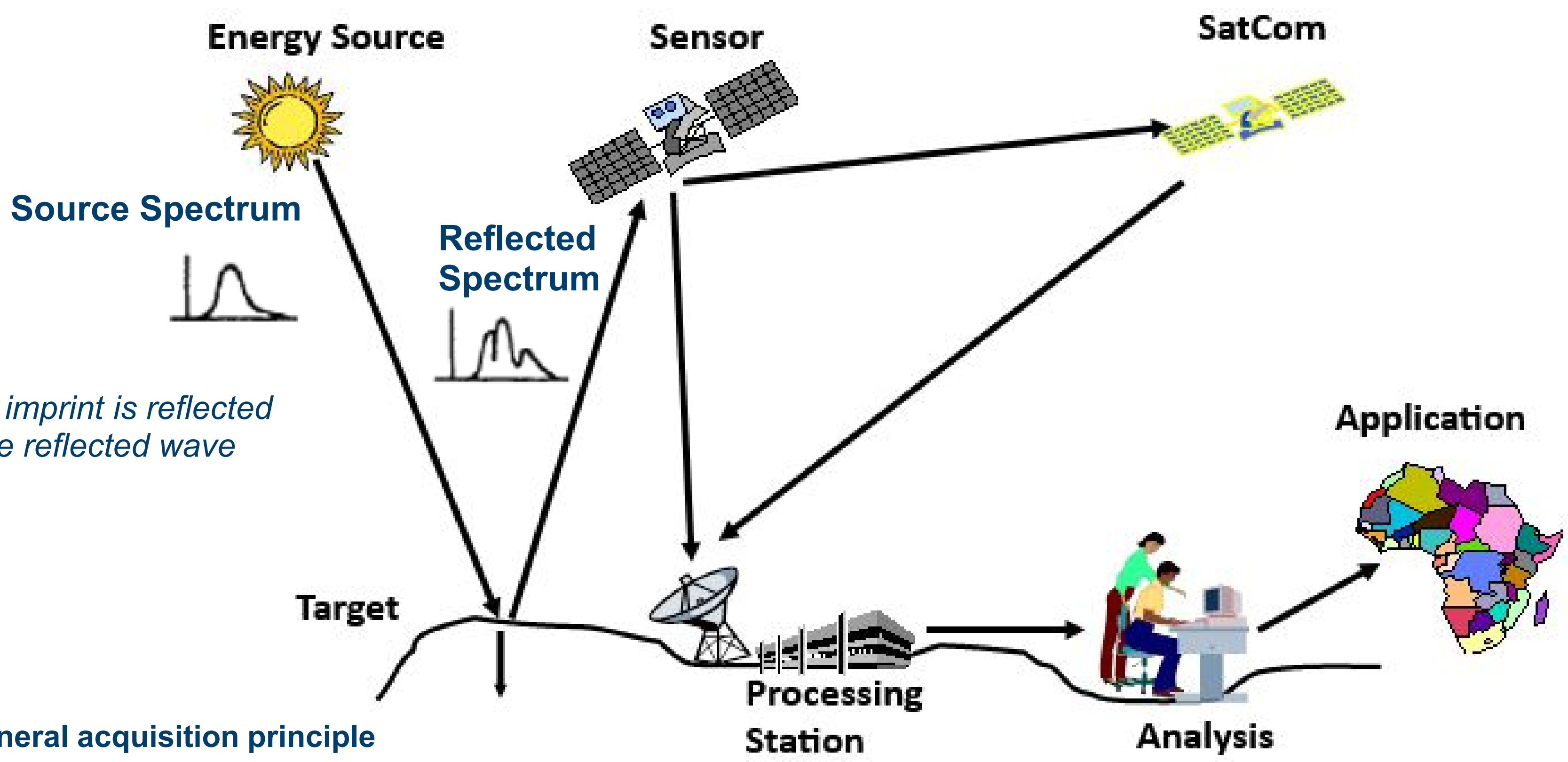


Definition of wavelength ranges commonly used in optical remote sensing



Visible and Near IR remote sensing

Passive Observation of the Earth's Surface

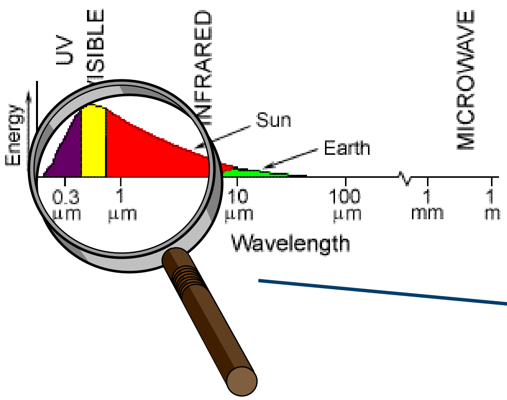


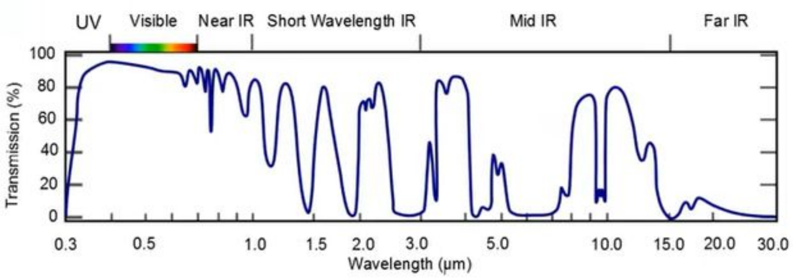
The surface spectral imprint is reflected in the spectrum of the reflected wave

General acquisition principle

Visible and Near IR remote sensing

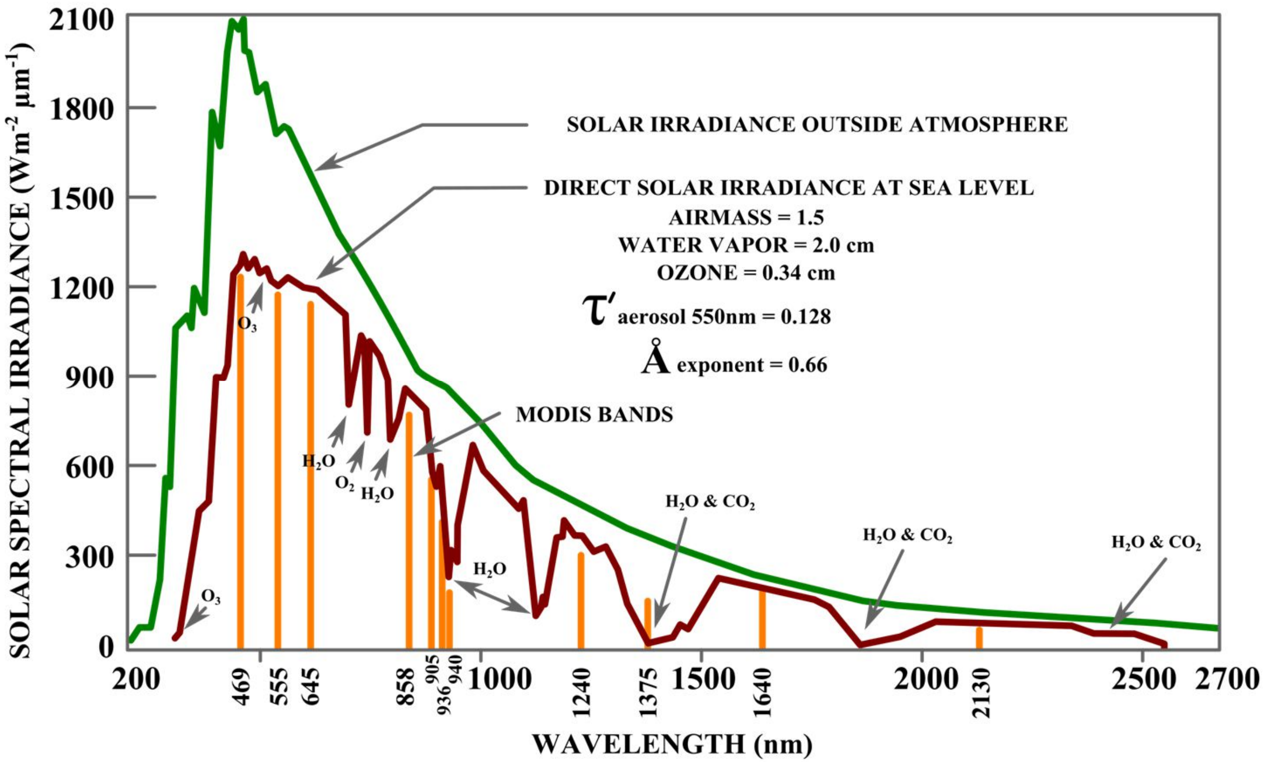
Solar illumination - Atmospheric attenuation of EM spectrum





Absorption bands by atmospheric constituents

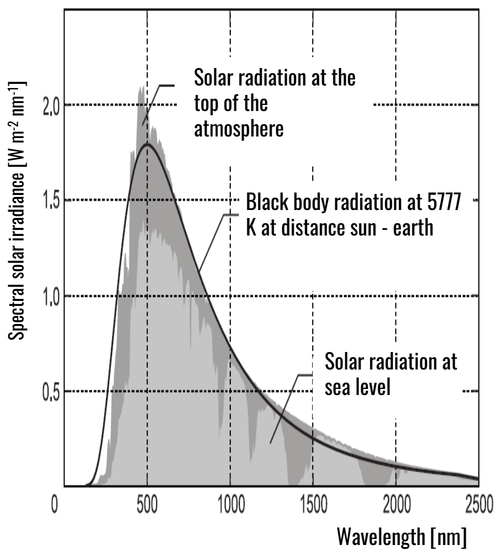
mainly H_2O, CO_2, O_2 at 1.9, 1.4, 1.12, 0.95, 0.76 µm



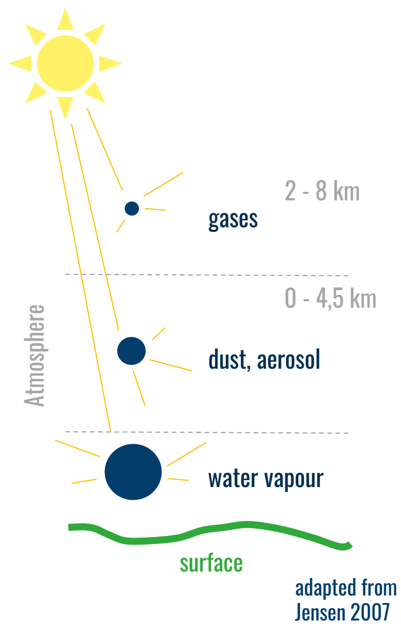
Visible and Near IR remote sensing

Interactions radiation – atmosphere

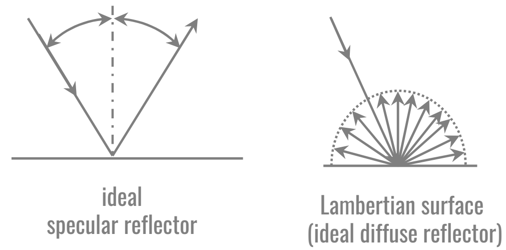
Absorption

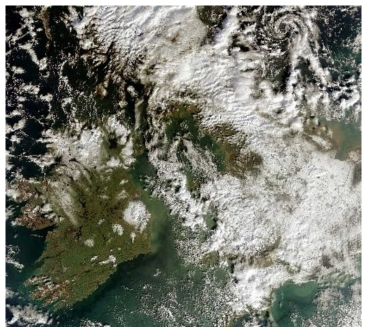


Scattering



Reflectance





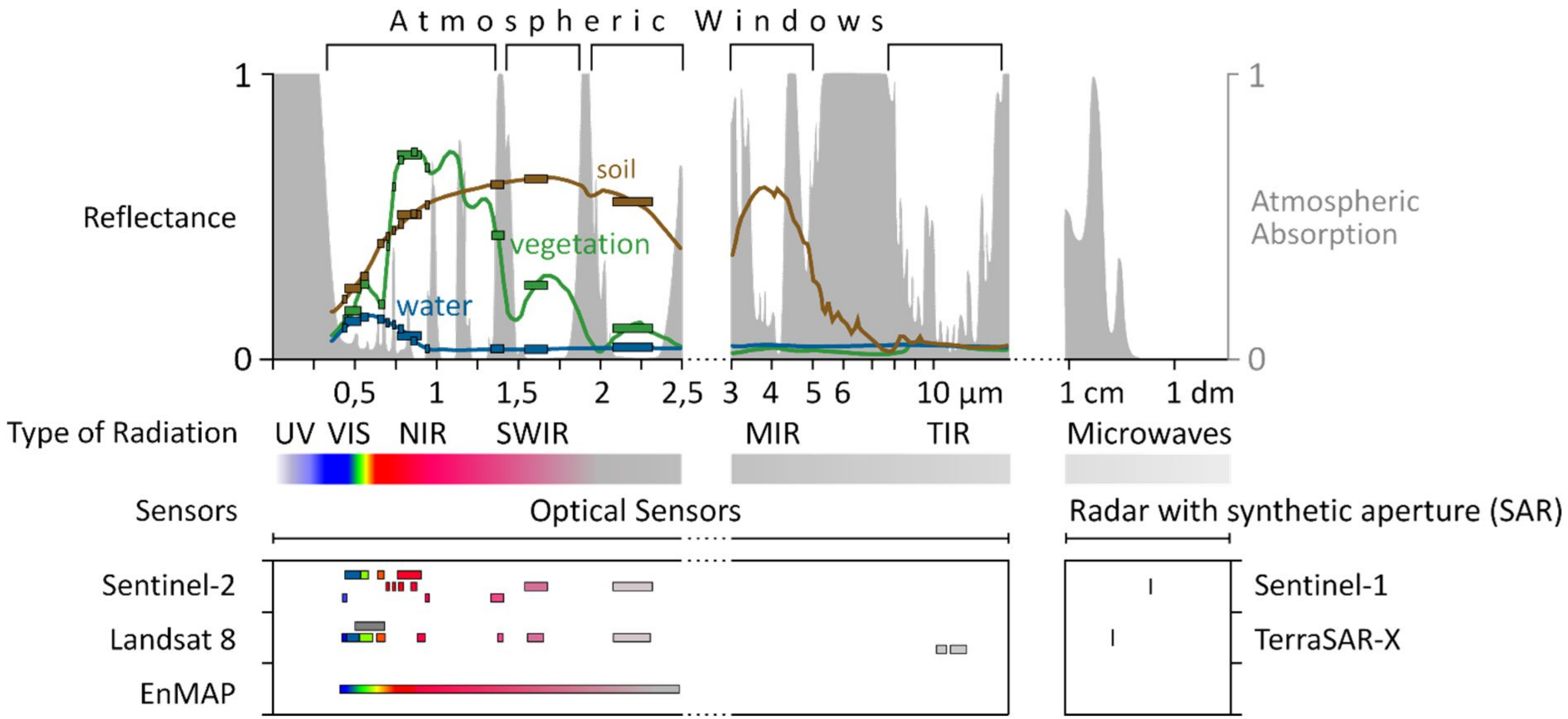
ESA 2009

→ dependance of optical remote sensing on cloud-free sky

The combined effect of absorption, scattering and reflectance on cloud surfaces can dramatically reduce the incoming radiation that reaches the Earth‘s surface

Visible and Near IR remote sensing

Atmospheric transmission and regions of operation for remote sensors



- Wavelength ranges of the spectrum that are mostly permeable to radiation are called **atmospheric windows**

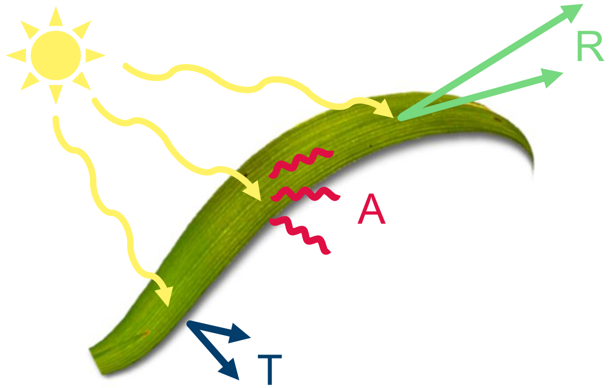
Visible and Near IR remote sensing

Interactions radiation – Earth's surface

When the energy (I) reaches the target, different interactions can occur:

- Absorption (A) - the energy is absorbed into the target
- Transmission (T) - the radiation passes through the target
- Reflection (R) - the radiation is reflected from the target

Radiant flux = Absorption (A) + Transmission (T) + Reflexion (R) = 1



Electromagnetic radiation that falls on a surface is (partly) reflected, absorbed and/or transmitted

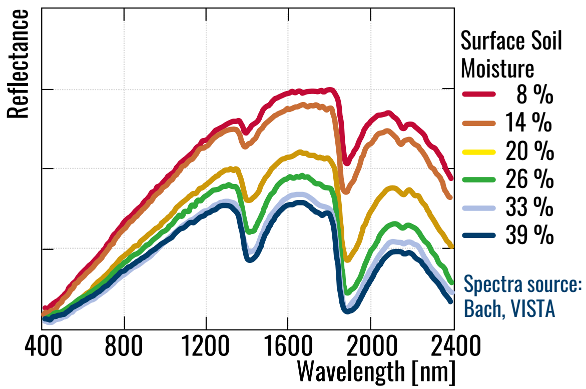
The fractions of absorbed, transmitted and/or reflected radiation vary depending on material and wavelength

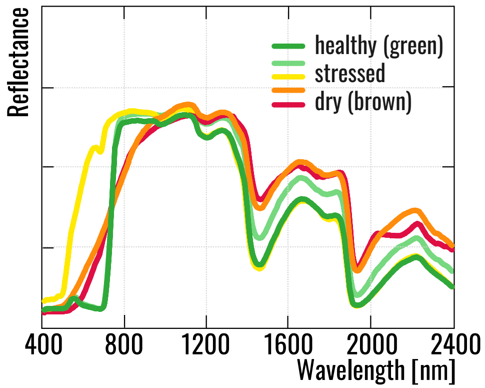
→ basis for remote sensing

Visible and Near IR remote sensing

Influencing factors: physics

- ❖ Moisture content
- ❖ Minerals
- ❖ Soil type
  - Organic content
  - Grain size
- ❖ Water
  - Organic matter
  - Phyto pigments
- ❖ Vegetation
  - Species
  - Vitality
  - Age
  - Phenology





