esa space solutions
Copernicus Academy
ÚSTAV GEOGRAFIE
Prírodovedecká fakulta UPJŠ v Košiciach

Deliverable 4.2

Applied Radar Remote Sensing

Lectures hand-book

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1. Radar Earth Observation and evolution – current and next generation missions, ESA EO Data Access and resources, applications

Purpose of The European Space Agency (ESA)

"To provide for and promote, for **exclusively peaceful purposes**, cooperation among European states in **space research** and **technology** and their **space applications.**"

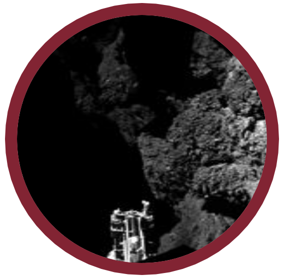
Article 2 of the ESA Convention

Source: https://www.isprs.org/proceedings/2018/2018-Dehradun-IPAC-Session/A6_ESA-Copernicus-HOSFORD.pdf

Activities

- ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

- Space science is a Mandatory programme, all Member States contribute to it according to GNP. All other programmes are Optional, funded by Participating States.


space science


human spaceflight


exploration


earth observation


launchers


navigation

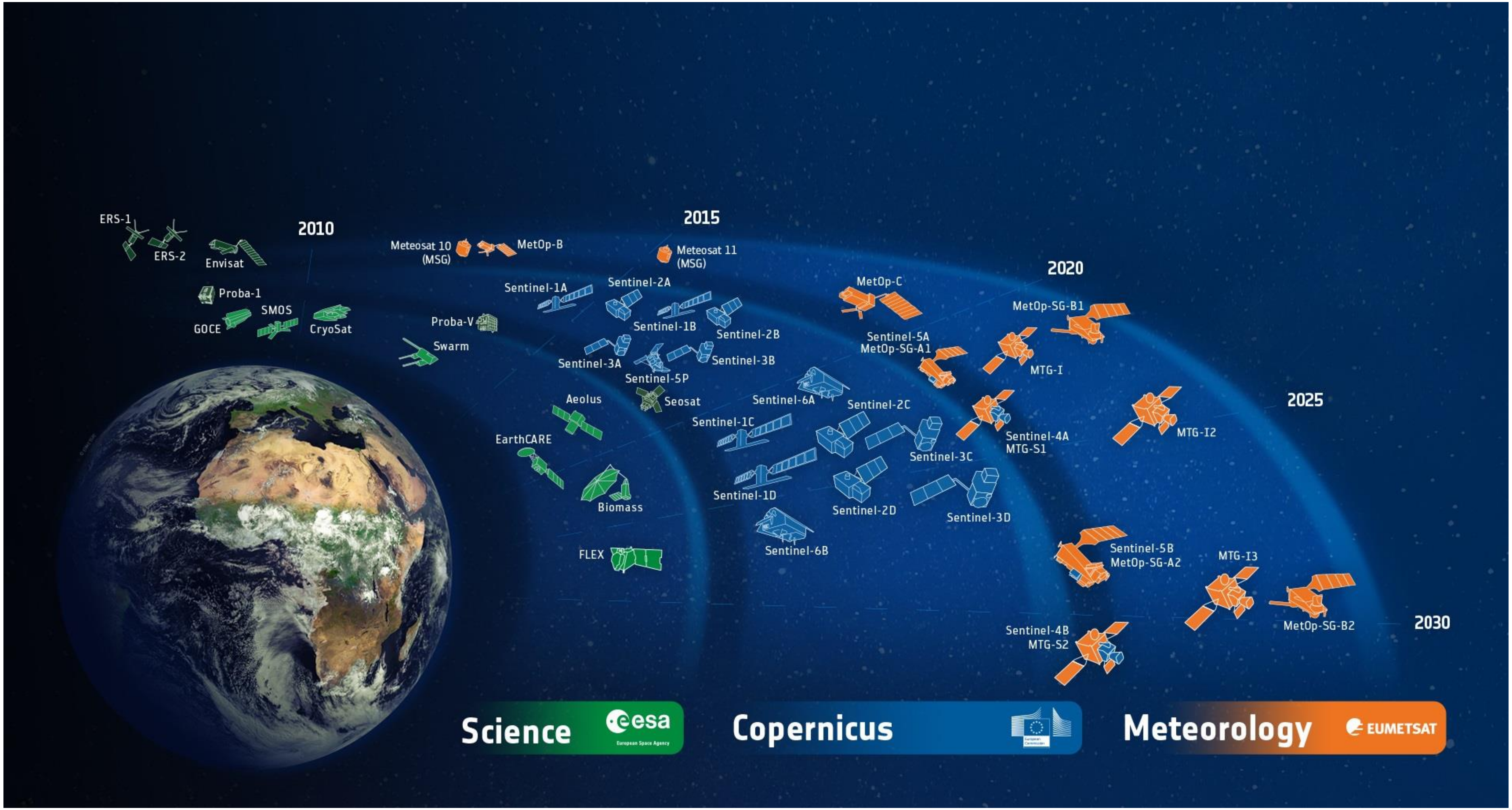

operations


technology


telecommunications

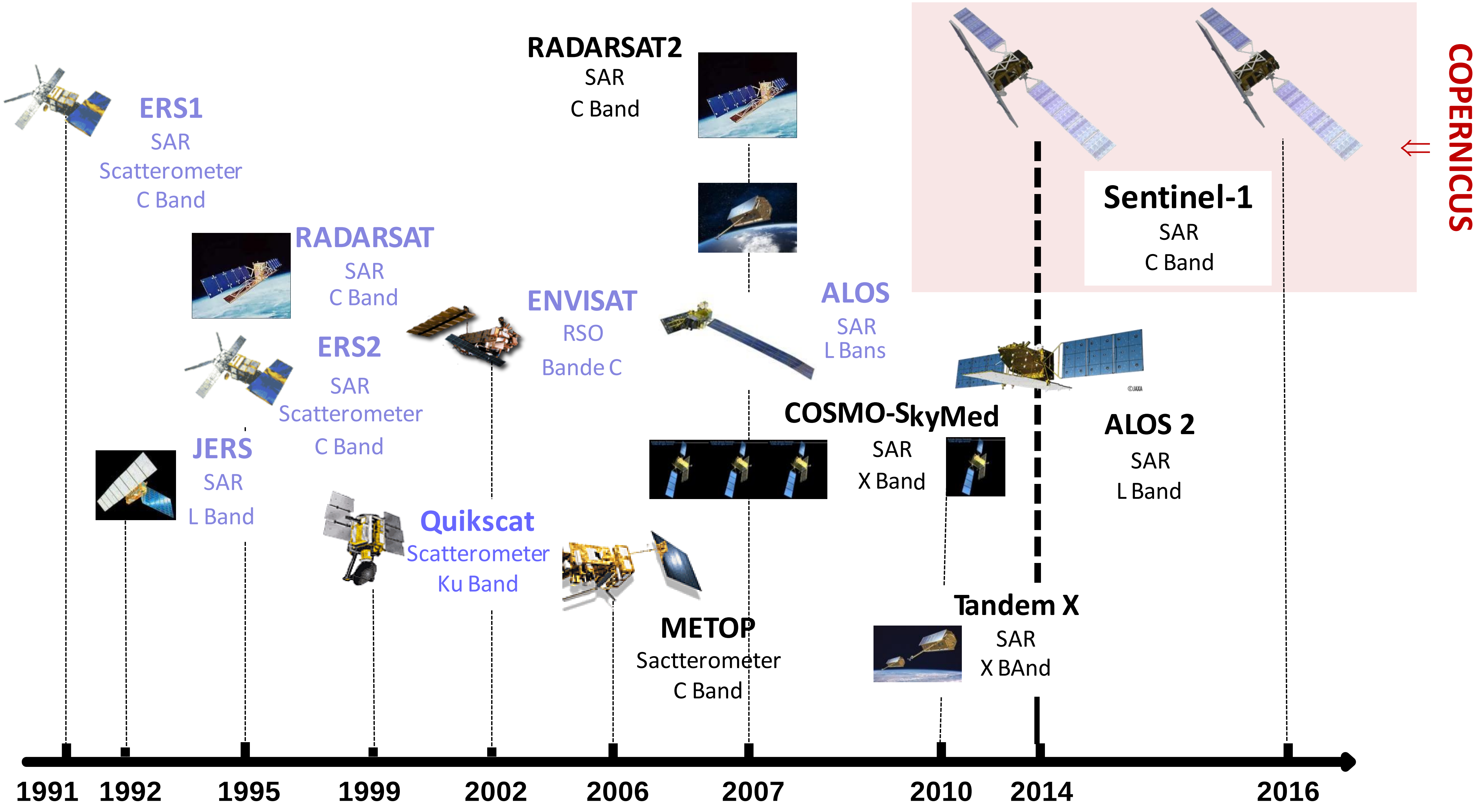
Source: https://esamultimedia.esa.int/docs/corporate/ESA_Corporate_Presentation_Fr.pdf

ESA-Developed Earth Observation Missions



Source: https://www.esa.int/Applications/Observing_the_Earth/Space_for_our_climate/Earth_Day_taking_the_pulse_of_our_planet

Examples of Spaceborne Radar sensors



Examples of Spaceborne Radar sensors

Satellite	Owner	Band	Resolution	Look Angle	Swath	Lifetime
ERS-1	ESA	C	25 m	23°	100 km	1991-2000
ERS-2	ESA	C	25 m	23°	100 km	1995-2012
Radarsat-1	Canada	C	10 m - 100 m	20°- 59°	50 - 500 km	1995-2013
ENVISAT	ESA	C	25 m - 1 km	15°- 40°	100 - 400 km	2002-2012
ALOS	Japan	L	10 m -100 m	35°- 41°	70 - 360 km	2006-2011
Cosmo	Italy	X	ca. 1 m - 16 m	…	…	2007-
TerraSAR-X	Germany	X	1 m - 16 m	15°- 60°	10 - 100 km	2007/2010-
& TanDEM-X Radarsat-2	Canada	C	3 m - 100 m	15°- 59°	10 - 500 km	2007-
ALOS-2	Japan	L	3 m – 100 m	8°-70°	25 – 350 km	2014-
Sentinel-1	ESA	C	5 m – 50 m	20°-46°	20 - 400 km	2014-

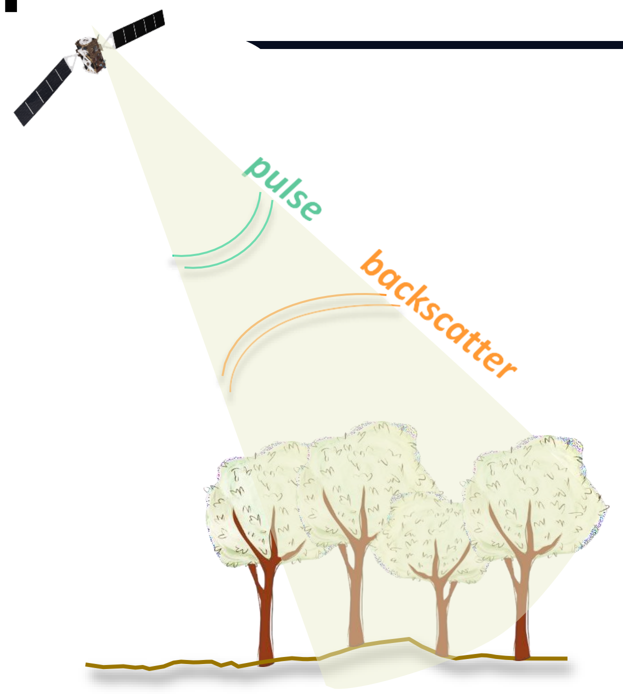
Sentinel-1 – Radar vision

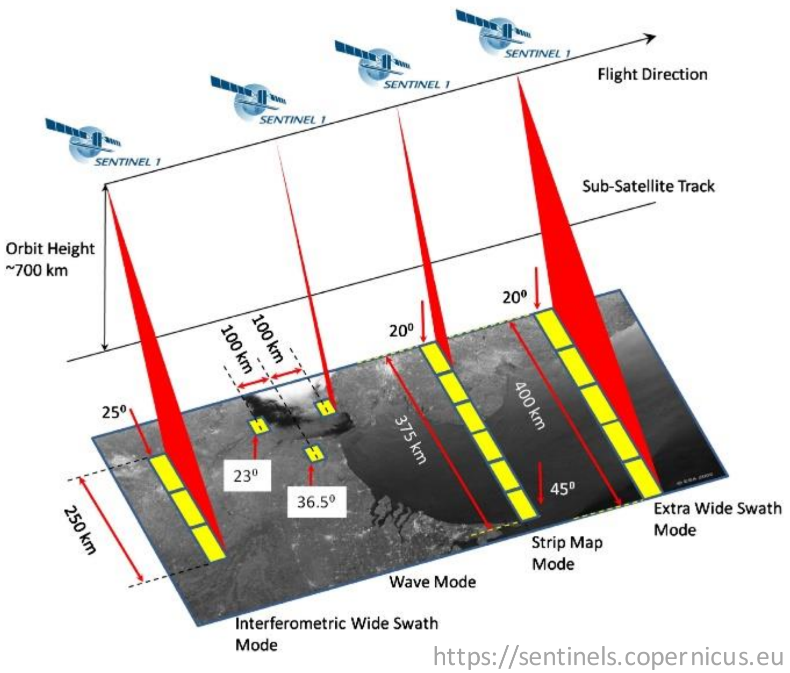
Mission objectives:

- Marime and land monitoring
- Emergency management

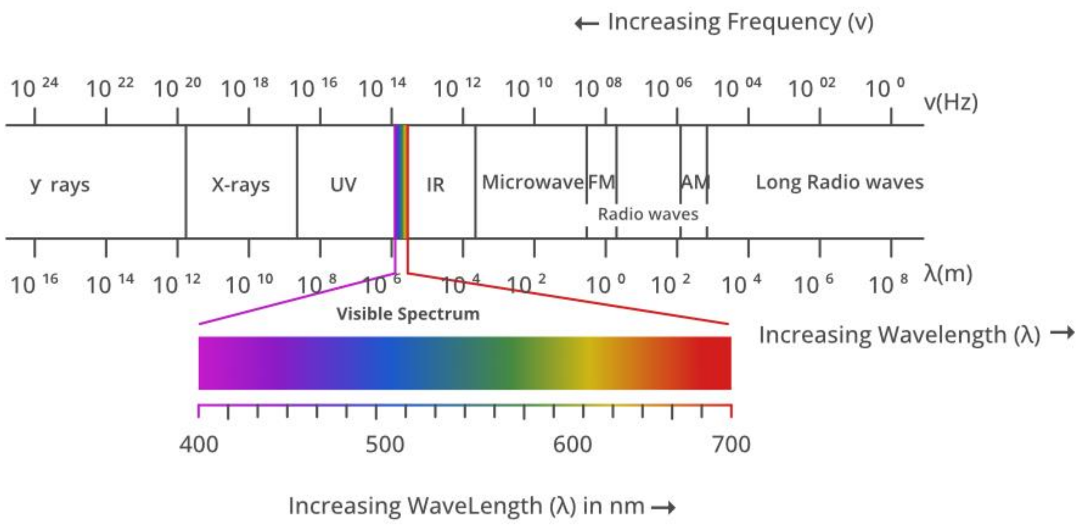
Mission profile:

