Introduction to Optical RS for Water and Hazards

Fabrizio Ramoino

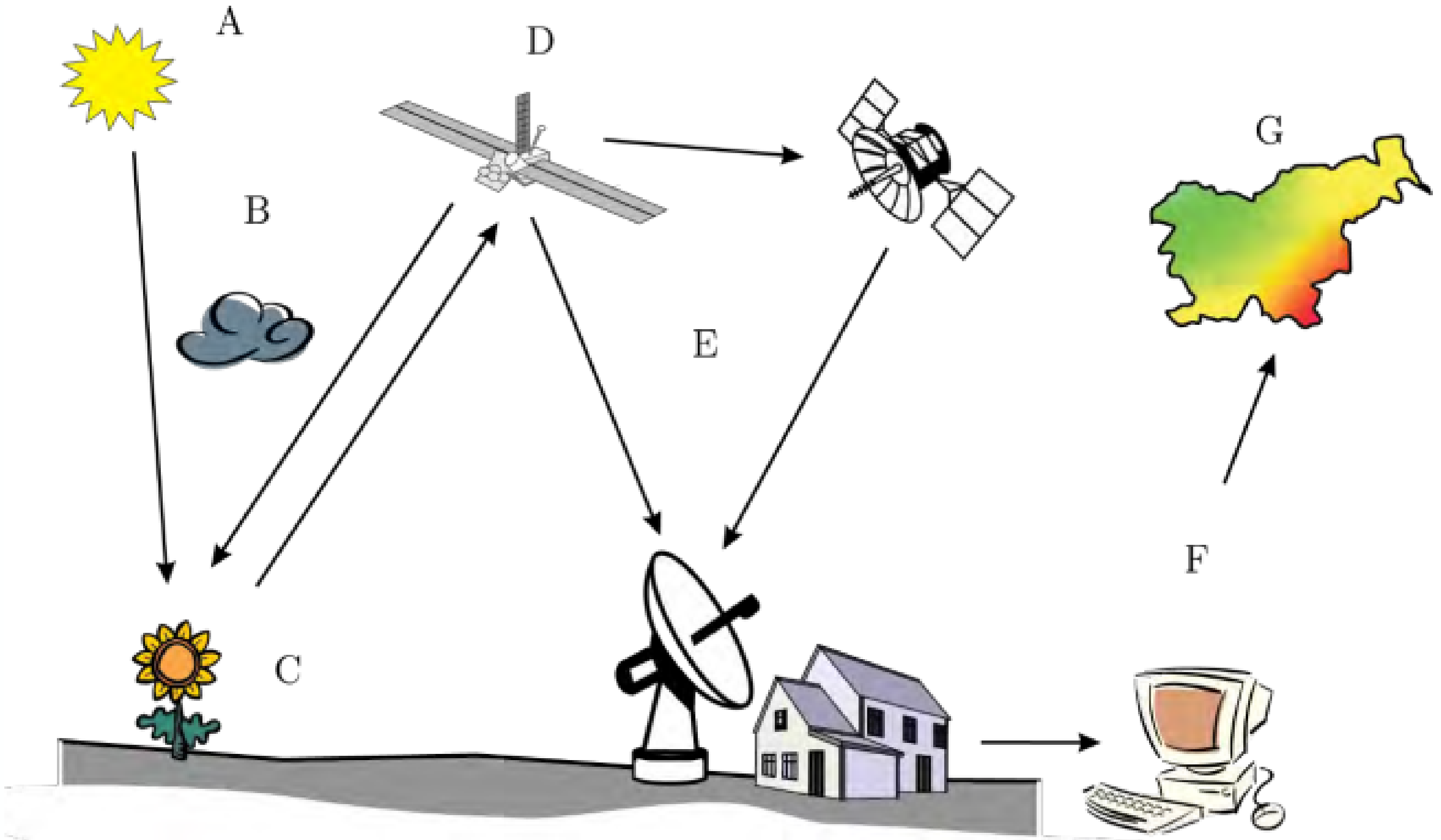
25th September 2023

Outline

- Optical instruments
- The interaction of electromagnetic radiation with the surface
- Interaction with the atmosphere and how to apply correction
- Pre-processing of optical data
- Why use Time Series
- How to retrieve Radiometric Indices for Water
- Example of Hazard monitoring using RS data

What is remote sensing?

Remote sensing is the science of obtaining information on Earth's surface without coming into direct contact with it. In doing so, we detect and record a reflected or radiated electromagnetic waves, process them, analyse them and use this information in different applications.



(A) Energy or Illumination Source

(B) Radiation and the Atmosphere

(C) Interaction with the Target

(D) Recording by the Sensor

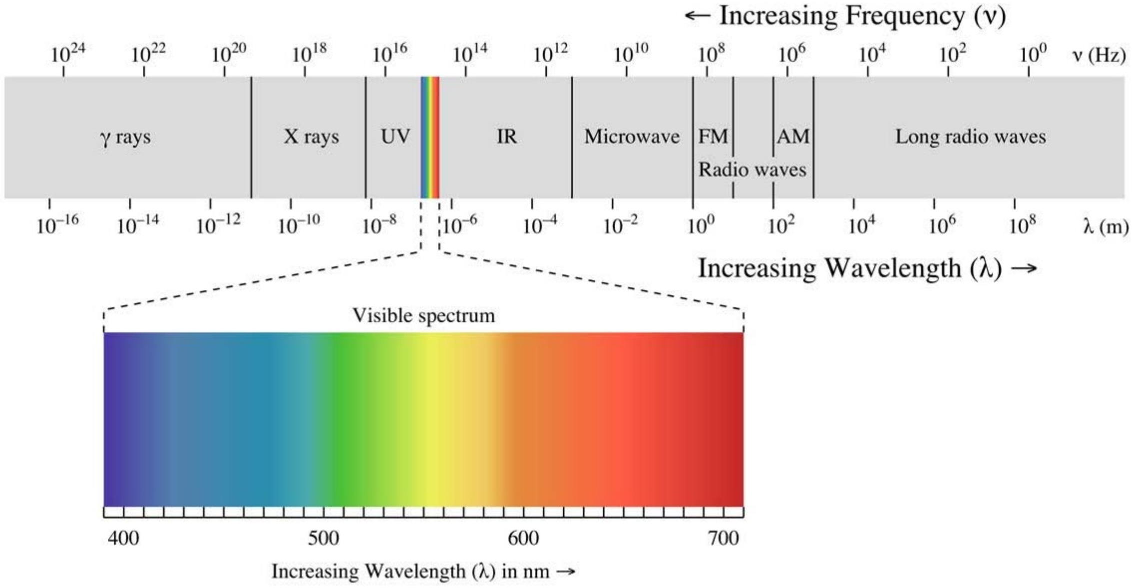
(E) Transmission, Reception, and Processing

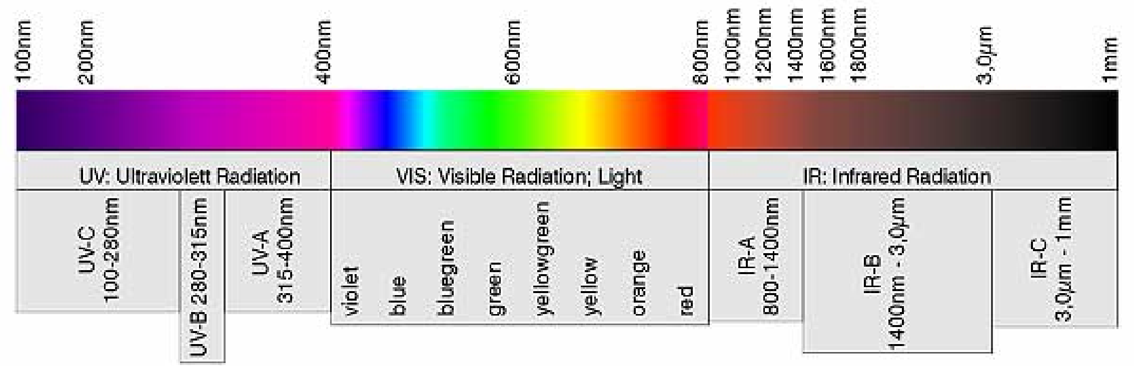
(F) Interpretation and Analysis

(G) Application

Spectrum EMR

The term **"optical radiation"** refers to electromagnetic radiation in the wavelength range between 100 nm and 1 mm. The terms **"light"** and **"visible radiation"** (VIS) refer to the wavelength range between 400 nm and 800 nm, which can be perceived by the human eye.



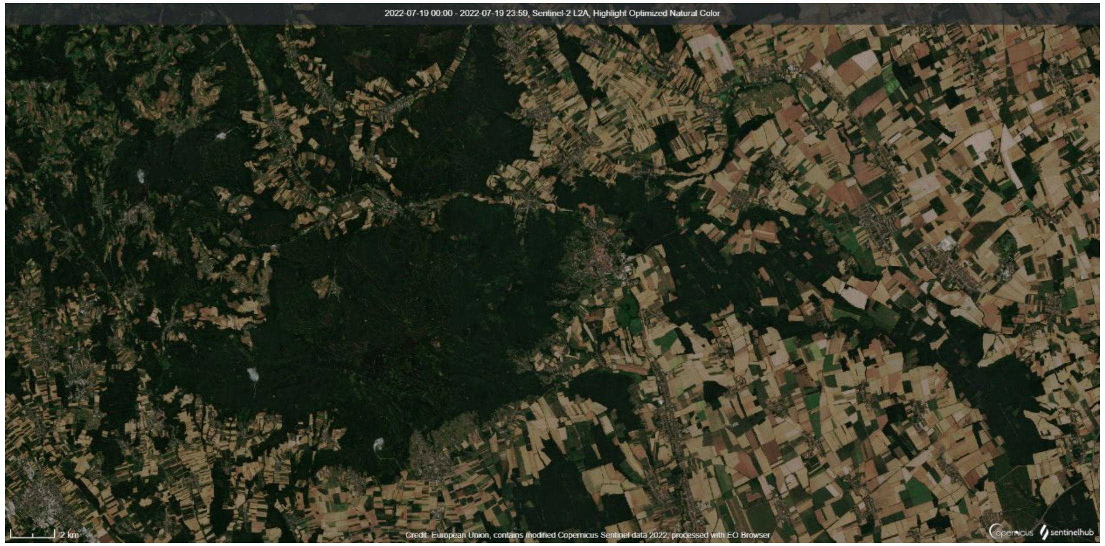


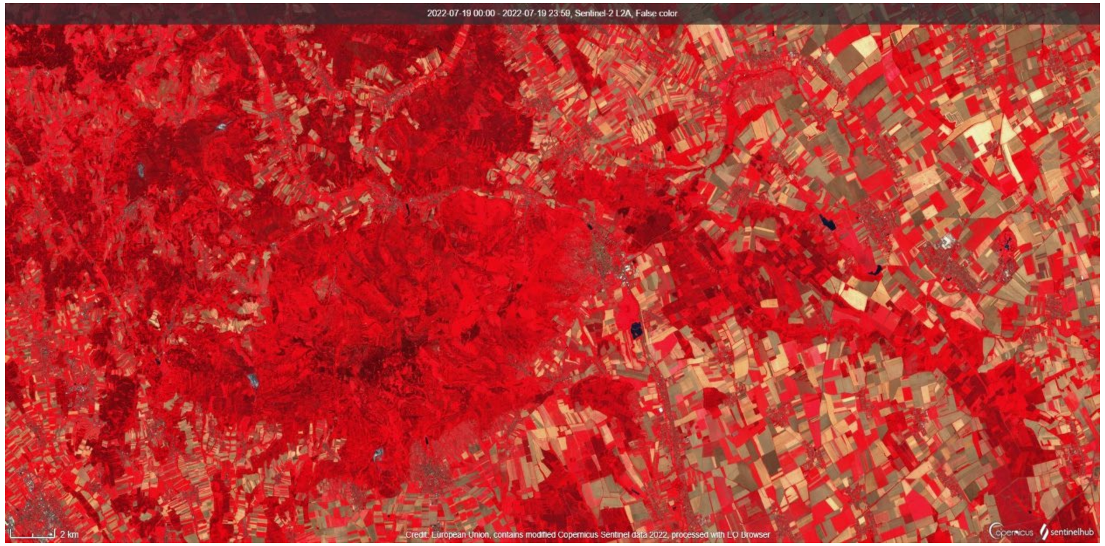
- **Visible (VIS)** 0.30 – 0.75 µm and 0.77 – 0.91 µm – perceived by the human eye
- **Near infrared (IR)** 1.55 – 1.75 µm and 2.05 – 2.40 µm
- **Thermal Infrared** 8.0 – 9.2 µm and 10.2 – 12.4 µm
- **Microwave (SAR)** 7,5–11,5 mm and 20 mm

The wavelength range of optical radiation (light-measurement.com)

Optical satellites

- Optical satellites are passive
- They use devices that are simples – lens and detectors
- They observe the surface of the Earth across a varied spectrum of wavelengths
- The number of spectral channels/bands and bandwidth is different
- Optical imagery is more accessible and easier to interpret





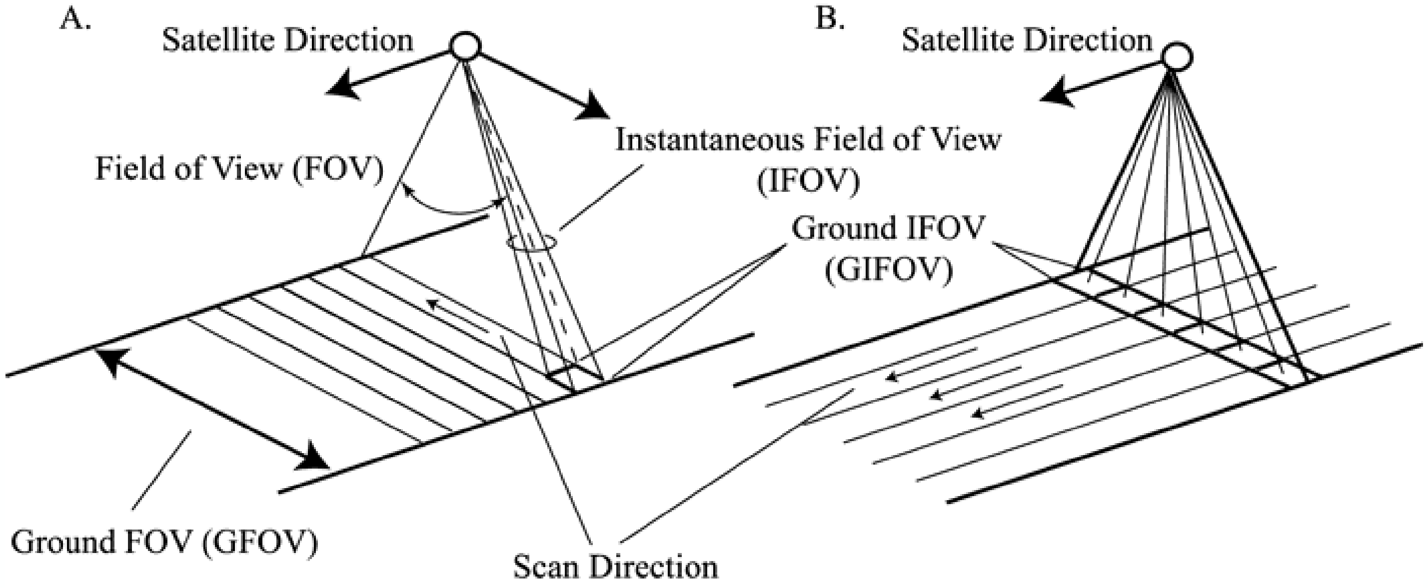
Optical scanners

Across track

- Landsat –up to 7

Along track

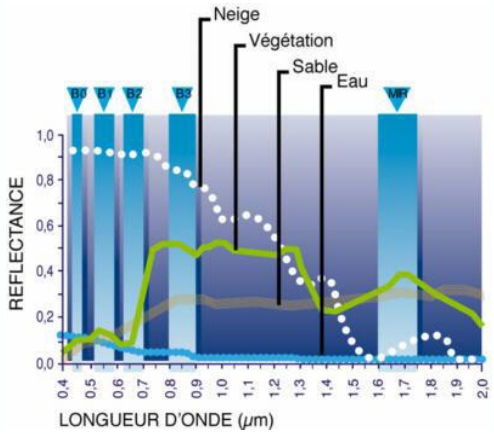
- All HR and VHR
- Sentinel-2
- Landsat 8



[An introduction to satellite sensors, observations and techniques (researchgate.net)](#)

Optical land remote sensing: 40 years of digital evolution

Spectral Resolution



Radiometric Resolution

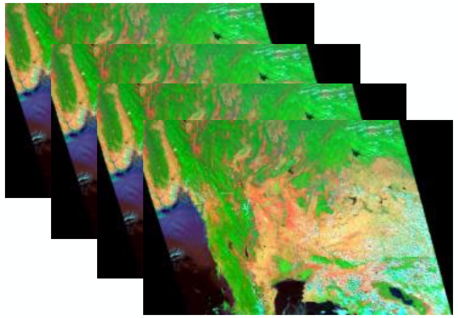
4 bits

16 bits

Unmanned Aerial Vehicle (UAV)