Visible and Near IR remote sensing

Spectral signature of surface materials

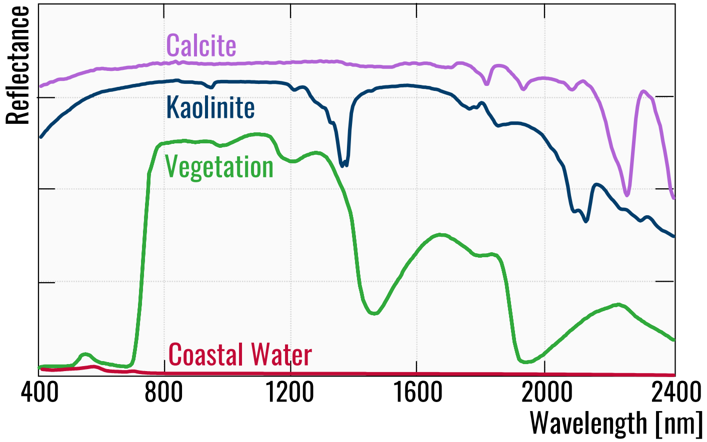
Spectral surface reflectance

⇩

Spectral signature of surface materials

⇩

Characterizing the observed surface

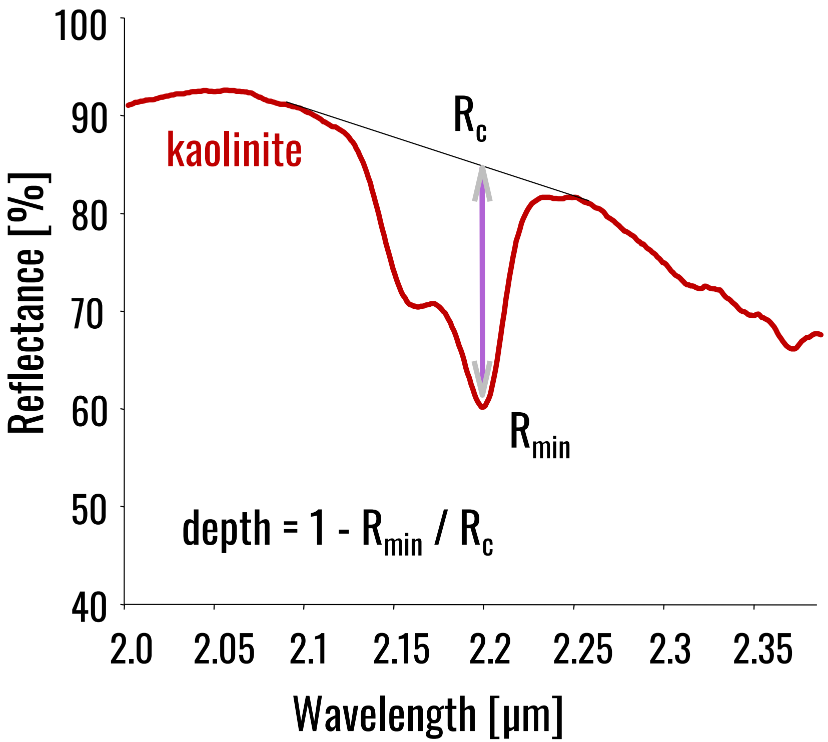


- Visible and NIR remote sensing detect reflected or emitted energy from an object in a number of different spectral bands of the EM spectrum.
- Spectral signature: diagnostic tool to remotely characterize an object.
- Spectral surface reflectance is derived after data pre-processing: radiometric calibration, (geometric correction,) and atmospheric correction. Therefore, it is independent of solar radiation and atmospheric state.
- Each material on the Earth‘s surface has a unique spectral characteristic.

Visible and Near IR remote sensing

From absorption bands to material identification and quantification

Absorption bands → spectral features in the spectrum of reflected radiation



Each material on the Earth's surface has a unique spectral characteristic

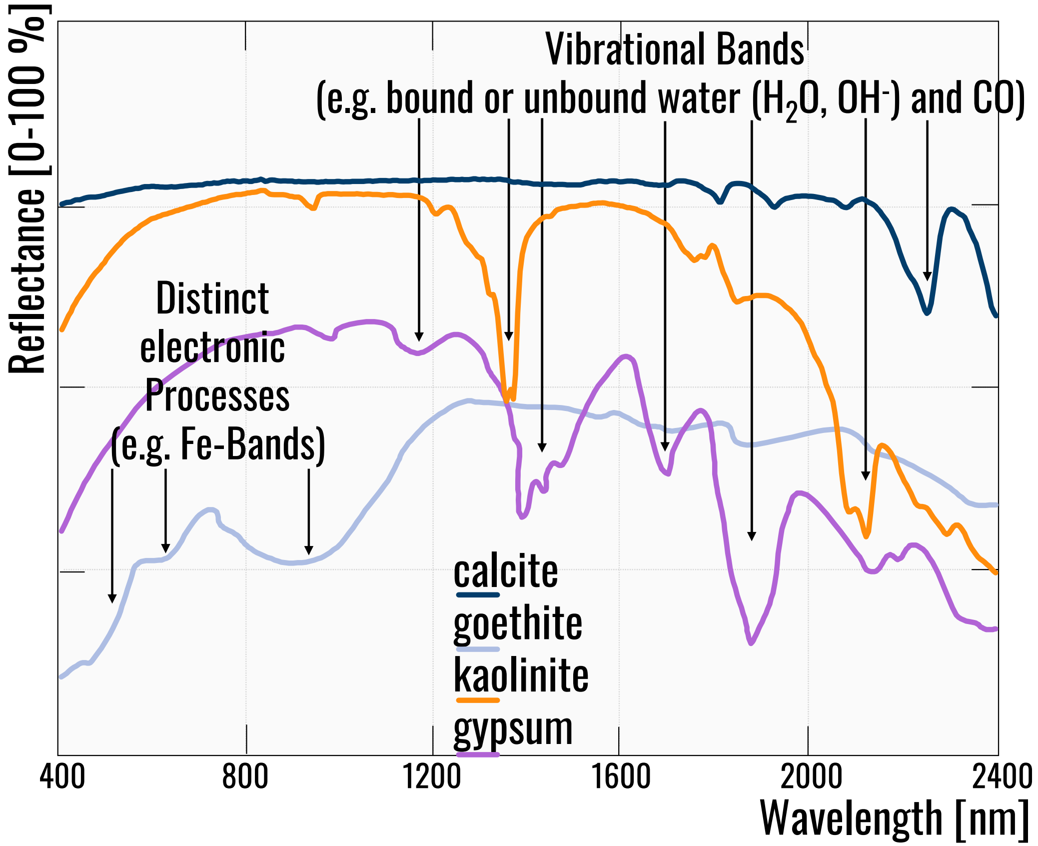
Pigments, minerals, man made objects ...

shape position → identification

depth → quantification

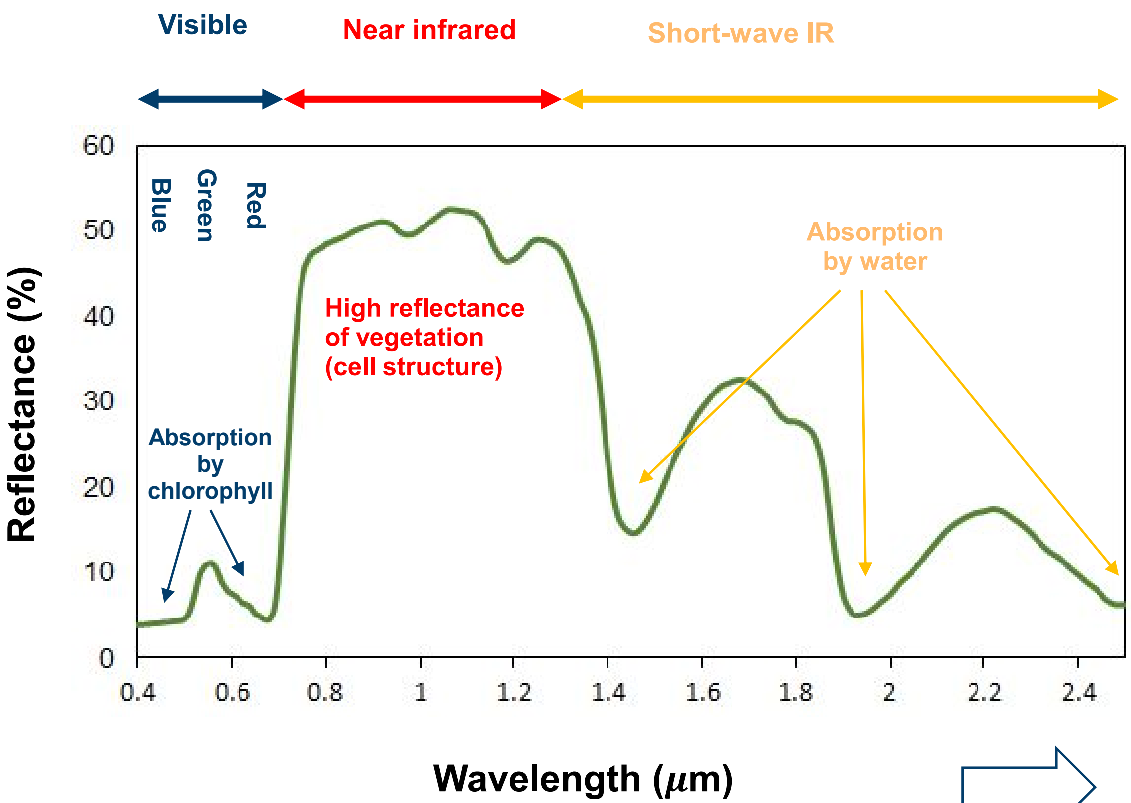
Visible and Near IR remote sensing

Reflectance of distinct minerals

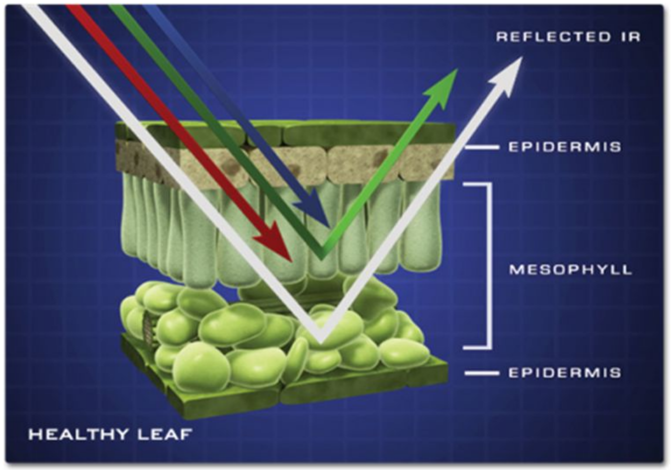


Visible and Near IR remote sensing

Spectral signature of vegetation

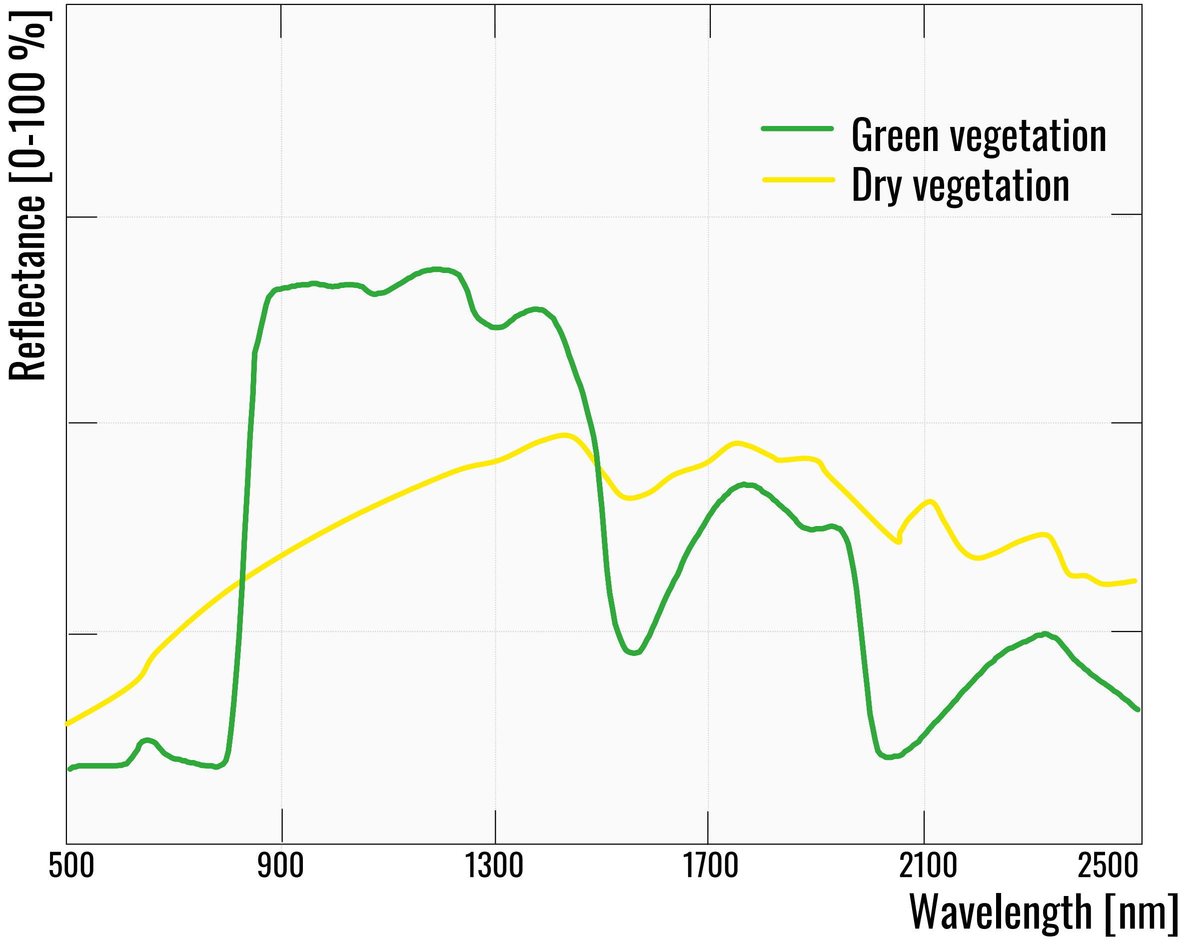


- The chlorophyll in the leaves strongly absorbs radiation at red and blue wavelengths, but reflects green radiation
- The internal structure of healthy leaves acts as an excellent reflector for infrared wavelengths.
- Infrared: an indicator of the health of vegetation



Selection based on the property to estimate

Reflectance of vegetation



Stipa *(Stipa tenacissima)*, Cabo de Gata, Spain

Visible and Near IR remote sensing

Moderate Resolution Imaging Spectroradiometer (MODIS)

onboard NASA's Terra (1999-…) and Aqua (2002-…) satellites

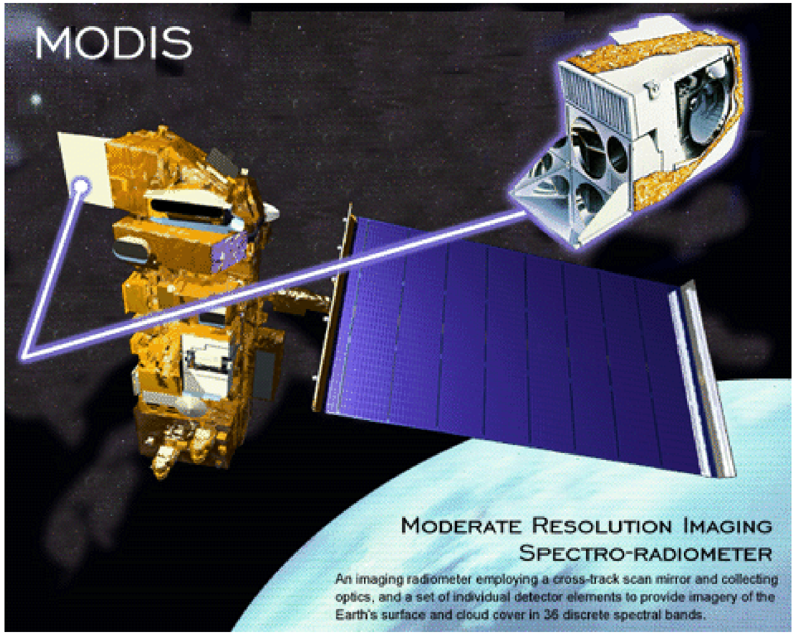
MODIS has 36 spectral bands ranging in wavelength from 0.4 µm to 14.4 µm and at varying spatial resolutions: 2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km.