- C-Band SAR mission at 5.4 GHz
- Multi-polarisation
- Sun synchronous orbit at 693 km mean alt.
- 6 days repeat cycle at Equator with 2 satellites
- 4 operation modes





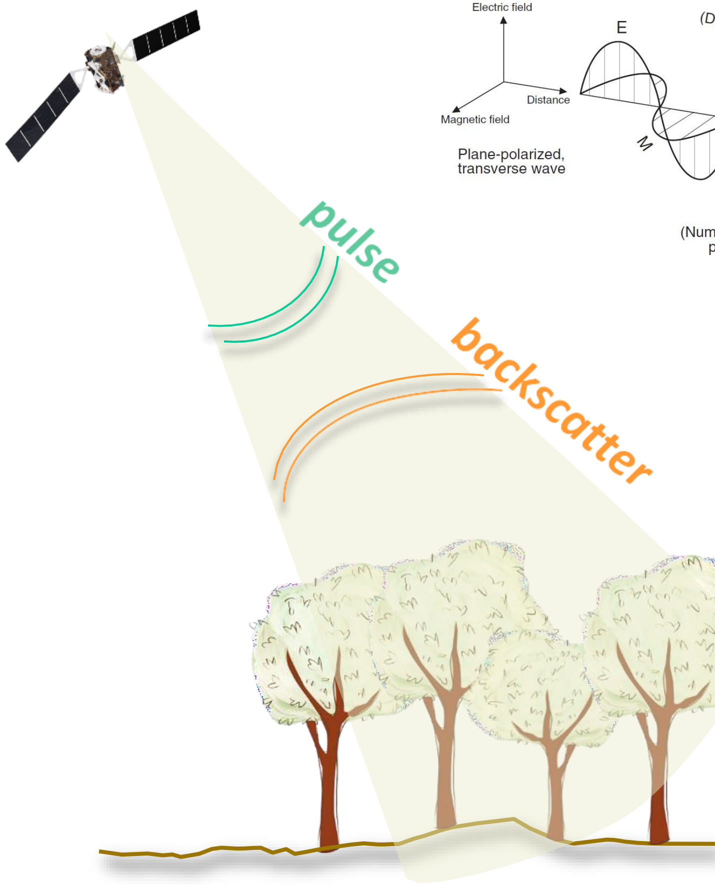
https://sentinels.copernicus.eu

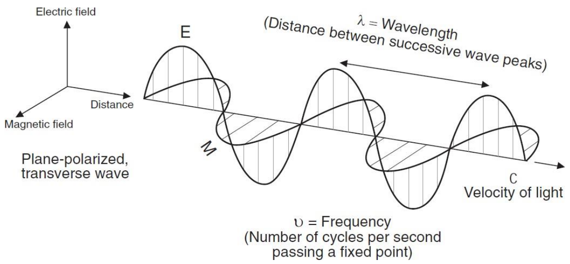


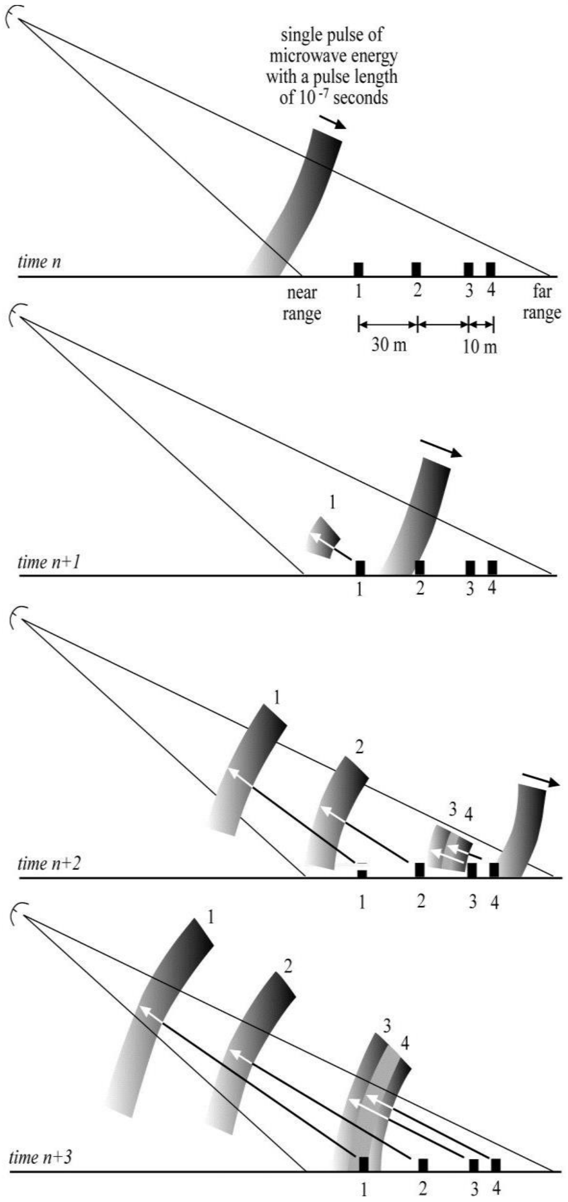
Active Radar Remote Sensing

Basic characteristics of radar systems/SAR sensors

Active ⇒ **independent of sun illumination**
(generate EM-waves)







Radar principle

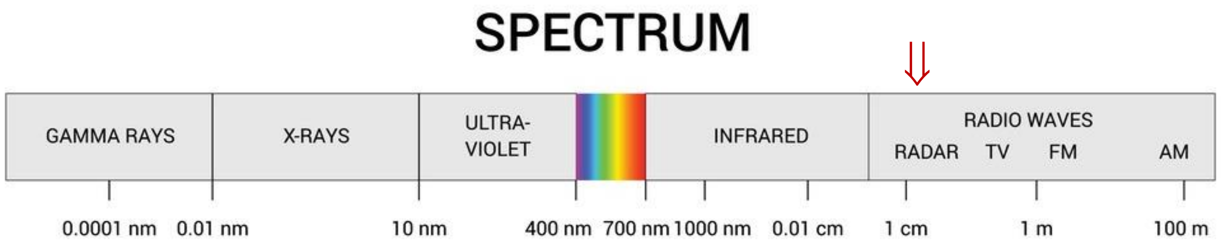
EMG transmitted in bursts of energy - pulses (approx. every 0.000 000 1 s)

The energy of a single pulse is reflected from objects on the surface in order of distance from source/transmitter on board

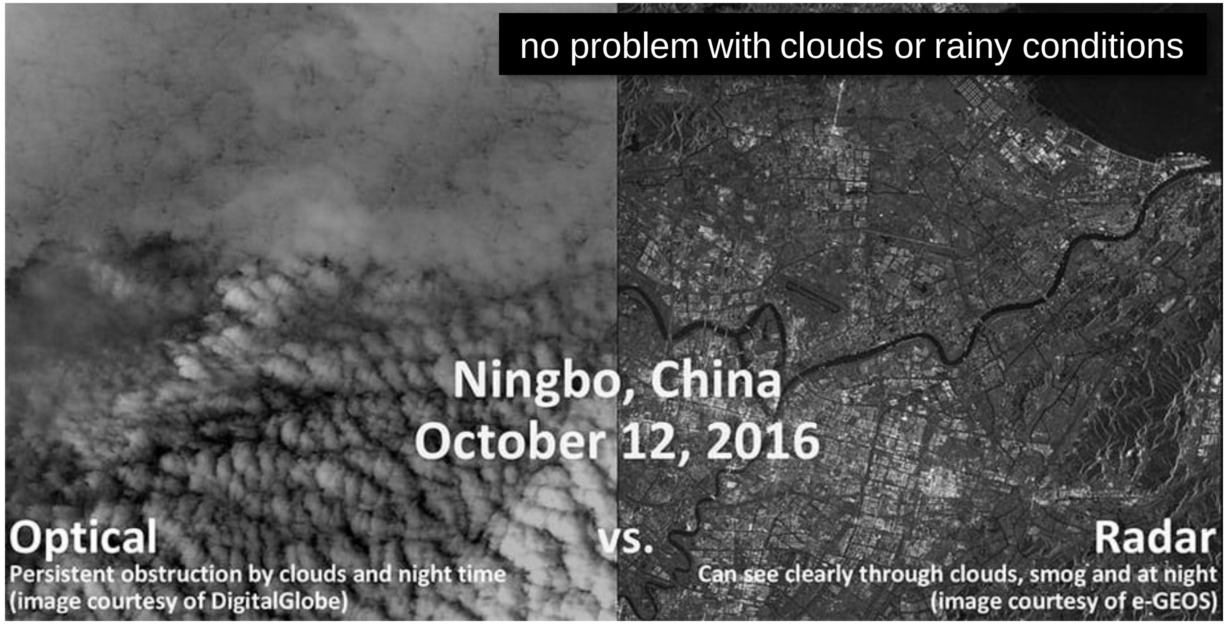
The intensity of the reflected energy and the time it takes for a given pulse to return are recorded