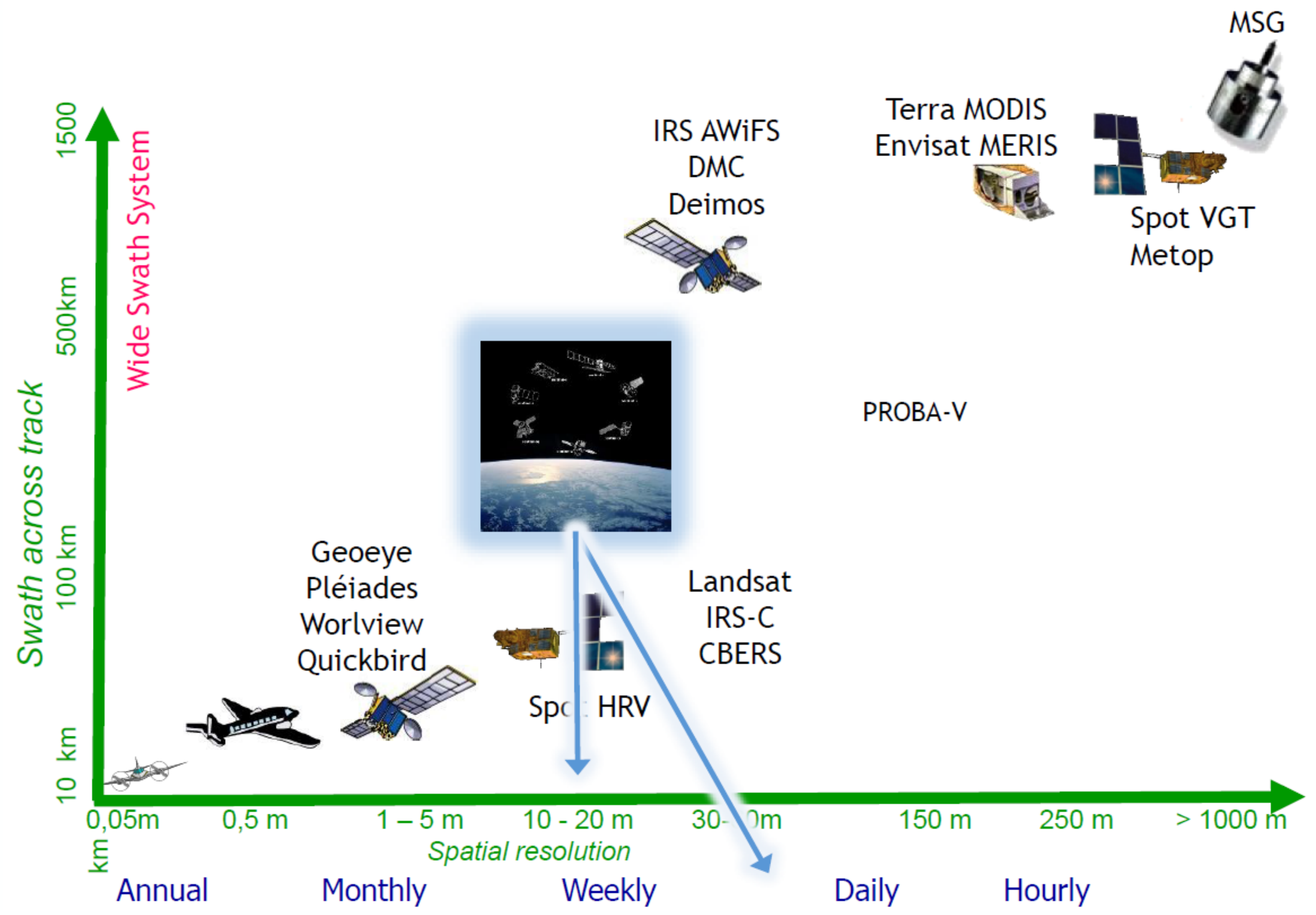
Spatial Resolution

Temporal Resolution



Instruments / platform for in situ measurements

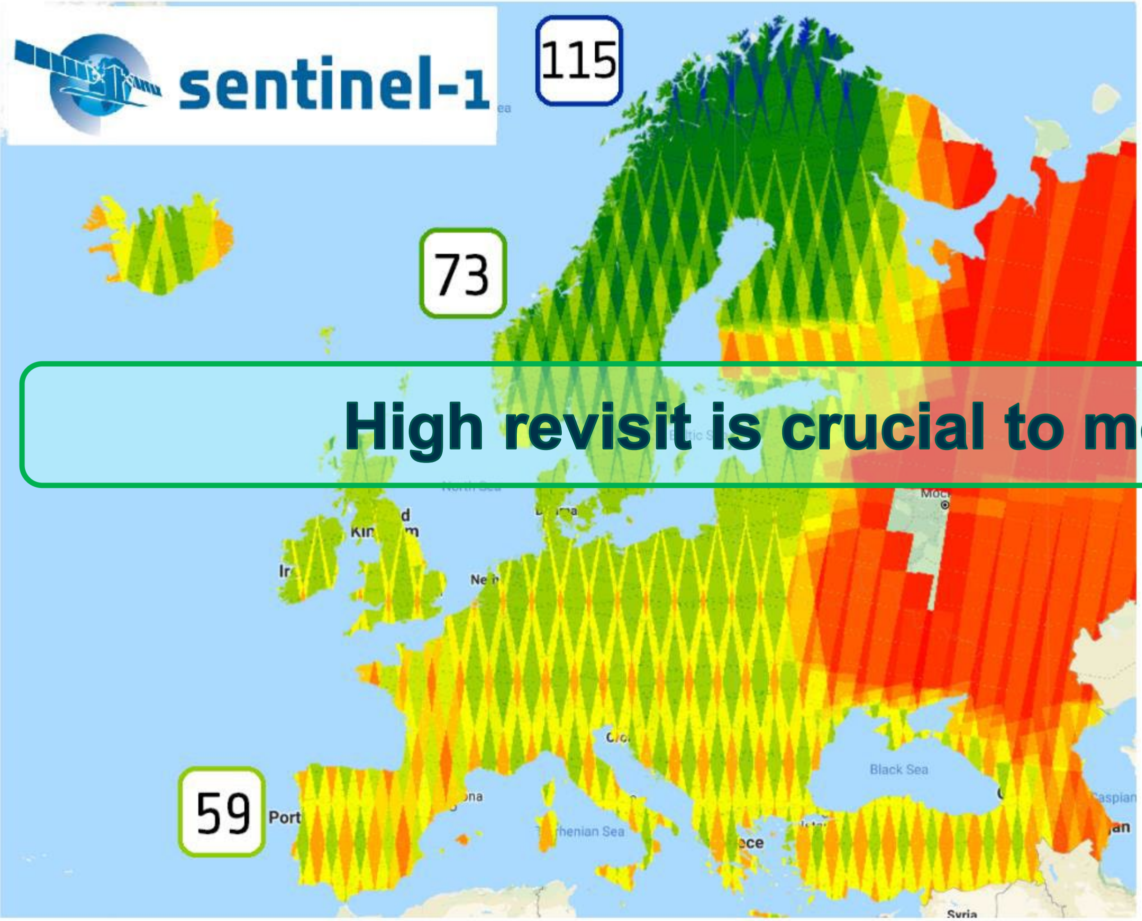
Optical land remote sensing



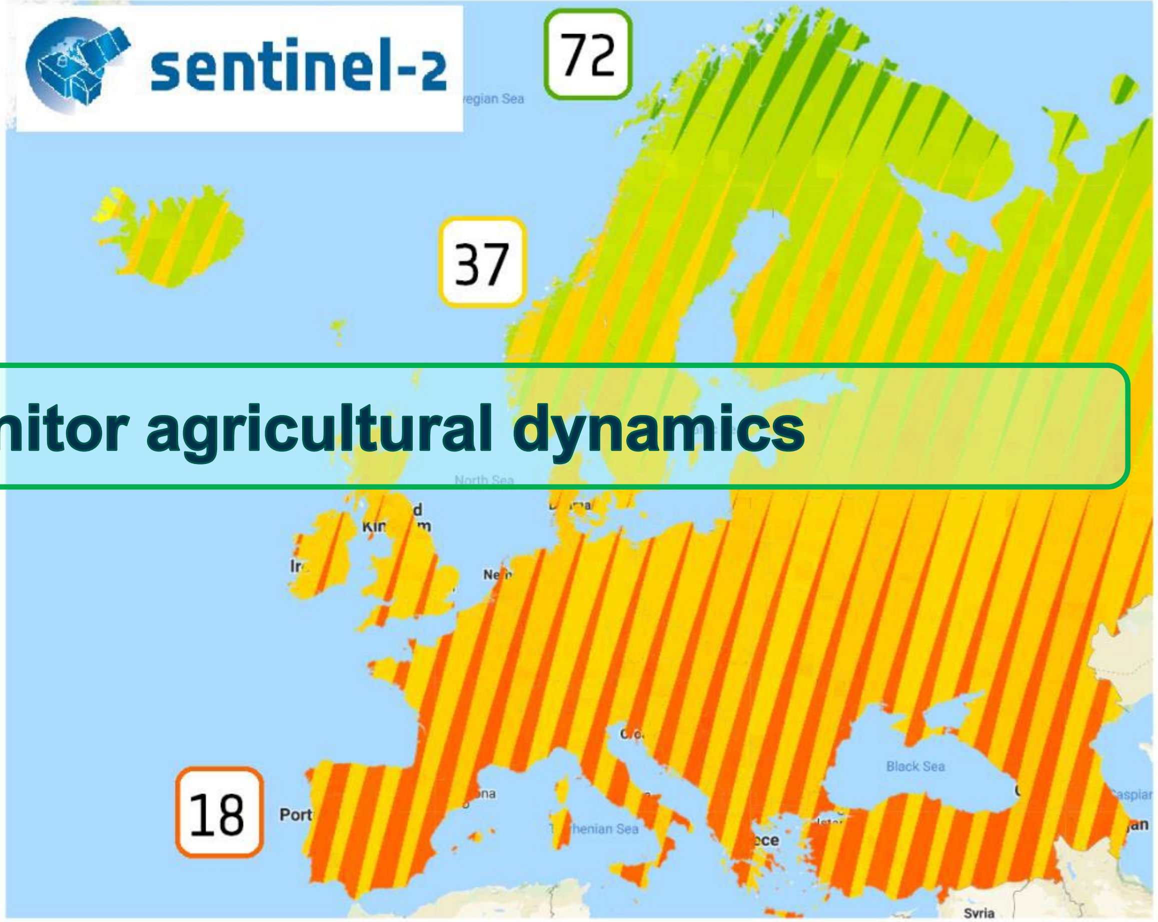
Sentinels as a game changer

Majority of Europe > 2-day revisit

Majority of Europe > 3-day revisit



S1A and S1B (July-Sept 2018)

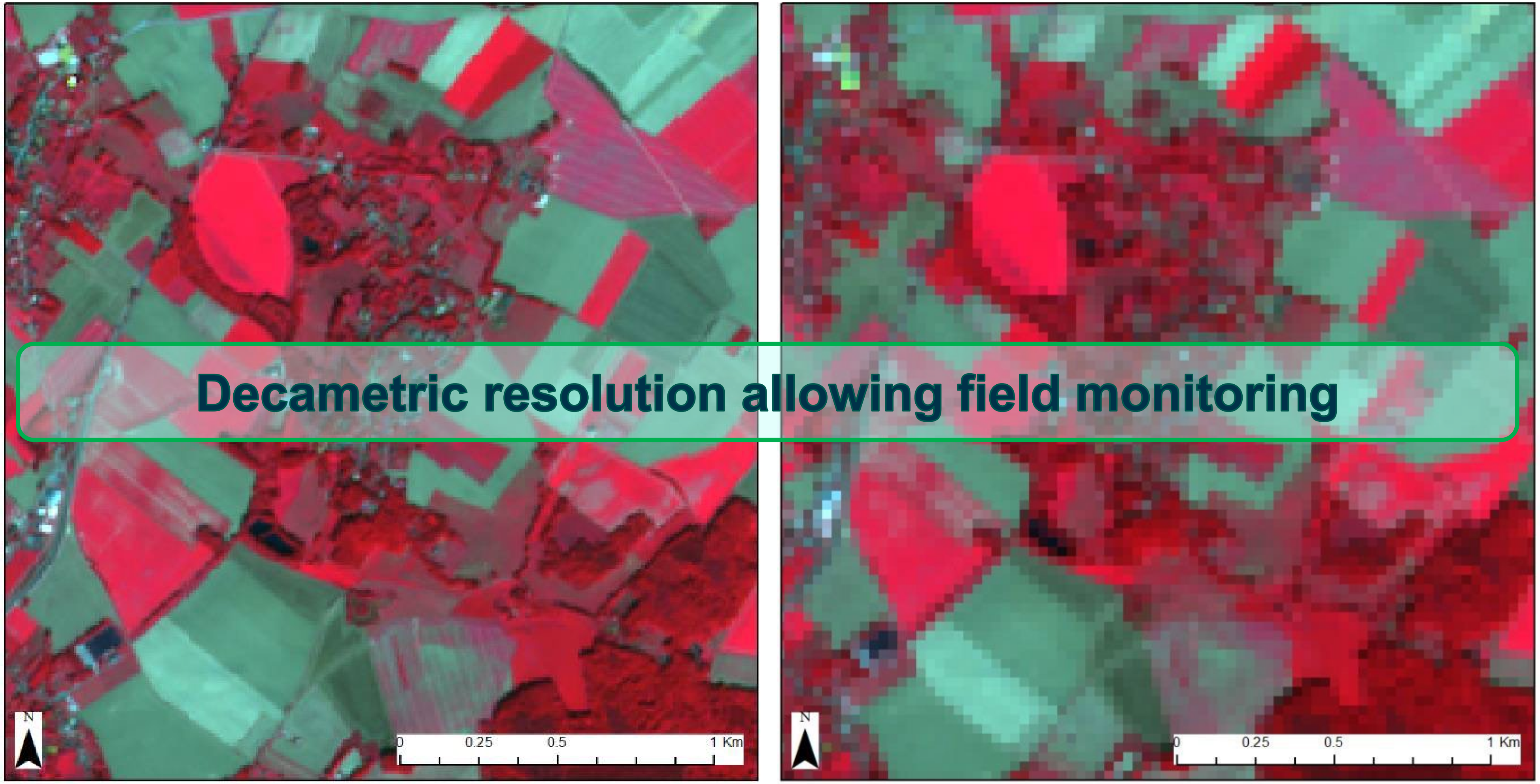


S2A and S2B (July-Sept 2018)

High revisit is crucial to monitor agricultural dynamics

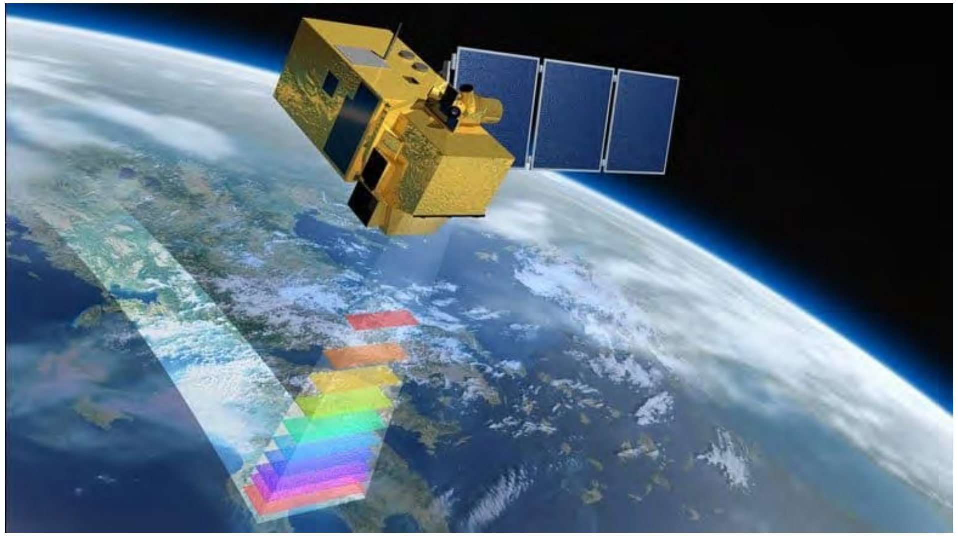
Sentinels as a game changer

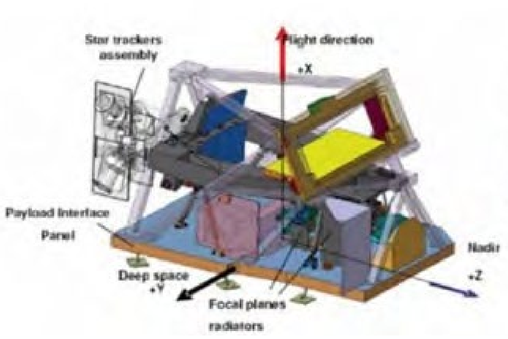
10 m | *30 m*

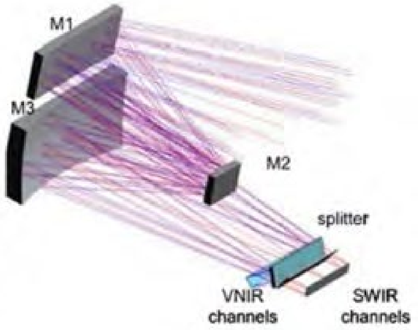


Decametric resolution allowing field monitoring

Sentinel-2 imaging

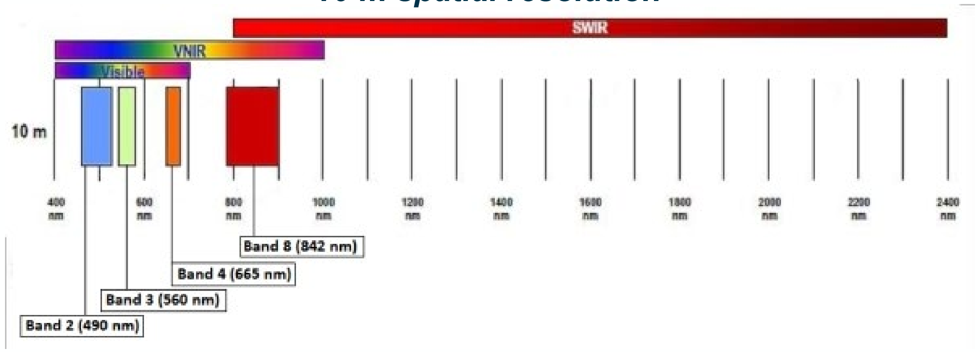




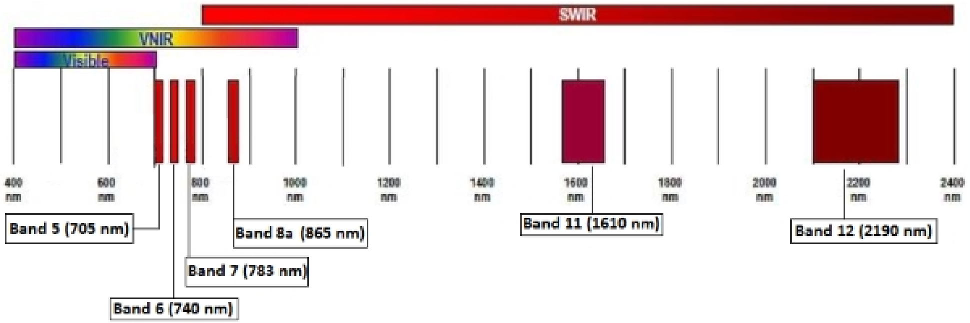


[MSI Instrument –Sentinel-2 MSI TechnicalGuide – Sentinel Online – Sentinel Online (copernicus.eu)]