Together the instruments image the entire Earth every 1 to 2 days

e.g., MCD15A2H Version 6.1 MODIS Level 4

- *Fraction of Photosynthetically Active Radiation (FPAR) and Leaf Area Index (LAI) product*
- *8-day composite dataset with 500 m pixel size*
- *The algorithm chooses the best pixel available from all the acquisitions of both MODIS sensors located on NASA's Terra and Aqua satellites from within the 8-day period*

-> Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard the NOAA's Suomi NPP satellite and the future NOAA's JPSS satellites



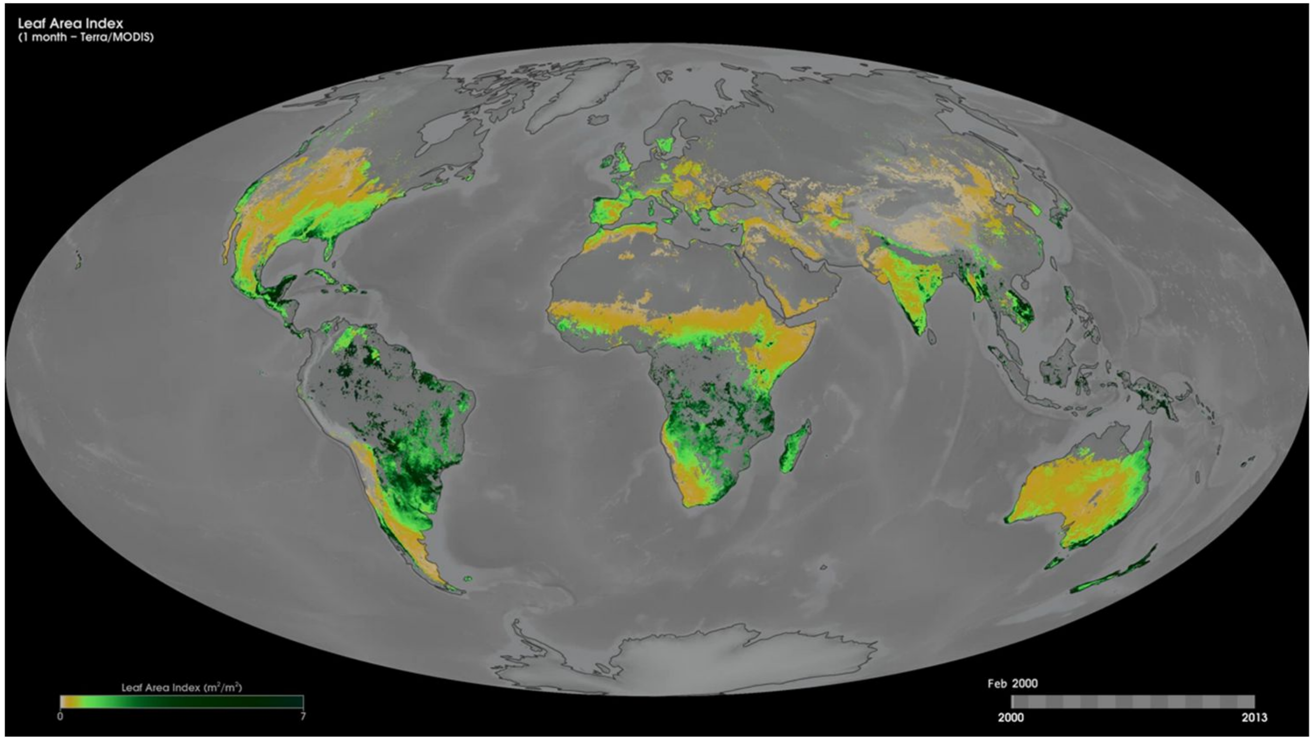
Visible and Near IR remote sensing

Moderate Resolution Imaging Spectroradiometer (MODIS)

onboard NASA's Terra (1999-…) and Aqua (2002-…) satellites

Monthly leaf area index using MODIS data

February 2000 to 2013

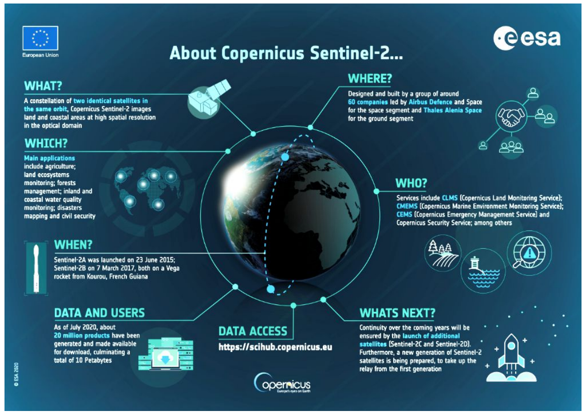


Knowing the total area covered by leaves helps scientists monitor how much water, carbon, and energy the trees and plants are exchanging with the air above and the ground below.

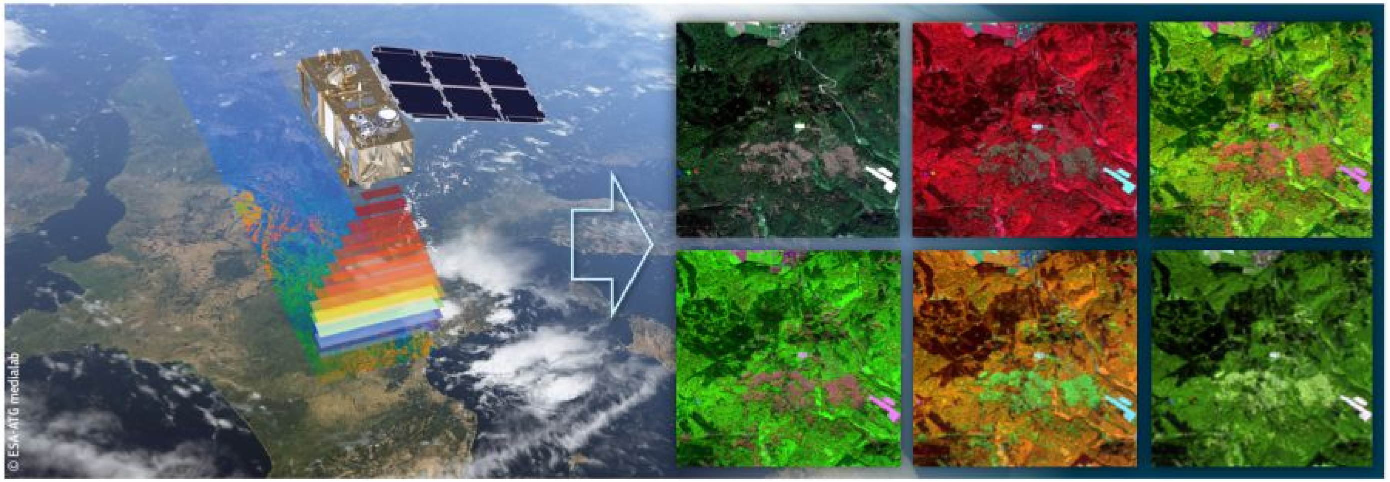
http://neo.sci.gsfc.nasa.gov/Search.html?datasetId=MOD15A2_M_LAI

Visible and Near IR remote sensing

ESA Sentinel 2 A/B



- Optical sensor with 13 channels - distributed in the EM spectrum from visible light via near-infrared to short-wave infrared (approx. 440-2200 nm)
- Ground resolution: 10-60 m per pixel
- High temporal coverage (every 10 days for 1 satellite, 5 days with 2 satellites, in higher latitudes also every 2-3 days)
- The swath width of 290 km is larger than that of Landsat 8 (185 km) or SPOT (120 km). Sentinel-2 images (tiles) have a size of 100 x 100 km.



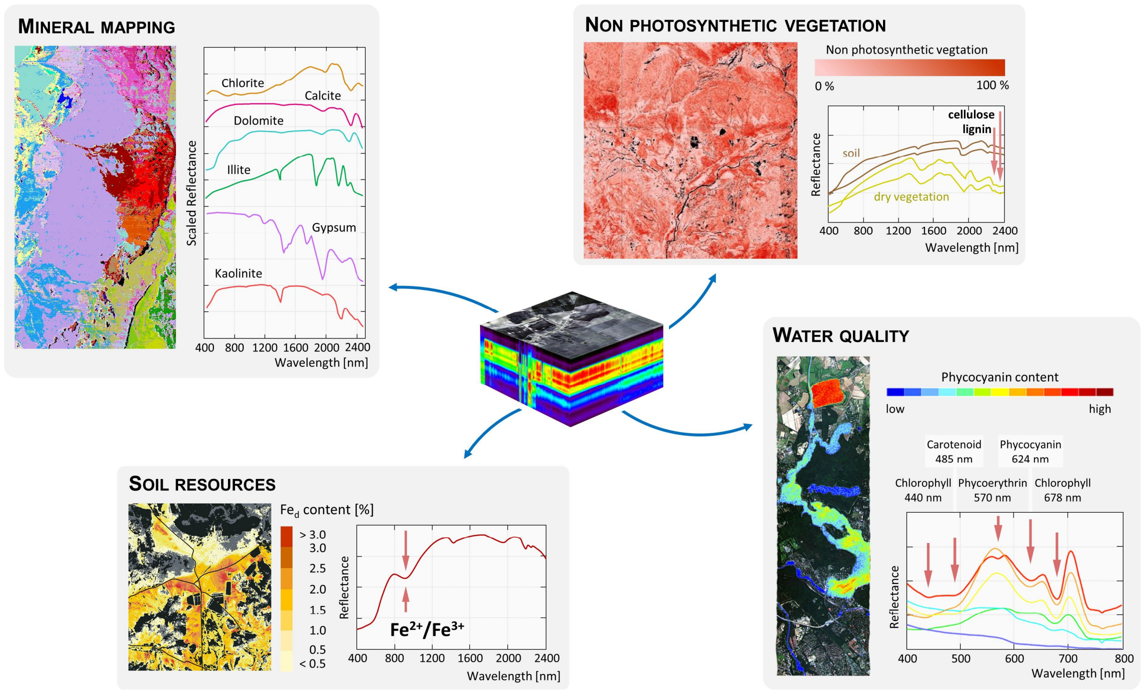
Hyperspectral Remote Sensing

Hyperspectral imaging (HSI) systems

❖ More than three decades of effort have been devoted to the development of imagers capable of acquiring contiguous spectra in different wavelength regions, thereby permitting precise and quantitative analysis of terrestrial and aquatic ecosystems.

❖ These **imaging spectrometers** have primarily been flown in **aircrafts** for experimental and commercial purposes:

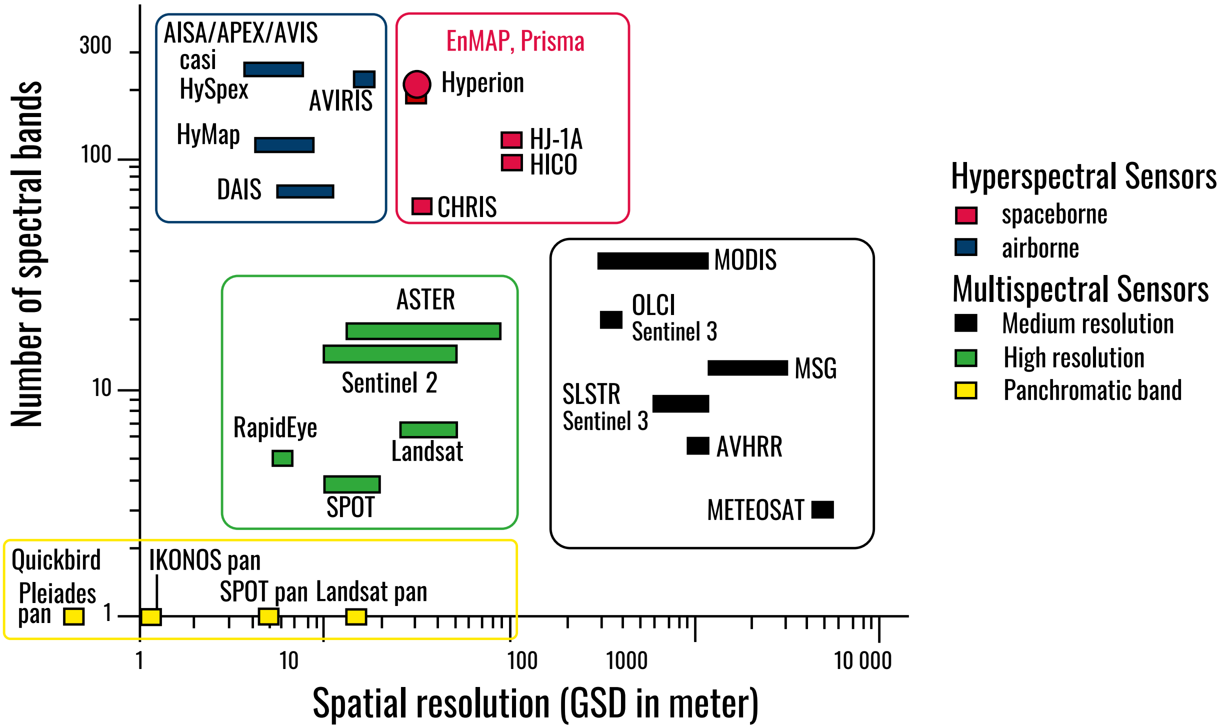
❖ However, data acquisition from an aircraft platform cannot provide a synoptic view of extended areas and repeated acquisitions are costly.



Hyperspectral Remote Sensing

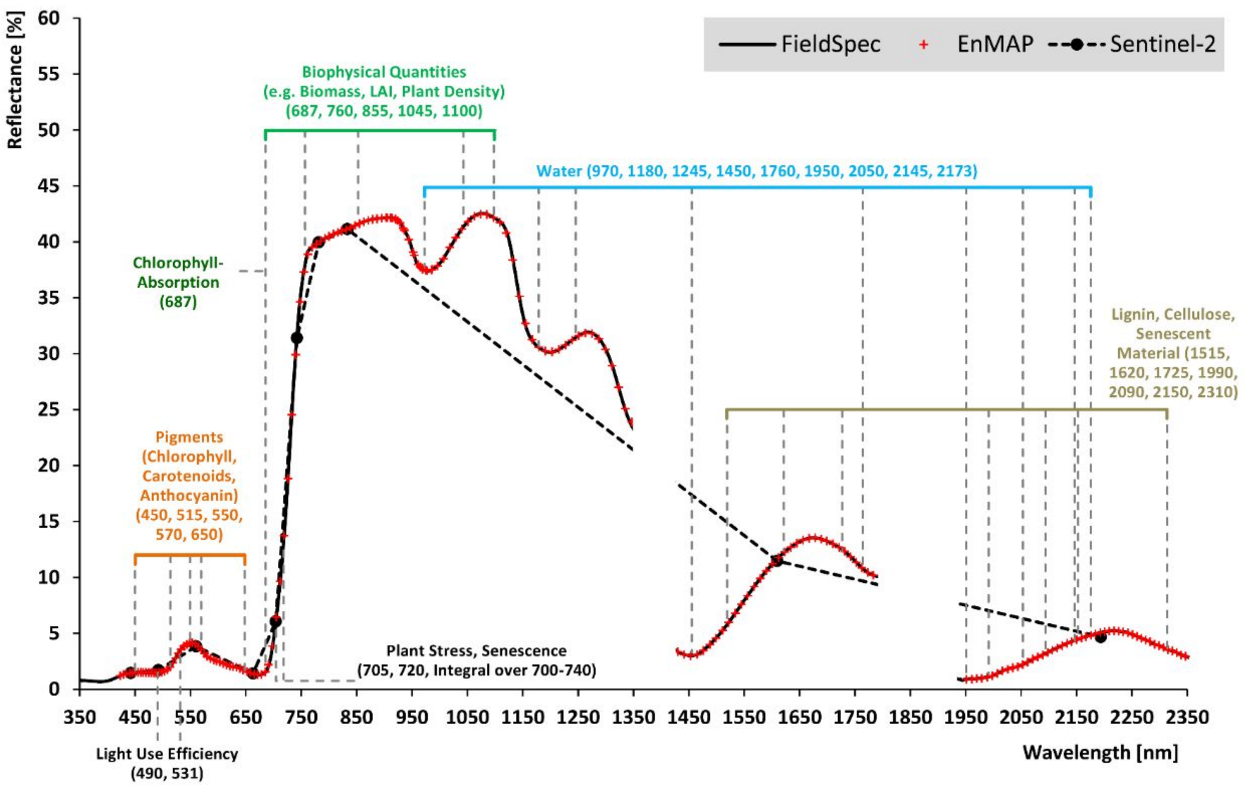
Spatial and spectral resolutions of selected EO sensors

A new generation of spaceborne hyperspectral (imaging spectroscopy) missions is underway



Hyperspectral Remote Sensing for Land Monitoring

Why should we prefer hyperspectral sensors over multispectral systems?



Spectral signature of common wheat (*Triticum aestivum*)

Image reprinted from Hank et. al. (2019)

Enhanced information content from hyperspectral data (e.g., from EnMAP – red crosses) opposed to multispectral sensing (e.g., from Sentinel 2 – black dashed line)

Hyperspectral Remote Sensing for Land Monitoring

Technology demonstrator and scientific precursor missions

PRISMA: PRecursore IperSpettrale della Missione Applicativa

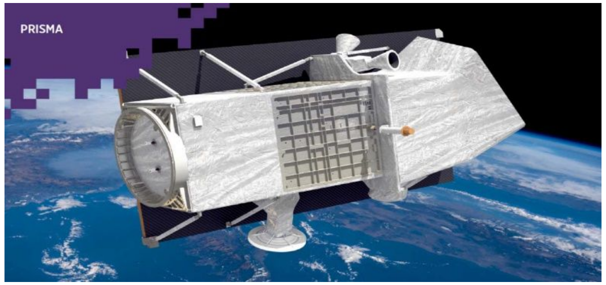


Image reprinted from ASI (2020)

The Italian mission aims to offer data for multiple applications within environmental monitoring and resources management, among those agriculture. PRISMA combines an hyperspectral sensor with a medium-resolution panchromatic camera. This combination offers the advantages of conventional earth observation by recognizing the geometric characteristics of a landscape.