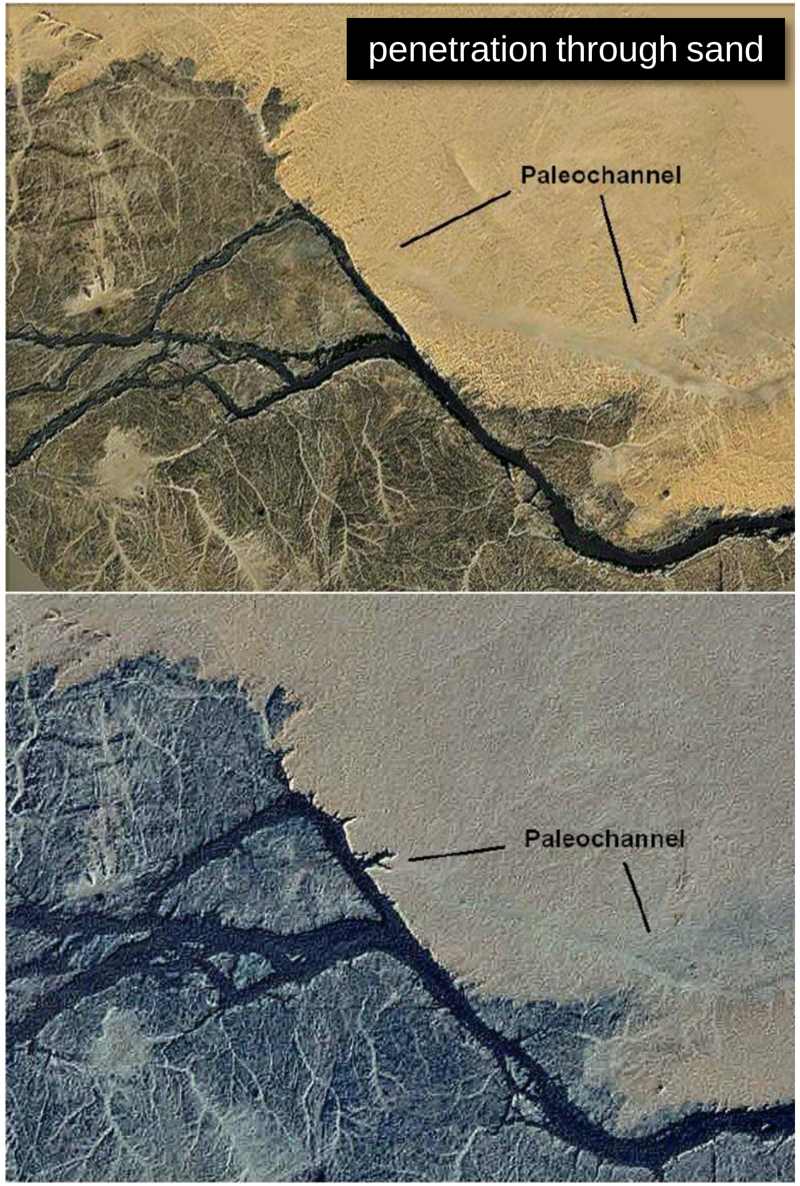
Active Radar Remote Sensing

Basic characteristics of radar systems/SAR sensors



Microwave ⇒ **penetrates into/through objects**

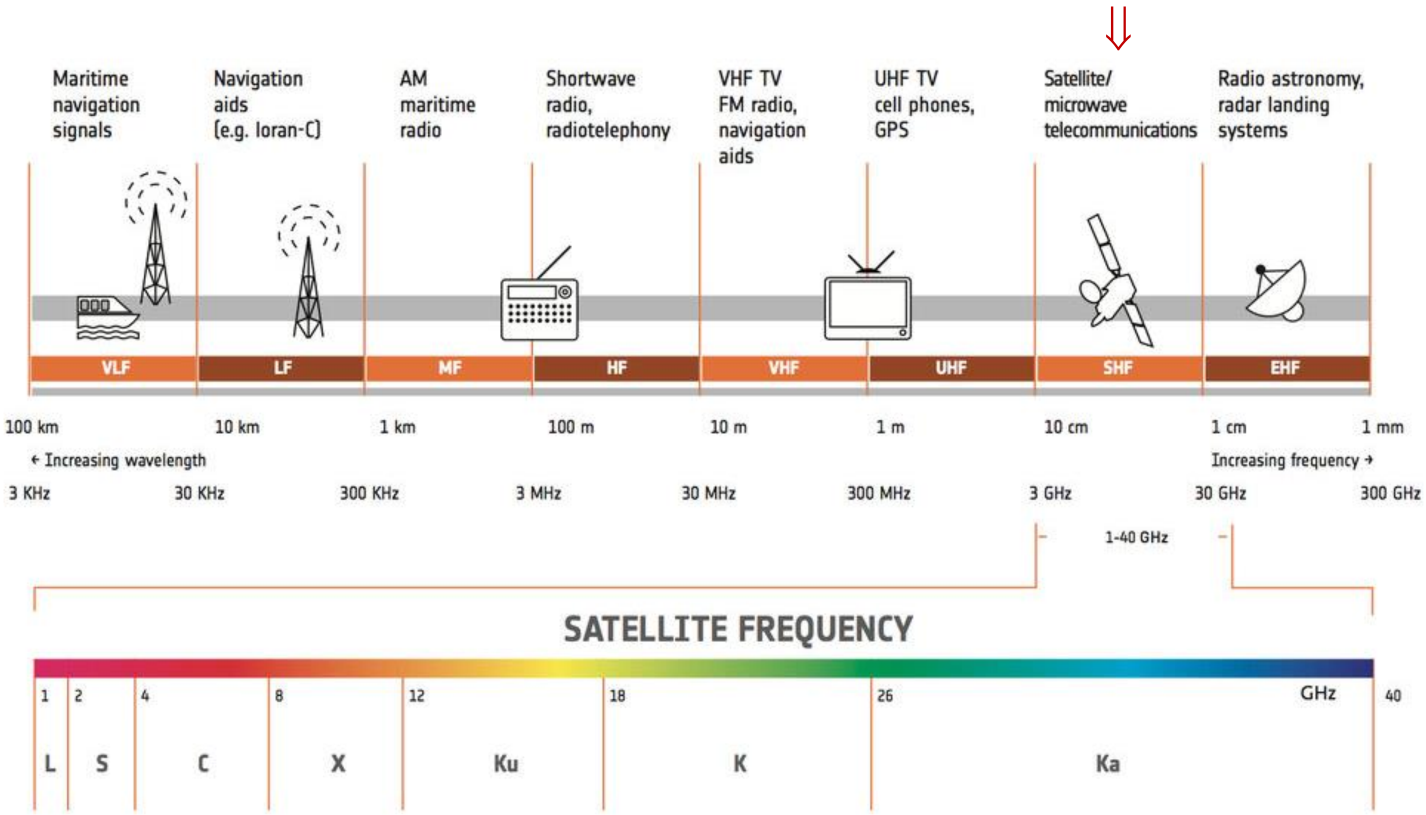


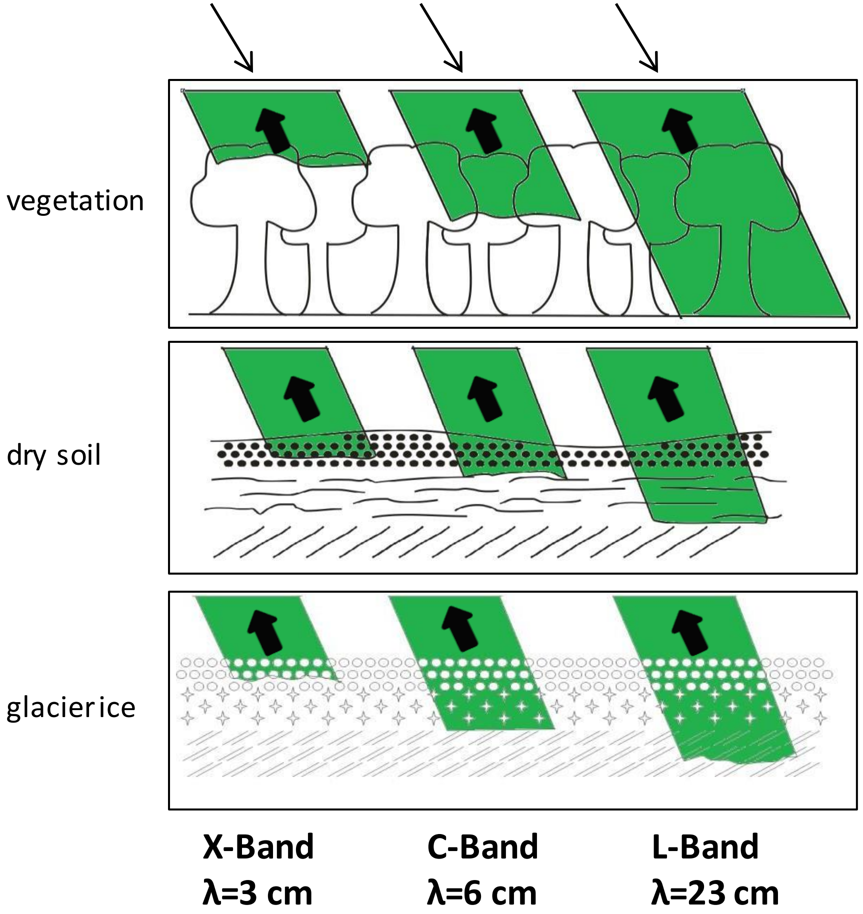


Active Radar Remote Sensing

RADAR band designations, wavelenghts and frequencies

- The penetration depth is depending on **wavelength** and **dielectric characteristics** of objects





Active Radar Remote Sensing

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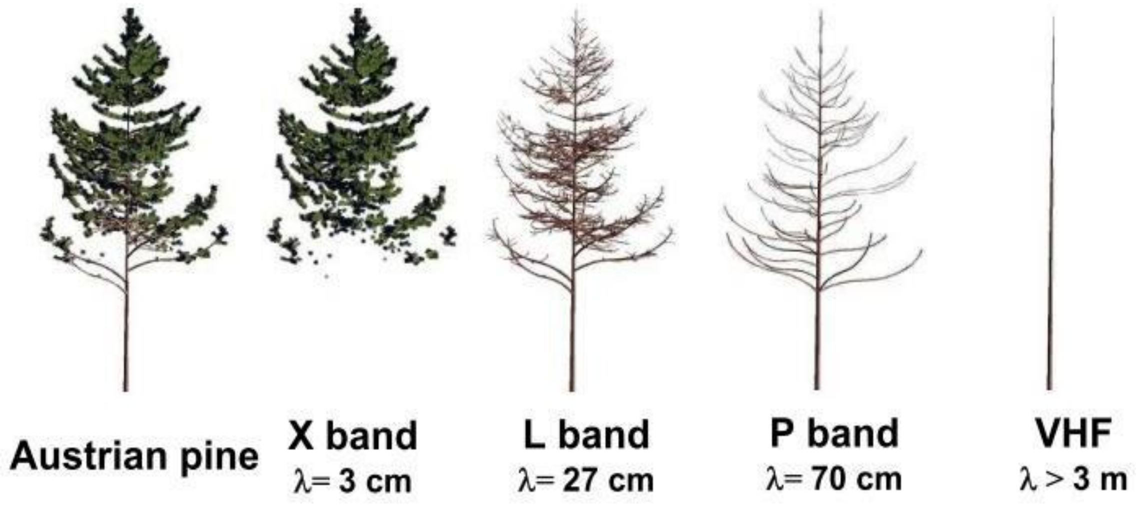
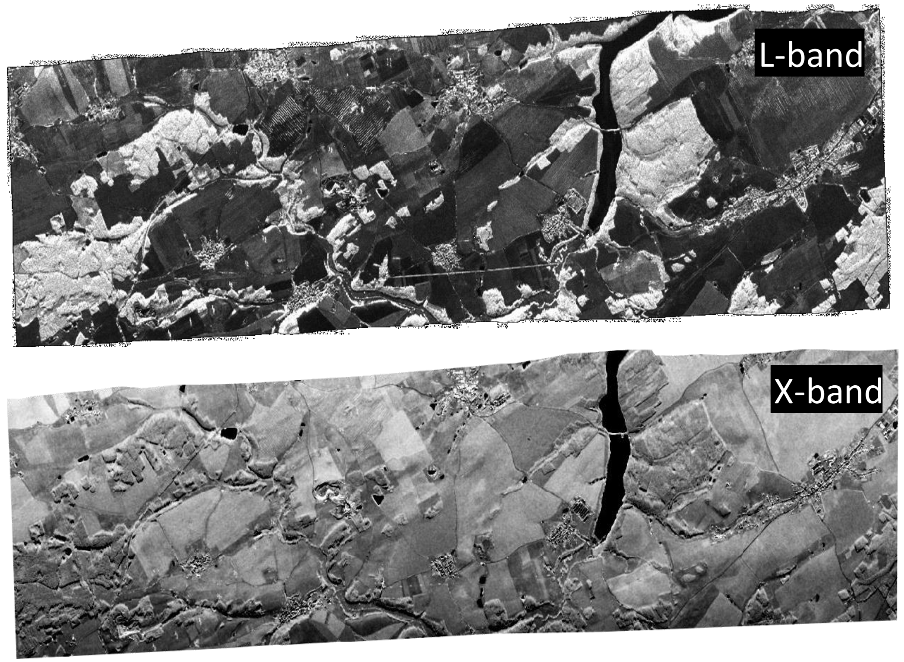




Active Radar Remote Sensing

- Radar altimetry
- Radar imaging
  - SLAR – side look-angle radar
  - INSAR – interferommetric synthetic aperture radar
    - D-insar
    - PS-insar

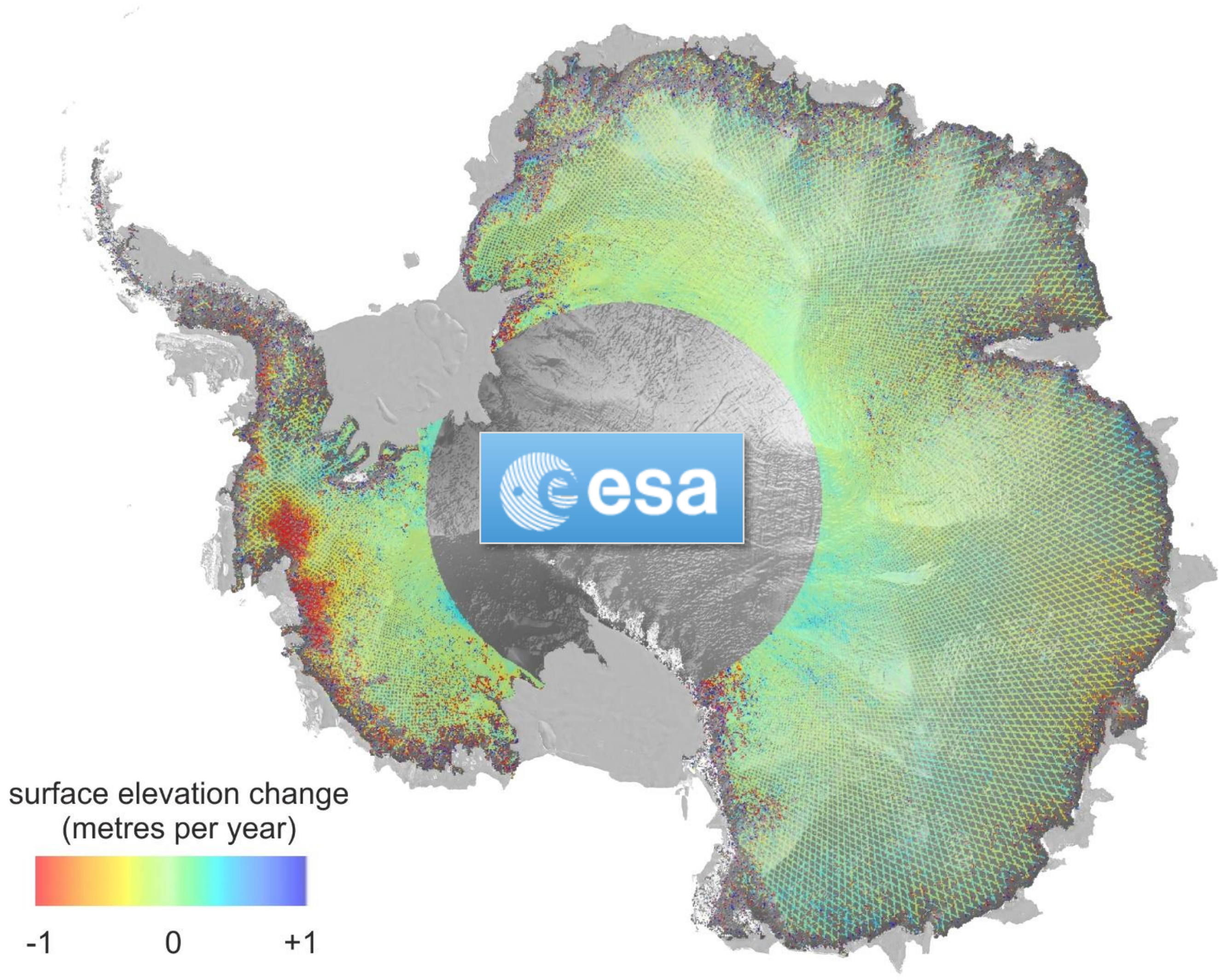
Radar Altimetry = measuring altitude / vertical height

Article ESA

video

video 2

Radar Altimetry = measuring altitude / vertical height



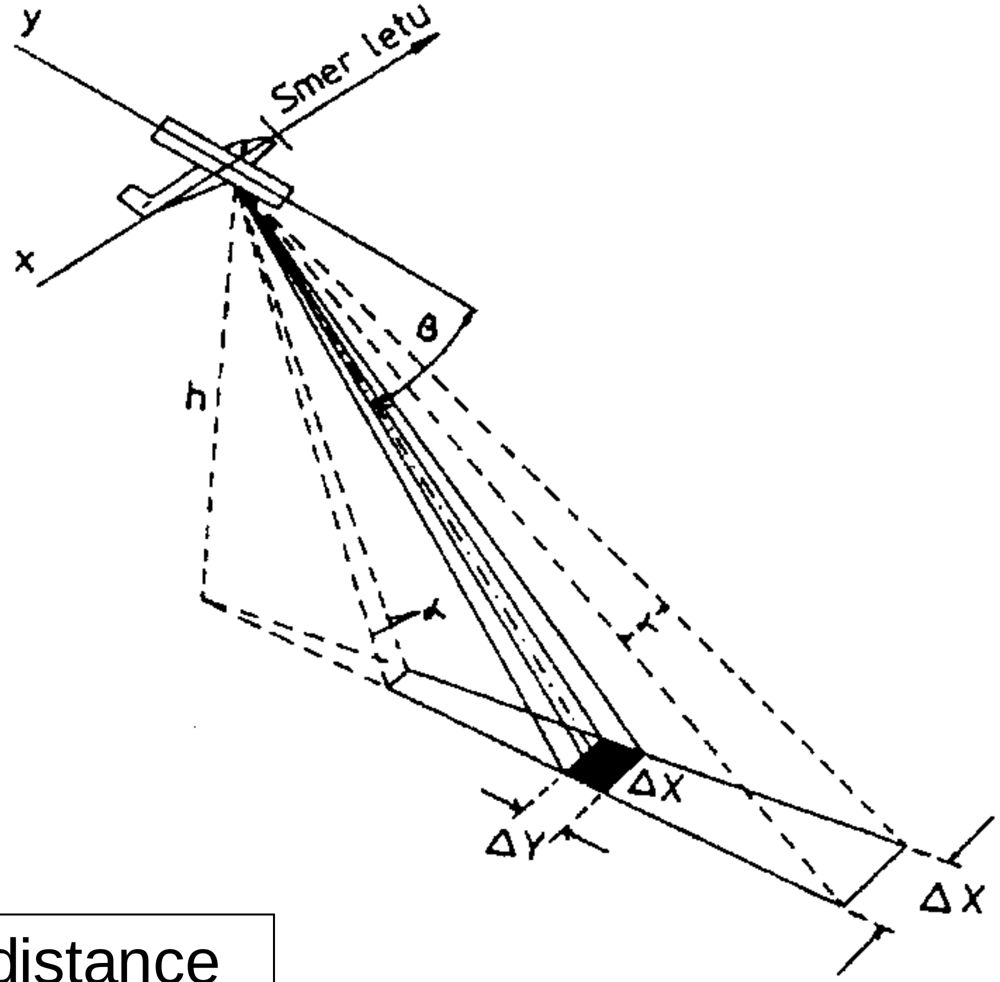
[Copernicus Sentinel-3 provides new measurements of Antarctic Ice Sheet
08 March 2019]