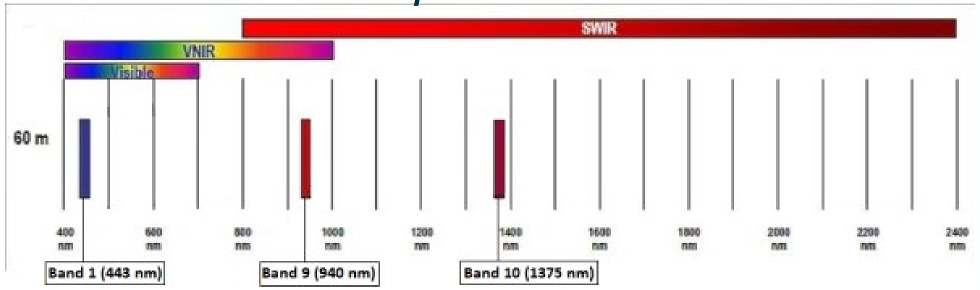
10 m spatial resolution



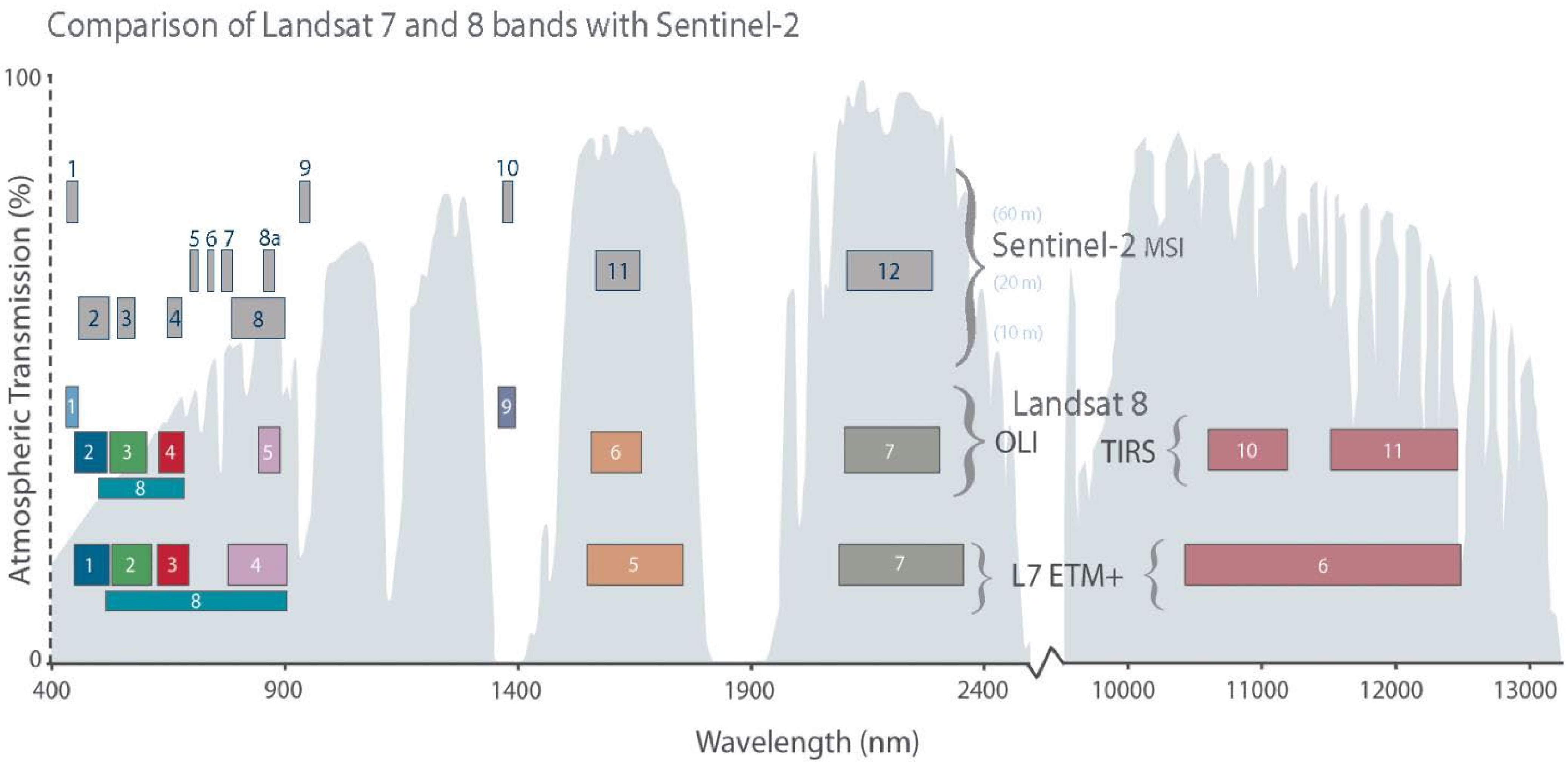
20 m spatial resolution



60 m spatial resolution

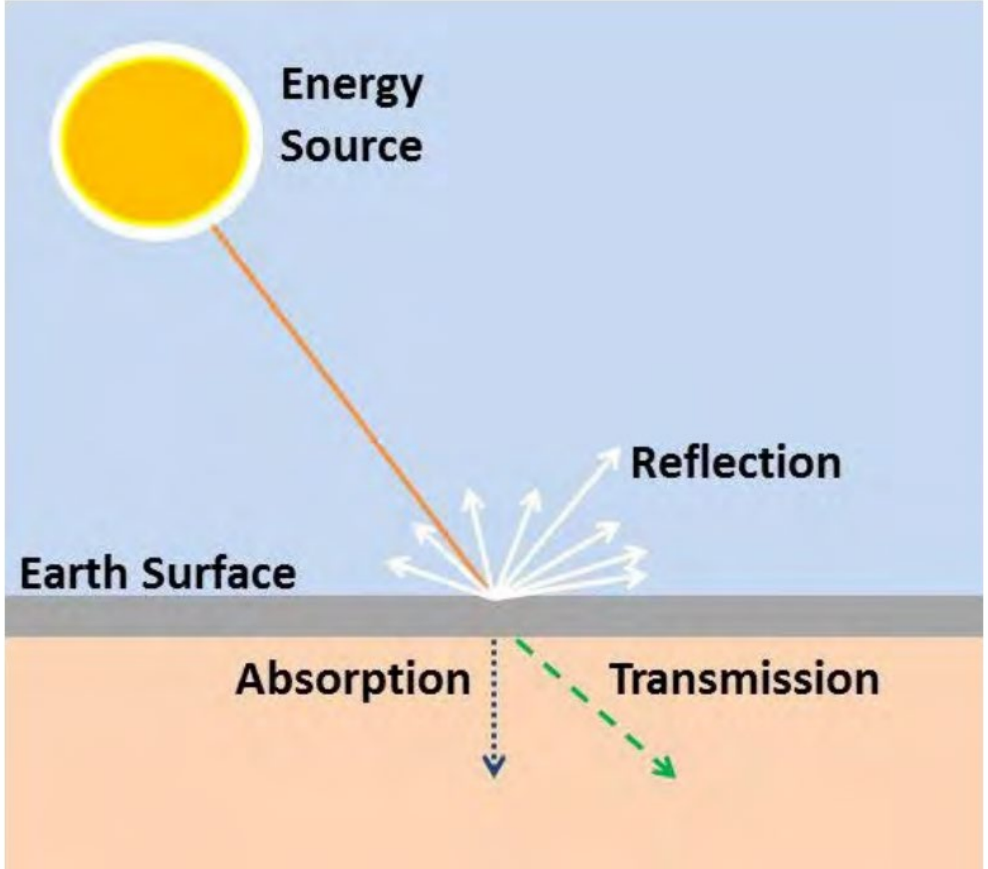


Comparison Sentinel-2 bands with Landsat-7 and 8



Interaction with the surface

- The interaction of electromagnetic radiation with the surface is driven by three physical processes: reflection, absorption, and transmission of radiation.
- Reflection involves the returning or throwback of the radiation incident on an object on the surface.
- Spectral reflectance refers to the amount of reflectance in a specified wavelength range.
- It depends on:
    - the type of material
    - the nature of the surface, particularly whether it is a rough surface or a smooth surface, diffuse and specular
    - the wavelength of the incident radiation
    - other factors, such as the slope of the surface, its condition …



[Electro-Magnetic Radiation (EMR) Interaction with Earth Surface Features (gisoutlook.com)](gisoutlook.com)

Spectral signature of water

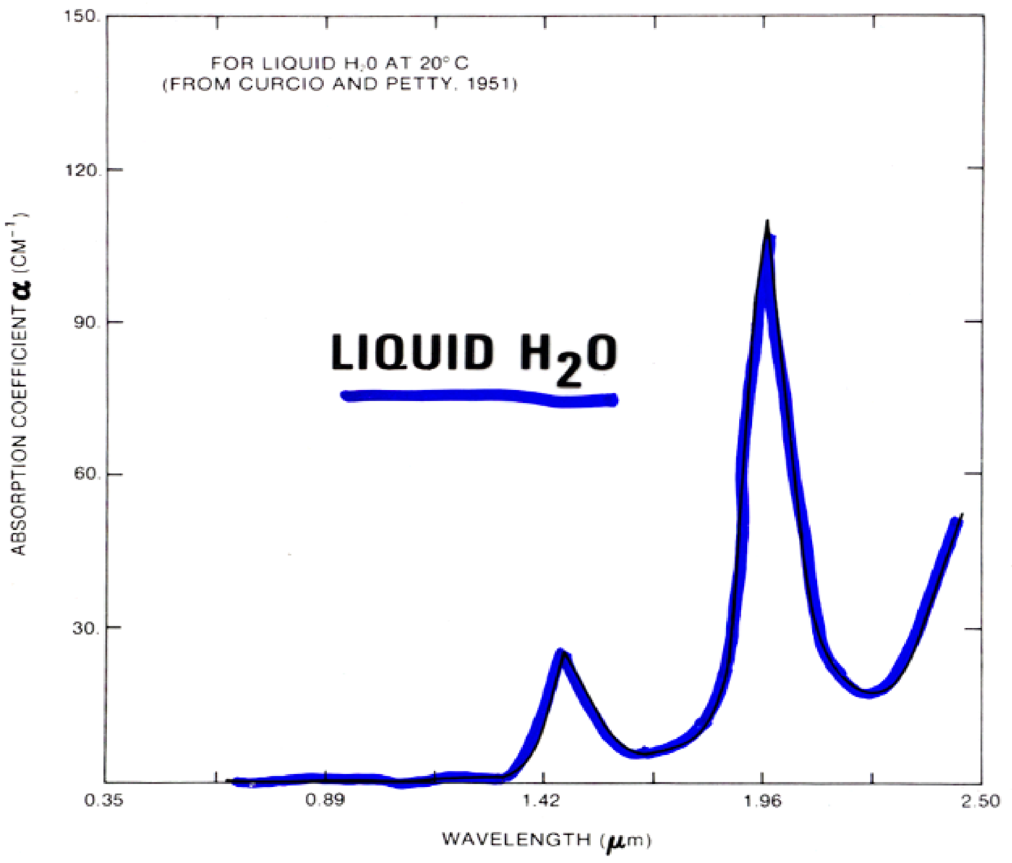
Incident radiation on liquid water is:

- partly reflected in a specular way
- partly refracted (and then absorbed or diffused)

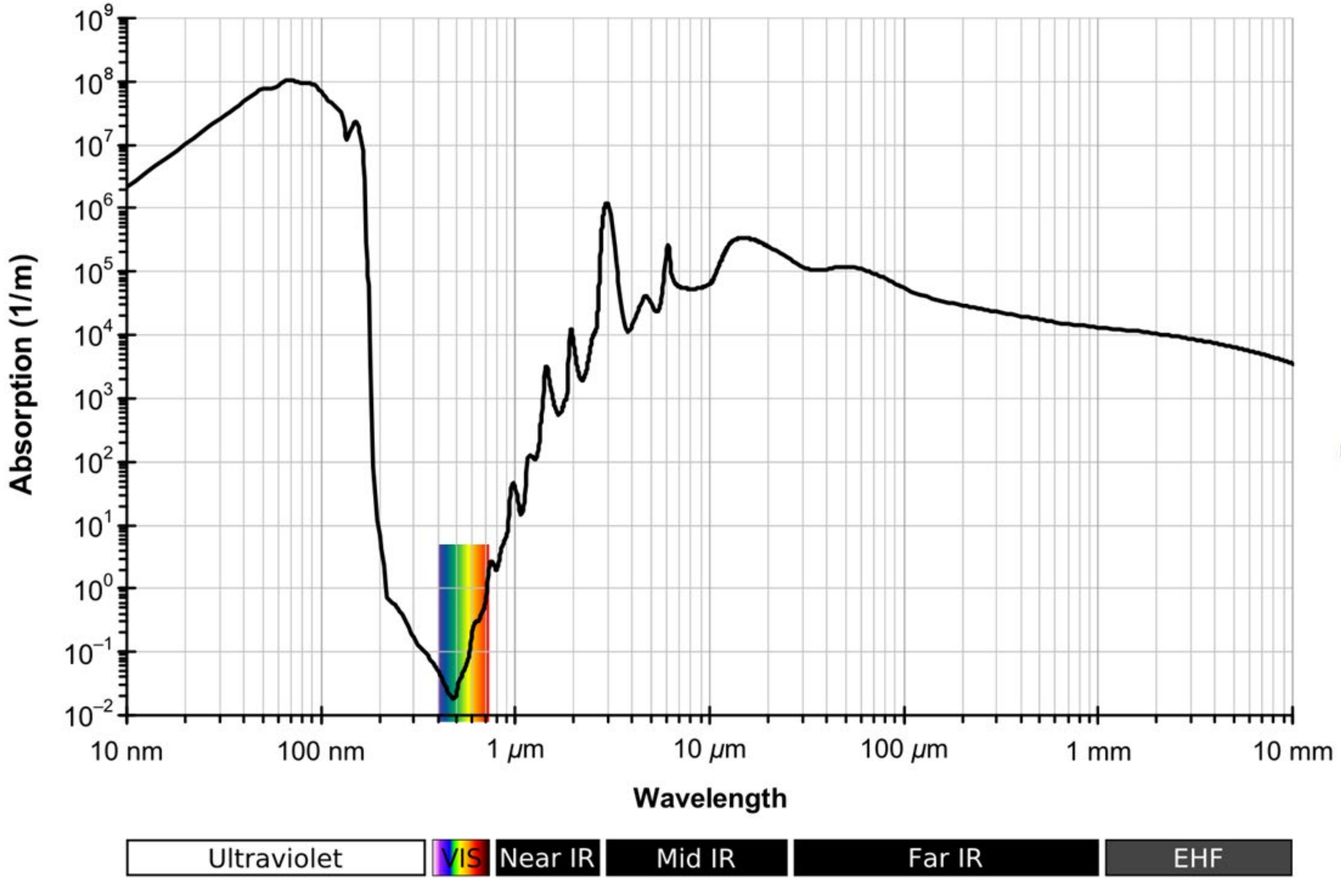
Influence of the suspended elements on the optical properties (chlorophyll, mineral or organic matter)

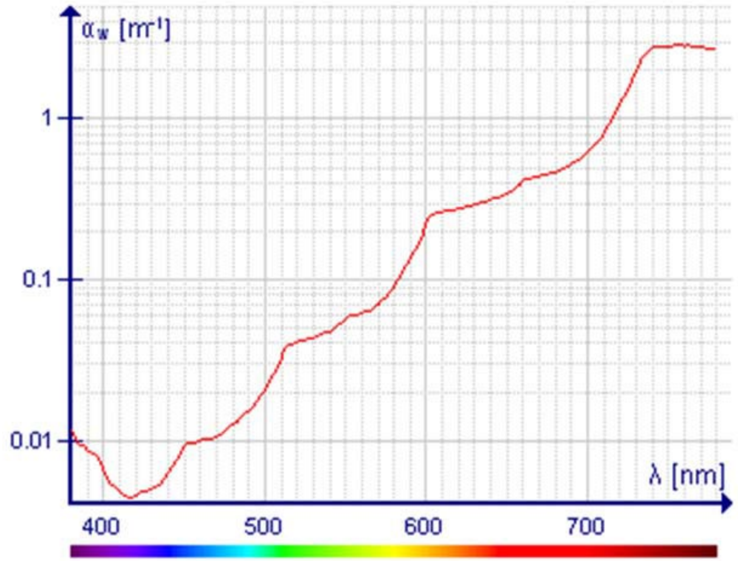
Reflects mainly in the visible, almost not in the NIR; 3 typical absorption bands

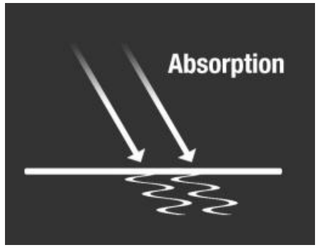
Growing absorption, almost exponential with wavelength