EnMAP: Environmental Mapping and Analysis Program

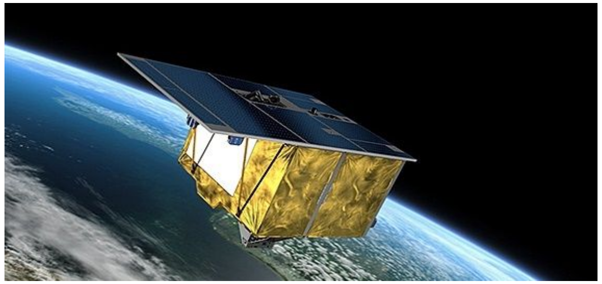


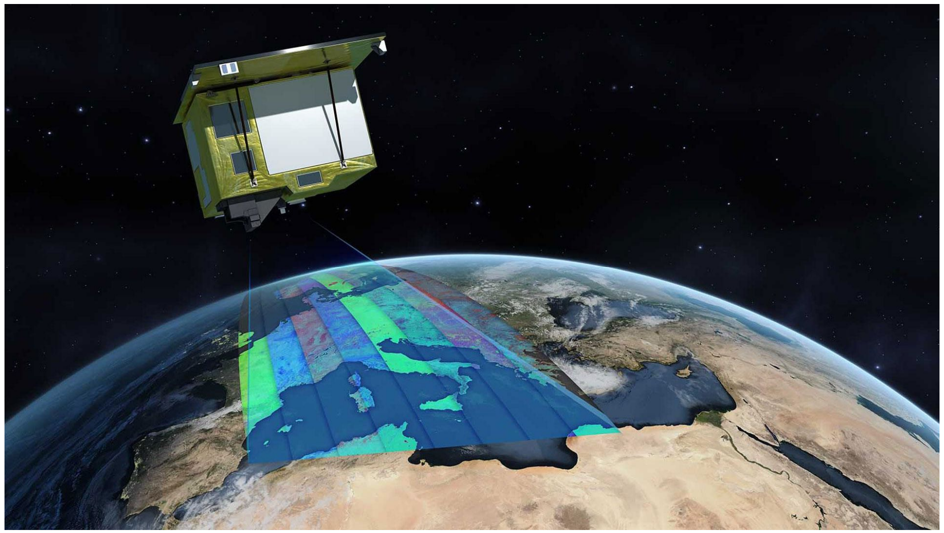
Illustration of EnMAP satellite with permission from DLR Space Agency

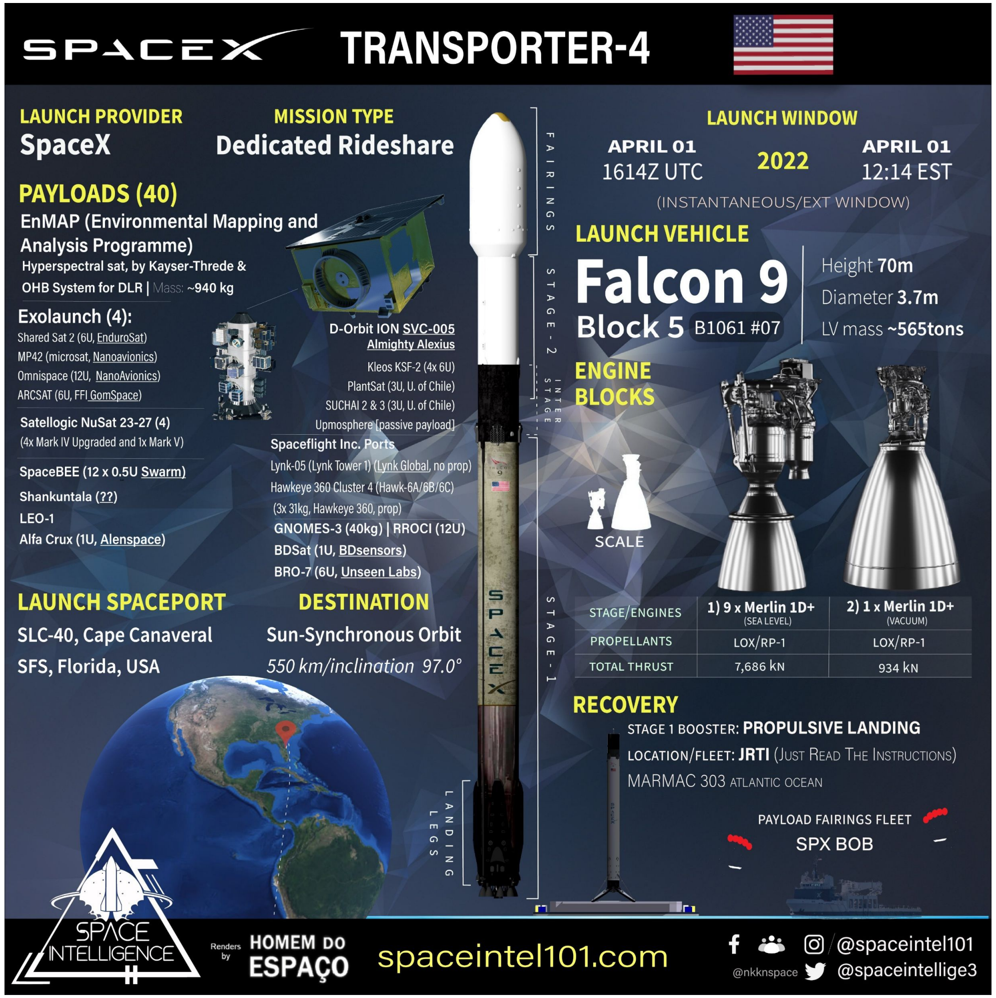
The German hyperspectral satellite mission that aims at monitoring and characterising Earth's environment on a global scale. EnMAP measures and models key dynamic processes of Earth's ecosystems by extracting geochemical, biochemical and biophysical variables that provide information on the status and evolution of various terrestrial and aquatic ecosystems. See also: https://www.enmap.org/mission

EnMAP launched on April 1st, 2022

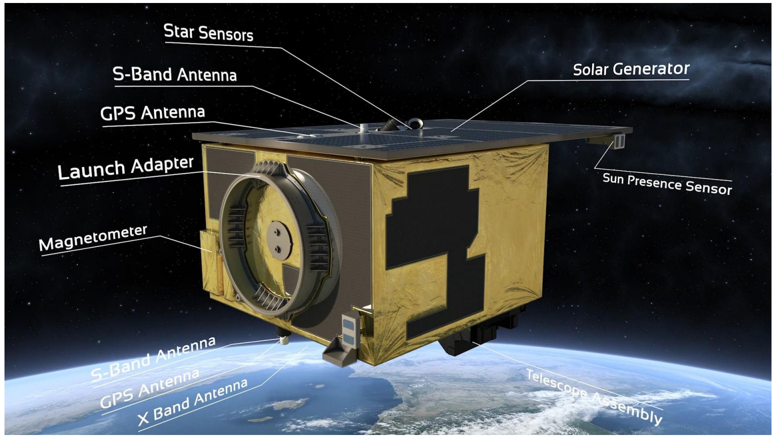
Allowing us to see the invisible - EnMAP will deliver high-quality environmental data. The German hyperspectral mission will provide insights into the extent of ecosystems in numerous natural habitats as well as their properties

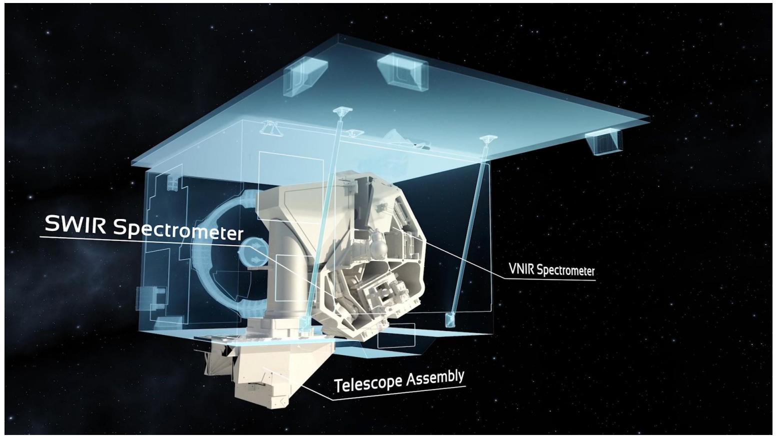
SpaceX's second small satellite dedicated rideshare mission of 2022, and 4th overall, with 40 mini/micro international payloads (microsatellites, CubeSats, picosatellites), launching onboard the Falcon 9 from Cape Canaveral in Florida.

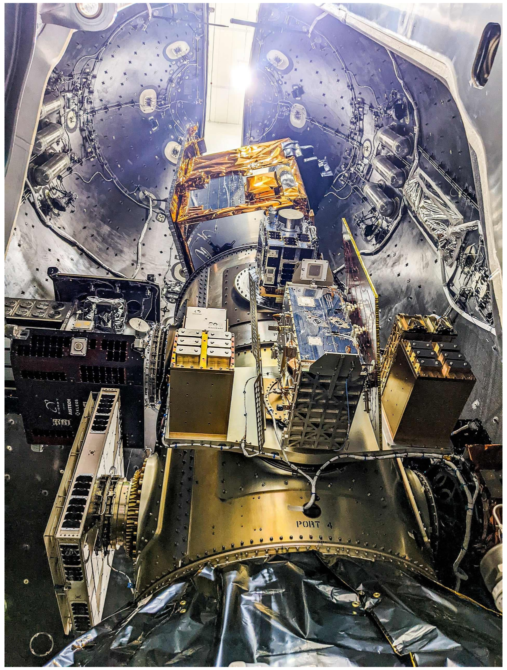




EnMAP launched on April 1st, 2022







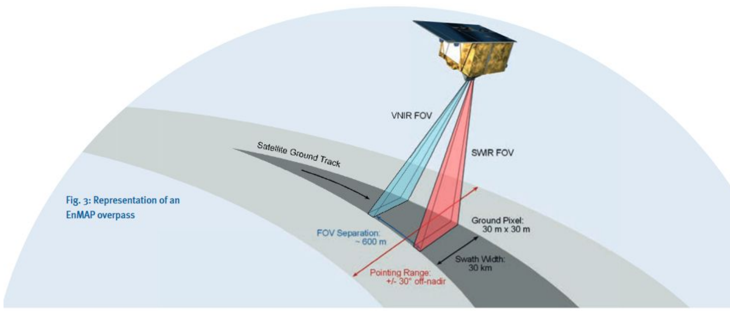


Fig. 3: Representation of an EnMAP overpass

Orbit characteristics		
Orbit / Inclination	sun-synchronous / 97.96°	
Target revisit time	27 days (VZA ≤ 5°) / 4 days (VZA ≤ 30°)	
Equator crossing time	11:00 h ± 18 min (local time)	
Instrument characteristics	***VNIR***	***SWIR***
Spectral range	420 - 1000 nm	900 - 2450 nm
Number of bands	88	154
Spectral sampling interval	6.5 nm	10 nm
Spectral bandwidth (FWHM)	8.1 ± 1.0 nm	12.5 ± 1.5 nm
Signal-to-noise ratio (SNR)	› 400:1 @495 nm	› 170:1 @2200 nm
Spectral calibration accuracy	0.5 nm	1 nm
Ground sampling distance	30 m x 30 m (at nadir; sea level)	
Swath width	30 km (field-of-view = 2.63° across track)	
Swath length	1000 km/orbit - 5000 km/day	

Hyperspectral Remote Sensing for Land Monitoring

Hyperspectral data analysis

Radiative transfer model (RTM) Inversion

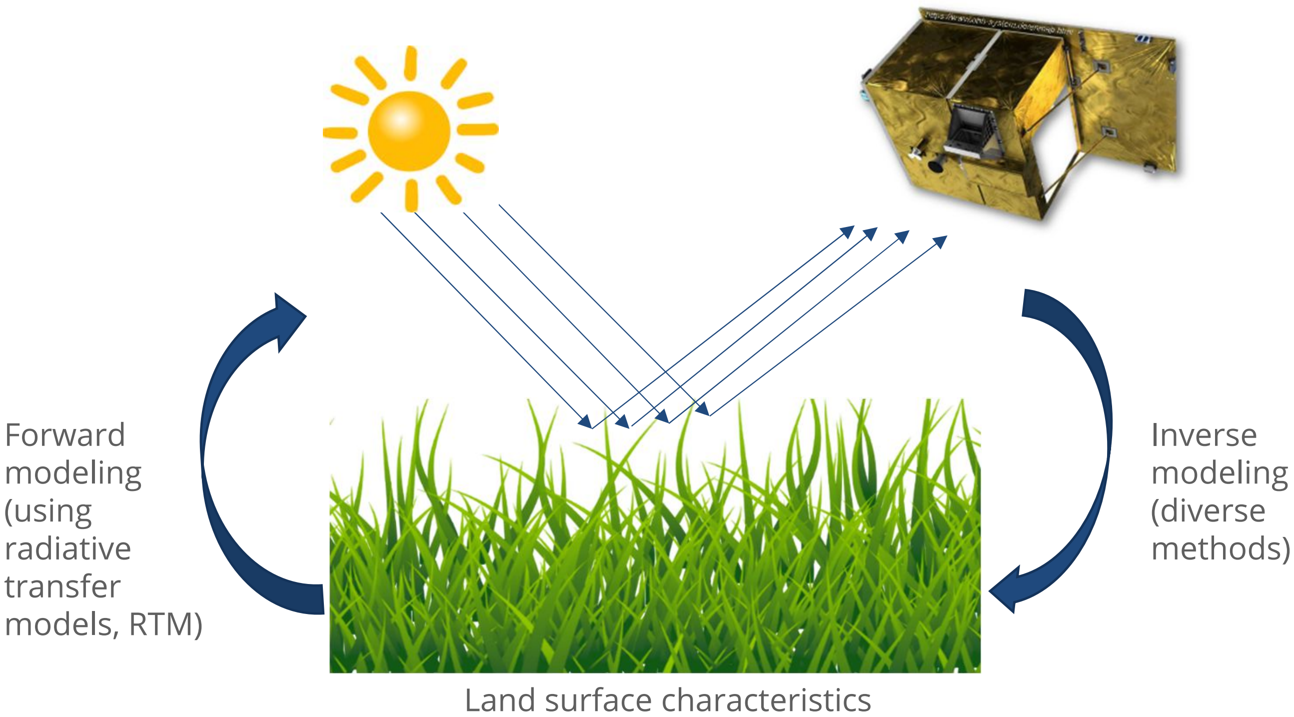


Illustration of the EnMAP satellite with permission from DLR Space Administration

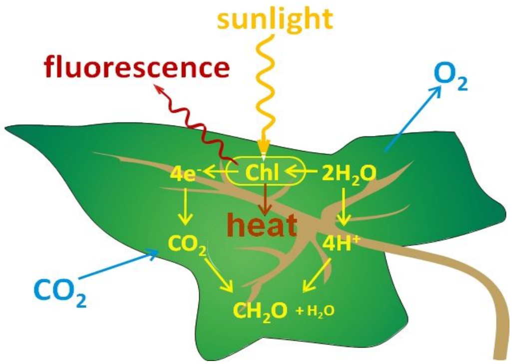
- Forward modelling creates spectra from input parameters
- To derive parameters from measured spectra, model inversion is needed.
- Major classes of inversion strategies are Numerical Optimization and Look up Table (LUT) based inversion (Buddenbaum & Hill 2015) and Neural Networks (Schlerf & Atzberger 2006).
- All suffer from the ill-posedness of the inversion problem: Very similar spectra can be created with vastly different input parameters, especially in models with many parameters.
- In addition, models are not perfect, and neither are measured spectra.

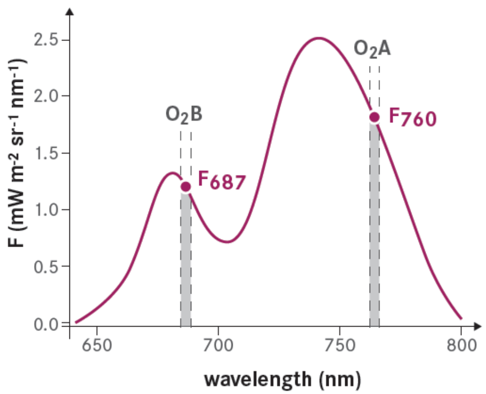
Hyperspectral Remote Sensing for Land Monitoring

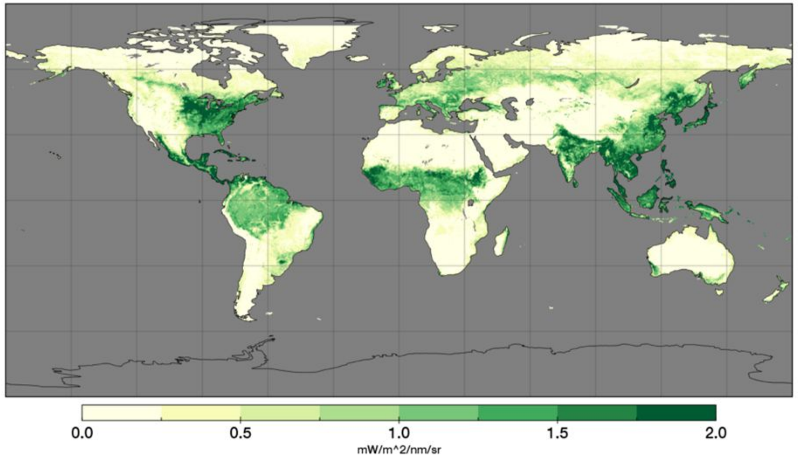
Ecosystem Health

Sun-induced fluorescence (SIF) from ESA Sentinel-5P

- Emission of Chlorophyll Fluorescence
- Indicator of photosynthetic activity
- Early detection of stress in vegetation







Average global observation of sun-induced chlorophyll fluorescence (SIF, mW m^{-2} nm^{-1} sr^{-1}) at 740 nm from TROPOMI and for August 2018

Jonard et al. *Agric. For. Meteorology* 2020

Hyperspectral Remote Sensing for Land Monitoring

Applications in Forestry

Hyperspectral remote sensing is well-suited for answering some pressing questions about forests:

- Some forest state variables like Nitrogen content can be measured at much higher precision with hyperspectral imaging systems than with multispectral data.
- Estimations of Pigments like carotenoids and anthocyanins require narrow hyperspectral bands.
- Information on Photosynthesis by combining several remote sensors (see FLEX mission design)
- Forest health can be estimated using the detailed spectral information of hyperspectral sensors.
- Plant functional type and trait diversity mapping benefit from high spectral resolution data.
- High spectral resolution also helps in tree species classification.