Side looking radar (SLAR)

$$\Delta x = \frac{h.\lambda}{L.\sin\beta}$$

$$\Delta y = \frac{c.\Delta t}{2.\cos\beta}$$

h – flight altitude, L – length of antenna, β - angle between the horizontal plane and the emitted beam

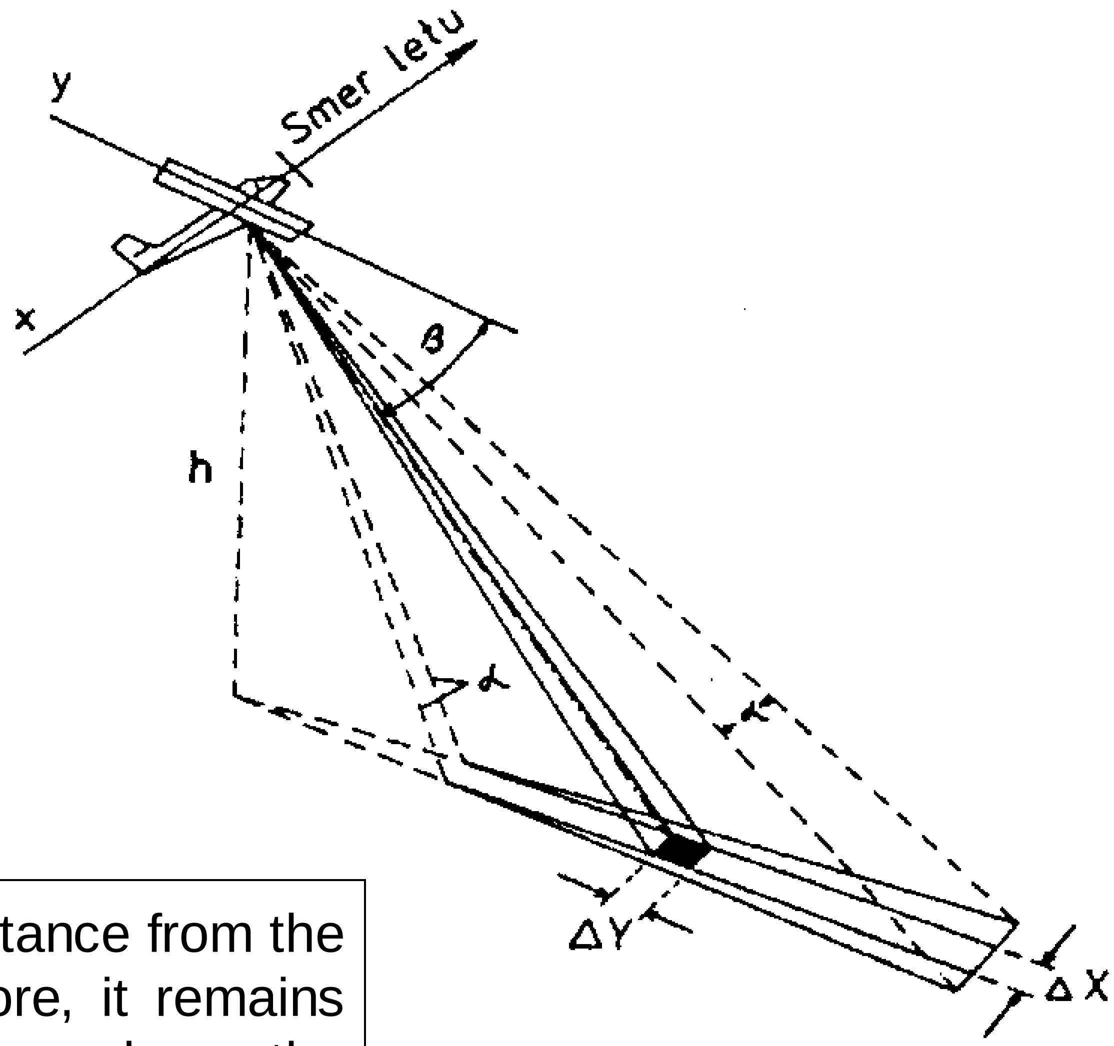


Spatial resolution deteriorates as the distance between the object and the antenna increases.

Synthetic aperture radar (SAR)

$$\Delta x = \frac{L}{2}$$

$$\Delta y = \frac{c.\Delta t}{2.\cos \beta}$$



h – flight altitude, L – length of antenna, β - angle between the horizontal plane and the emitted beam

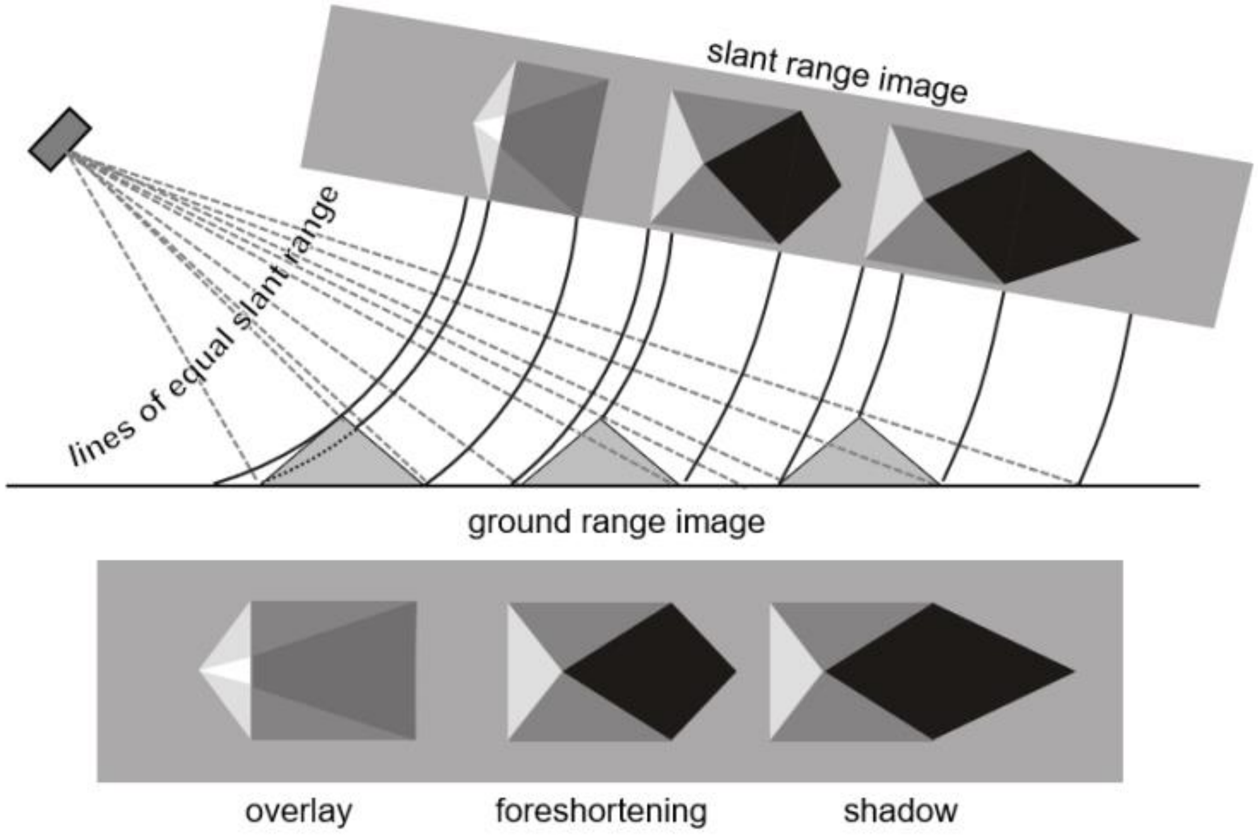
Spatial resolution is independent of the distance from the antenna in the direction of flight. Therefore, it remains constant in the flight direction, while it depends on the viewing angle perpendicular to the flight direction.

Geometric Effects in SAR images

Effects of side-looking geometry

→ Side looking geometry of SAR systems cause some typical geometric effects

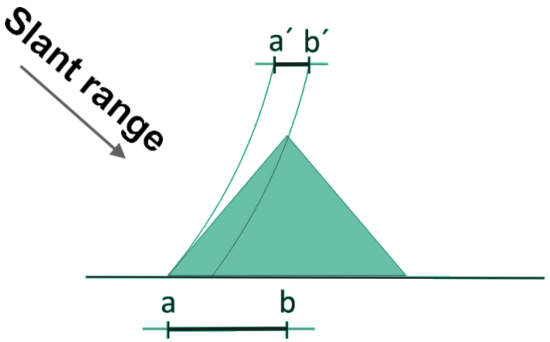
- The effects are:
  - ❖ Foreshortening
  - ❖ Layover
  - ❖ Radar shadow
- Controlled by:
  - ❖ Incidence angle
  - ❖ Topography



Geometric distortions in radar images (Braun 2019)

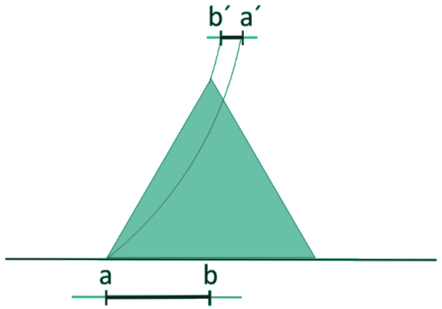
Geometric Effects in SAR images

Foreshortening



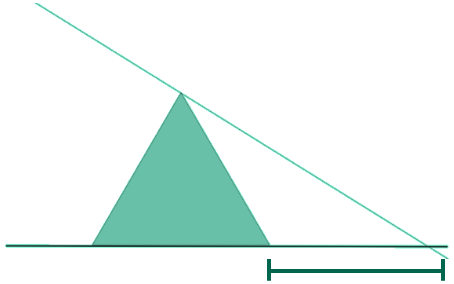
- Slopes oriented to the SAR appear compressed (Distance between a and b is shortened)
- Appears as very bright area
- More pronounced in near range (small incidence angle) than in far range (high incidence angles)

Layover



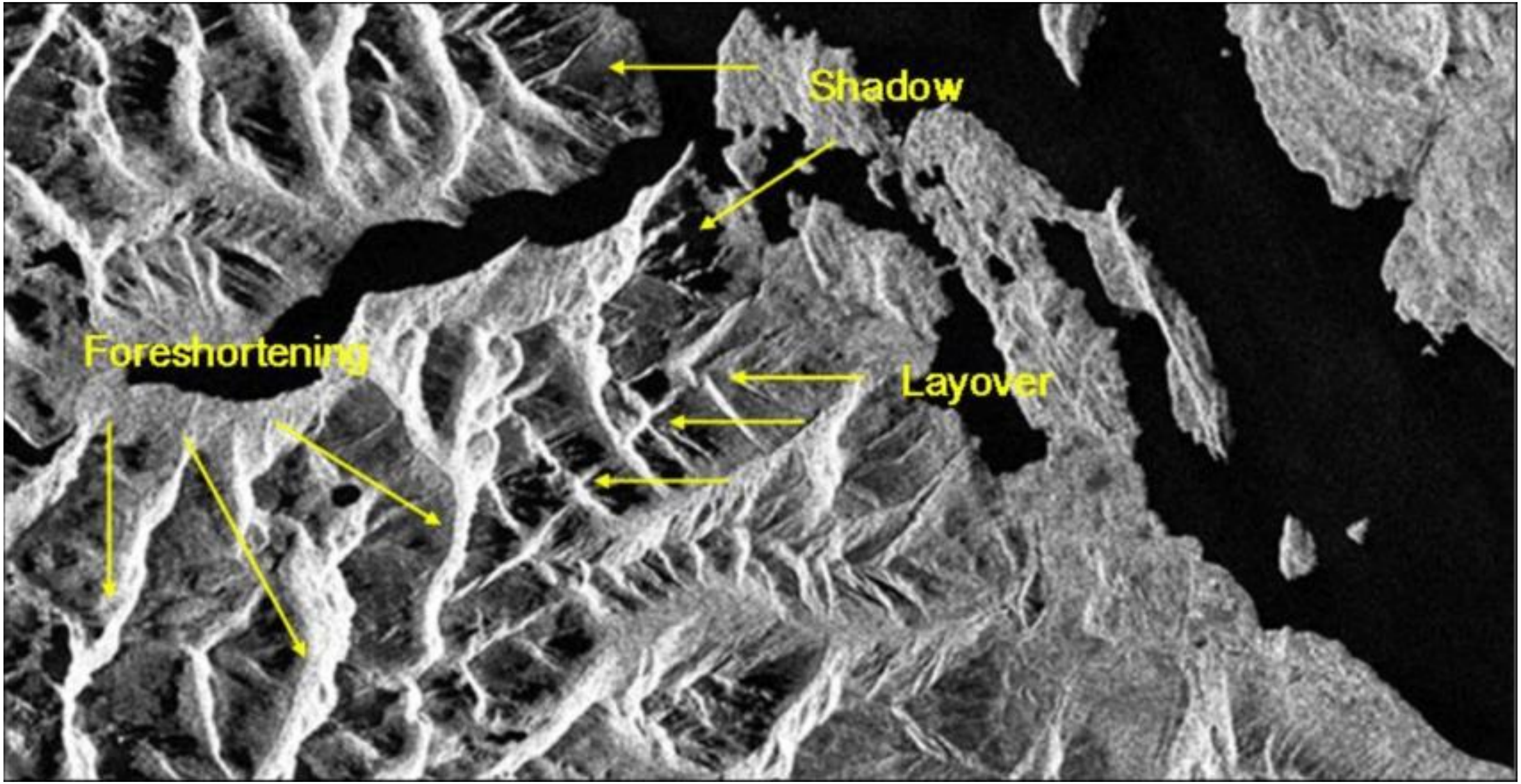
- Steep slopes oriented to the SAR lead to ghost images
- When radar beam reaches the top of a high feature (b) before it reaches the base (a)

Radar shadow



- Steep slopes oriented away from the SAR return no signal
- No signals can be transmitted to this area (as it is blocked by the slope), thus no signals can be scattered back from these areas
- Appears as black area in the image