Interaction of liquid water and VIS – IR - TIR





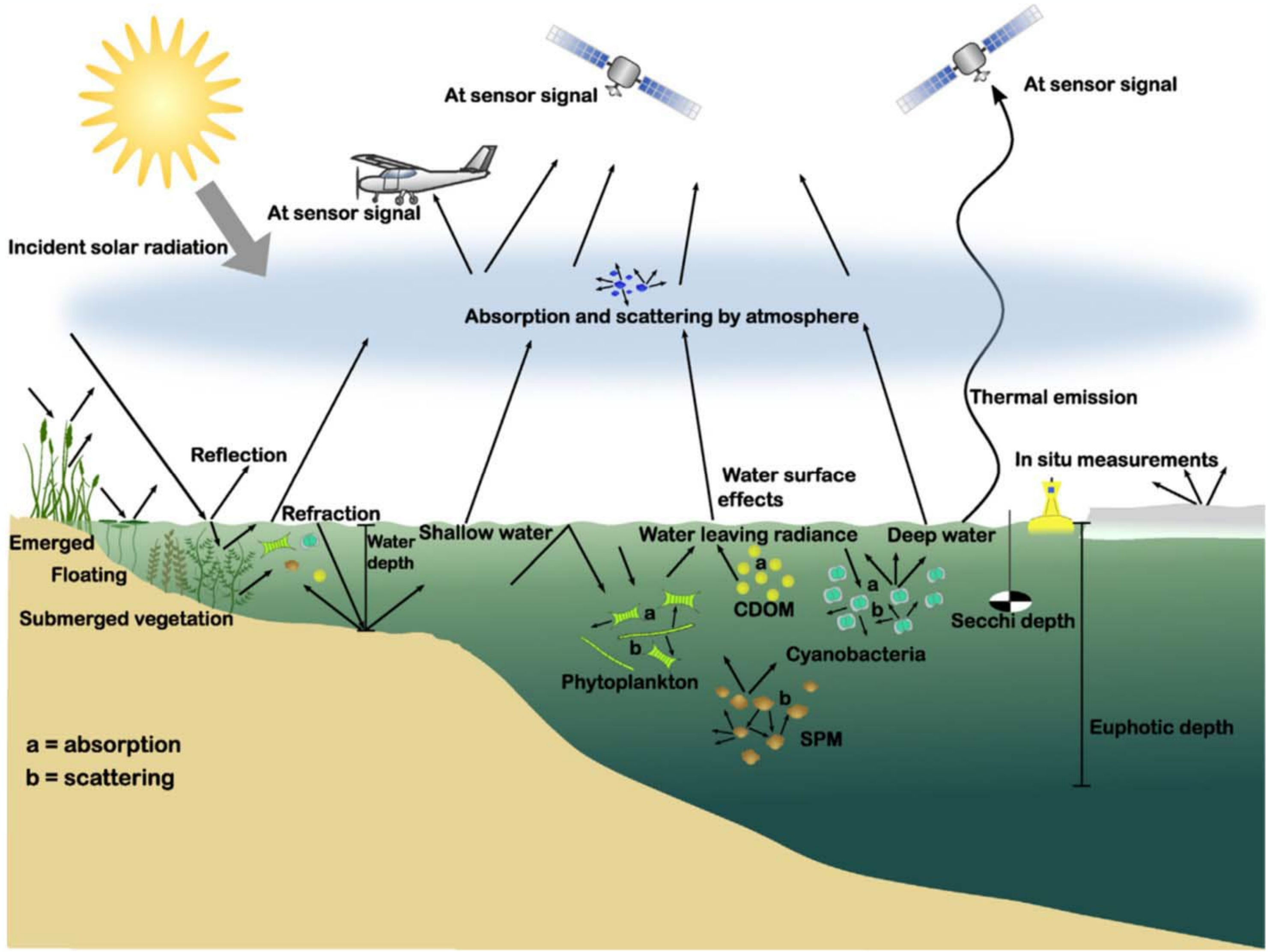


Absorption

- Low at the shorter λ in VIS
- Quickly increased from blue to TIR

Sources:
Kebes at English Wikipedia
NASA (2010)

Interaction of real water bodies and VIS



Complex interactions:

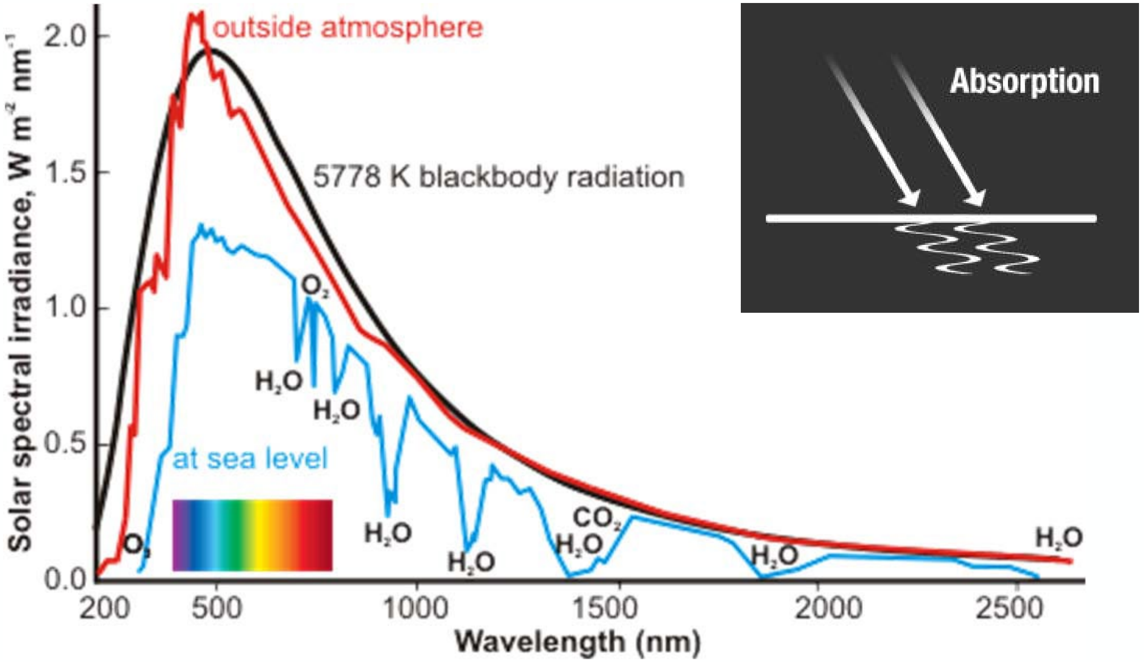
Reflection and refraction at the surface

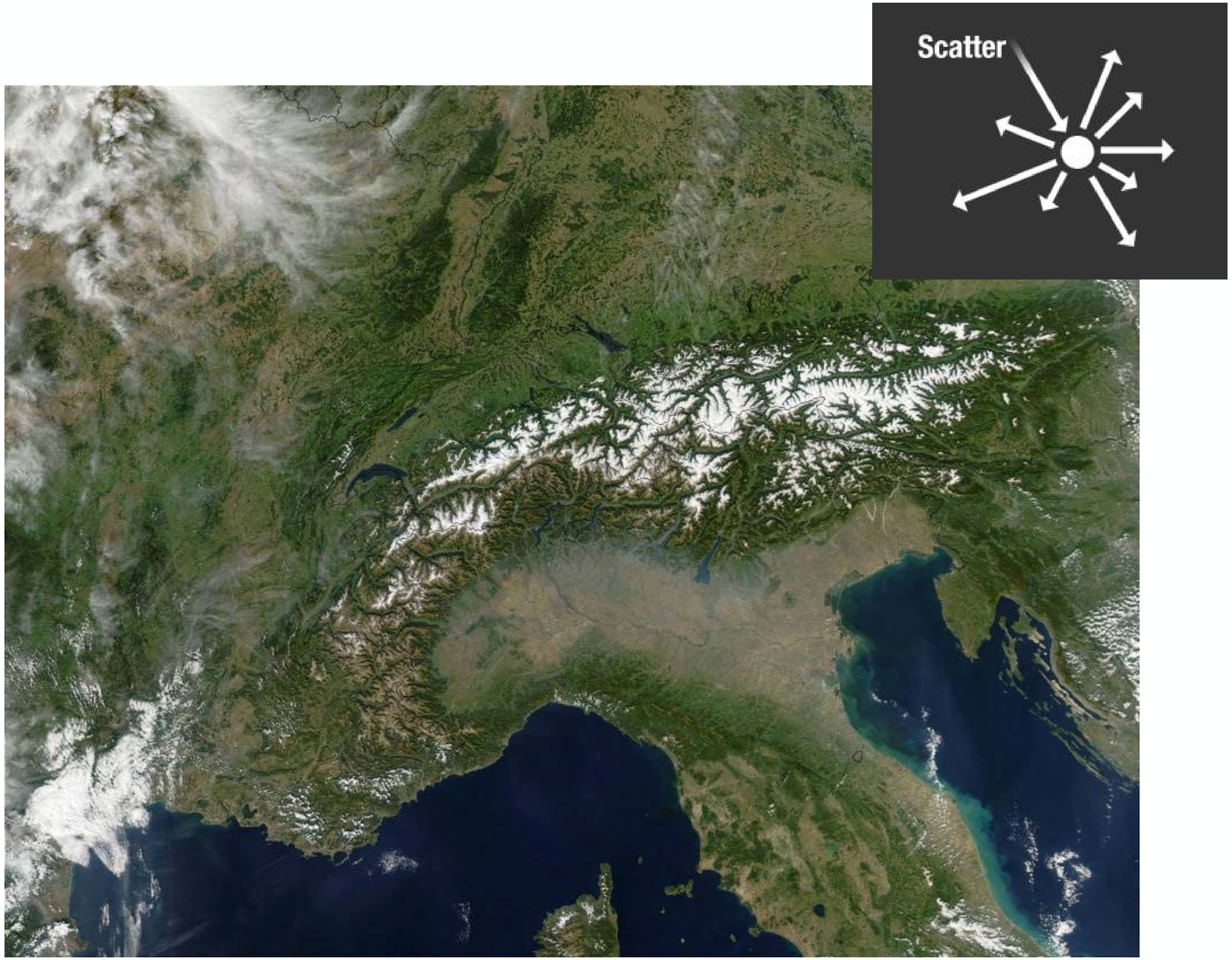
Absorption by water and other dissolved and suspended/floating constituents

Scattering (backscatter) by suspended/floating constituents

Source: Dörnhöfer & Oppelt (2016)

Interaction of water in the atmosphere and VIS - IR





Source: Chaplin (2018)

Absorption by vapour (gas), scattering by droplets (liquid and ice)

Source: www.wikiwand.com

Spectral signature of bare soil

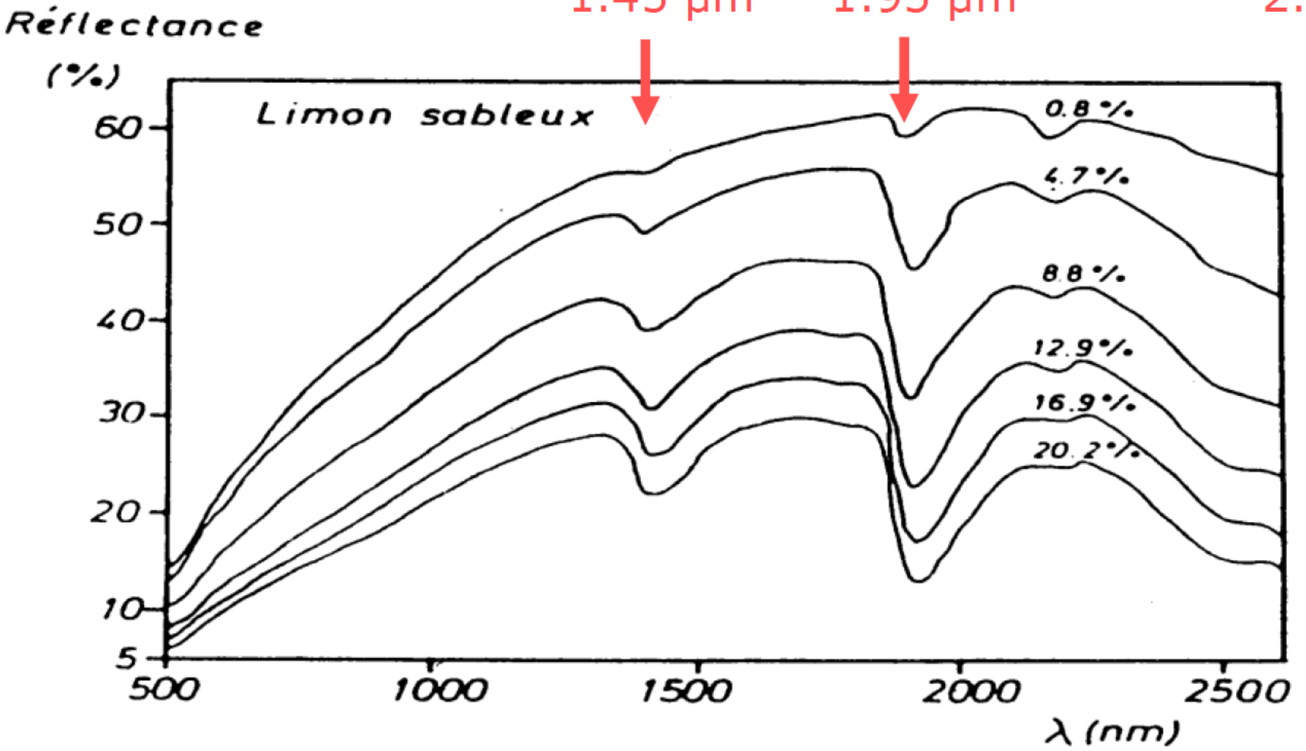
Incident radiation can be:

- only related to soil-atmosphere interface (superficial layer - not related to soil depth)
- influenced by soil structure, texture and stony component, soil surface moisture and soil colour (org. matter, Fe, Ca)
- reflectance slightly increases from the visible to the IR