Hyperspectral Remote Sensing for Land Monitoring

Applications in Agriculture – Precision farming

Precision agriculture (PA) application fields:

- ❖ Crop monitoring
- ❖ Irrigation management
- ❖ Nutrient application
- ❖ Disease and pest management
- ❖ Yield prediction

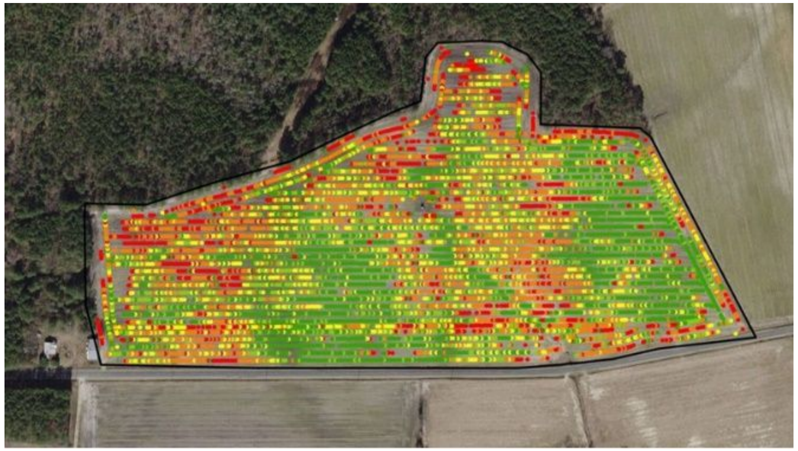


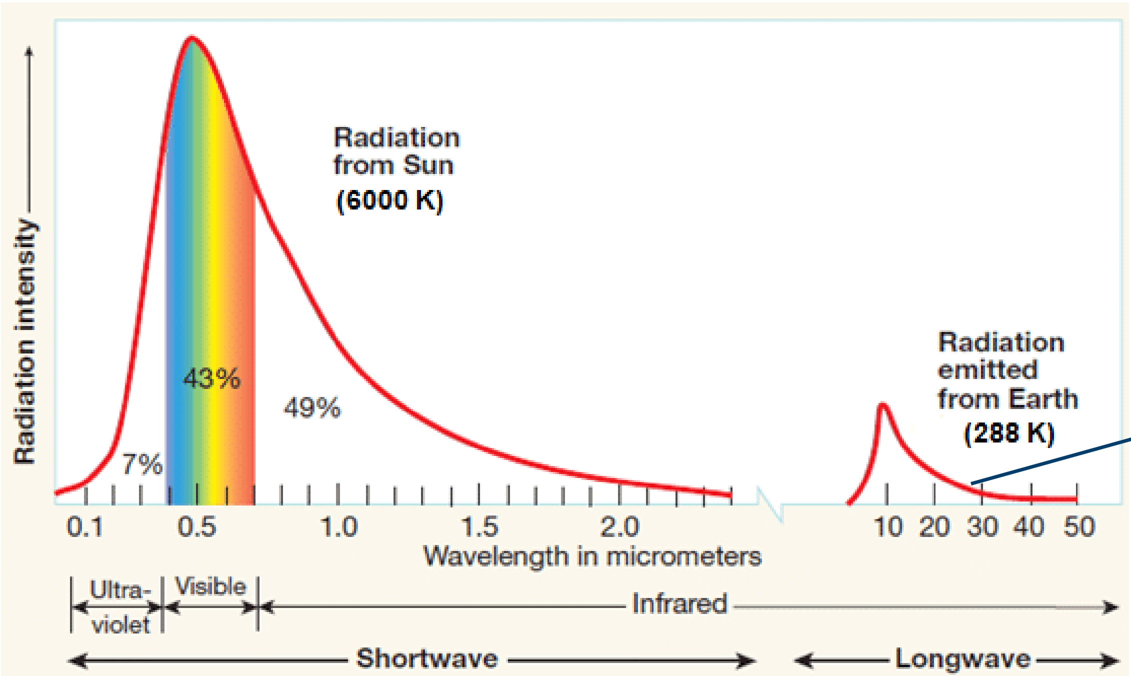
Image reprinted from Austin, R. (2019)

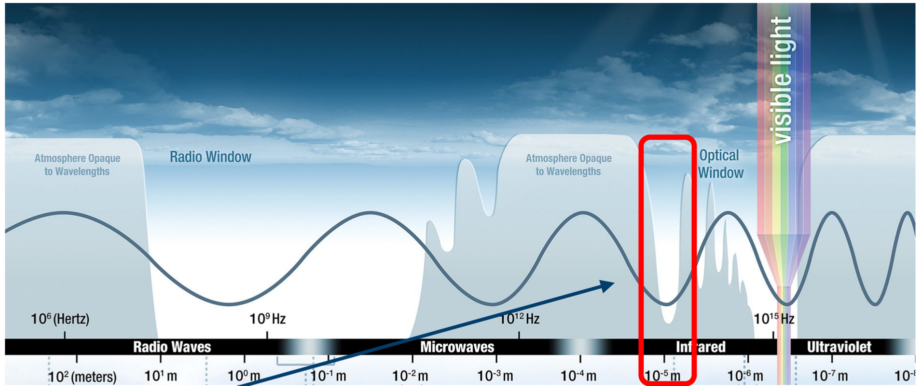
Mainly vegetation indices are being used in PA (NDVI, REIP). There is a strong potential for more advanced methods, such as machine learning or hybrid methods (Verrelst et al., 2019) to be implemented in retrieval workflows for precision farming management.

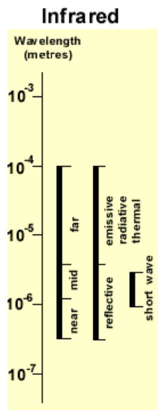
Thermal Infrared Remote Sensing

Thermal IR Remote Sensing

Thermal emission from the Earth's surface







Thermal infrared (TIR):
wavelengths from 3 µm-15 µm

Thermal IR Remote Sensing

Spaceborne TIR sensors

- Essentially the same design as the VIS/NIR
- Many satellite systems incorporate a TIR channel:
  - NASA Landsat 4-9 satellites (1982 -)
  - ESA Envisat satellite (2002 – 2012; one of *the largest space debris in orbit around the Earth*)
  - ESA Sentinel-3 A/B satellites (2016 -)

Thermal IR Remote Sensing

Sentinel-3 - Sea and Land Surface Temperature Radiometer (SLSTR)

SLSTR measures sea surface temperature, land surface temperature, sea-ice and land ice temperature, atmospheric aerosols, cloud properties and fire radiative power

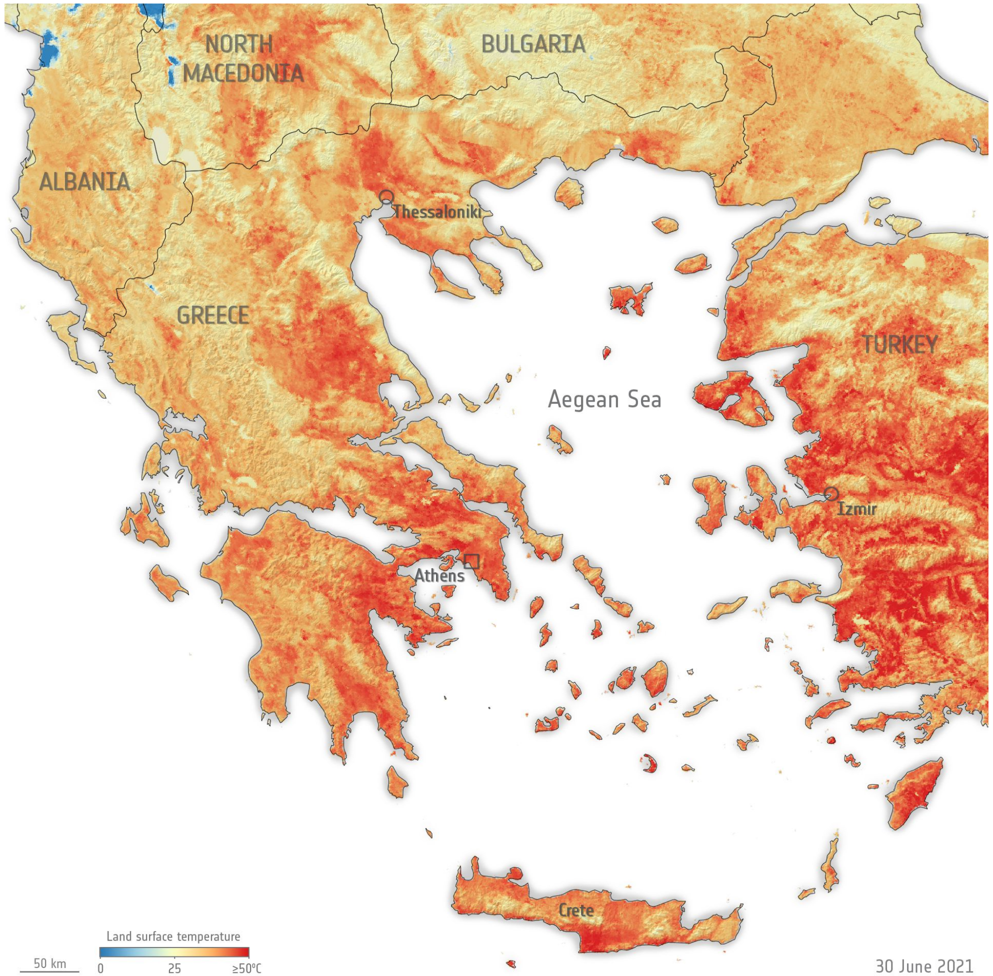
- Swath width: dual view scan, 1420km (nadir)/750km (backwards).
- Spatial sampling: 500m (VIS, SWIR), 1km (MWIR, TIR).
- Spectrum: 9 bands [0.55-12] µm.
- Noise equivalent dT: 50mK (TIR) at 270K.
- Launch mass: 90kg.
- Size: 2.116m3.
- Design lifetime: 7.5 years

Thermal IR Remote Sensing

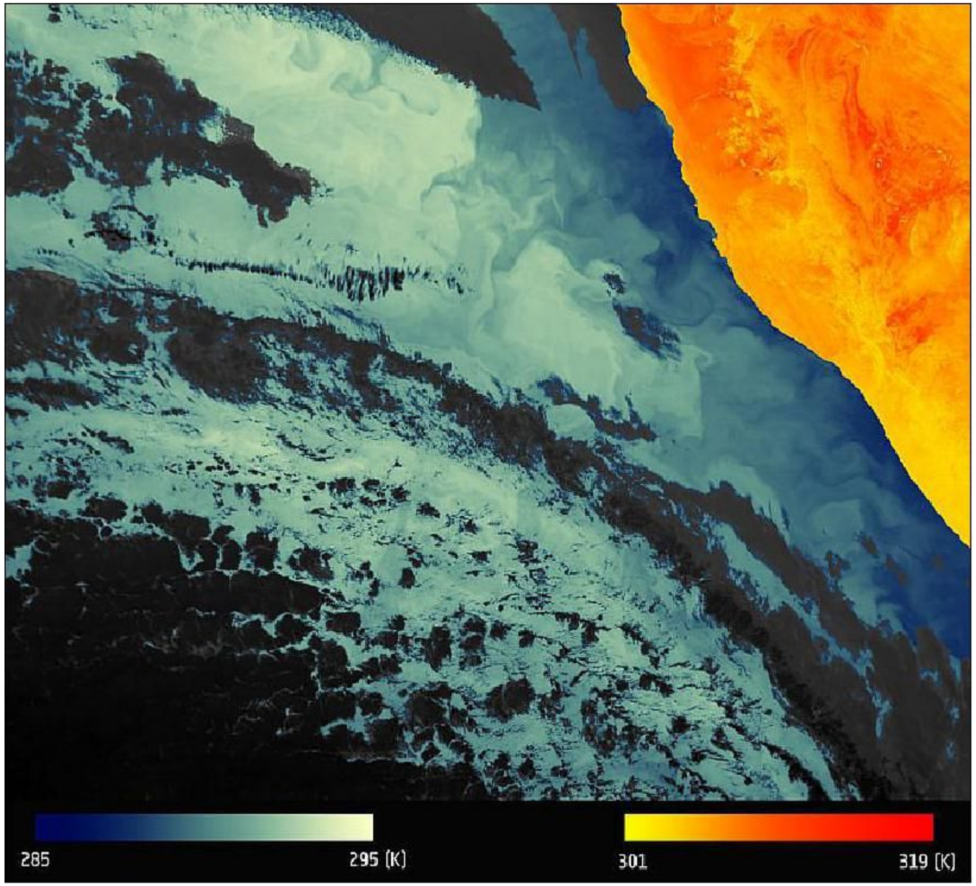
Mediterranean heatwave

This map shows the land surface temperature of Greece and surrounding countries on 30 June. The data show that surface temperatures reached over 50°C in many locations including the northwest of Athens and many regions in Turkey. The blue spots visible near Albania are clouds.

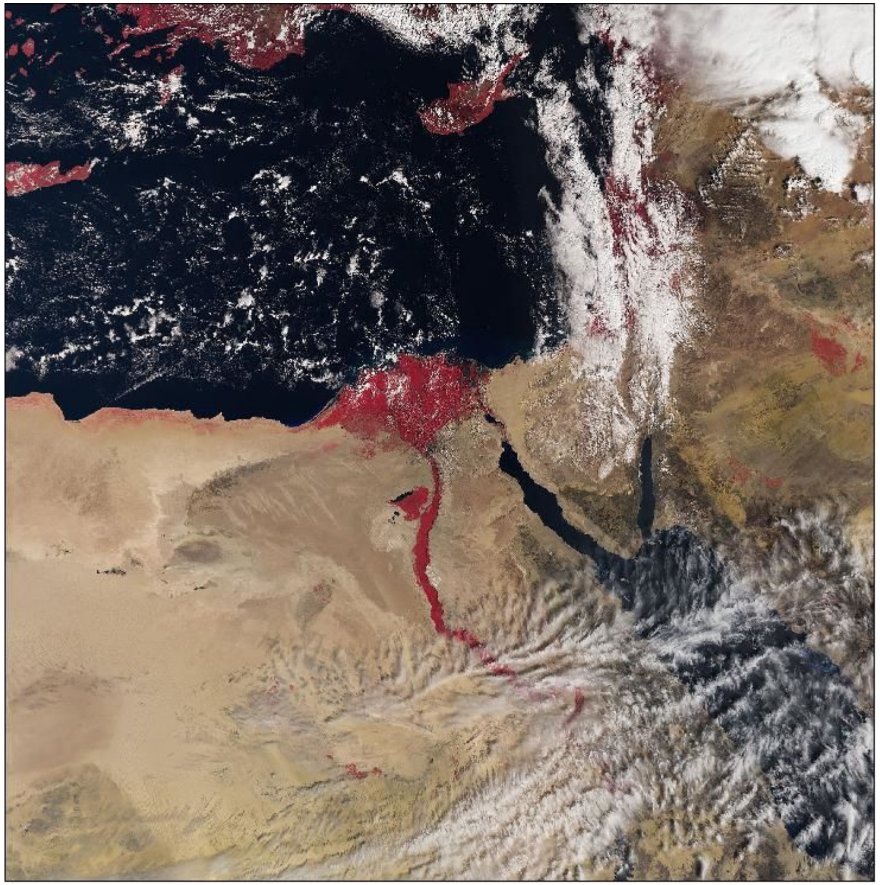
The map has been generated using the Copernicus Sentinel-3's Sea and Land Surface Temperature Radiometer. Whereas weather forecasts use predicted air temperatures, the satellite measures the real amount of energy radiating from Earth – therefore this map better represents the real temperature of the land surface.



Thermal IR Remote Sensing



Thermal signature of the Namibian coastline observed by SLSTR on Sentinel-3A (image credit: ESA, the image contains modified Copernicus Sentinel data (2016))

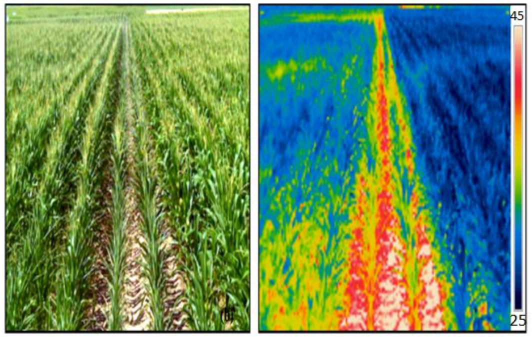


This SLSTR (Sea and Land Surface Temperature Radiometer) image of Sentinel-3A was acquired on March 3, 2016 showing the River Nile and the extensive Nile Delta (image credit: ESA, the image contains modified Copernicus Sentinel data [2016], processed by ESA)

Thermal IR Remote Sensing

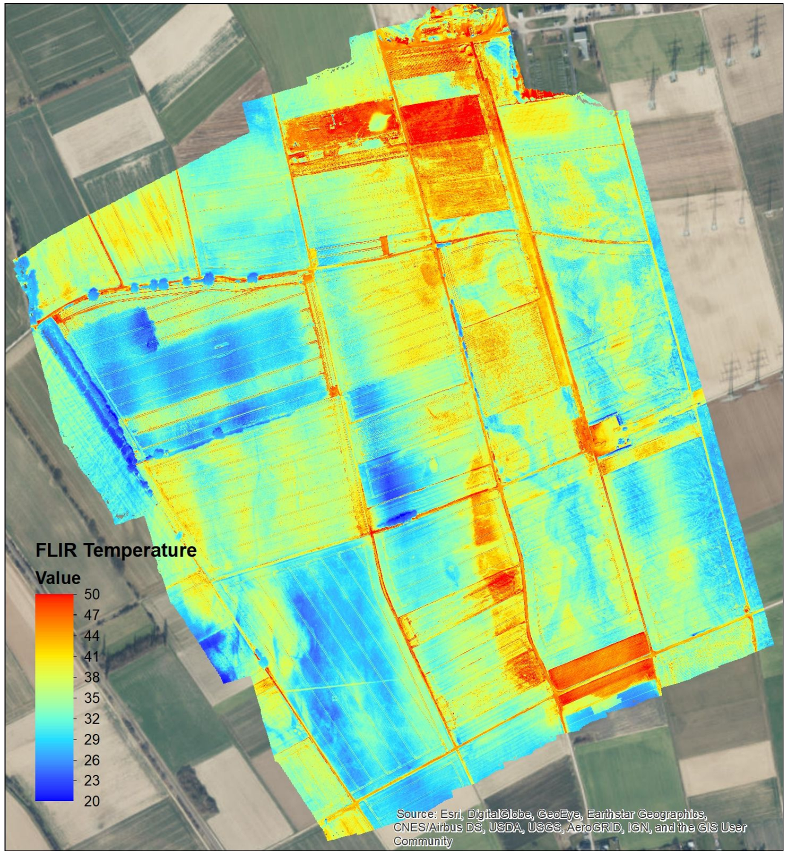
Vegetation surface temperature --> f (stress)

Early detection of plant stress: a major issue in agriculture



Many sources of error

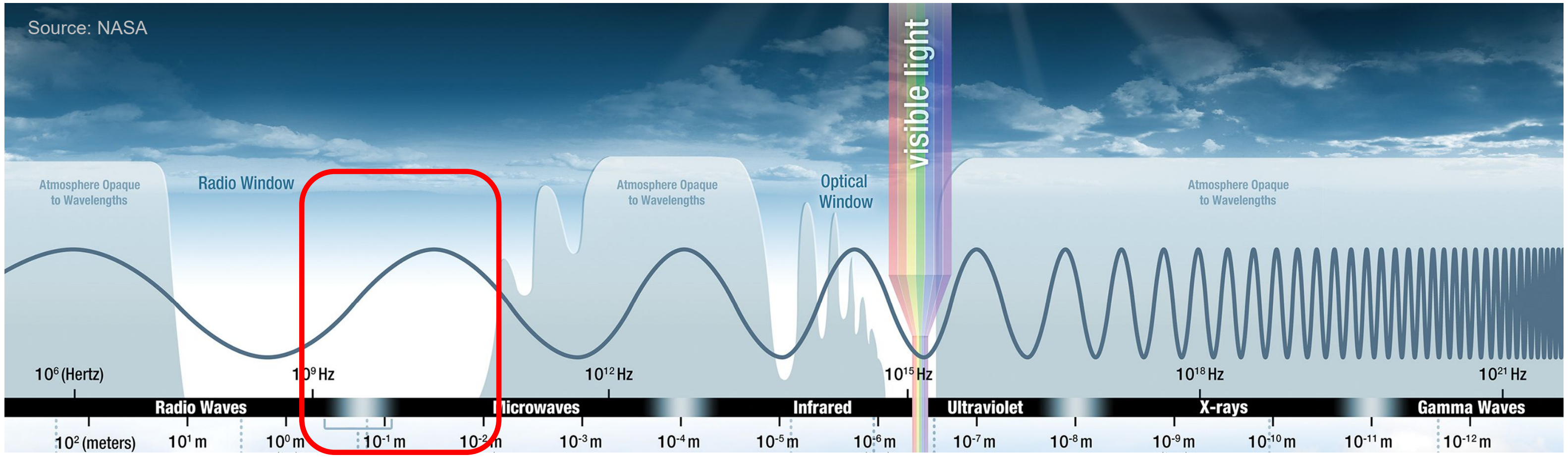
Thermal bands are used to measure the surface temperature of soils, vegetation, buildings, oceans, clouds, etc.