Geometric Effects in SAR images

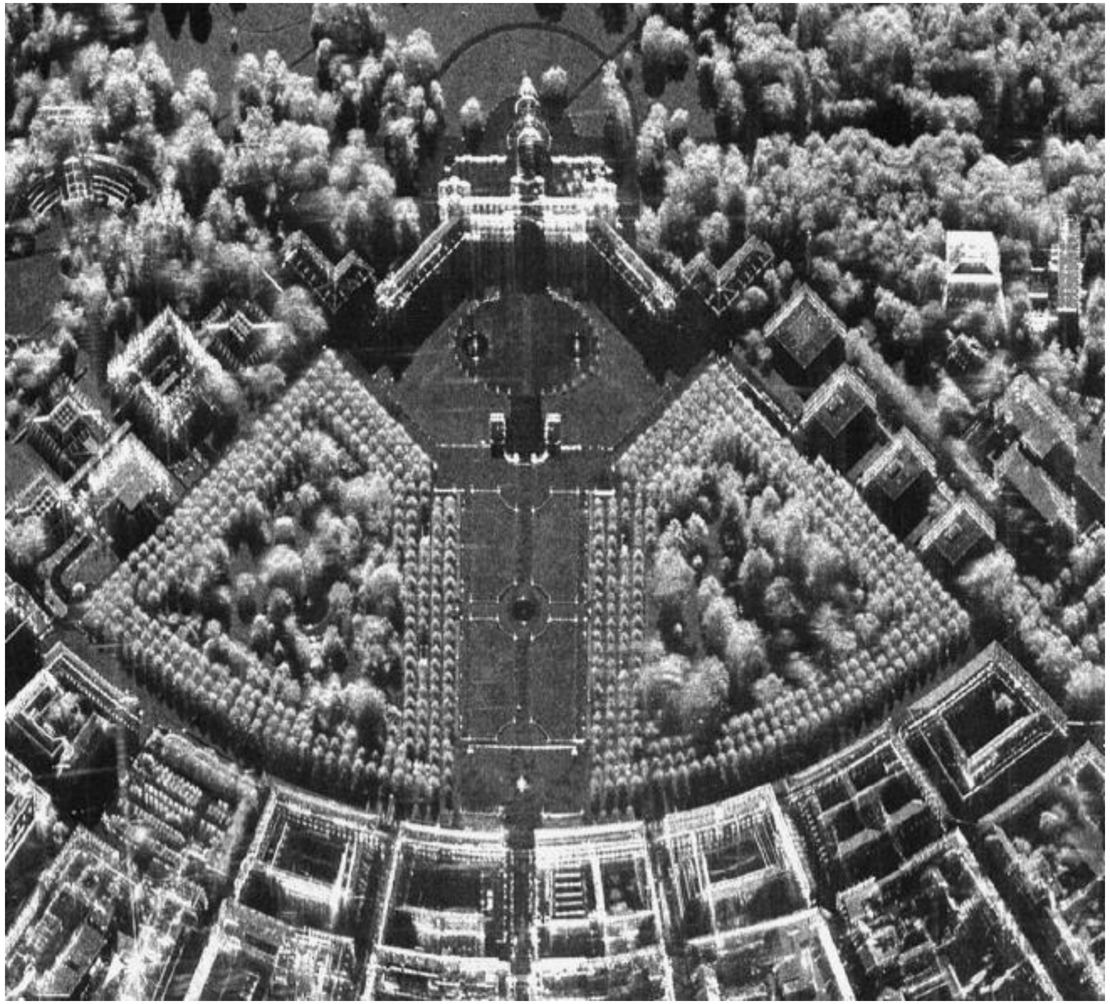


Source: https://www.researchgate.net/profile/M-Lenzano/publication/263124688/figure/fig23/AS:614356547039256@1523485423960/Figura-9-Efectos-de-shadowi-ng-foreshortening-y-layover-en-una-imagen-SAR-de-RADARSAT-1.png

Geometric Effects in SAR images

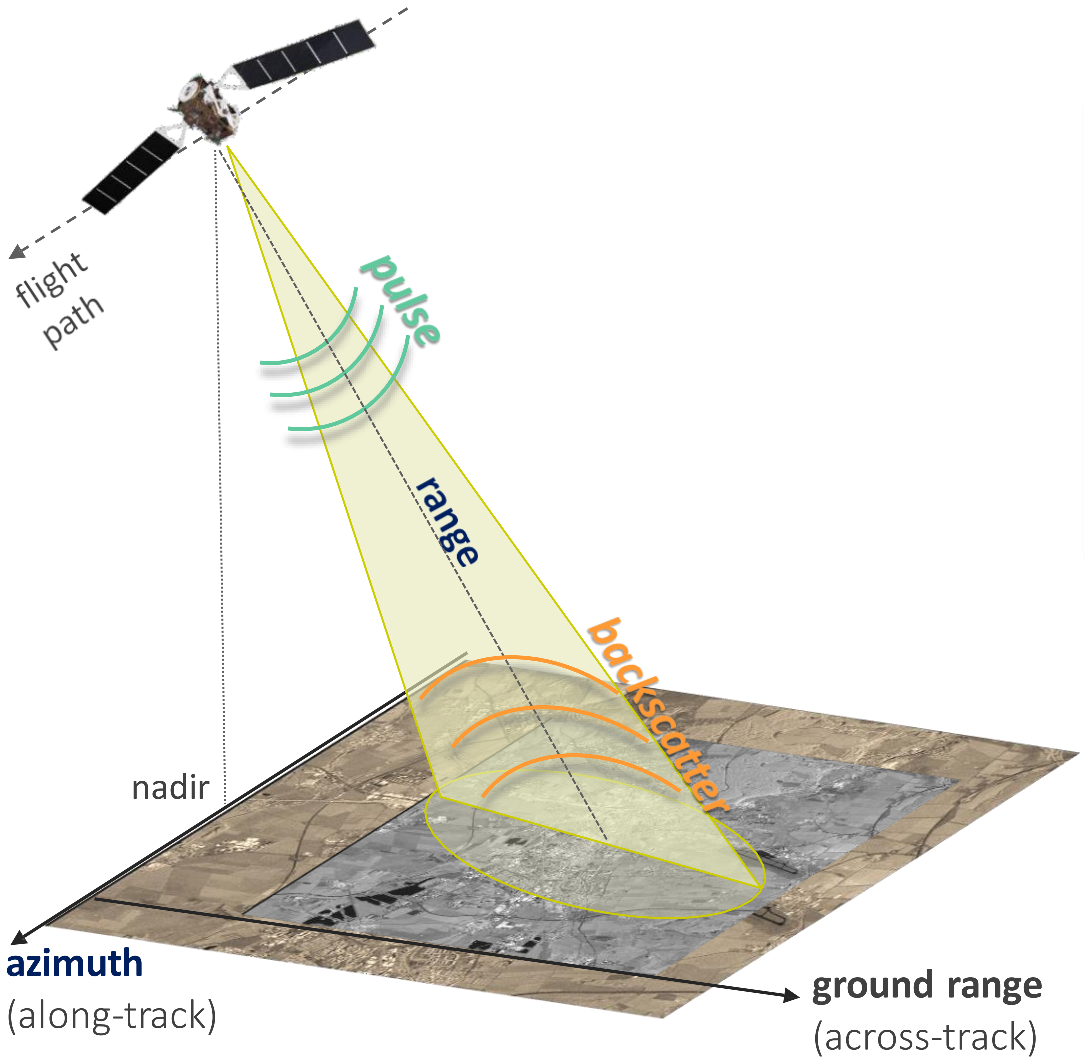
Effects of side-looking geometry

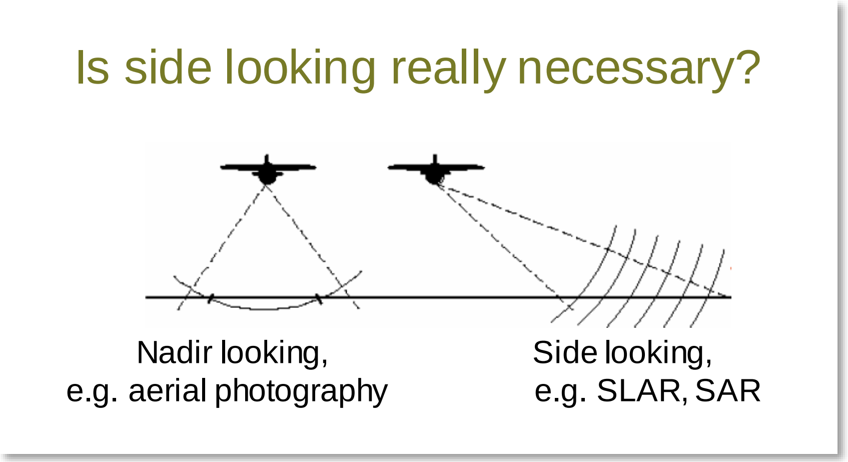
Google maps



Andreas R. Brenner and Ludwig Roessing, Radar Imaging of Urban Areas by Means of Very High-Resolution SAR and Interferometric SAR, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 46, NO. 10, OCTOBER 2008 (X-band)

Radar side looking imaging geometry

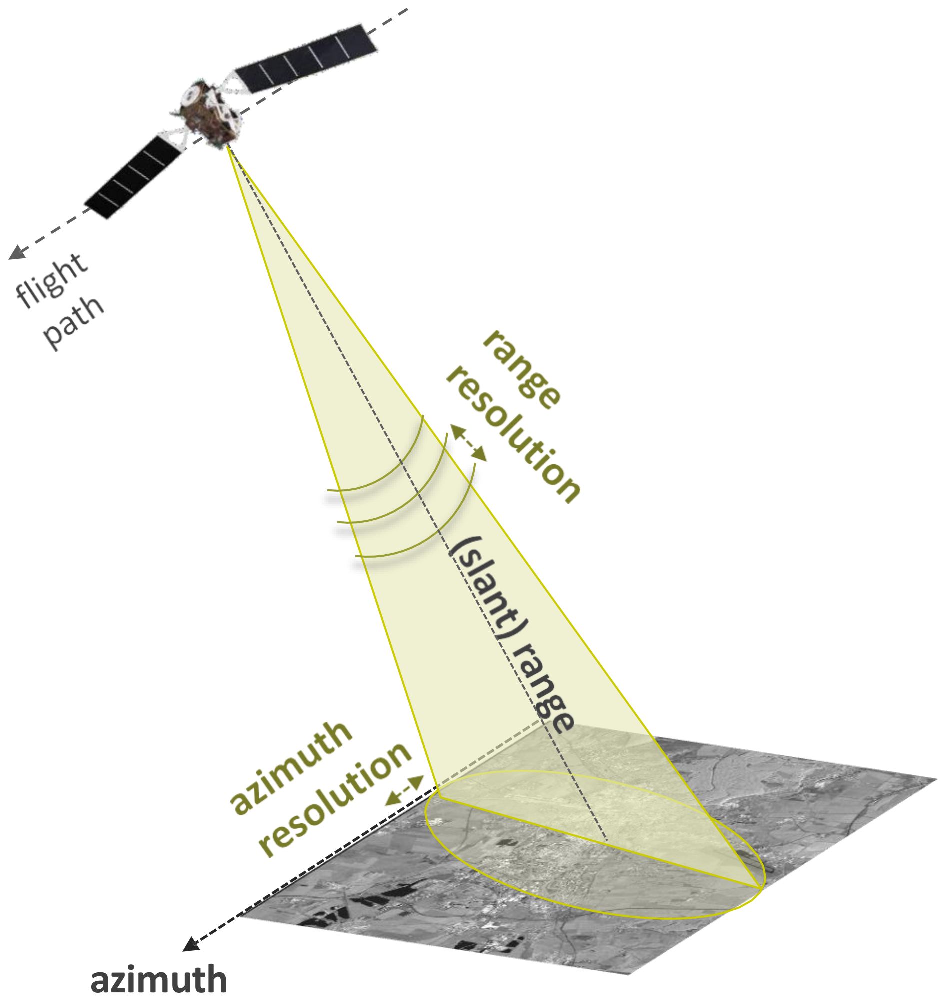




range: scanning in the look direction at the speed of light

azimuth: scanning in flight direction at the speed of the sensor

Radar side looking imaging geometry



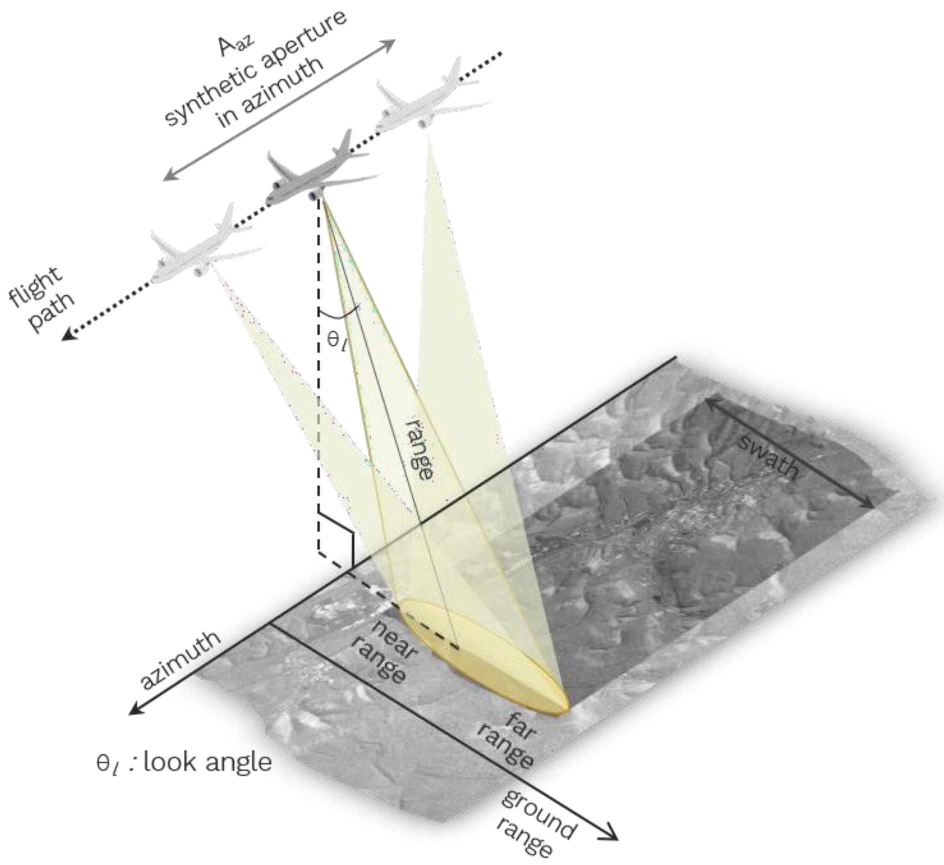
slant-range resolution depends on the **bandwidth of the system**