Growing and convex curve, evolving with wavelength

Water absorption bands

1.45 µm 1.95 µm 2.9 µm

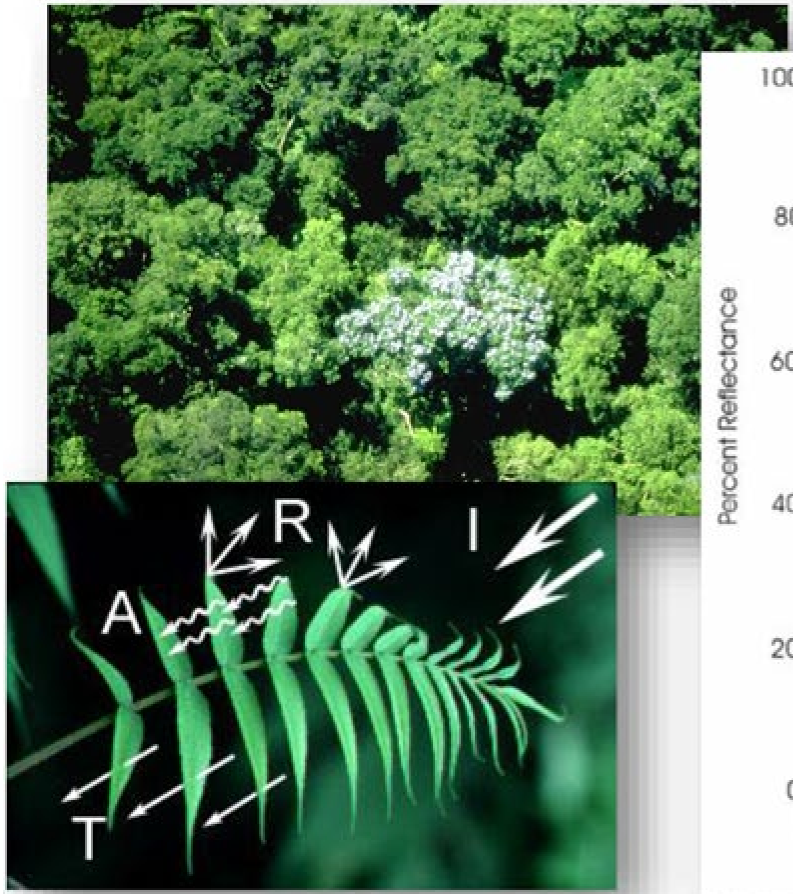


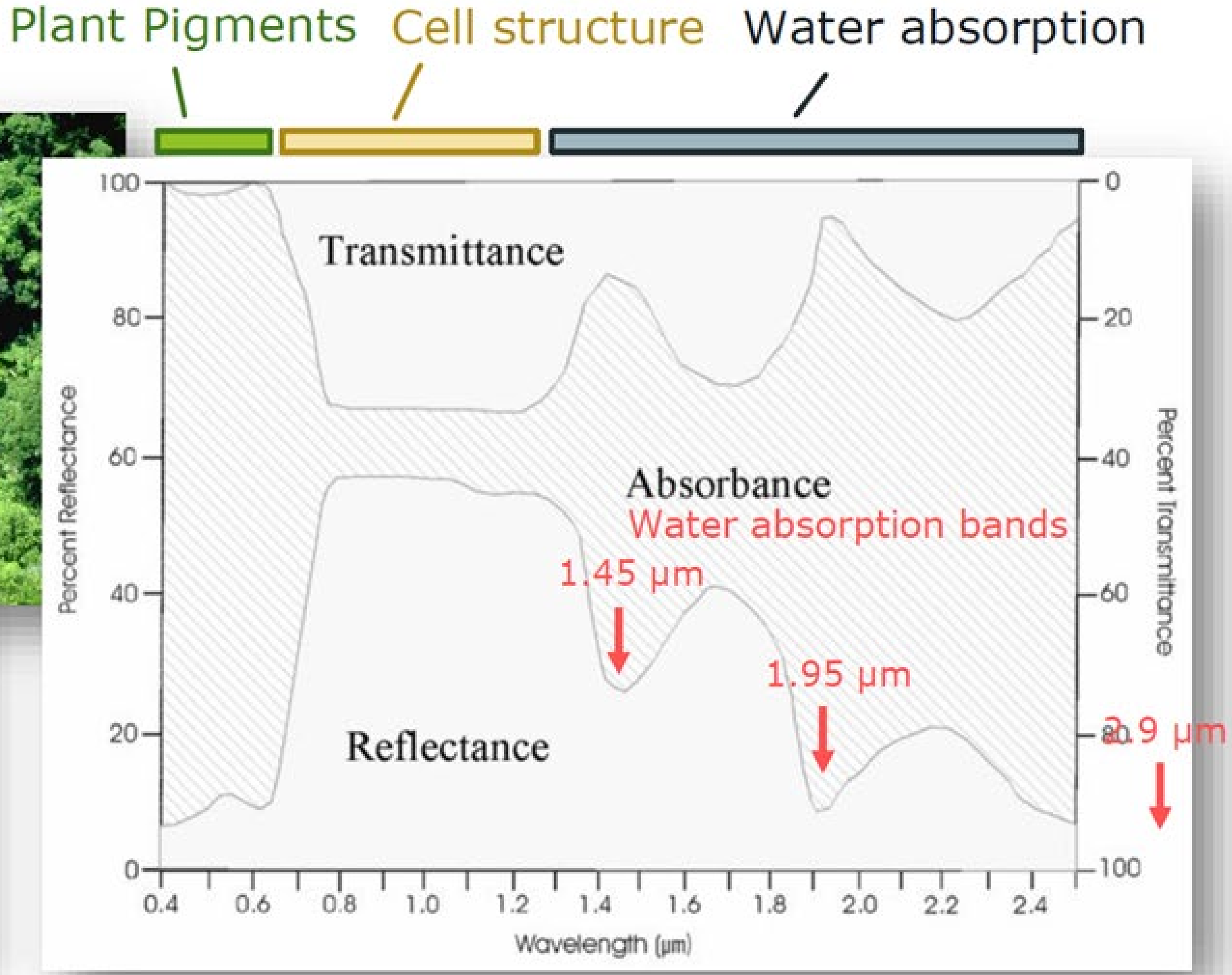
Spectral signature of green vegetation

Incident radiation

- Reflected
- Absorbed
- Transmitted
- Emitted

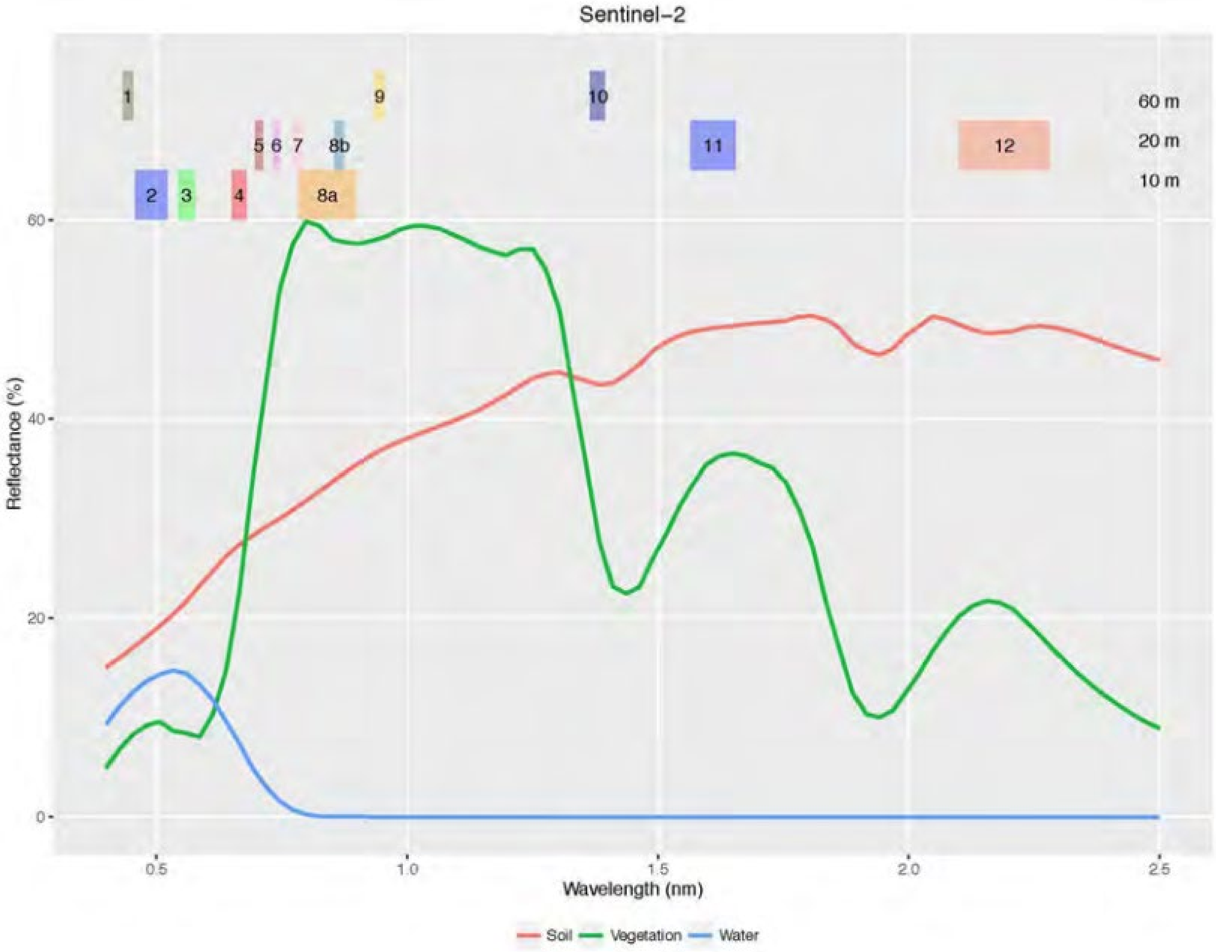
By plant tissues

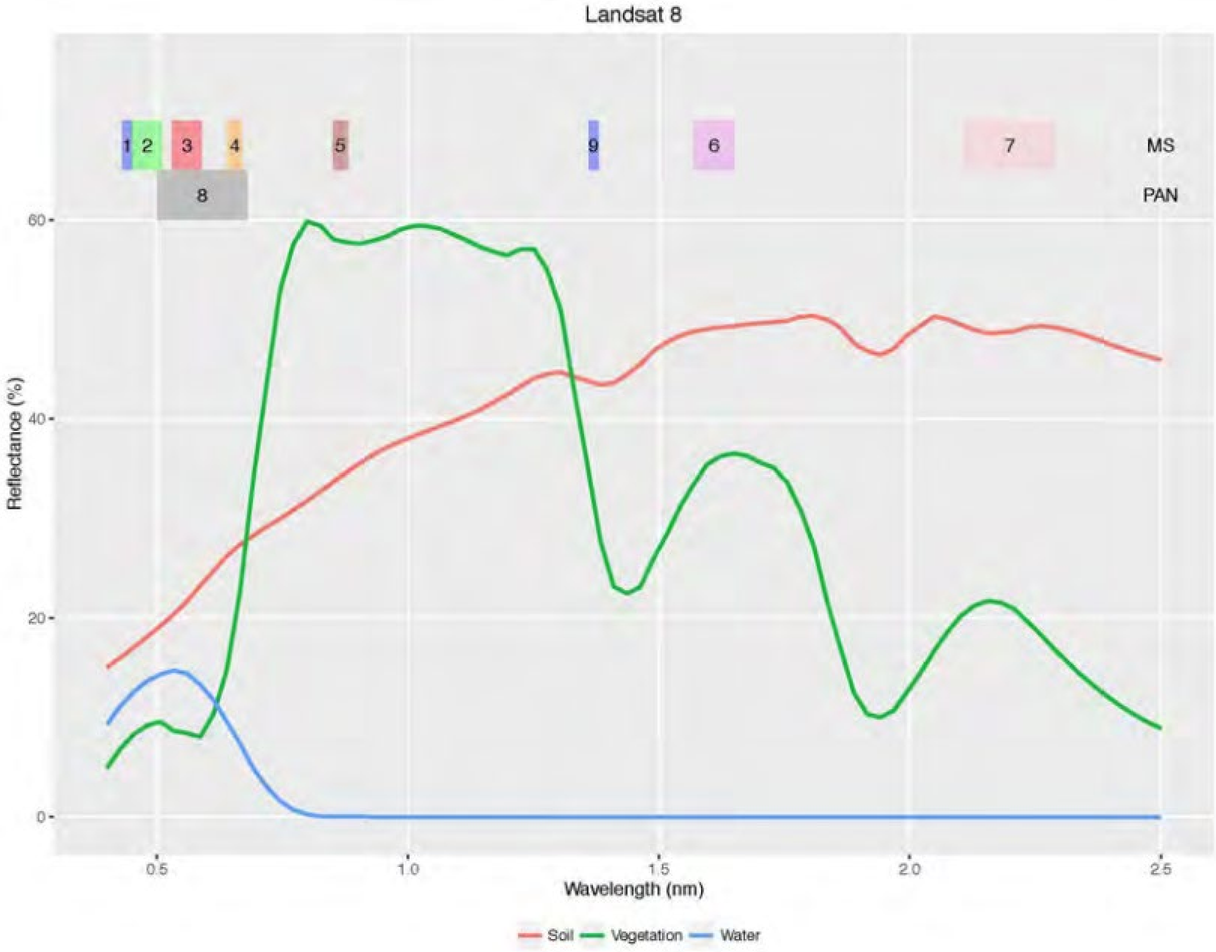




Interaction with vegetation and water

Sentinel-2 and Landsat 8 bands





Pre-processing of optical data

Pre-processing chain includes all the steps needed to generates cloud-free surface reflectance products taking as input Top Of Atmosphere data. For each of the module in the pre-processing chain different methods and algorithm can be applied.

- Cloud detection and removal (mono-temporal or multi-temporal)
- Atmospheric correction
- Reprojection
- Resampling
- Co-registration

Cloud detection and removal

A large portion of the earth surface is covered by clouds, consequently, most earth observation images in the visible spectral domain include a significant amount of cloudy pixels.

An image pixel can be:

- cloud free (there are no water droplets or ice crystals in the atmosphere which change the surface reflectance)
- partly cloudy (comprises all intermediate situations where the measured reflectance is a mixture of a significant portion of the surface reflectance, but modified due to the presence of a cloud)
- totally cloudy (the optical thickness is so high that the portion of surface reflectance at the signal measured by the satellite is negligible)

Cloud detection methods can be categorized in the following classes [Brockmann et al., 2008]:

- Spectral threshold methods (spectral characteristics, such as temperature, brightness, whiteness or height of the scatterer are tested against a threshold value)
- Feature extraction and classification (the spectral data space, if transformed into a feature space, can be statically or dynamically separated into cloud or clear classes)
- Learning algorithms (cloud probability or cloudiness index values are generated after training the algorithm with simulated or measured data)
- Multi-temporal analysis (Pixels are not always cloud covered and a time series of data is used to separate cloudy from clear cases)
- Multi-sensor approach (where multiple sensors are on the same platform and perform simultaneous measurements, the synergetic algorithms can be used to better identify clouds)

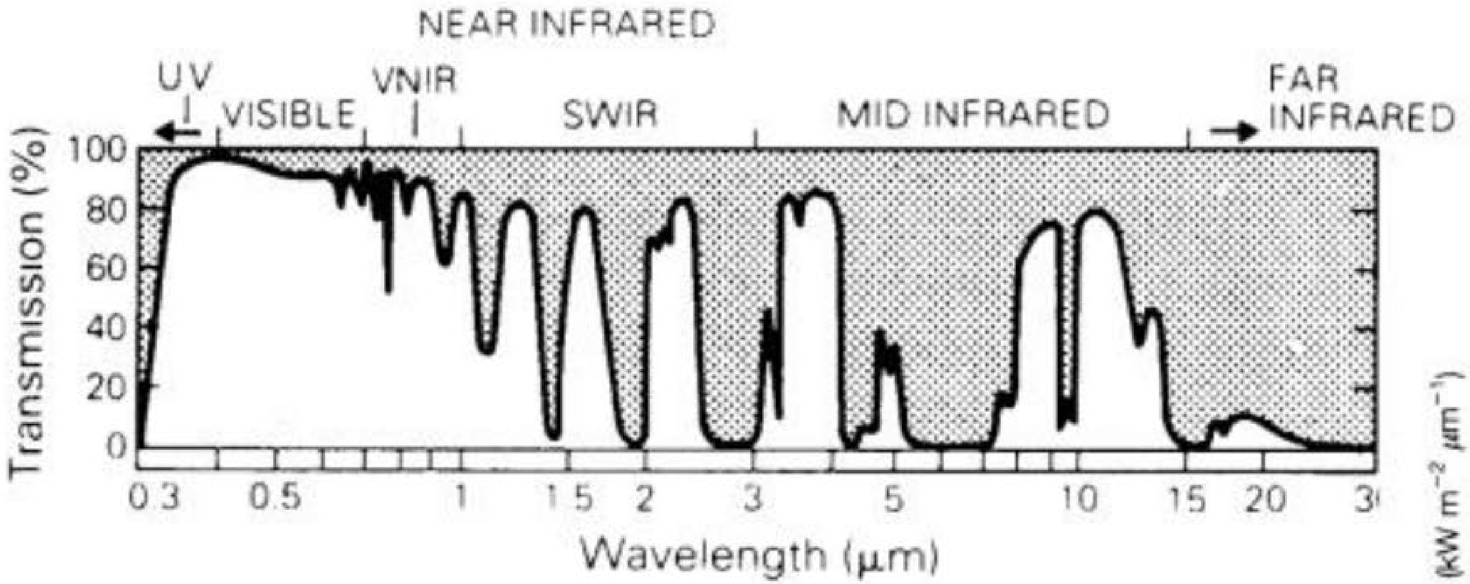
Interaction with the atmosphere

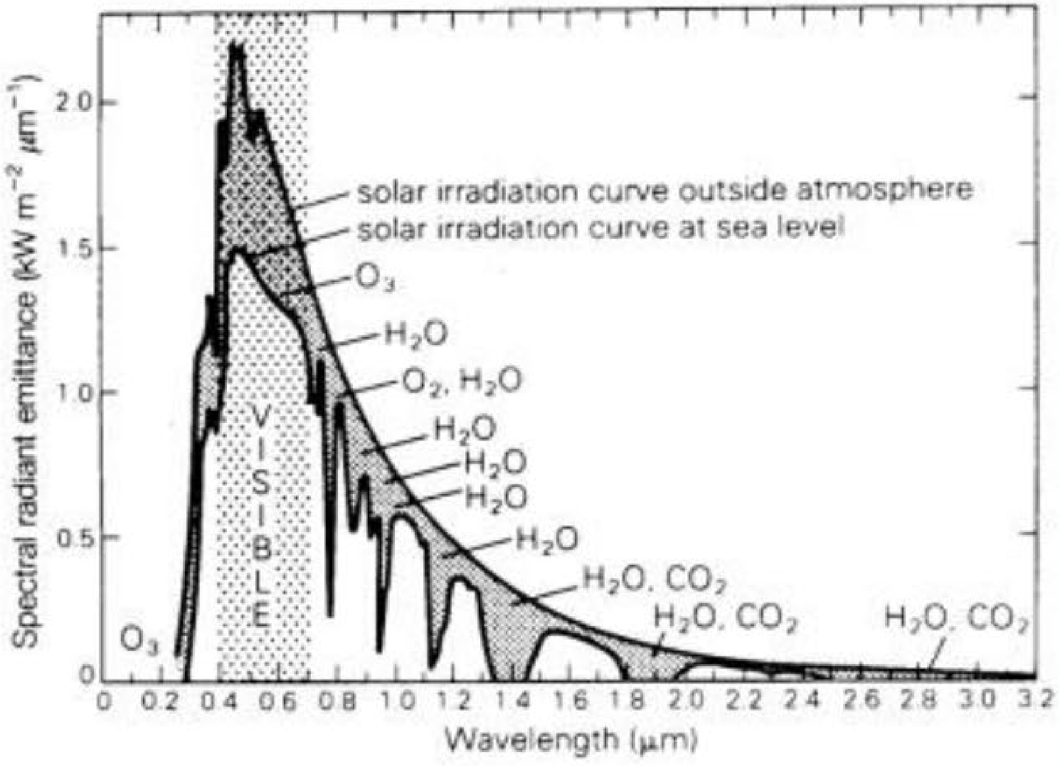
- Before radiation used for remote sensing reaches the surface it has to travel through some distance of the atmosphere.
- Particles and gases in the atmosphere can affect the incoming light and radiation.
- These effects are caused by the mechanisms of:
    - Scattering (Rayleigh – Mie)
    - Absorption

Scattering occurs when particles or large gas molecules present in the atmosphere interact with and cause the electromagnetic radiation to be redirected from its original path.

Absorption In contrast to scattering, this phenomenon causes molecules in the atmosphere to absorb energy at various wavelengths.

Atmospheric Windows





Some wavelengths are more effected by the atmosphere than others.

Those with little effect on signal are ‘windows’ for remote sensing.

Retrieval of Surface Reflectance

For further analysis we want to use a surface reflectance product

1) Allows comparison between images
2) Allows repeatable measurements (e.g., ground spectra comparison to satellite observations)
3) Represents a known physical unit.

To retrieve surface reflectance we need to ‘add back’ the component ‘lost’ in the atmosphere.

At Sensor Refl = Surface Refl + Atmospheric Refl

What is in the atmosphere?

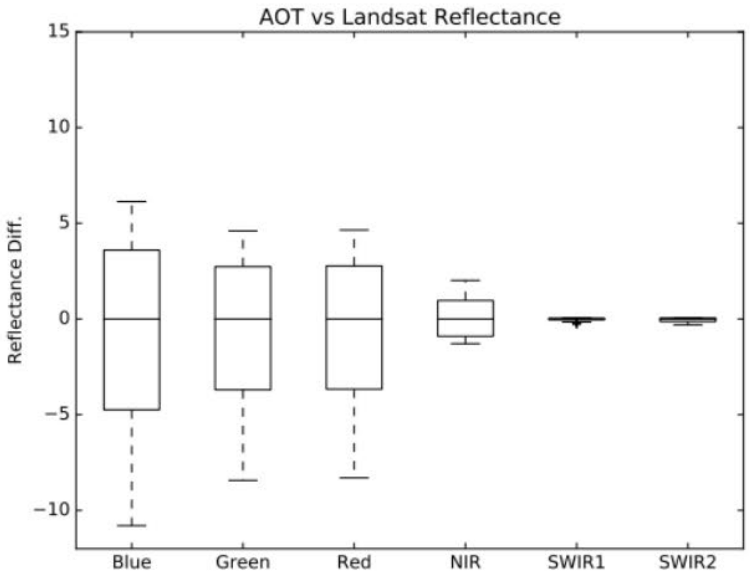
Aerosols

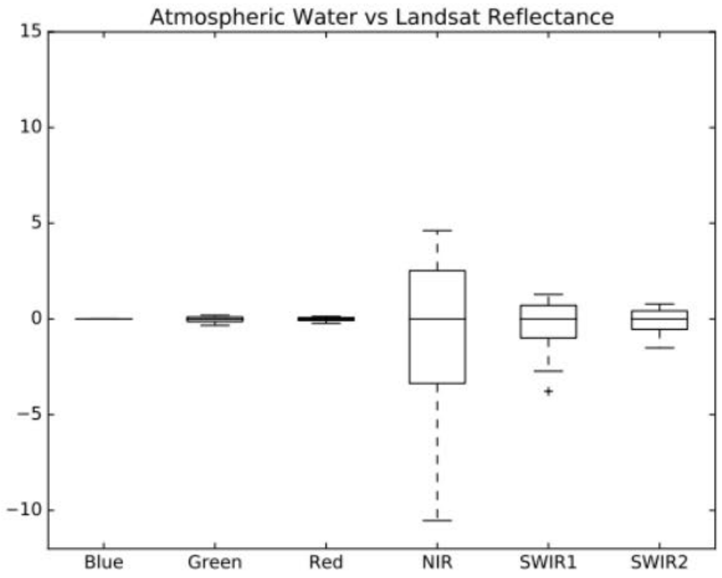
- E.g., fine dust, sea salt, water droplets, smoke, pollen, spores, bacteria.
- Has a significant effect on the visible wavelengths (Blue, Green and Red).
- Aerosol Optical Depth (AOD)
- Aerosol Optical Thickness (AOT)

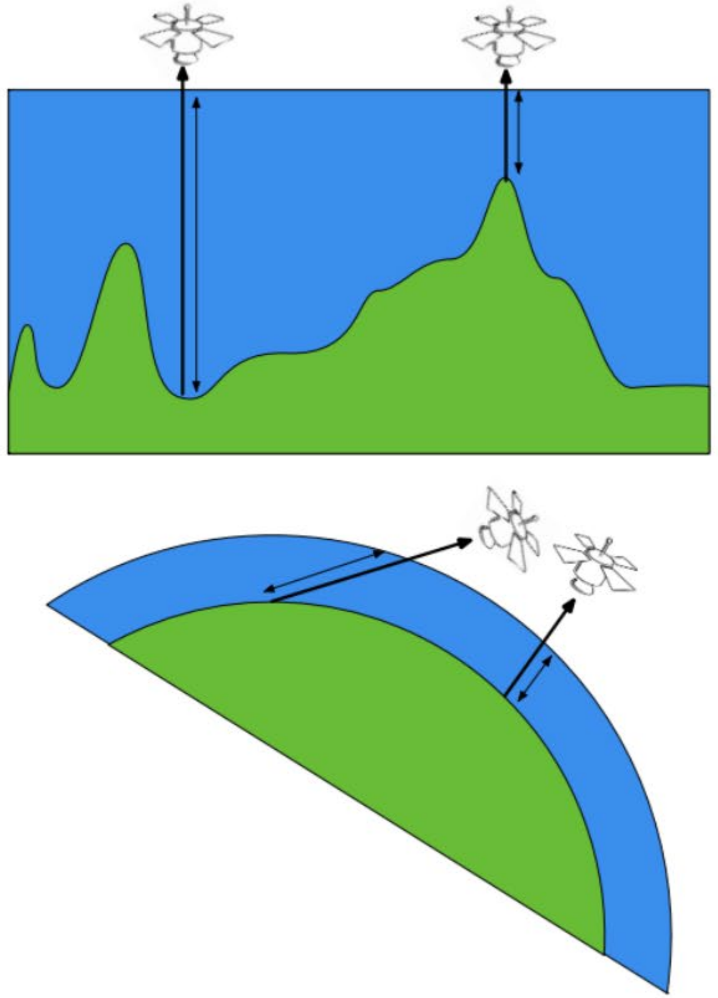
Water Vapour

- Particularly, effects the SWIR bands

What effects atmospheric correction?