Experimental site of the Research Centre Jülich, Germany - 2019

Microwave Remote Sensing

Microwave Remote Sensing



Advantages

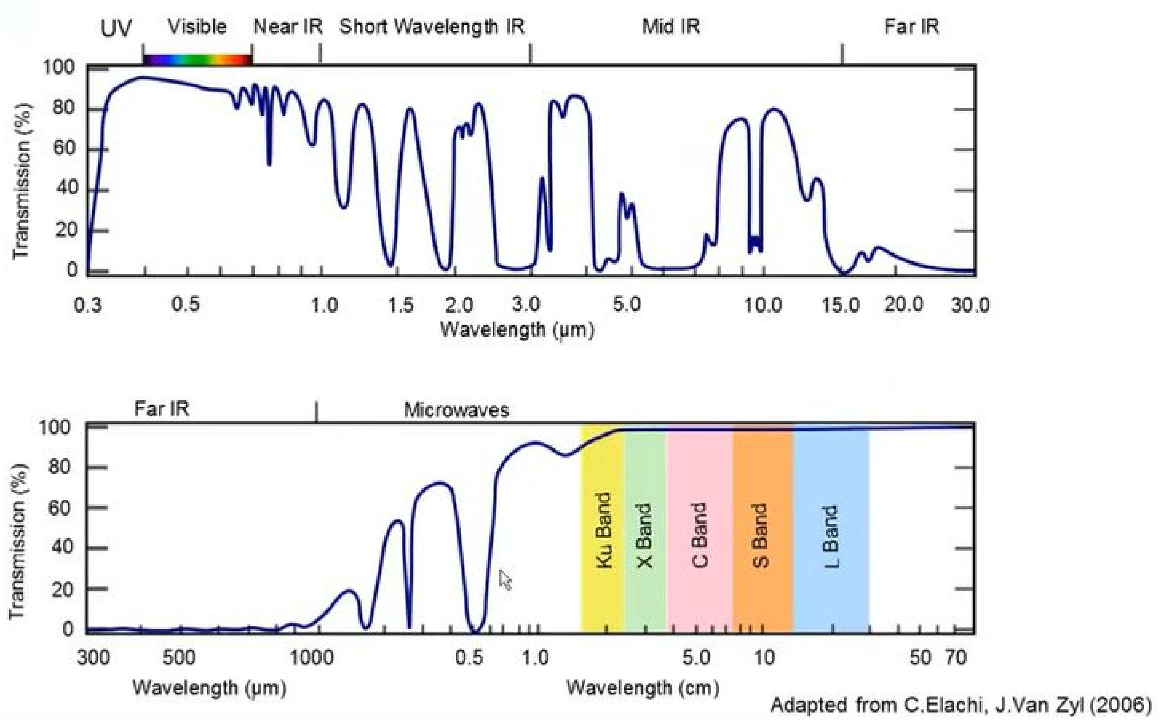
- Nearly all-weather capability (microwaves can penetrate clouds and rain)
- Day or night observations
- Penetration through the vegetation canopy
- Penetration through the soil
- Minimal atmospheric effects
- Sensitivity to dielectric (intrinsic) properties
- Sensitivity to geometric (shape, 3D structure) properties

Disadvantages

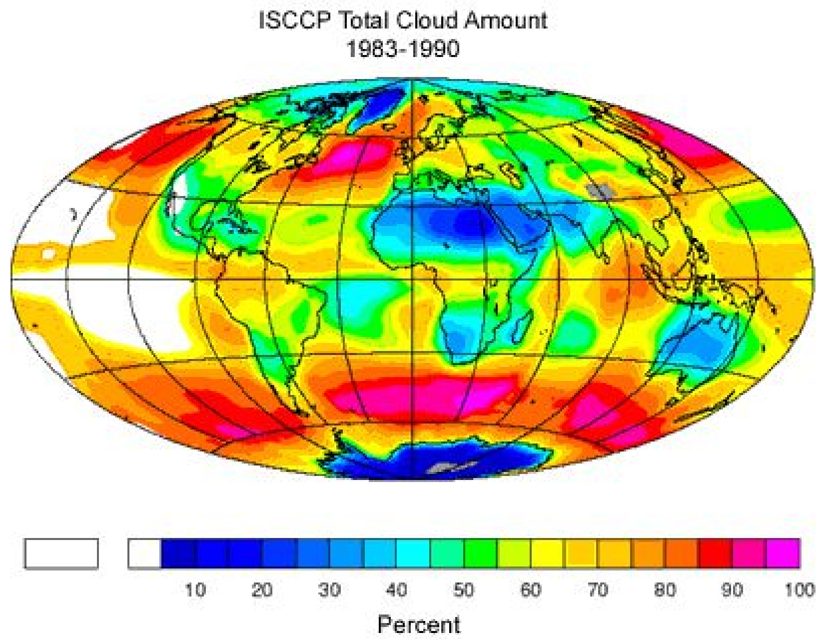
- Information content is different than optical and sometimes difficult to interpret
- Speckle effects (graininess in the image)
- Effects of topography

Microwave Remote Sensing

Atmospheric attenuation of microwave bands



Earth atmospheric transmissivity of the EM spectrum at Zenithal direction (in clear sky conditions)



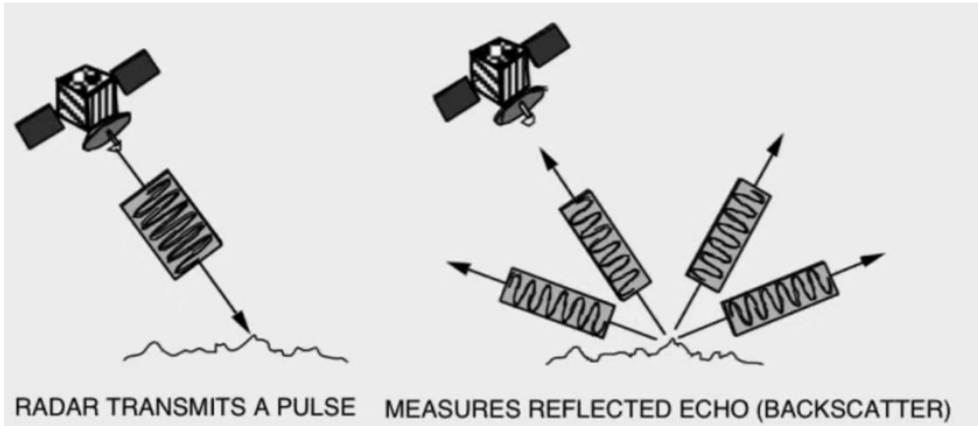
Total fractional cloud cover annual averaged from 1983-1990. Image credit: NASA

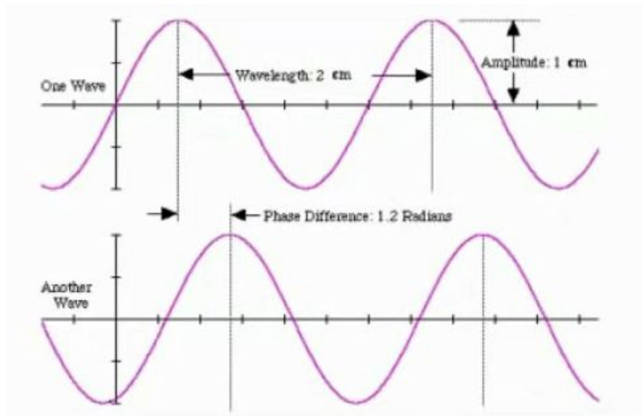
Microwave Remote Sensing

Active Systems: Radar – Radio Detection And Ranging

Review of Radar Image Formation

- Radar can measure amplitude (the strength of the reflected echo) and phase (the position of a point in time on a waveform cycle)
- Radar can only measure the part of the echo reflected back towards the antenna (backscatter)
- Radar pulses travel at the speed of light
- The strength of the reflected echo is the backscattering coefficient (sigma naught) and is expressed in decibels (dB)





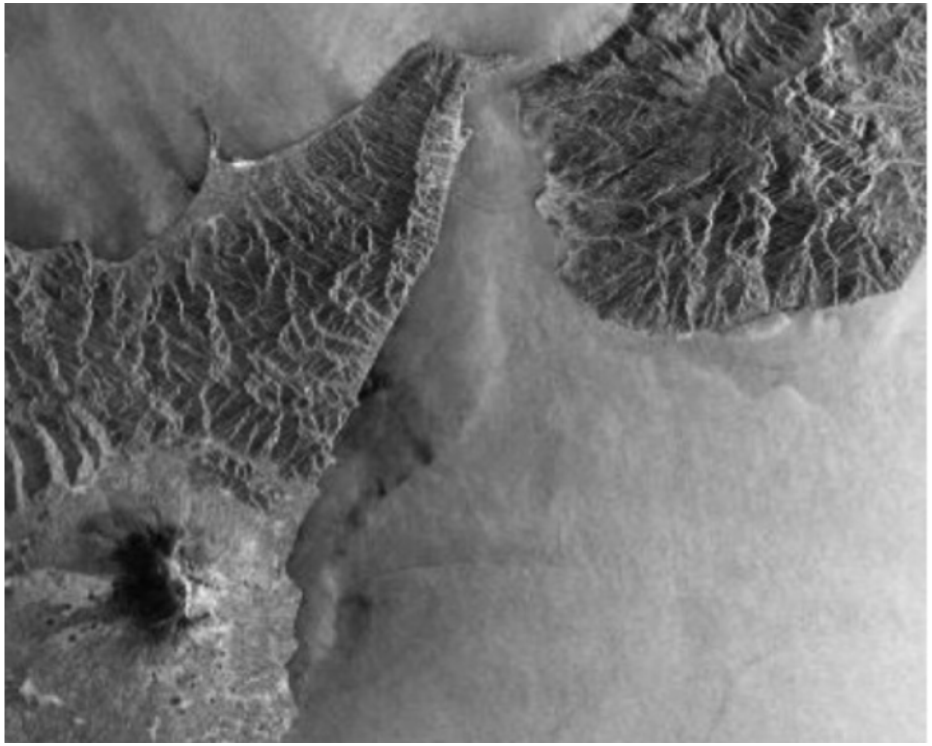
Source: ESA-ASAR Handbook

Microwave Remote Sensing

Capability to “observe” even in presence of clouds

Optical Image

Radar (SAR) Image



Same time of acquisition

De Luca, C. 2017

Microwave Remote Sensing

Microwaves can volcanic ash clouds

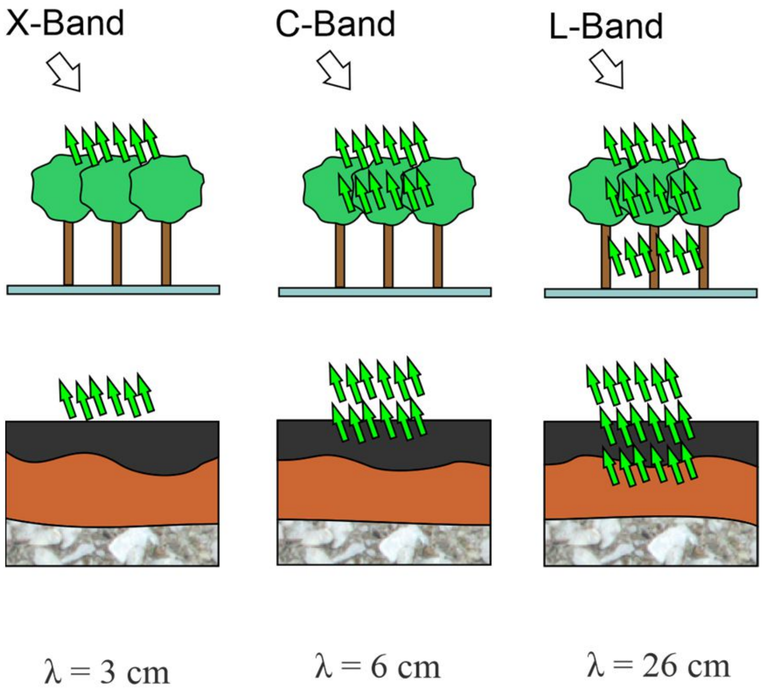
Optical Image **Radar (SAR) Image**

Volcano in Kamchatka, Russia, Oct 5, 1994

Image Credit: Michigan Tech Volcanology

Microwave Remote Sensing

Microwave wavelengths and applications



Relationship between emission depth and wavelength

L-band measurements can achieve a higher canopy penetration and soil sensing depth than X-band

Commonly Used Frequency Bands

Frequency band	*Frequency range*	*Application Example*
• VHF	300 KHz - 300 MHz	Foliage/Ground penetration, biomass
• P-Band	300 MHz - 1 GHz	biomass, soil moisture, penetration
• L-Band	1 GHz - 2 GHz	agriculture, forestry, soil moisture
• C-Band	4 GHz - 8 GHz	ocean, agriculture
• X-Band	8 GHz - 12 GHz	agriculture, ocean, high resolution radar
• Ku-Band	14 GHz - 18 GHz	glaciology (snow cover mapping)
• Ka-Band	27 GHz - 47 GHz	high resolution radars

Microwave Remote Sensing of Soil Moisture

Soil Moisture Active and Passive (SMAP) satellite – NASA (2015-…)

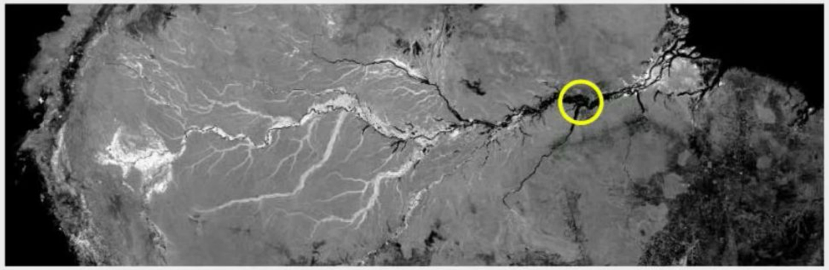
The objective of SMAP is to optimally combine the complementary sensitivities of passive and active L-band signals with respect to soil moisture and vegetation/soil surface roughness and the different spatial resolutions of the sensors

- ❑ Instruments:
- - L-band radiometer

  Operated at 1.41 GHz - Spatial resolution: 30 km
- - Synthetic aperture radar (SAR) - *(failed in 2015)*

  Operated at 1.26 GHz - Spatial resolution: 1-3 km
- ❑ Orbit: 685 km
- ❑ Revisit frequency: 2-3 days
- ❑ Coverage: global

SMAP Radar Mosaic of the Amazon Basin April 2015 (L-band, HH, 3 km)



Microwave Remote sensing of Precipitation

Tropical Rainfall Measuring Mission (**TRMM**)
satellite – NASA/JAXA (1997-2015)

Global Precipitation Mission (**GPM**) Core Observatory
satellite – NASA/JAXA (2014- …)

- Instruments:

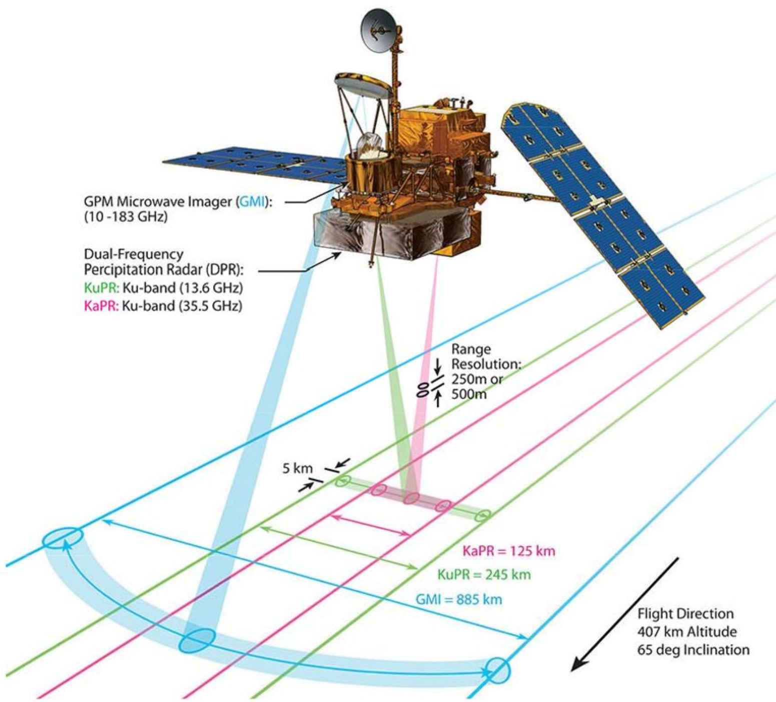
- GPM Microwave Imager (GMI):
  MW radiometer operated at 13 different frequency/polarization channels from 10 to 183 GHz

- Dual-Frequency Precipitation Radar (DPR):
  Radar operated at Ku-band (13.6 GHz) and Ka-band (35.5 GHz)

- Orbit: 407 km

- Revisit frequency: 2-4 h
(11-12h for TRMM)