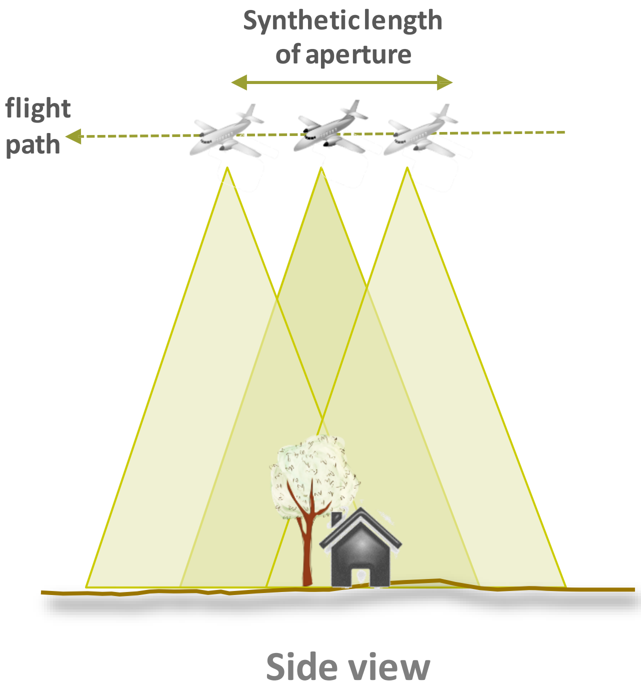
azimuth resolution is a function of the **antenna length** and **sensor height** over the Earth's surface

Synthetic Aperture Radar (SAR)

The principle of extending the antenna

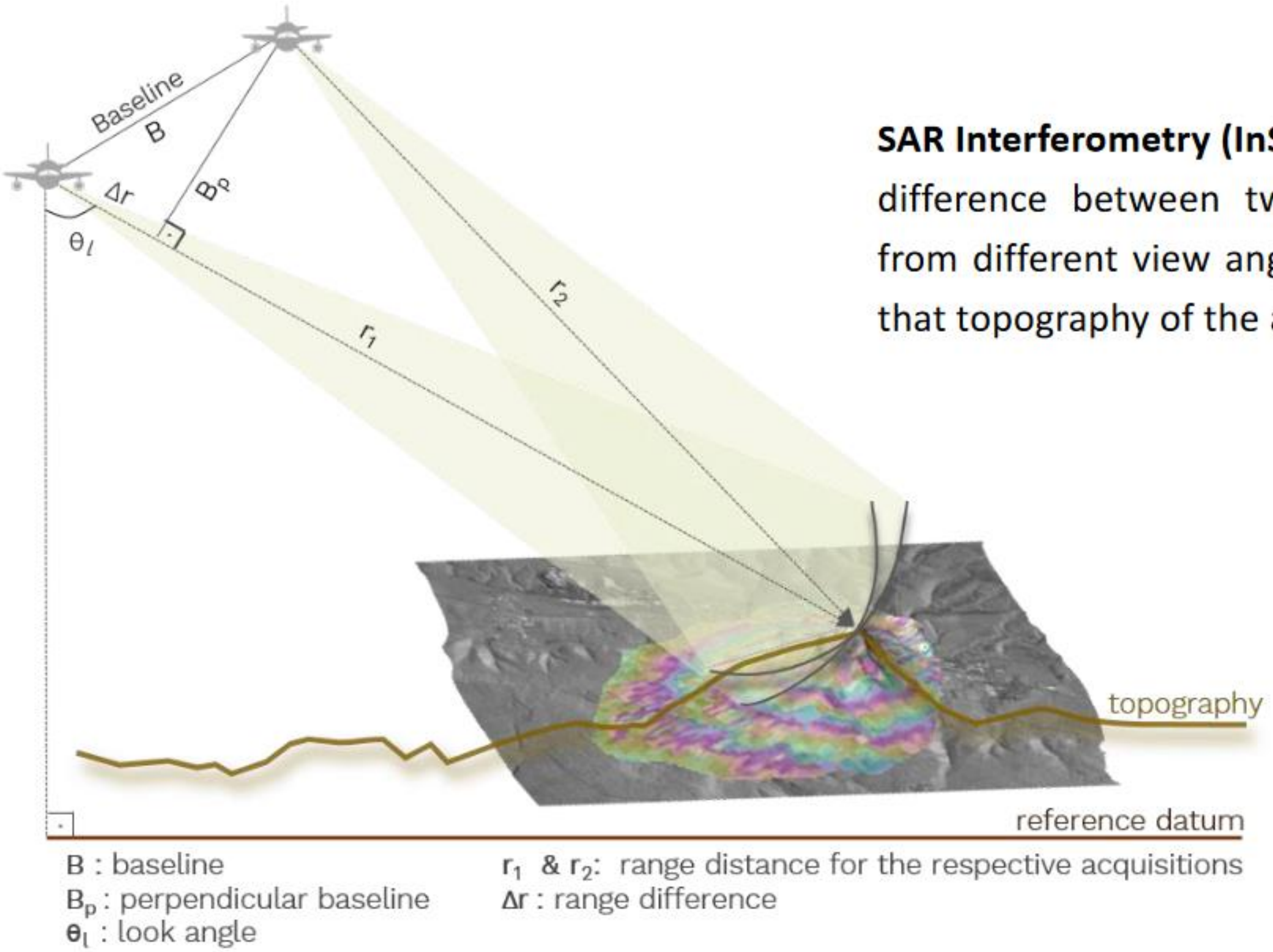
The key factor that is utilized in SAR is to synthesize a much longer antenna in azimuth direction by making use of the motion of the SAR sensor in order to achieve finer resolution.





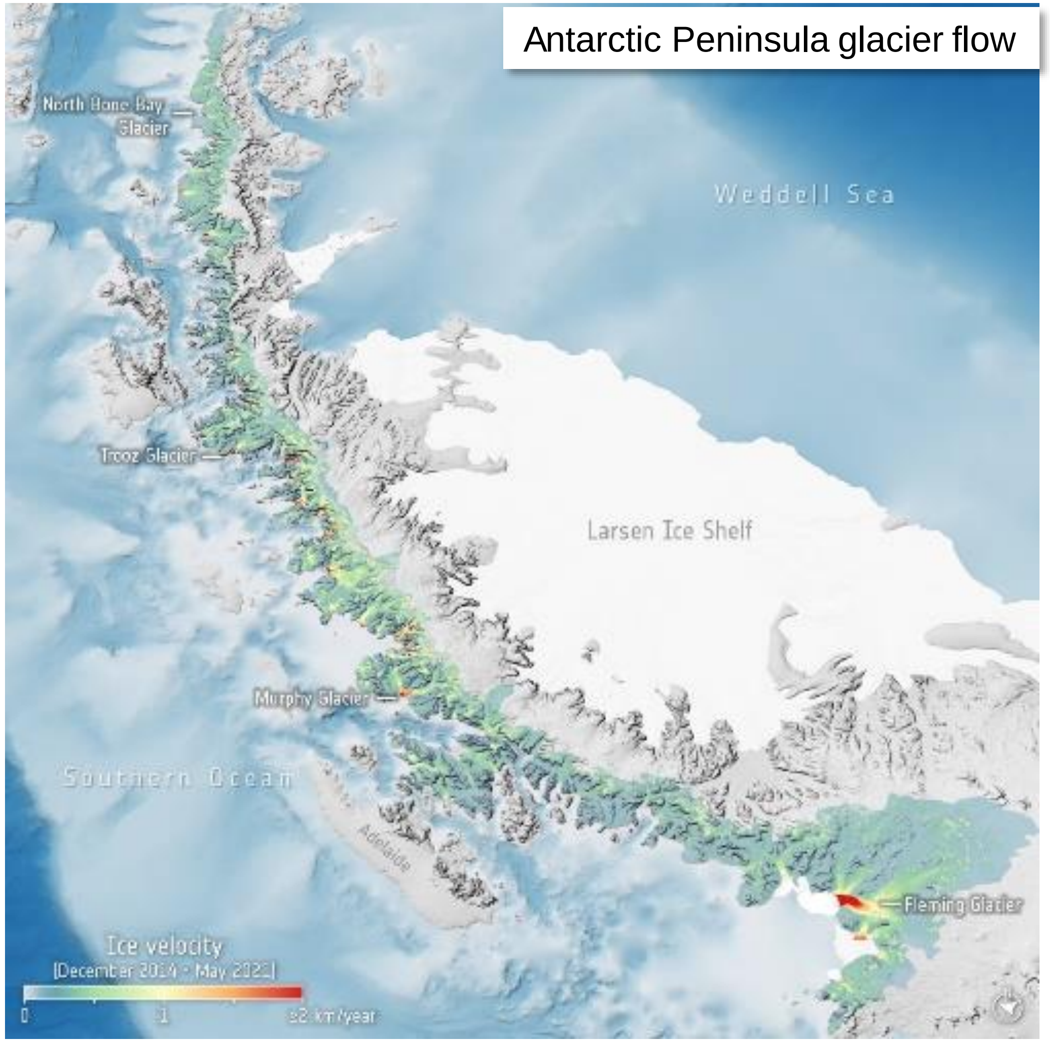
Synthetic Aperture Radar (SAR)

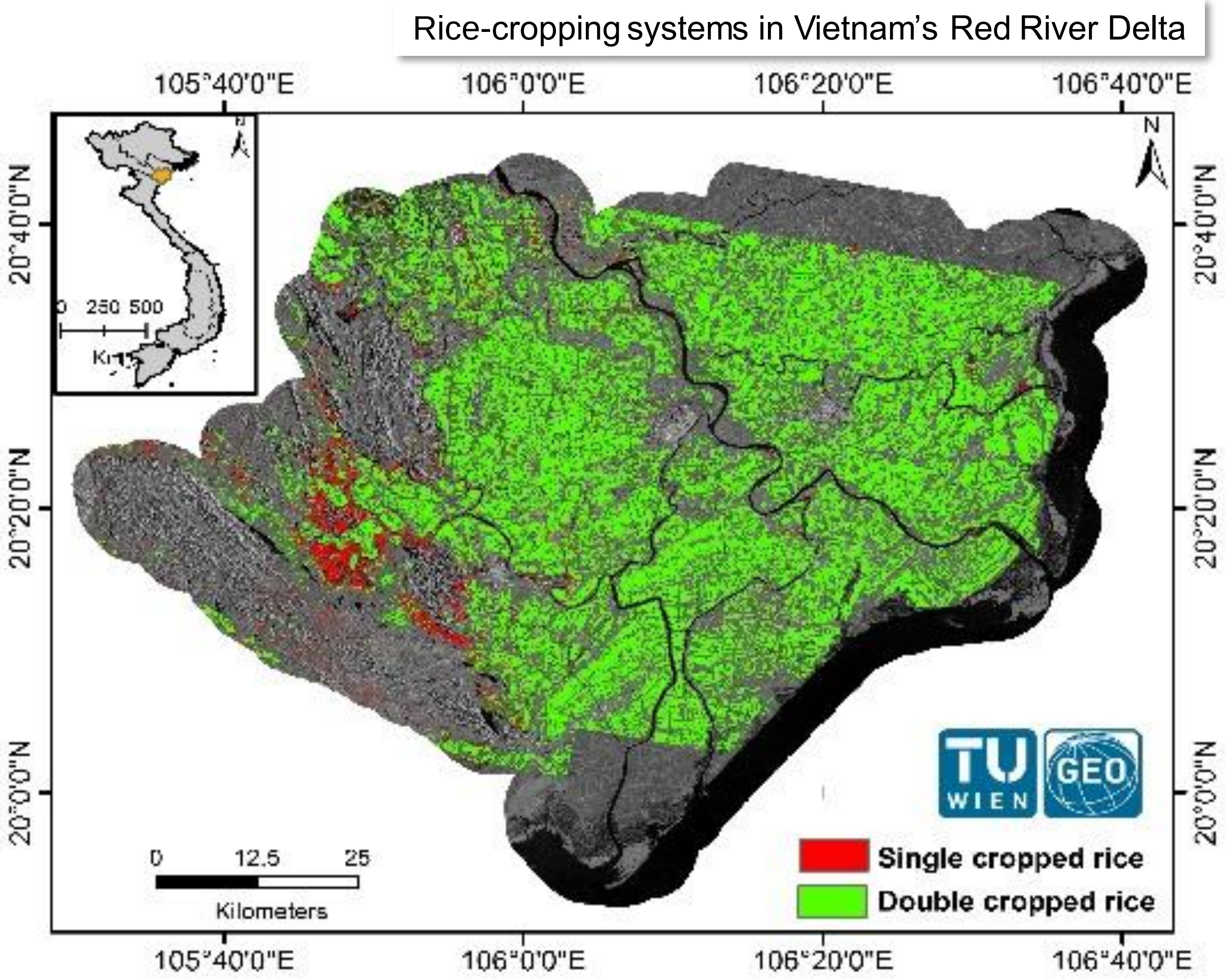
Determining elevation



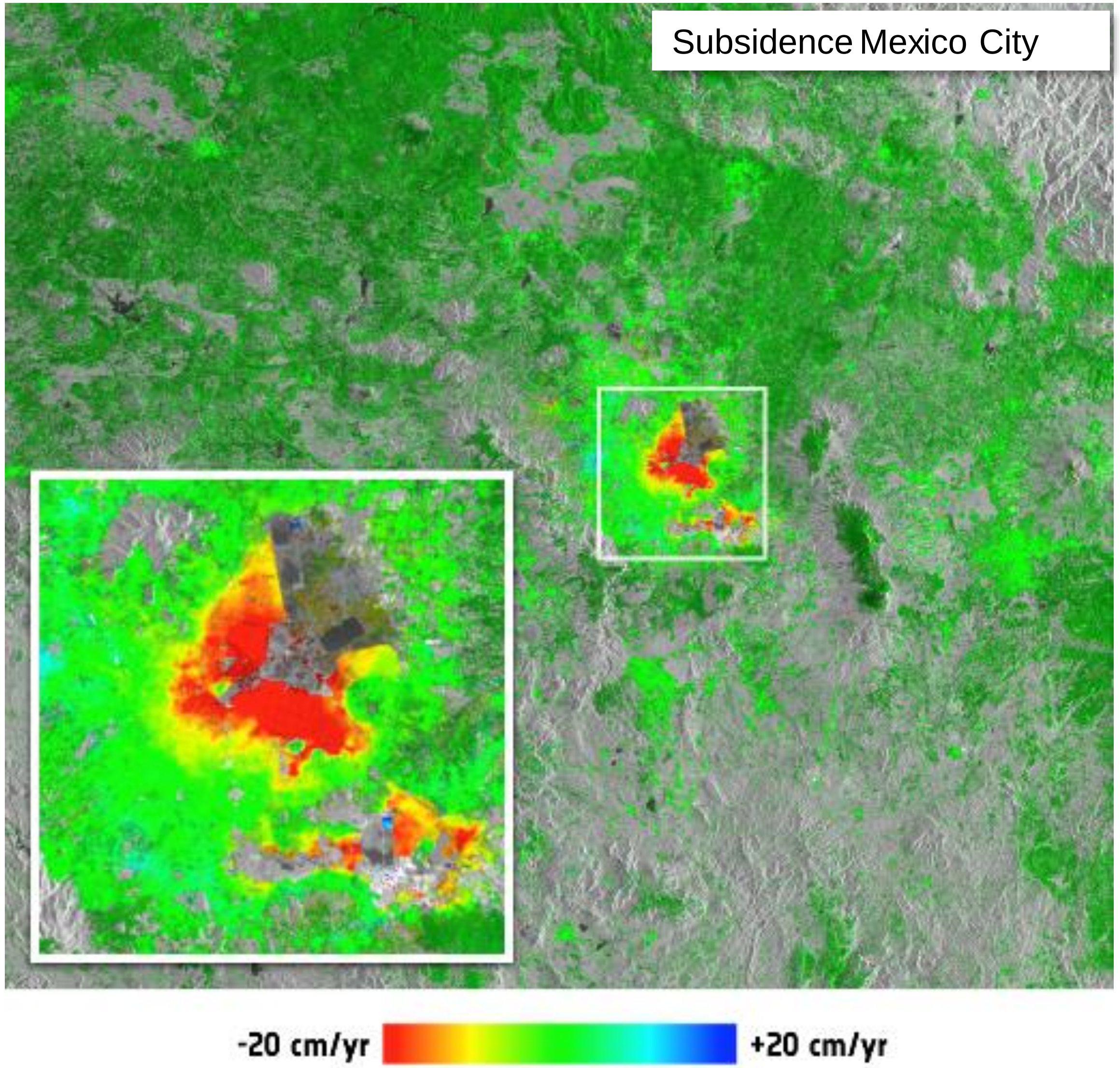
SAR Interferometry (InSAR) makes use of the phase difference between two complex valued images from different view angle, i.e. forming baseline, so that topography of the area can be imaged.