Relative contributions:

AOT = 80%

Water Vapour = 15%

Altitude = 4%

Cloud detection and removal

Sen2Cor (developed by Telespazio Germany)

It is a mono-temporal processor for Sentinel-2 L2A product generation and formatting. Uses a single L1C product as input data. The algorithm can create 4 different classes of clouds, together with classifications of shadows and ice. Additional outputs are Aerosol Optical Thickness (AOT) map, Water Vapour map, and Scene Classification map. The program is available as SNAP plugin.

MAJA (developed by CESBIO/CNES)

The most significant difference of MAJA is being a multi-temporal processor, which means that it uses multiple L1C images of the same area in time series, this method improves the accuracy of masking. It can process Landsat, Sentinel-2, and Venus products.

IdePix (developed by Brockmann Consult)

IdePix (Identification of Pixel) is a pixel identification tool. It needs a Sentinel-2 L1C product for masking. Like Sen2Cor, it is available as a SNAP plugin. So that it has similar advantages of Sen2Cor in terms of user-friendliness. In the output, the program provides one class for each pixel.

Fmask (developed by USGS)

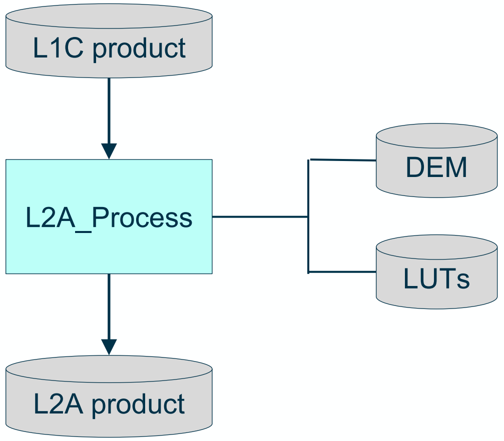
It is a pixel-based mono-temporal processor. Single L1C product is the input. It was initially developed for Landsat images but later extended for S2 images. Cloud, cloud shadow, snow, and water masking are possible with it. The program needs MATLAB environment.

Sentinel Hub's Cloud Detector

It is a single scene, a pixel-based program by a combination of Fmask, Sen2Cor, MAJA, and machine learning. It is available as a python package and doesn't have a GUI. The code is easy to follow with Jupyter-Notebook.

Sen2Cor – Overview

- Single image processing algorithm with orthorectified L1C granule in input
- Cloud Screening and Classification
- Atmospheric Correction over land surface (inherited from ATCOR DLR)
- Radiative Transfer code: LibRadtran (Look-Up-Tables)
- Python application:
    - Command line tool
    - Plug-in of SNAP
    - Integrated in S2 Ground Segment
- Processing configuration: 3 XML files

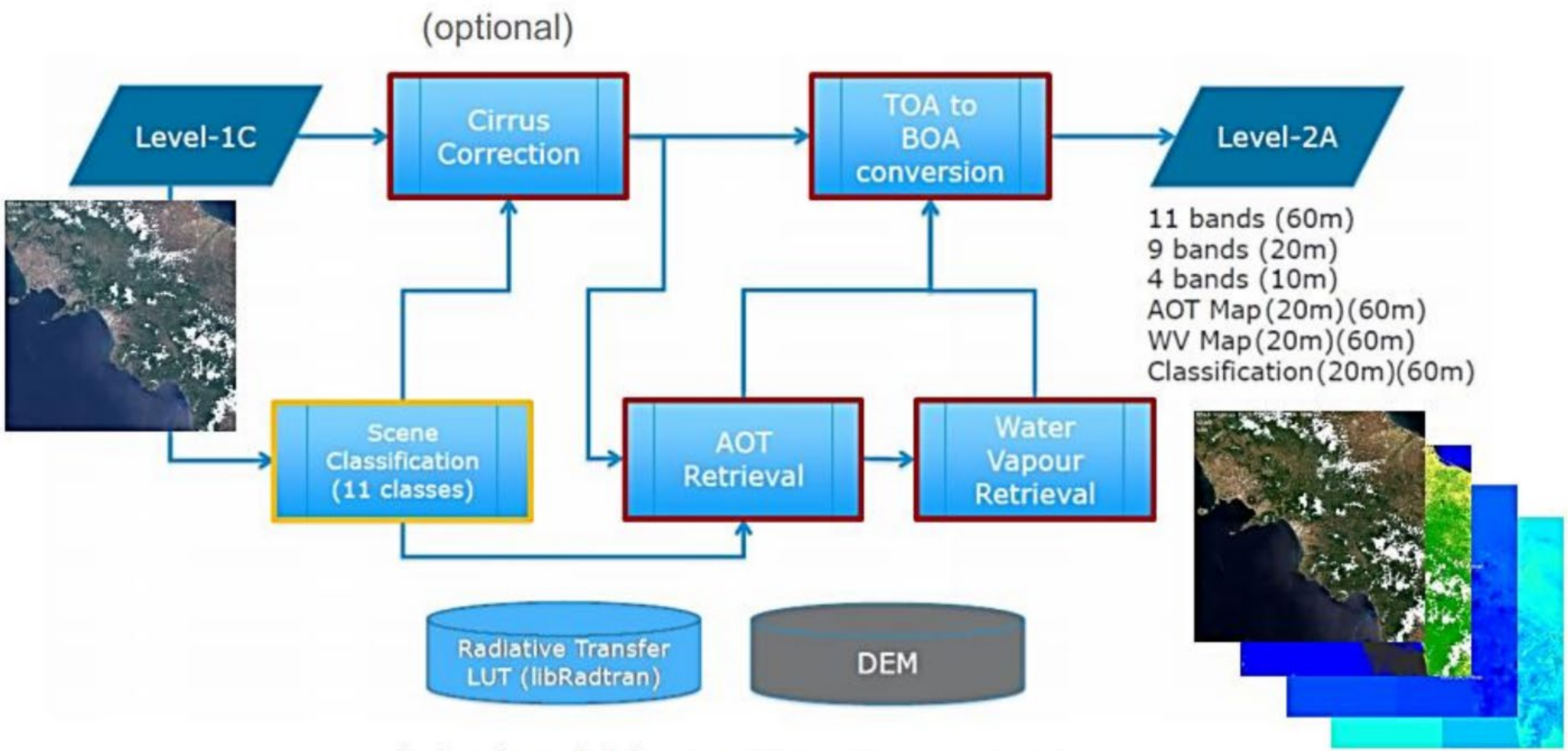


Using the Copernicus DEM@90m, the only differences between L2A “Toolbox” and L2A “Core” Products are reported in the table

Category of Difference	Difference	L2A Toolbox	L2A Core Products
Product Format	HTML Folder	No	Yes
	Manifest	Same Set of Items but arranged in different order	
	Product Quality Metadata	Copied from L1C	Generated by L2A On-line Quality Check (OLQC)
	JPEG2000 encoding library	OpenJPEG	Kakadu
	Processing baseline	99.99	Official, e.g. **05.09**

The evolution of the processing baseline used to process Sentinel-2 L2A Core Products in Ground Segment are reported in the L2A Data Quality Report

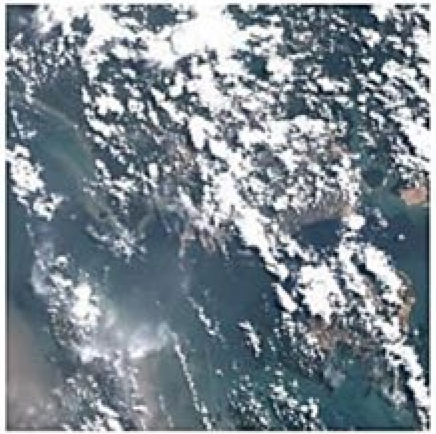
Sen2Cor – Main Processing Steps



- **Look-up tables** (rural & maritime aerosols)
- **DEM** (default: SRTM v4 CGIAR)
  (or DTED provided by user)

Sen2Cor – Cloud Screening and Classification

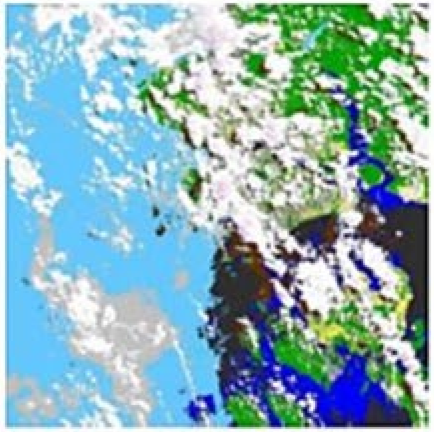
ESA CCI Support



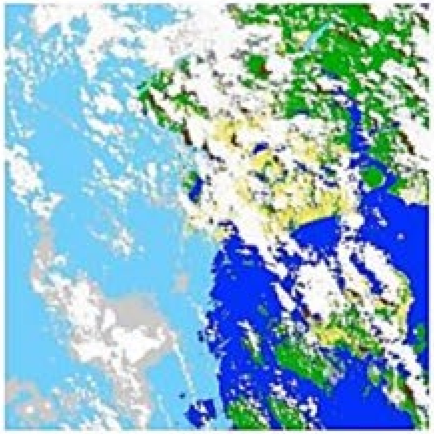
Satellite : S2A
Level: 1C
Type: RGB composition
Tile: 48NUG
Date: 20170730
Area: Singapore

ESA CCI Data Package:

- ESA CCI Land Cover (300 m)
- ESA CCI Water Bodies (150 m)
- ESA CCI Snow Occurrence (500 m)



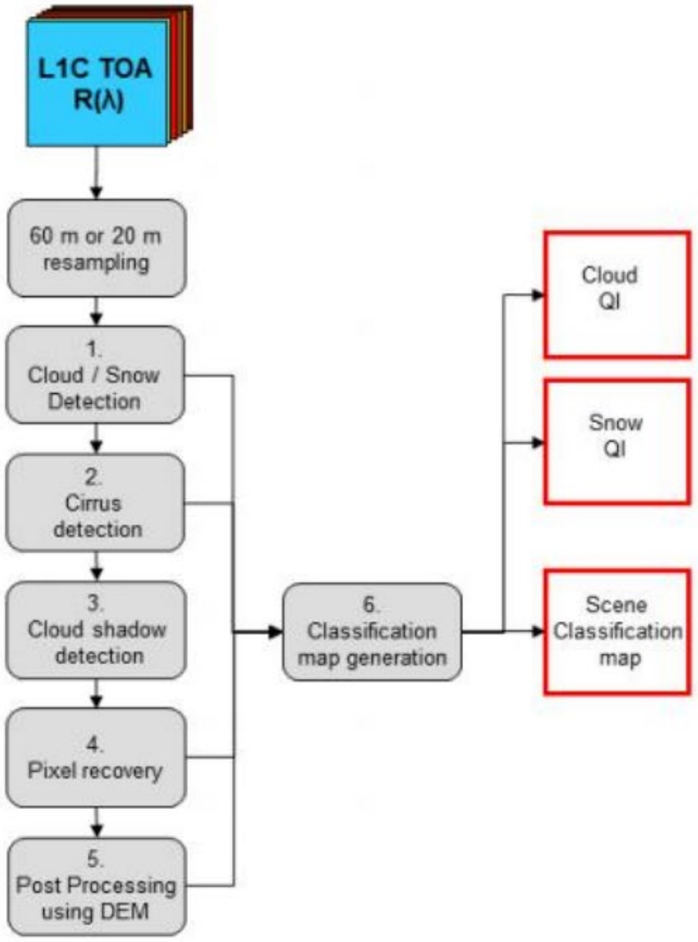
Without ESA CCI

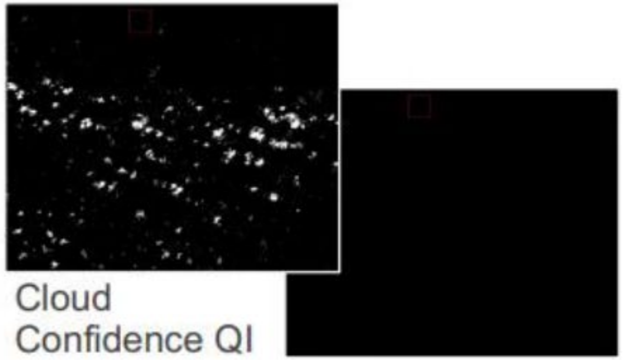


With ESA CCI

- Introduced with Sen2Cor version 2.5
- Water detection improved
- Bright targets (urban and soils)
  Less false cloud detection
- Activated in Sentinel-2 PDGS in October 2018 (L2A PB 02.09).

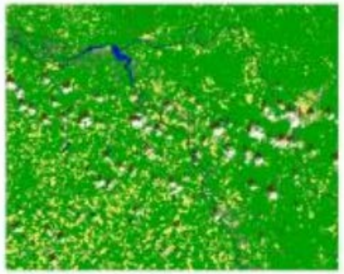
Sen2Cor – Cloud Screening and Classification





Cloud Confidence QI

Snow Confidence QI



Scene Classification

Label	Classification
0	NO_DATA
1	SATURATED_OR_DEFECTIVE
2	DARK_AREA_PIXELS
3	CLOUD_SHADOWS
4	VEGETATION
5	NOT_VEGETATED
6	WATER
7	UNCLASSIFIED
8	CLOUD_MEDIUM_PROBABILITY
9	CLOUD_HIGH_PROBABILITY
10	THIN_CIRRUS
11	SNOW

Sentinel-2 L2A data overview

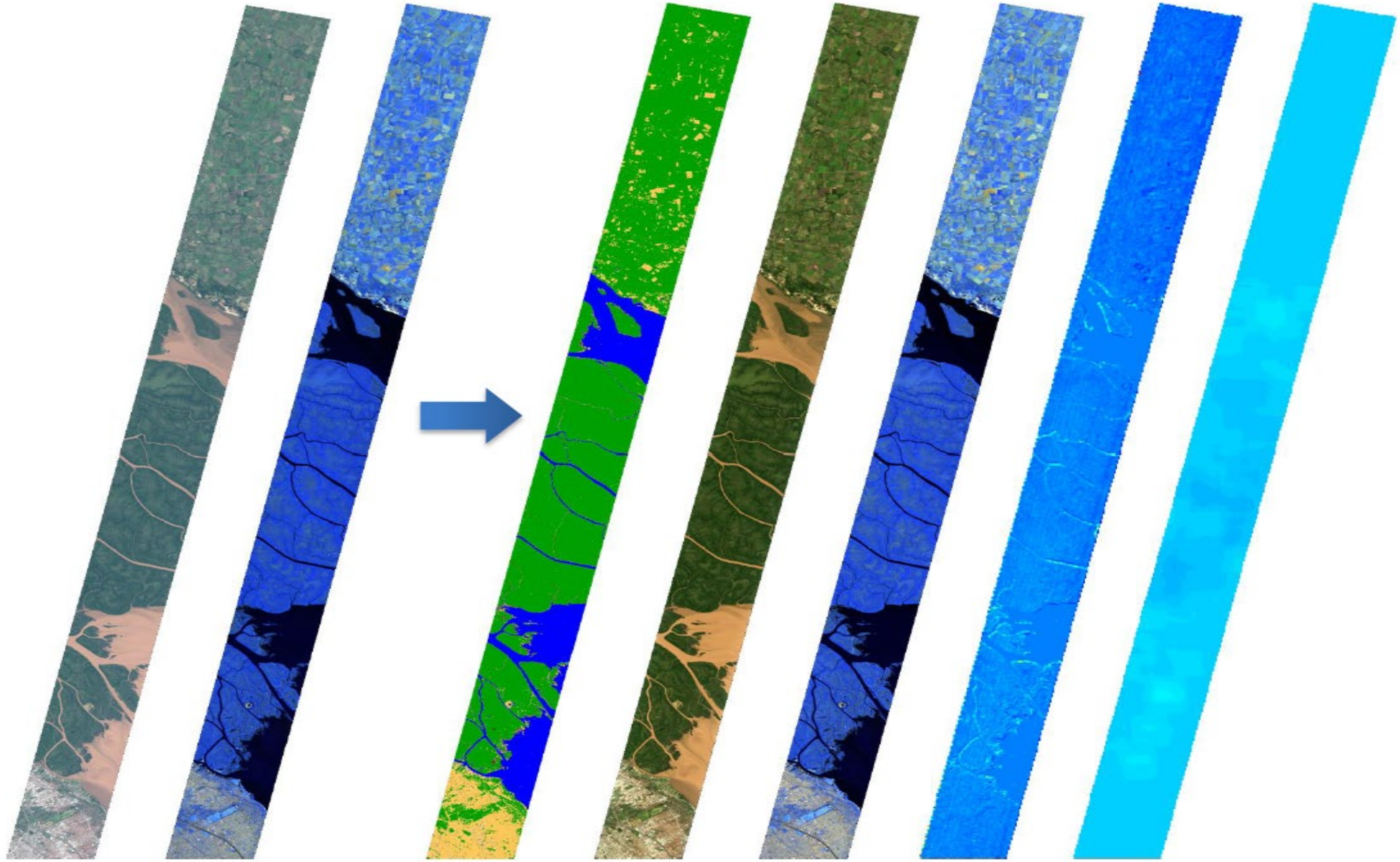
From left to right:

Level-1C [TOA]

- *[RGB] B4-B3-B2*
- *[RGB] B12-B11-B8a*

Level-2A [BOA]

- *Scene Classification*
- *[RGB] B4-B3-B2*
- *[RGB] B12-B11-B8a*
- *Water Vapour*
- *Aerosols Optical Thickness*



Reprojection, resampling and co-registration

Reprojection

If the input of the time series come from several sources with different CRS the reprojection to a common CRS is needed.