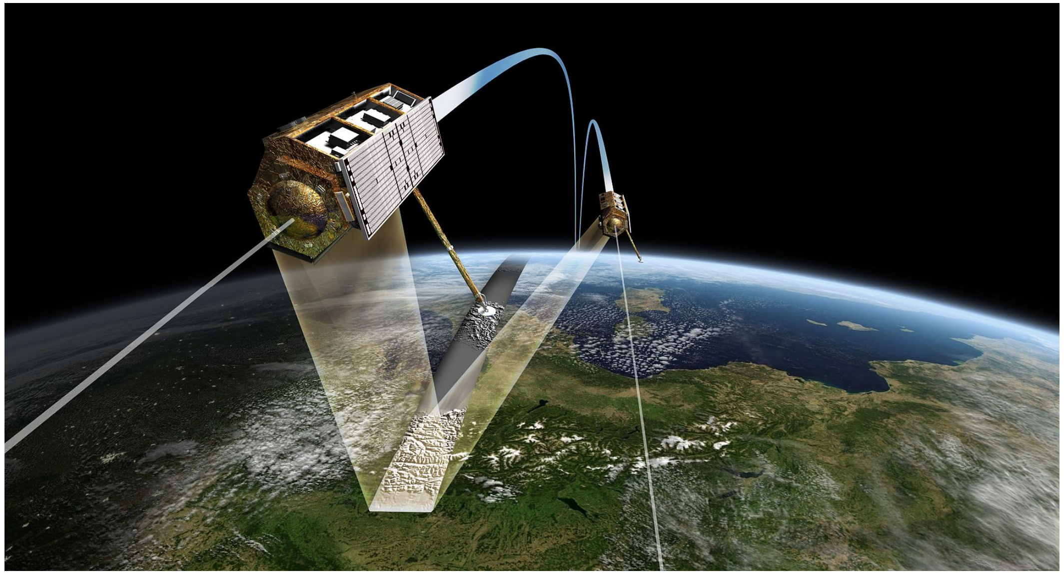
- Coverage: between 65°N and 65°S
(between 35°N and 35°S for TRMM)



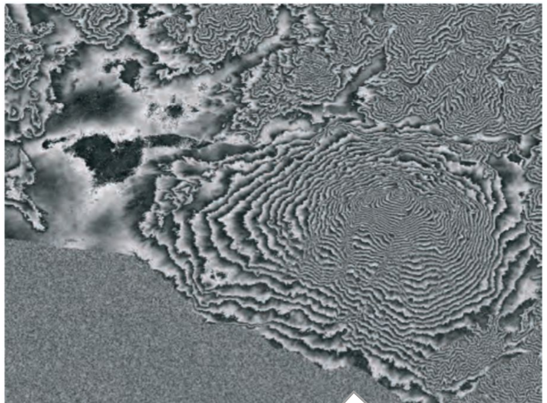
https://www.nasa.gov/mission_pages/GPM/spacecraft/

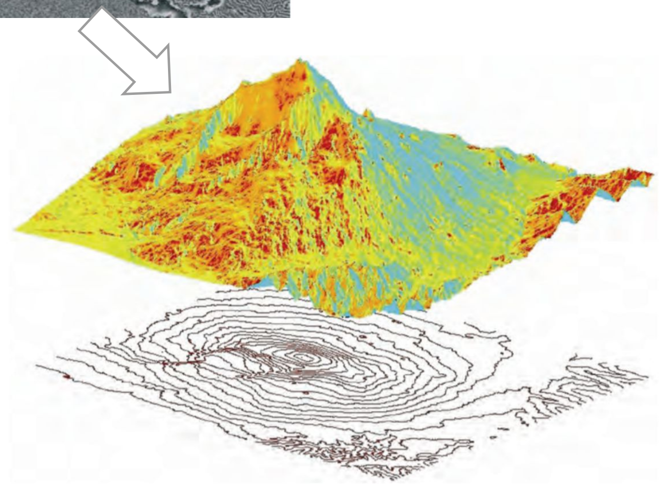
Active Microwave Remote Sensing

SAR Interferometry for Digital Elevation Model



DLR’s TerraSAR-X (2007-) and TanDEM-X (2010-)





InSAR – SAR Interferometry

By comparing two images acquired from slightly different positions (spatial baseline), you can get 3-D images of the Earth's surface, measuring the topography.

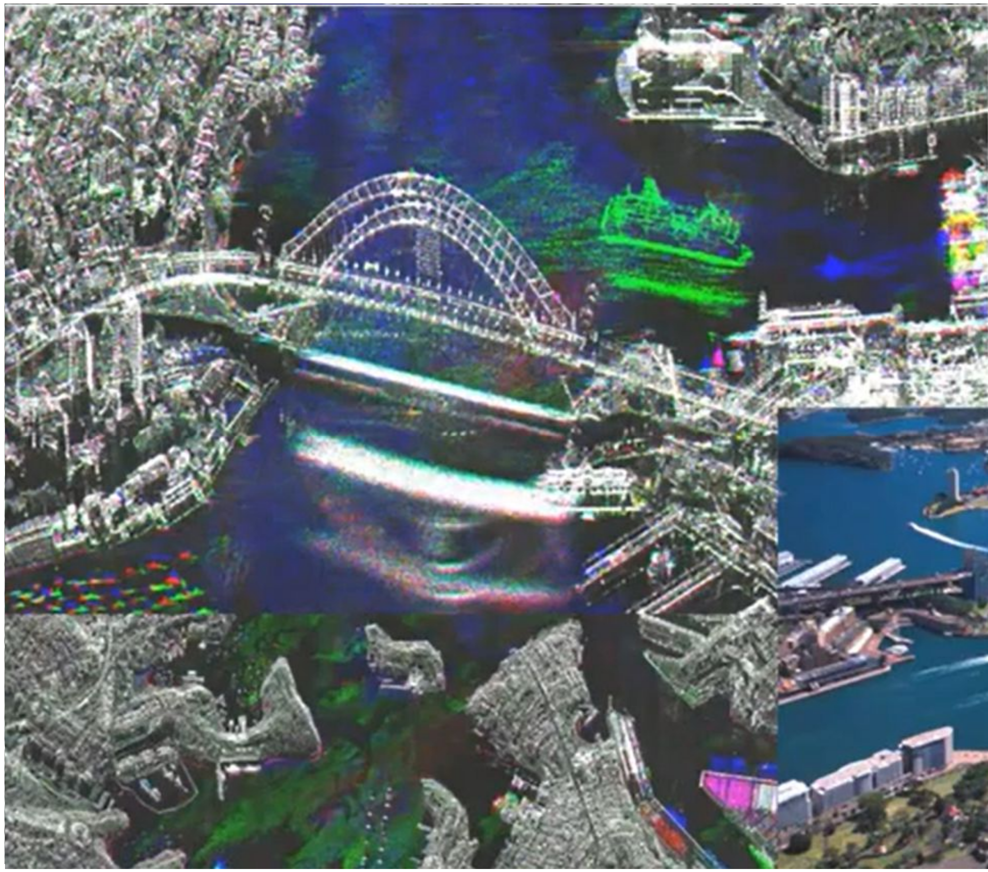
Active Microwave Remote Sensing

TerraSAR-X High Resolution Spotlight

DInSAR

Differential SAR Interferometry

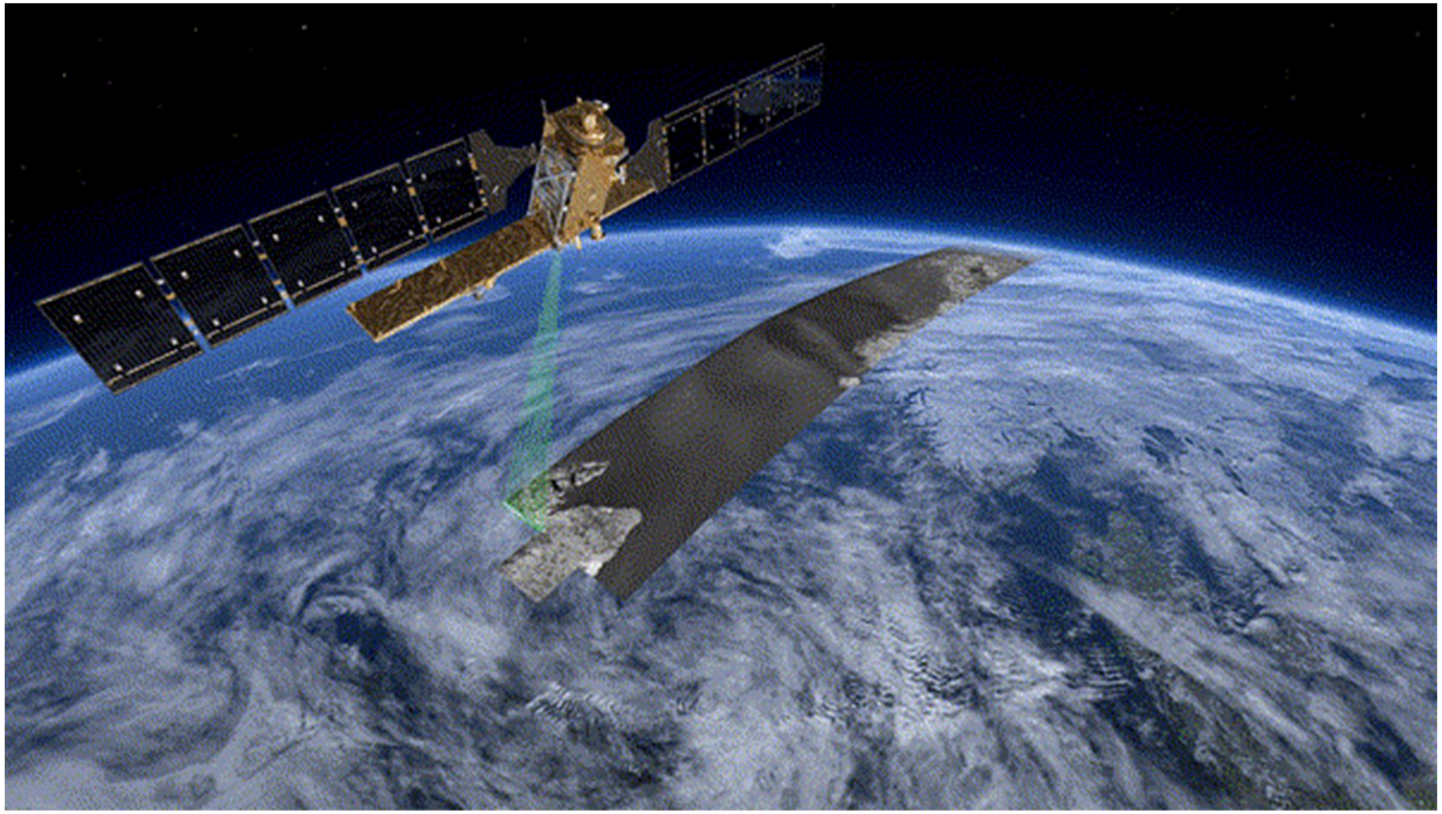
When two images are acquired in different times (temporal baseline), using the DInSAR technique, it is possible to measure the changes of the surface.



- A high resolution spotlight repeat pass scene acquired with 300 MHz bandwidth of the transmitted radar pulse over Sydney is shown.
- The color composite corresponds to
  - 12.01.2008 (red),
  - 21.12.2007 (green)
  - 1.01.2008 (blue)
- The radar response from the water surface is different in three acquisitions and therefore colourful.

Active Microwave Remote Sensing

ESA Sentinel-1 A/B



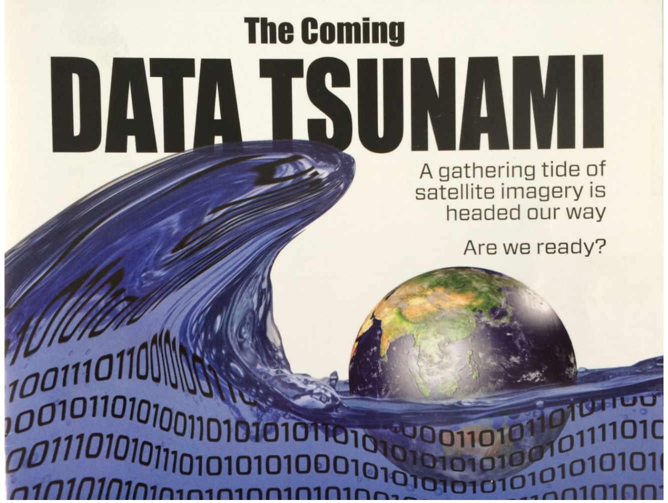
- 2014 (S1-A) et 2016 (S1-B)
- SAR instrument
- C-band : 5.56 cm
- Polarisation HH, HH+HV, VV, VV+VH
- Repeat cycle: 12 (6) days
- Resolution : 5x20 m²

Shift of Paradigm and Challenges in Spaceborne Remote Sensing

Shift of paradigm and challenges

Shift of paradigm in spaceborne remote sensing

- Most of the early remote sensing satellites were developed exclusively by government agencies in a small number of countries.
- Now, many countries are either developing or flying remote sensing satellites and many of these satellites are developed, launched, and operated by commercial firms.
- The capabilities of remote sensing satellites have also dramatically increased:
  - Number of spectral channels available has grown from a few to several hundred
  - Resolutions of a few meters or less are now available from commercial vendors
  - Synthetic aperture radars are now capable of collecting images on demand in many different modes
  - Satellites are now acquiring images of other planets in more spectral channels and with better resolutions than what was available for the Earth two decades ago
- As the remote sensing data have become more available, the number of applications has grown -> The limitation has shifted from the technology that acquires the data to the techniques to optimally exploit the information embedded in the remote sensing data.



SPACENEWS

Shift of paradigm and challenges

New Players - A drastic modification of the Space Landscape

Besides “institutional” space (NASA, ESA, etc), new *private* (and investing) actors :

- **Launchers** : Space-X (Falcon-9, 1st stage and fairing reusable ➔ decrease of costs), Orbital Sciences Corporation (Pegasus, Taurus, Minotaur), Rocket Lab (Electron)
- **Spaceships** : Space-X (Crew Dragon), Boeing (CST-100 Starliner), Blue Origin (New Shepard), Virgin Galactic (SpaceShipTwo), Orbital Sciences (Cygnus), Sierra Nevada (Dream Chaser) : in addition to ISS, orientation towards private passengers and astronauts.
- **Telecoms** : SES (ASTRA), Space-X (Starlink),…
- **Constellations of mini- et nano-satellites** - smaller, easier to replace in case of failure, equipment off-the-shelve, revisit time much smaller : Planet Labs, Spire Global, …
- **Many start-ups** worldwide to offer commercial services based on these constellations
- **In E.O.**, these new systems cover VIS/NIR (multi-/hyperspectral constellations) and microwaves (radar constellations).

Crew Dragon approaching the International Space Station (ISS)

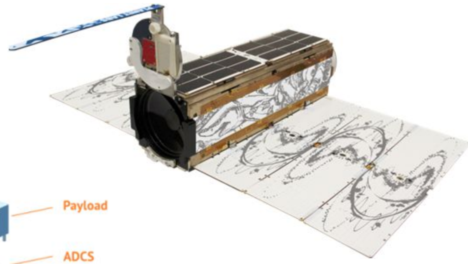
A Falcon 9 v1.0 being launched with a Dragon spacecraft to deliver cargo to the ISS in 2012.

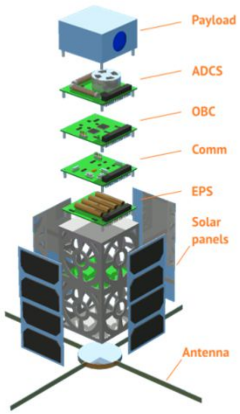
Shift of paradigm and challenges

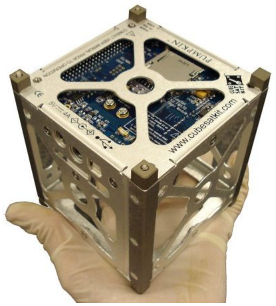
Nanosatellites –> VIS-NIR

The company Planet Labs (www.planet.com) operates more than 130 Doves (3U CubSats), 21 SkySats (50 cm resolution) and 5 RapidEye satellites (5 m resolution – retired in 2020) that acquire multispectral imagery of the entire Earth's landmass daily

Planet manages the world’s largest constellation of satellites in orbit.