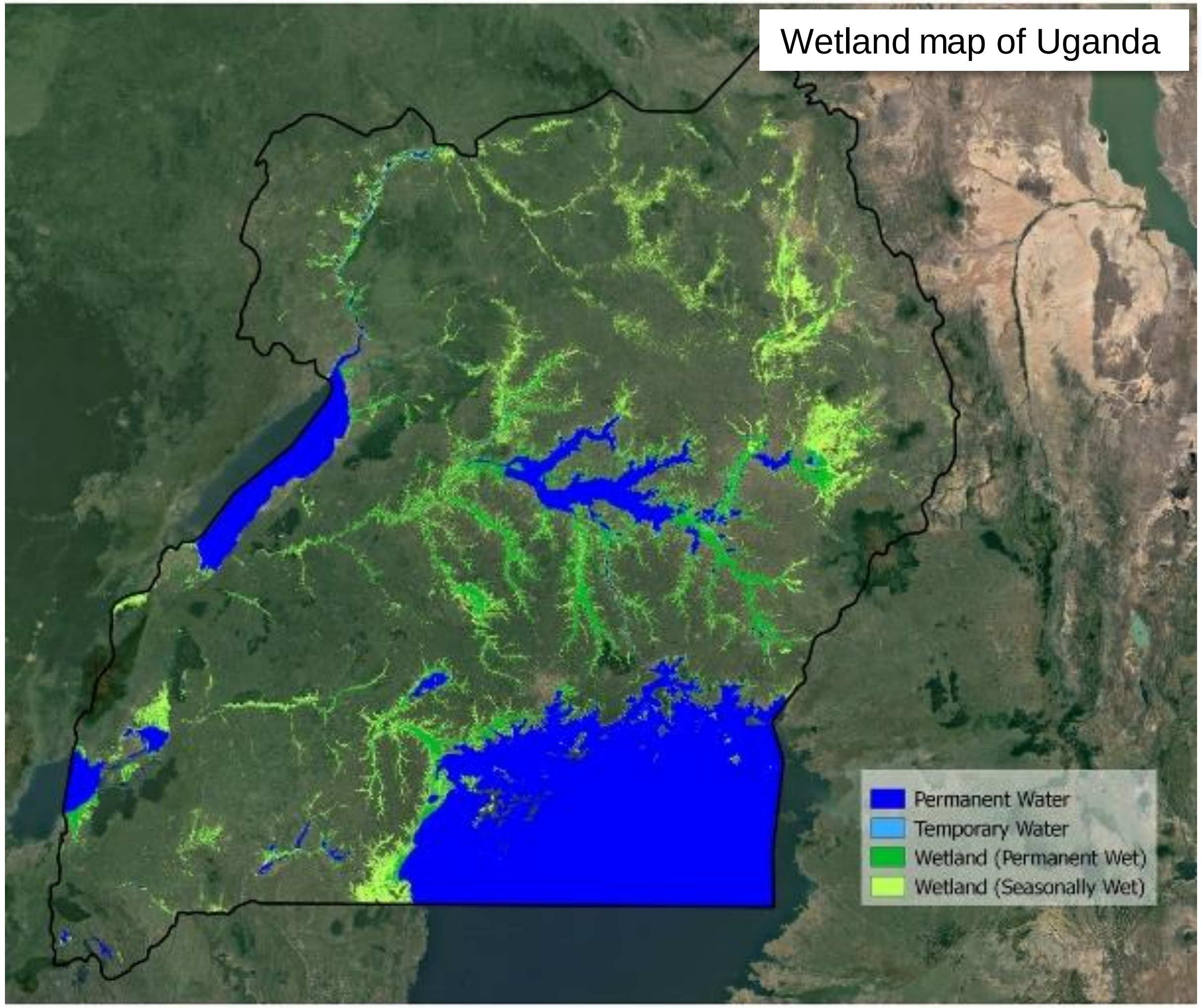
Sentinel-1 – Applications



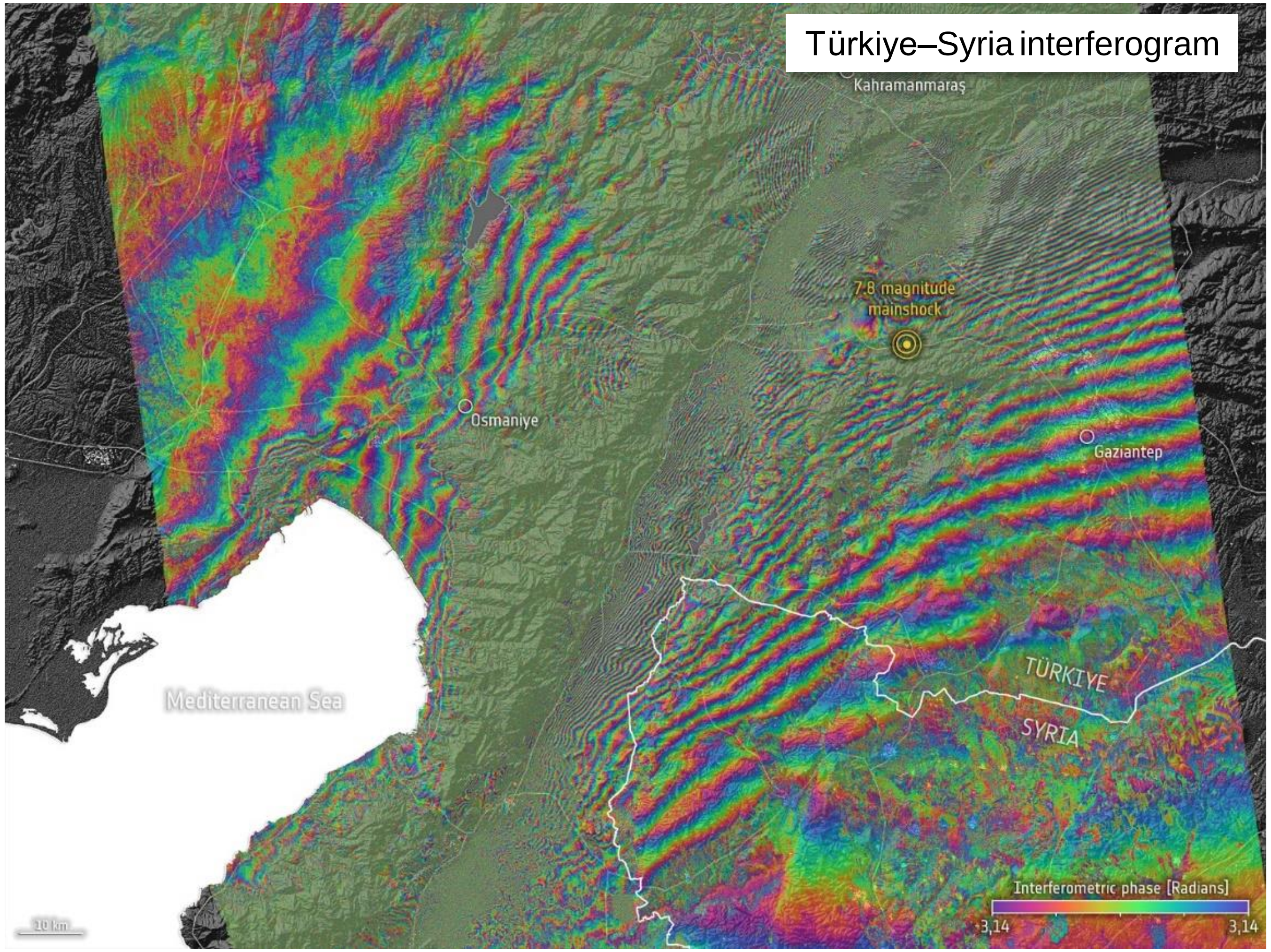


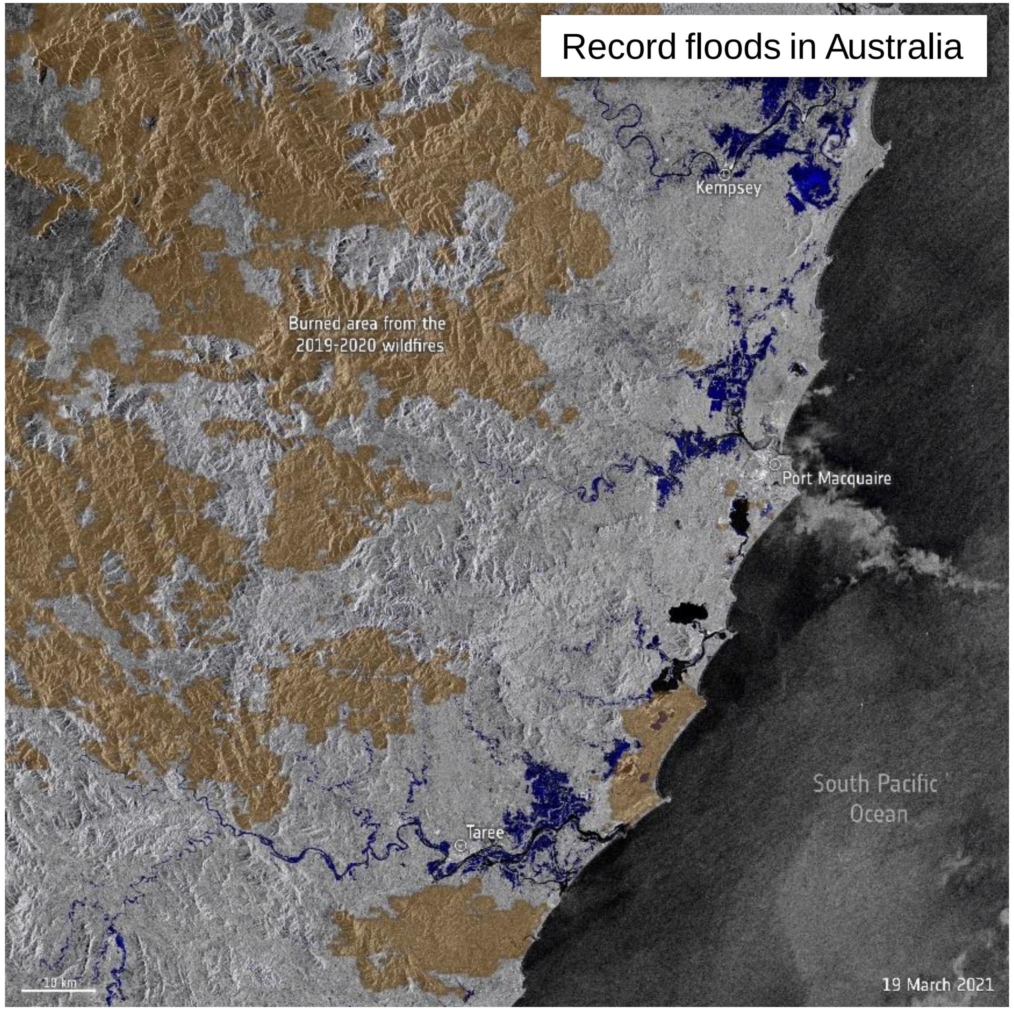
Sentinel-1 – Applications





Sentinel-1 – Applications






ESA EO Data Access and resources
Sourcenttps://rare-gallery.com/4510158-
space-3d-digital-art-europe-planet-night.html

ESA Earth Observation Data Policy

- To stimulate a balanced development of Science, Public Utility and Commercial Applications
- To maximize the use of data from ESA EO satellites

ERS and Envisat

Earth Explorers

- *Free datasets*

(Free of charge; User registration and acceptance of ESA Terms & Conditions are required → Open access)

- *Restrained datasets*

(Free of charge; User registration, submission of a “Project (Full) Proposal” and acceptance of the ESA Terms & Conditions are required, after its evaluation a quota will be assigned)

ESA Third Party Missions

- Data Policy of individual data providers

In some case, a reproduction cost (e.g. ALOS) or Specific Restrictions (limitations of quota, geographical restrictions, etc.) to the use of data may be applied for TPM