Resampling

Data coming from different sources could have different spatial resolution, therefore in this case before to analyse the time series a resampling is necessary.

Nearest Neighbour:

- Pros: Very simple and fast; No new values are calculated by interpolation
- Cons: Some pixels get lost and others are duplicated; Loss of sharpness

Bi-linear interpolation:

- Pros: Extremes are balanced; Image losses sharpness compared to Nearest Neighbour
- Cons: Less contrast compared to Nearest Neighbour; New values are calculated which are not present in the input product

Cubic convolution:

- Pros: Extremes are balanced; Image is sharper compared to Bi-linear Interpolation
- Cons: Slow and less contrast compared to NN; New values are calculated which are not present in the input product

Co-registration

In order to maximise the geolocation accuracy, even if the input data come from the same satellite/constellation, the coregistration is need specially if you work with VHR and HR data.

Why use time series

A time series is defined as a set of satellite images taken over the same area of interest at different times

It makes use of different satellite sources to obtain a larger data series with short time interval between two images

Time Series of Satellite observations offer opportunities:

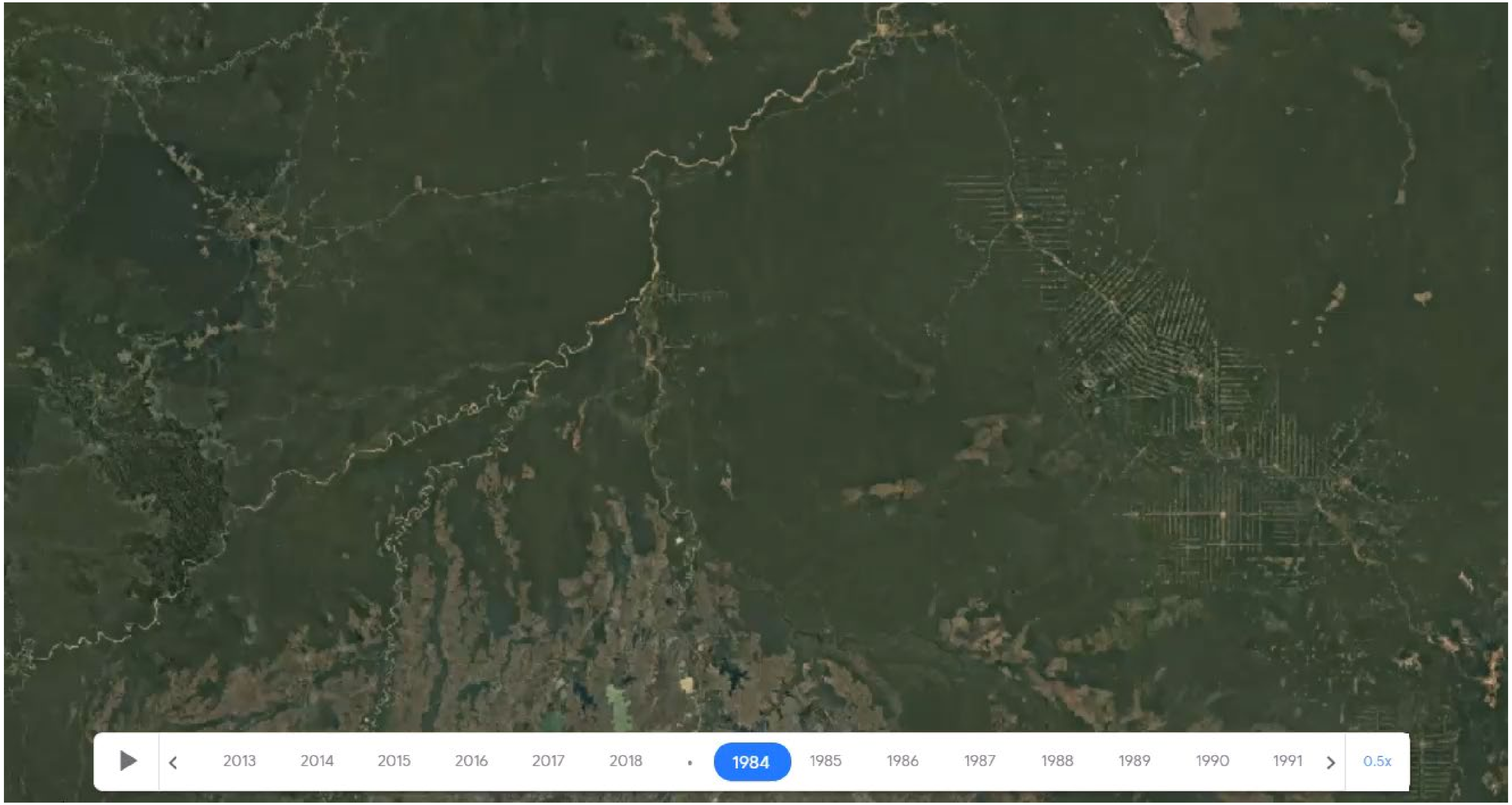
- for understanding how Earth is changing
- for determining the causes of these changes
- for predicting future changes

Remotely sensed data, combined with information from ecosystem models, offers an opportunity for predicting and understanding the behaviour of the Earth's ecosystem.

Temporal components integrated with spectral and spatial dimensions allows the identification of complex patterns concerning applications connected with environmental monitoring and analysis of land-cover dynamics.

Theewaterskloof Dam change by S2 time series

Rondônia deforestation by Landsat time series



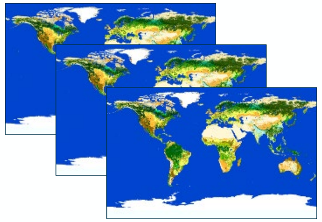
ESA CCI LandCover

Medium Resolution Land Cover products [300m]

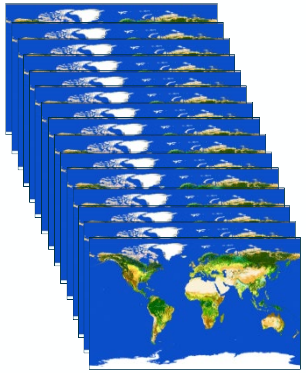
GlobCover 2005

GlobCover 2009

CCI LC epoch maps
2000 – 2005 - 2010



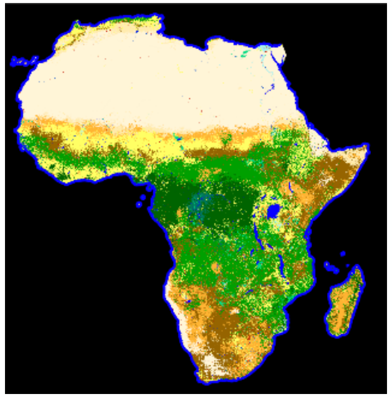
CCI LC yearly maps
1992 » 2015



From 2016 onwards C3S

High Resolution Land Cover products

S2A Prototype LC map - Africa 2016 @20m



S2A/B Prototype LC map
Mexico & Central America 2016-2017 @10m

ESA WorldCover 2020 & 2021

Radiometric Indices on SNAP

A radiometric index is a quantitative measure used to indicate the relative abundance of features of interest, usually formed from combinations of several spectral bands, whose values are added, divided, or multiplied.

Vegetation indices

- *DVI, RVI, PVI*
- *NDVI, WDVI, TNDVI, GNDVI*
- *SAVI, TSAVI, MSAVI, MSAVI2*
- *GEMI*
- *ARVI*
- *NDI45*
- *MTCI, MCARI, PSSRa*
- *S2REP, REIP, IRECI*

Soil indices

- *BI*
- *BI2*
- *RI*
- *GEMI*

Water indices

- *NDWI*
- *NDWI2*
- *MNDWI*
- *NDPI*
- *NDTI*

Second Normalized Difference Water Index (NDWI-2)

The second Normalized Difference Water Index was developed by McFeeters (1996) to detect surface waters in wetland environments and to allow for the measurement of surface water extent. The equation is similar to NDVI, except that it uses Green (B3) and the Near InfraRed (NIR) wavelengths.

$$NDWI2 = \frac{(Green - NIR)}{(Green + NIR)} = \frac{(B3 - B8)}{(B3 + B8)}$$

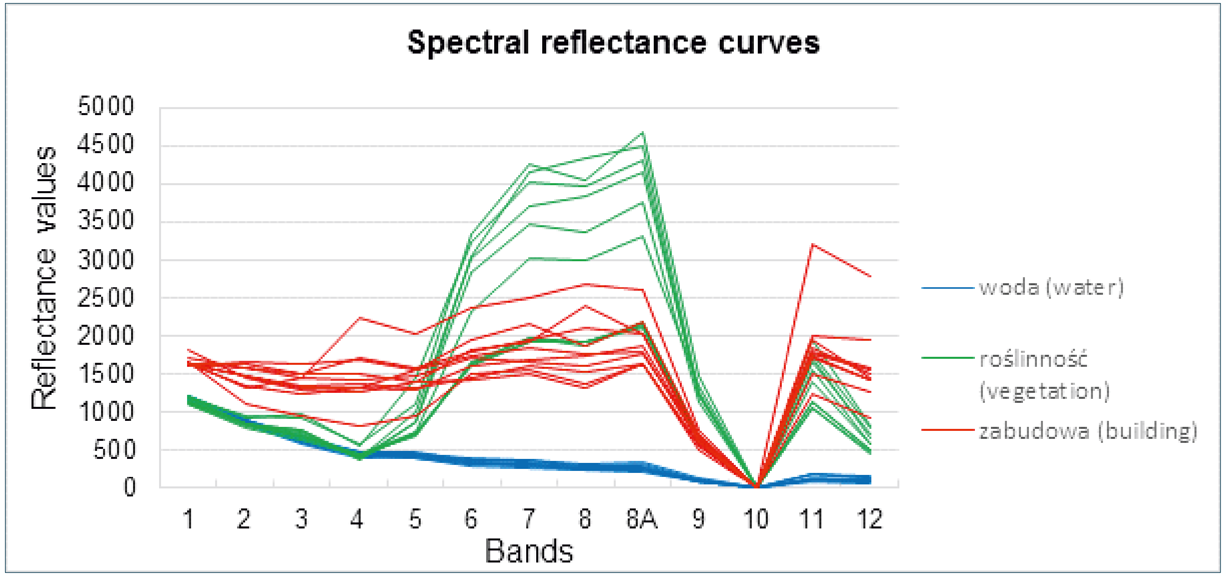
The NDWI-2 makes use of reflected near-infrared radiation and visible green light to enhance the presence of such features while eliminating the presence of soil and terrestrial vegetation features.

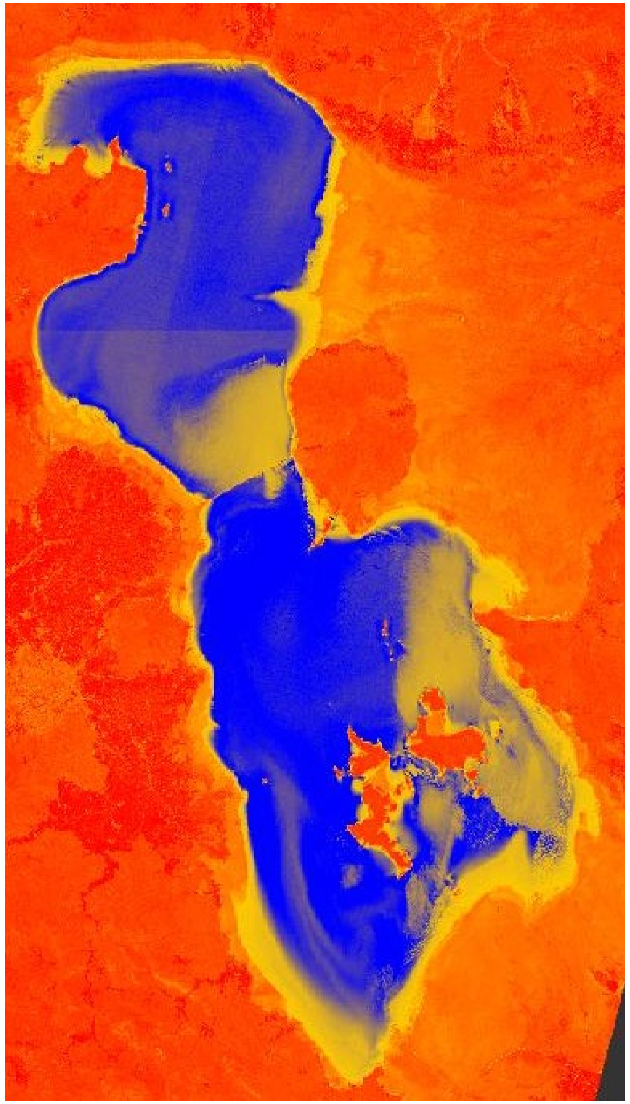
A high NDWI-2 value generally indicates presence of water.

The water curve is characterised by a high absorption at near infrared wavelengths range and beyond. Because of this absorption property, water bodies as well as features containing water can easily be detected, located and delineated with remote sensing data.

Sentinel Water Mask (SWM)

The Sentinel Water Mask algorithm was presented by Marta Milczarek during ESA Land Training Corse 2017 winning the best poster award in the category "Optical Remote Sensing". SWM provides quick and effective detection of water.





After analysis of spectral reflectance curves for water and other types of land cover (Figure above), two bands with the highest reflectance for water (Blue and Green) and two with the lowest one (NIR and SWIR) were selected and new index formula was developed:

$$SWM = \frac{(Blue + Green)}{(NIR + SWIR)} = \frac{(B2 + B3)}{(B8 + B11)}$$

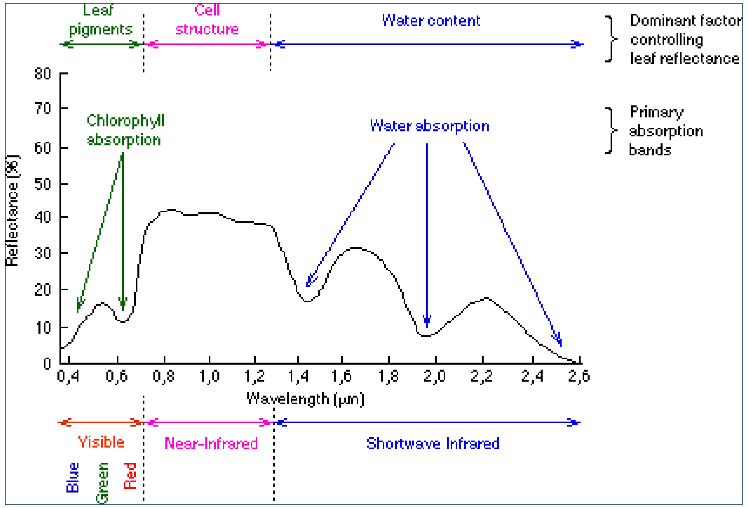
Normalized Difference Vegetation Index (NDVI)

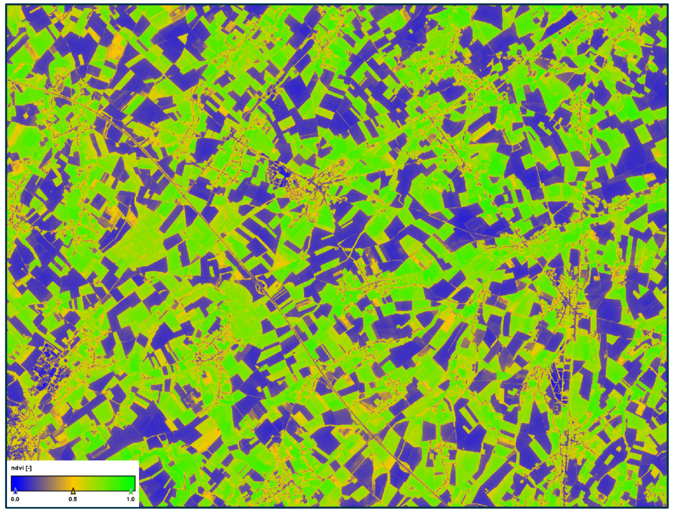
The Normalized Difference Vegetation Index (NDVI) algorithm exploits the strength and the vitality of the vegetation on the earth's surface.

Even if it is an old and classic method it is still much used to estimate the health of green vegetation and post processed high definition images for precision agriculture.