PlanetScope image – August 31, 2019 – Liège
Spatial resolution: 3 m - RGB and NIR bands

Shift of paradigm and challenges

Minisatellites –> Radar

ICEYE launched a constellation of SAR satellites achieving global daily coverage

ICEYE (www.iceye.com)

- First constellation of radar mini-satellites (85kg)
- 18 scheduled, currently 4 in orbit
- X-band
- Various acquisition modes: 1m (Spotlight), 3m (Stripmap), 20m (ScanSAR)
- Daily revisit

Capella Space is deploying a SAR CubeSat satellite constellation that will provide hourly imagery with a global coverage

Capella Space (www.capellaspace.com)

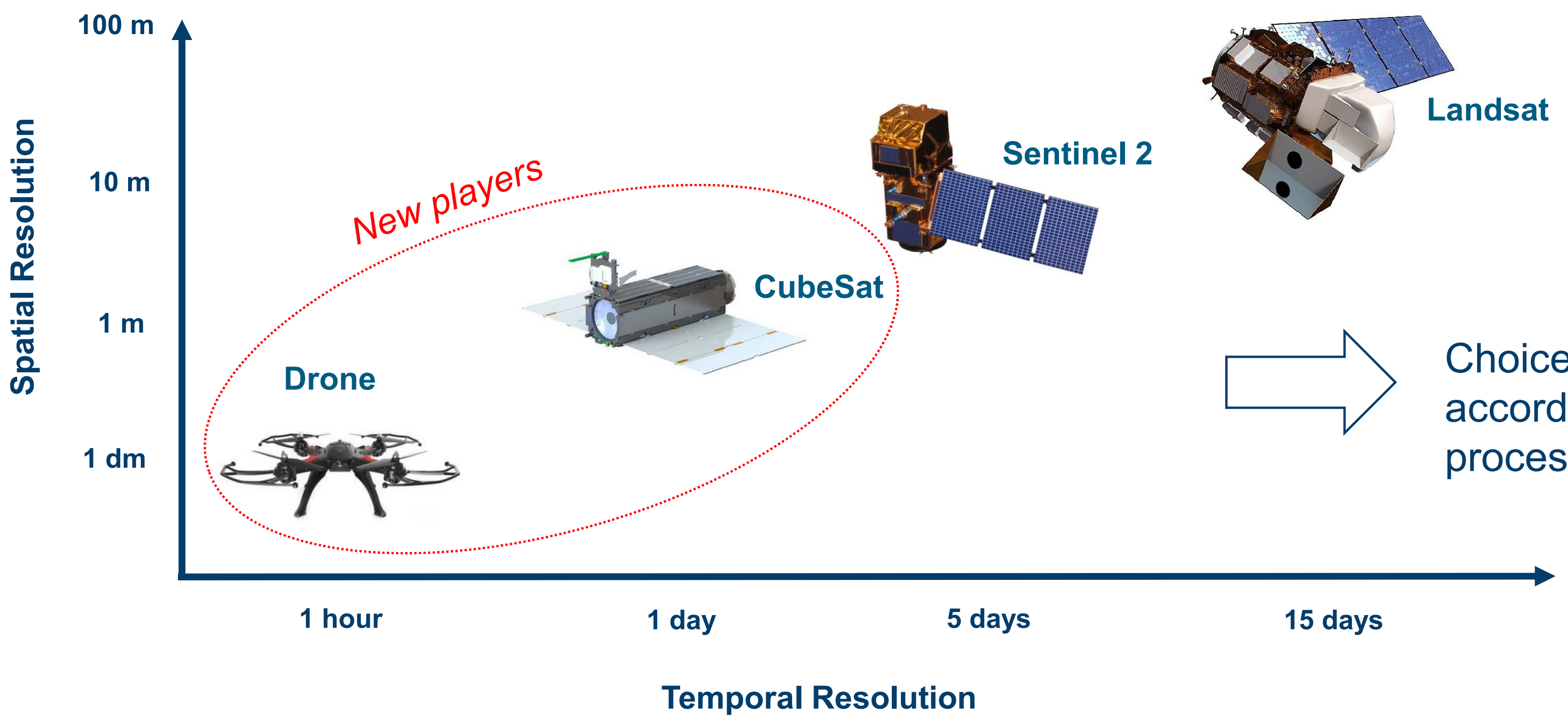
- Constellation of radar mini-satellites (50 kg)
- 36 scheduled, currently 6 in orbit
- X band
- Resolution < 50 cm
- Contracts with NRO and USAF

Shift of paradigm and challenges

Ultra-high spatial resolution with UAV remote sensing

Shift of paradigm and challenges

Spatial and Temporal resolution

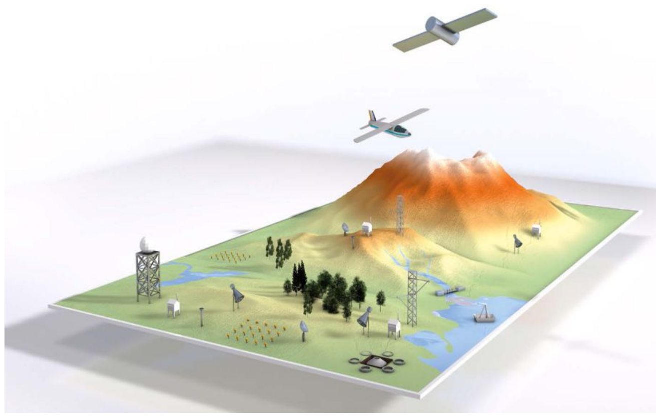


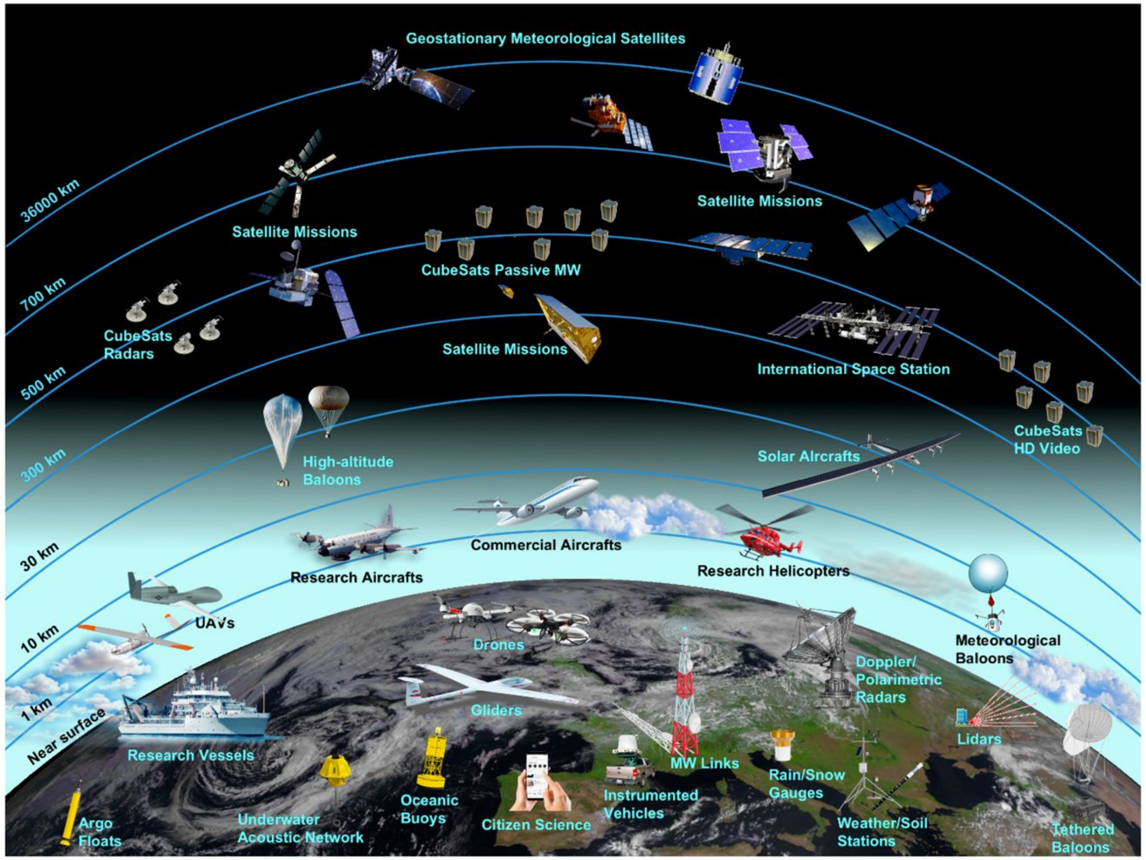
Choice of resolution according to the process studied

Shift of paradigm and challenges

Multiscale and multiresolution observations

Many processes/variables can be observed from spaceborne, airborne and ground-based remote sensing techniques at different scales (i.e., field, catchment, regional and global scale) and at different spatio-temporal resolutions and accuracies.



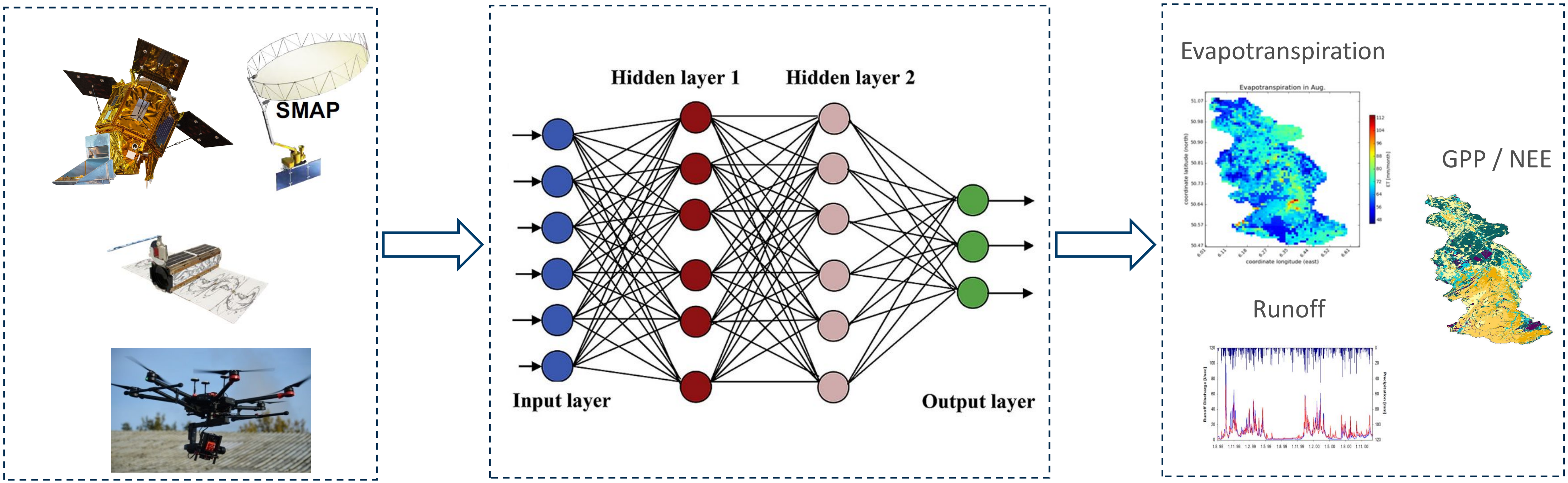


A global observing system

(e.g., of the water cycle)

Shift of paradigm and challenges

EO Data Analysis - Data-driven approach



Multi-Source EO data

Artificial Neural Network

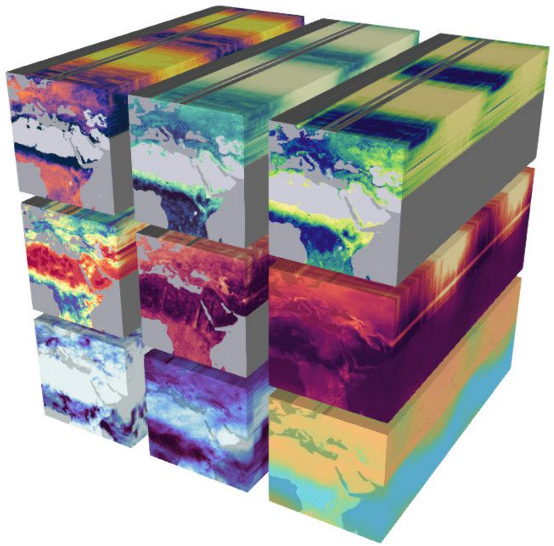
Earth System
Parameters and Processes

Shift of paradigm and challenges

Big Data and Data Cubes

Challenge to store, process, analyze, visualize and share Big EO data

- ❑ Each stream of spatial data can be thought of as a **data cube** (across space, time and variable)
  - Multiple data streams can be analyzed together through time to study the complex processes and interactions that govern the Earth system
  - Extreme events can be seen as spatiotemporal clusters in the data cube and can be analyzed to better understand their causes and impact
- ❑ Emerging **cloud technologies**, such as Google Earth Engine (GEE) and Amazon Web Services (AWS)
- ❑ Solutions such as **Virtual Earth Labs** used to share data cubes of land surface properties or model results with potential end-users

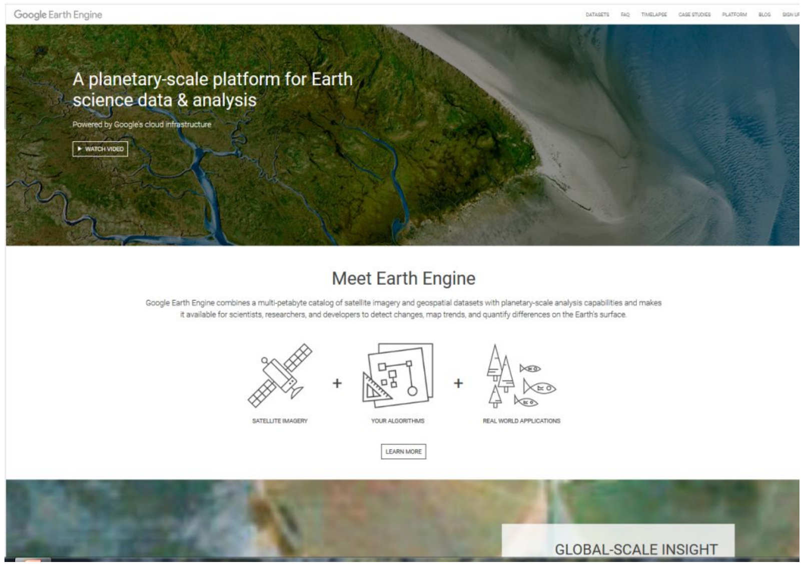


ESA's Earth System Data Lab

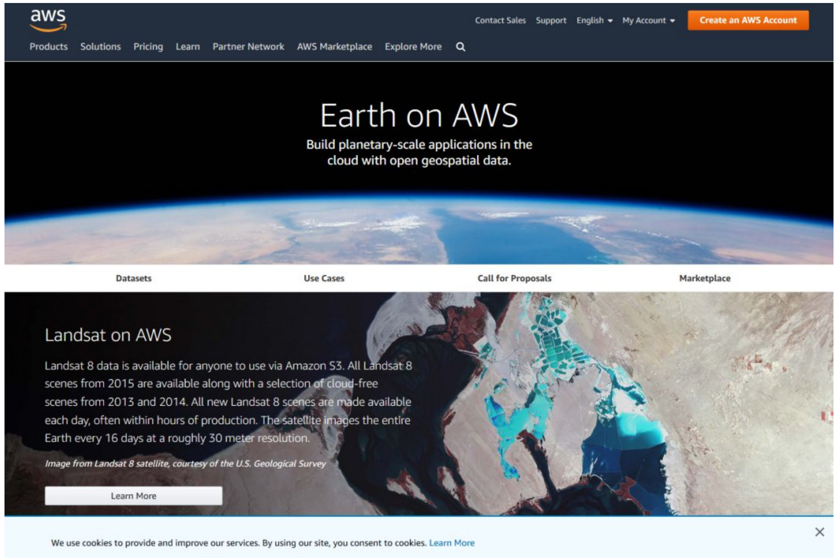
Shift of paradigm and challenges

EO Cloud Processing Platforms (storage and analytics platforms)

Google Earth Engine
http://earthengine.google.com



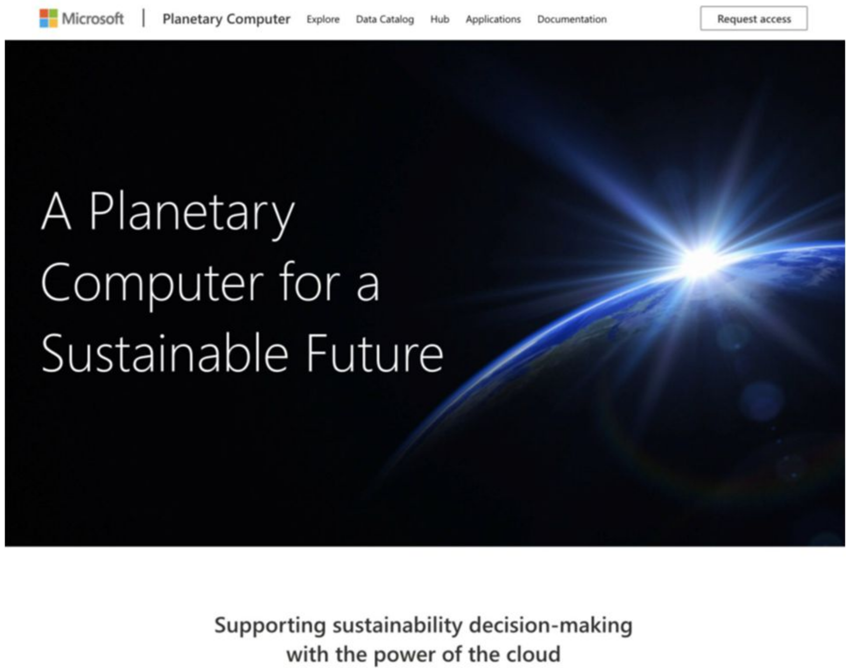
Amazon Web Services
https://aws.amazon.com/earth/



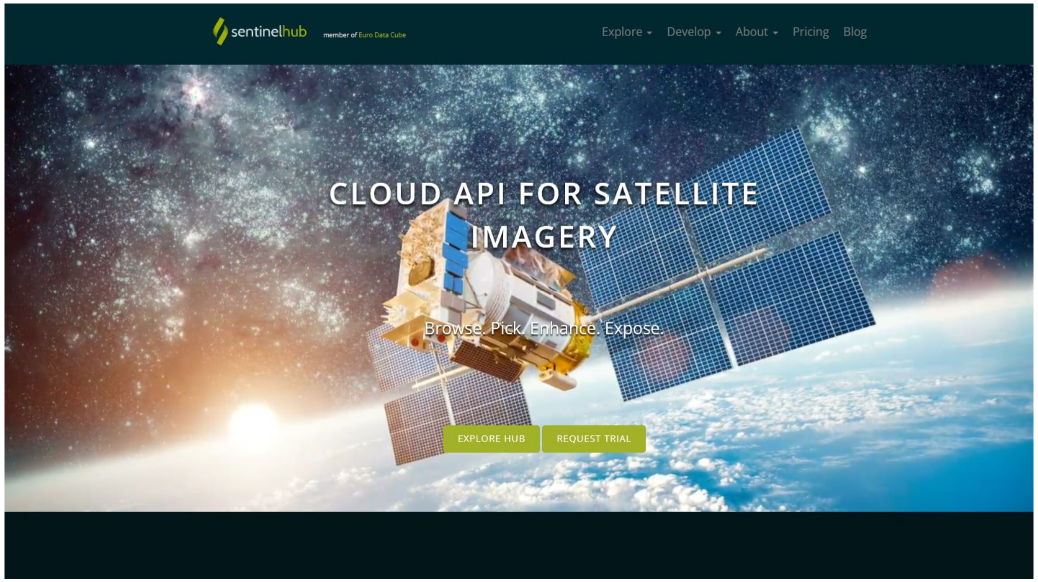
Shift of paradigm and challenges

EO Cloud Processing Platforms (storage and analytics platforms)

Microsoft Planetary Computer
https://planetarycomputer.microsoft.com/



Sentinel-Hub
https://www.sentinel-hub.com/



Additional resources

Reference books and online training

More info ⇨ SPAT0032-2 Remote Sensing

- ARSET-NASA: https://appliedsciences.nasa.gov/join-mission/training/english/arset-fundamentals-remote-sensing
- ESA: https://www.esa.int/Education/
- EO College: https://eo-college.org/welcome