- *Vegetation has high NIR and low Red reflectance*
- *Other land cover have NIR and Red which are much close together*
- *-1.0 to +1.0*
- *vegetation from 0.3 to 0.8, depending on health/intensity*
- *water (sea, lakes, rivers) low positive or even negative*
- *bare soil low positive values from 0,1 to 0,2*

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$



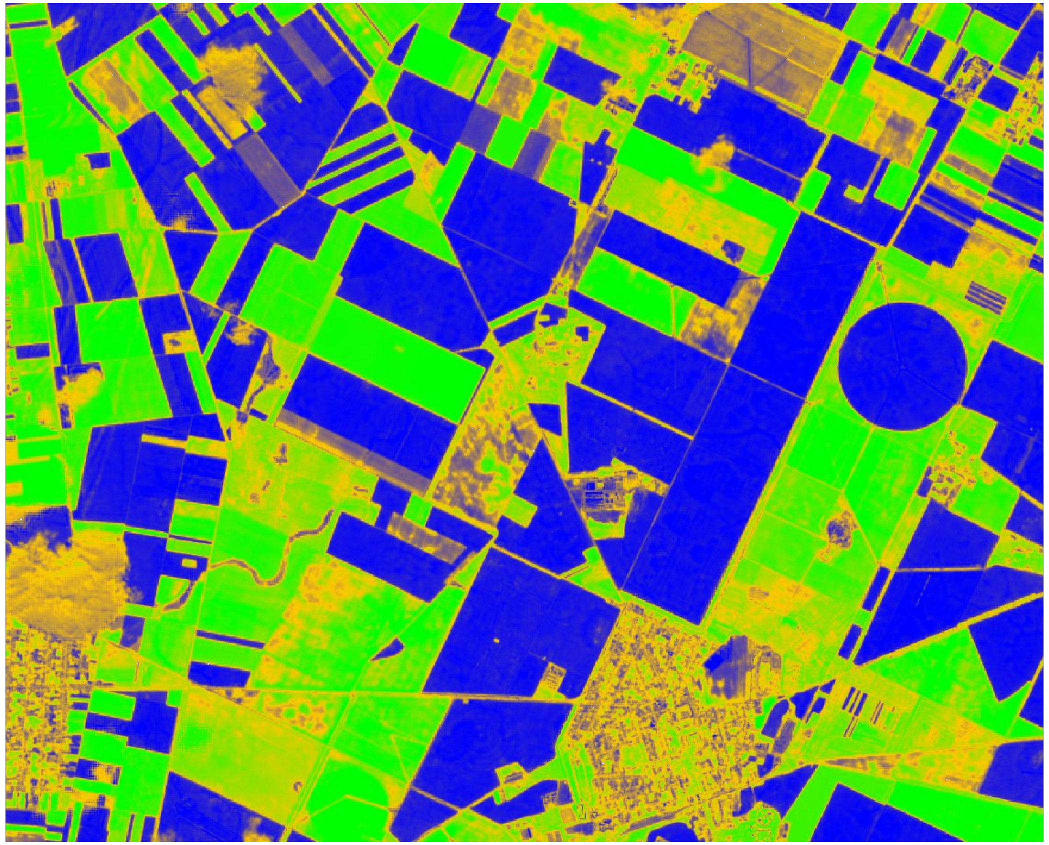


Normalized Difference Moisture Index (NDMI)

The Normalized Difference Moisture Index (NDMI) detects moisture levels in vegetation using a combination of near-infrared (NIR) and short-wave infrared (SWIR) spectral bands. It is a reliable indicator of water stress in crops.

NDMI can detect water stress at an early stage, before the problem has gone out of hand. Further, using NDMI to monitor irrigation, especially in areas where crops require more water than nature can supply, helps to significantly improve crop growth.

$$NDMI = \frac{NIR - SWIR_1}{NIR + SWIR_1}$$



Example of Hazard monitoring using RS data

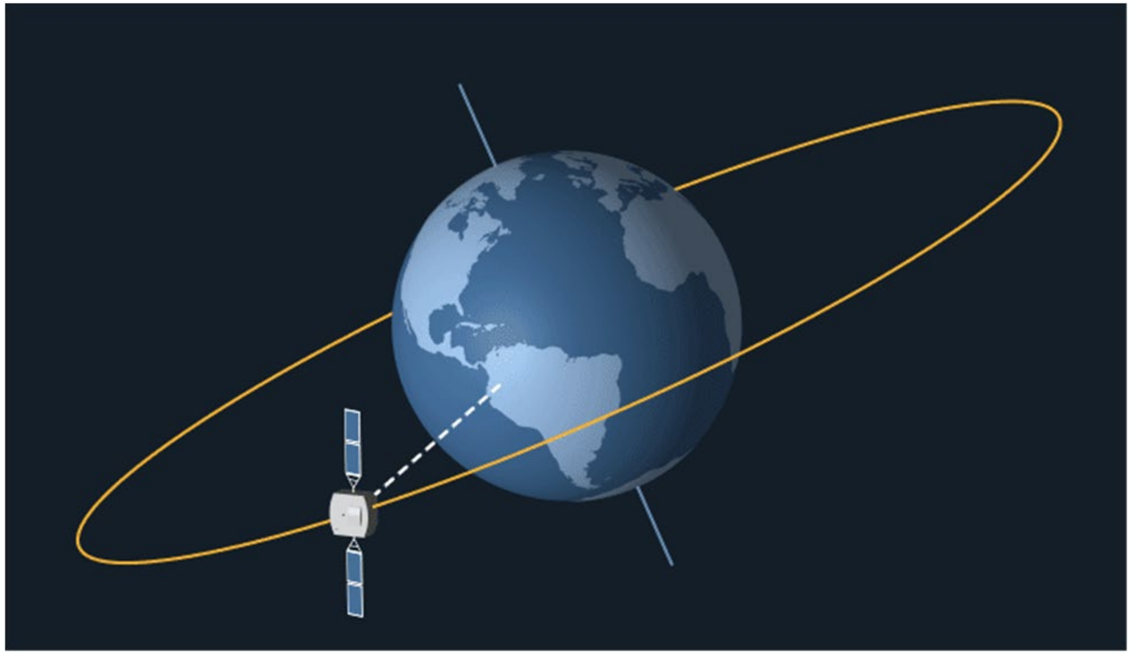
Flood in Emilia Romagna (Italy)

Satellite remote sensing of precipitation

Geostationary orbit:

- 36,000 km above the Equator
- 1-10 km spatial resolution
- 15-30 minutes temporal resolution
- Increasing geometric distortion towards the poles due to Earth curvature

Source: http://www.seos-project.eu/...



(Quasi)polar orbit:

- 200-1000 km above surface
- 1-1000 m spatial resolution
- 1-14 days temporal resolution (depending on constellation & geographic location)
- Less geometric distortion in an image due to Earth curvature

Source:https://dlmultimedia.esa.int/…

Satellites map aftermath of Emilia-Romagna floods

The Italian region of Emilia-Romagna was devastated by severe floods in May 2023, claiming lives and displacing thousands of people, resulting in an estimated €8.8 billion in damages. With the region still grappling with the aftermath, satellites have been instrumental in assessing the damages of the affected areas.

Between 16-18 May 2023, 350 million cubic metres of water, equivalent to six months' worth of rain, fell within 36 hours across Emilia-Romagna, one of Italy's most important agricultural regions. The heavy rain led to the overflow of 23 rivers across the region, affecting 100 municipalities and triggering more than 400 landslides, which in turn damaged and closed off hundreds of roads.

The floods were preceded by a drought that dried out the land, reducing its capacity to absorb water.

Earth observation imagery and data are crucial for emergency services, as they provide the ability to assess potential impacts of natural disasters and assist in emergency management activities, but they can also support post-event analysis and damage assessment.

Satellites map aftermath of Emilia-Romagna floods

The SaferPlaces platform (https://saferplaces.co/), co-funded by the ESA InCubed programme (https://incubed.esa.int/), has been utilised by the Civil Protection of the Emilia-Romagna region to generate flood water and depth maps to take crucial decisions after the disaster and support the assessment of the damages of the affected areas. The platform utilises satellite, climate data and AI-based models combined into a cloud computing environment to provide insights into areas prone to floods across the globe.

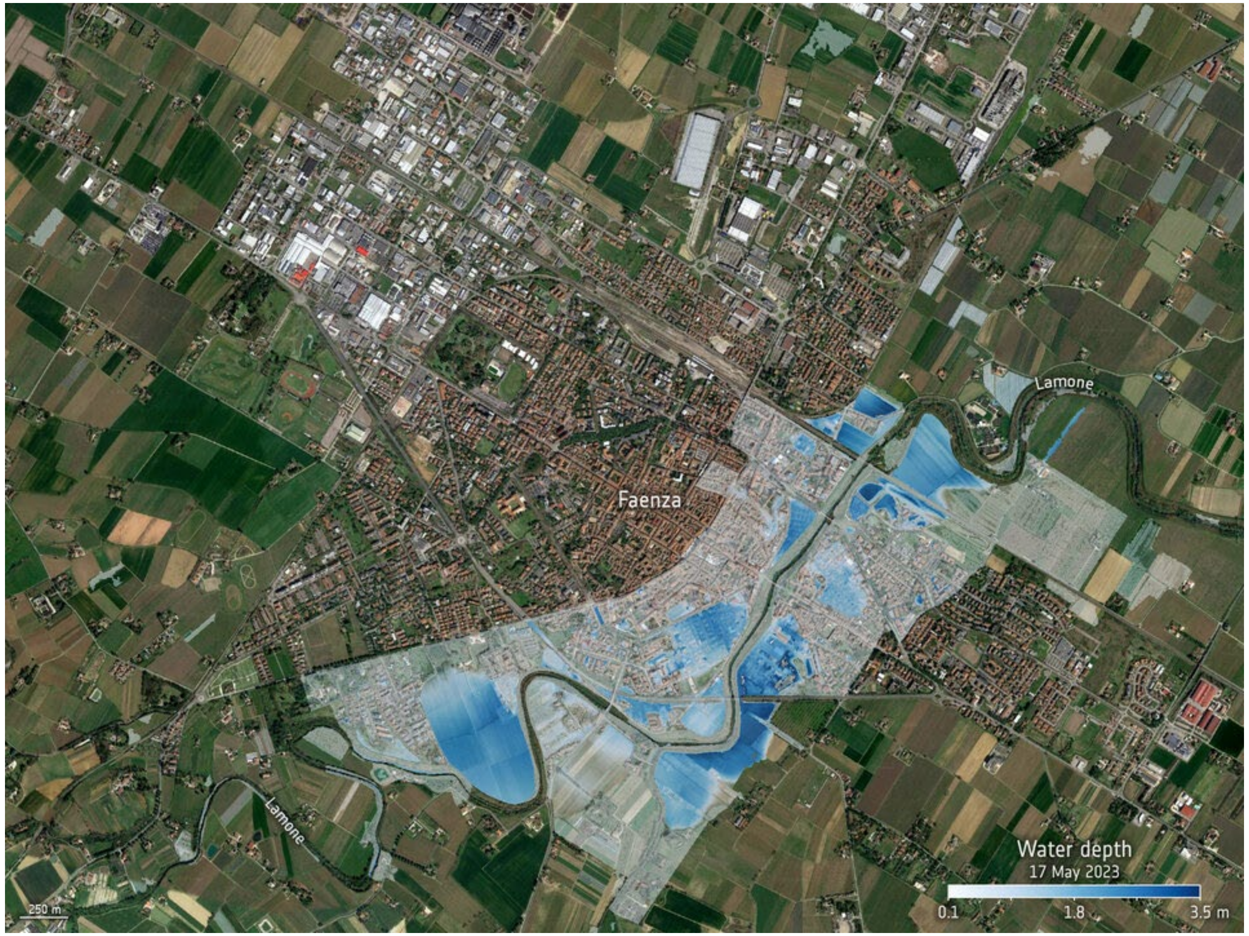
SaferPlaces' AI-based algorithms were used to process terrain data and information on the flooded areas obtained by merging in situ data with multiple satellite sources including: Copernicus Sentinel-1 and Sentinel-2, CosmoSky-Med, Planet and SPOT.

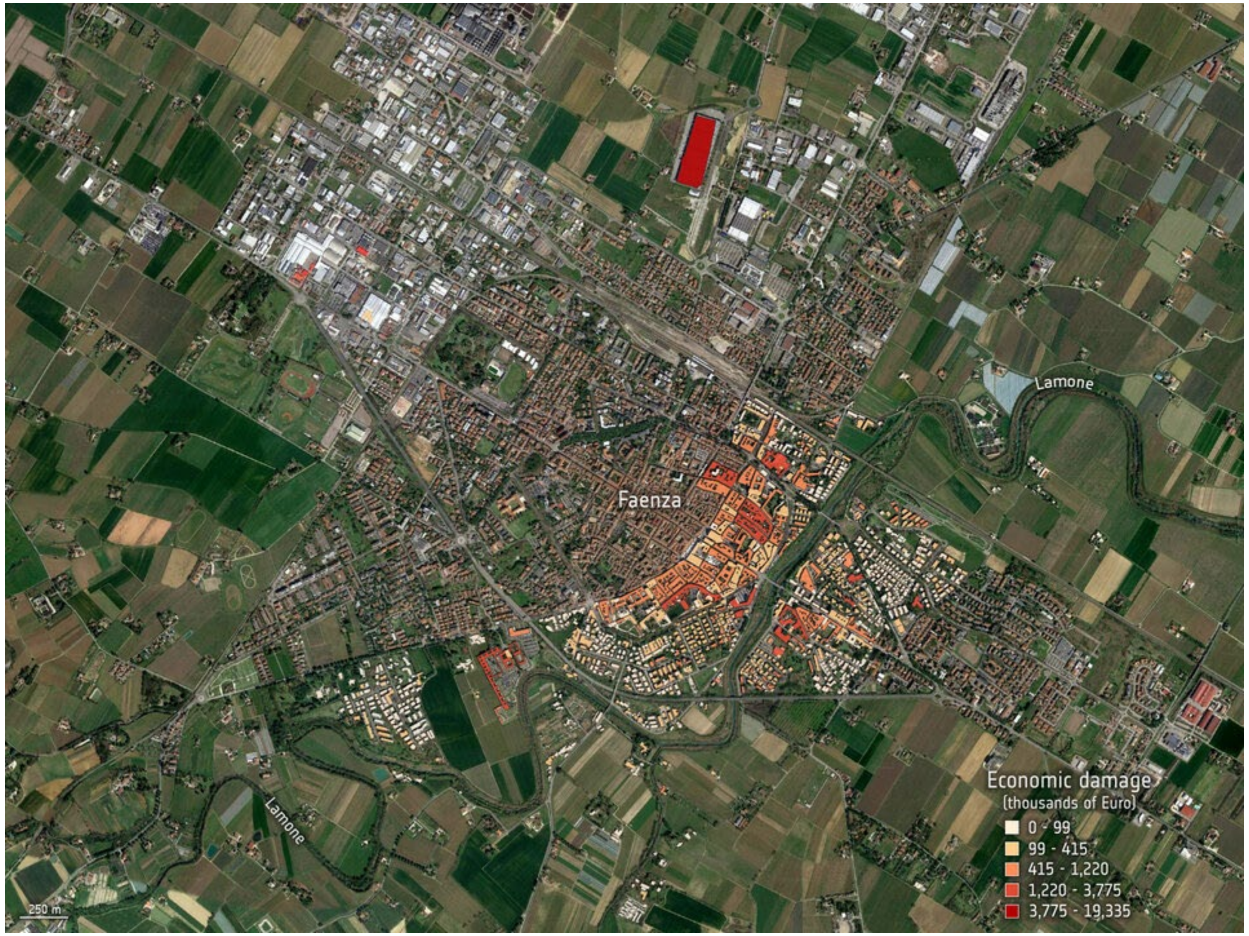
Information on the flooded areas and the affected buildings conducted by local municipalities and data provided by the Emilia-Romagna Civil protection were also integrated to fill the gaps and increase the accuracy of urban flooded areas when not captured by satellites.

Maps portraying the extent of the flooded areas in the most affected municipalities, Faenza, Cesena, Forlì and Conselice, were generated with information on the depth and volume of the water.

Emilia Romagna – area affected by the flood

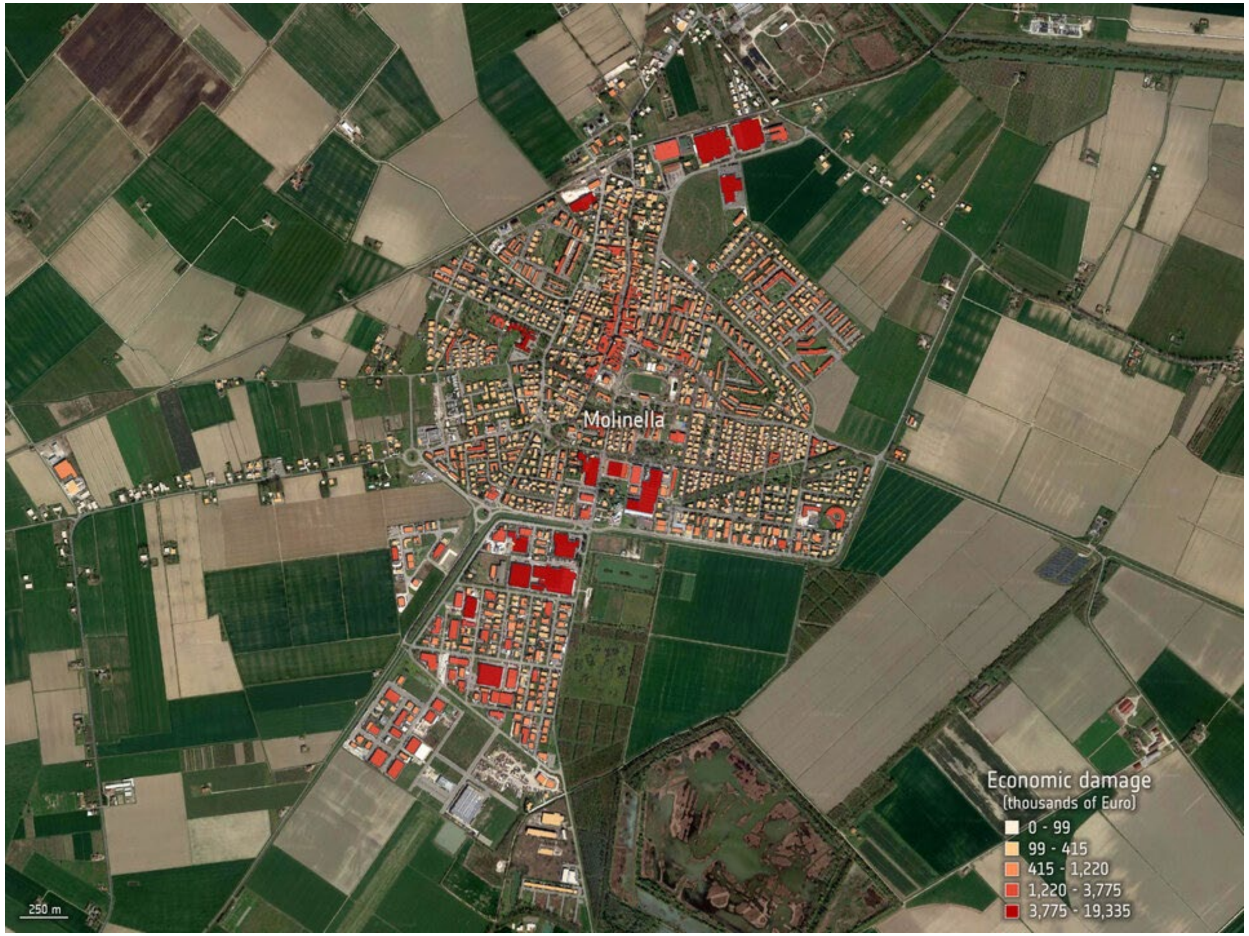
Faenza - Estimated economic losses





The image on the left shows the water depth over Faenza from 17 May 2023, while the image on the right shows the estimated economic losses for residential buildings.

Molinella - Estimated economic losses



The image on the left shows the water depth over Molinella from 17 May 2023, while the image on the right shows the estimated economic losses for residential buildings.