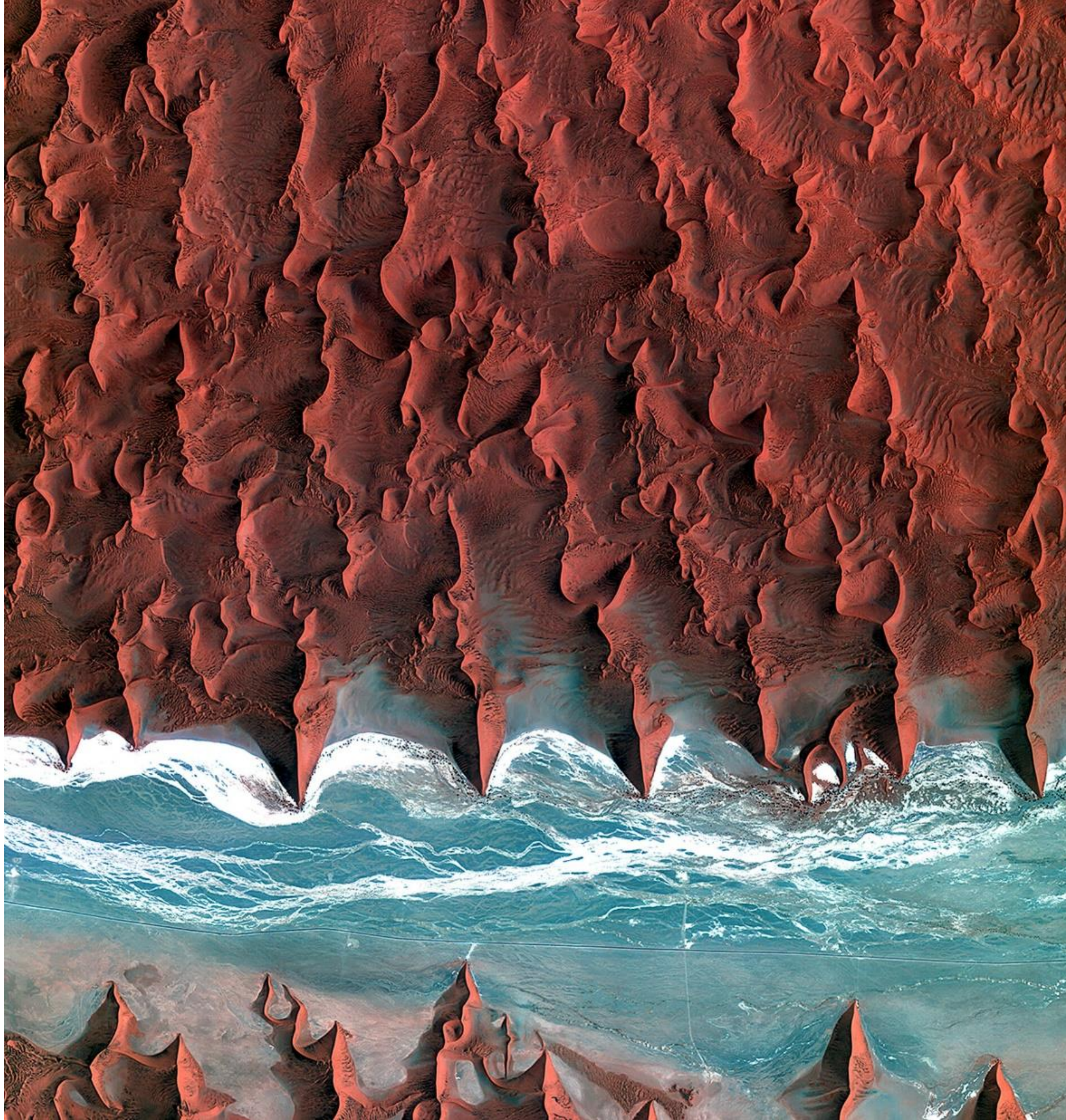
Source: https://www.esa.int/Applications/Observing_the_Earth/Envisat/ESA_declares_end_of_mission_for_Envisat, https://earth.esa.int/eogateway/news/esa-s-excellent-earth-explorer-missions-extended-to-2025/esa-s-ice-mission , https://www.esa.int/ESA_Multimedia/Images/2012/12/Pleiades#.XoNYGqecnA8.link

EO data access

Free open source platforms

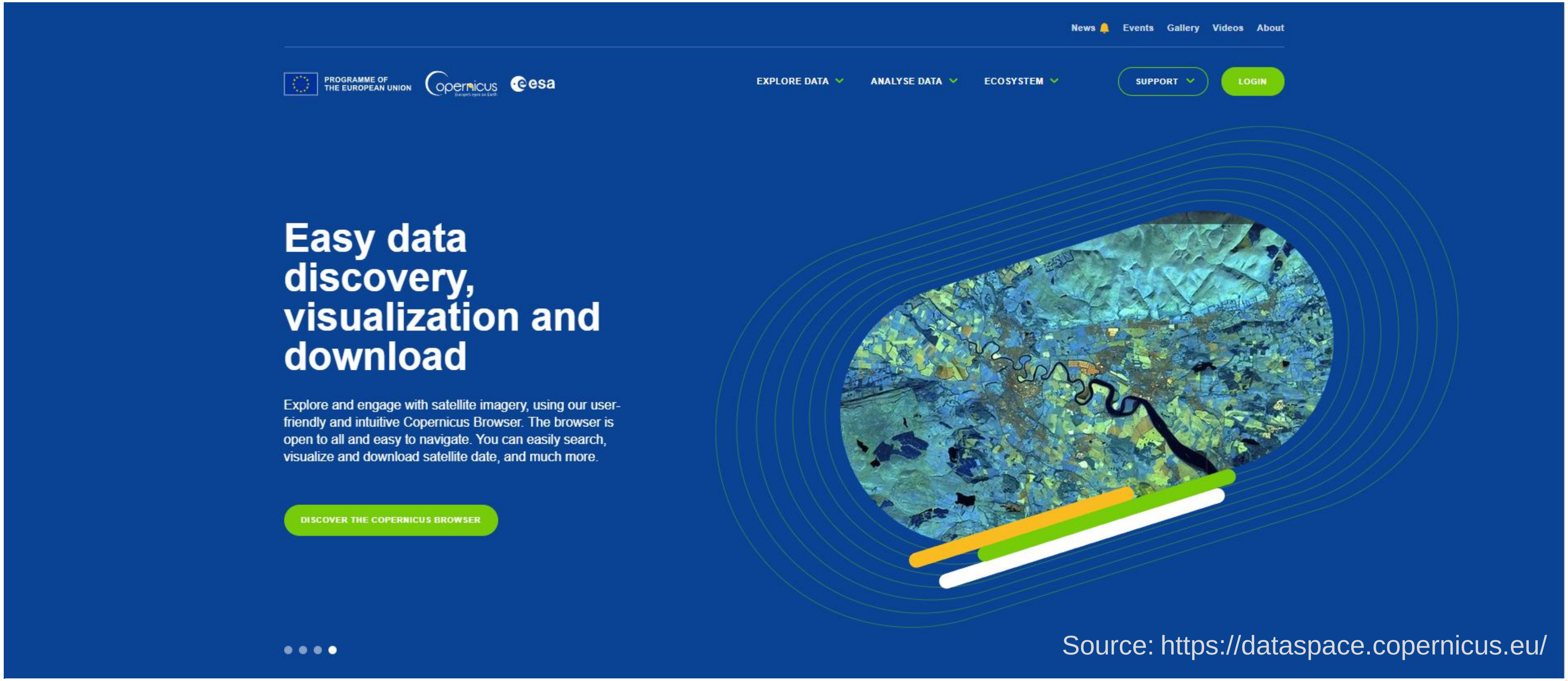
- **Copernicus Open Access Hub**
- Earth System Lab
- ESA Thematic Exploitation Platforms
- Alaska Satellite Facility
- Copernicus Global Land Service
- **Copernicus Data Space Ecosystem**
- **Sentinel Data Access Service**
- USGS Earth Explorer
- Sentinel Application Platform software
- Open Data Cube

Source https://business.esa.int/sites/business/files/Guide%20-%20Where%20to%20access%20EO%20data.pdf, https://www.esa.int/ESA_Multimedia/Images/2013/04/Namib_Desert:



Copernicus Data Space Ecosystem

https://dataspace.copernicus.eu/

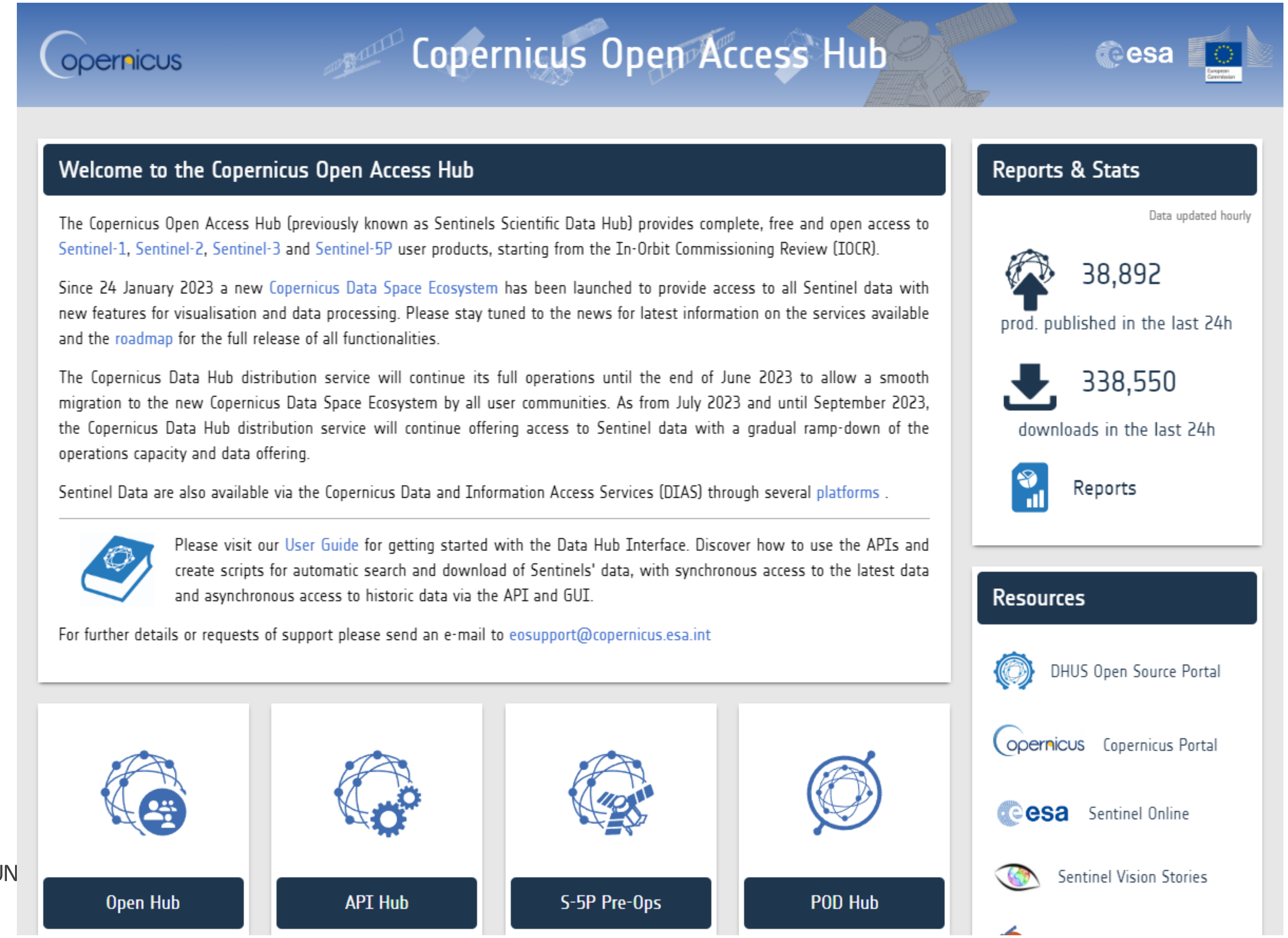


Source: https://dataspace.copernicus.eu/

- Since 24 January 2023 a new Copernicus Data Space Ecosystem has been launched to provide free and open access to EO data from all Sentinel satellites with new features for visualisation and data processing.

Copernicus Open Access Hub

https://scihub.copernicus.eu/

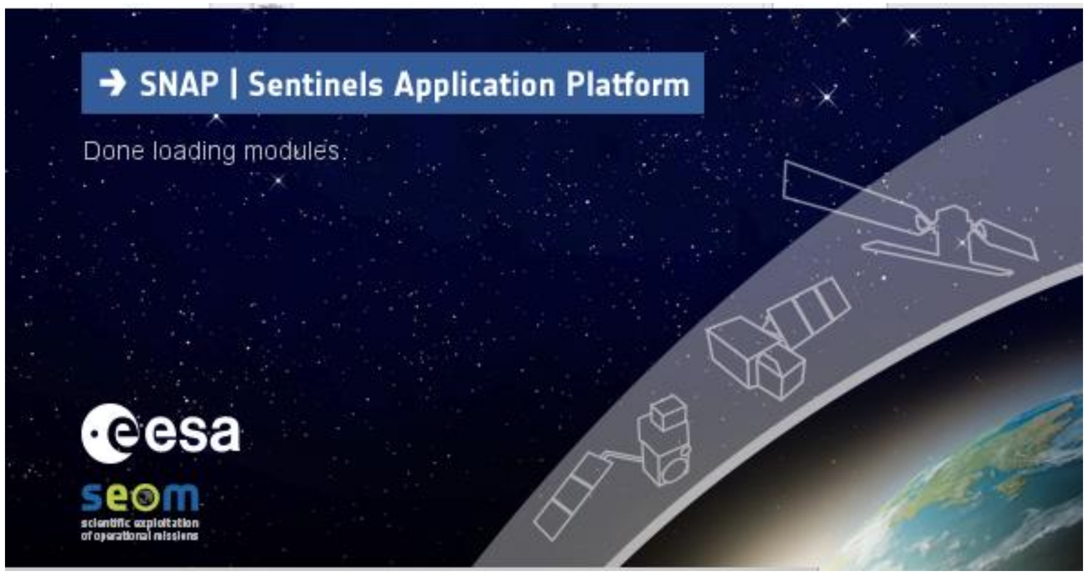


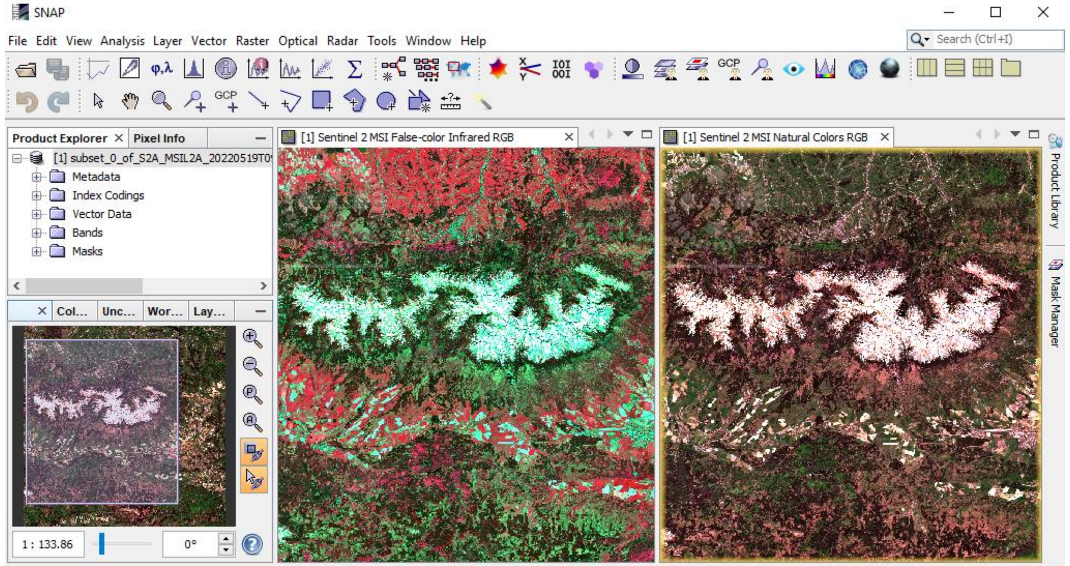
- The previous Copernicus Open Access Hub provided complete, free and open access to Sentinel-1, Sentinel-2, Sentinel-3 and Sentinel-5P user products

Source: https://scihub.copernicus.eu

SNAP (Sentinel Application Platform) software

http://step.esa.int/main/download/snap-download/





- ESA Sentinel Application Platform (SNAP) is a software toolkit developed by the ESA for processing and analyzing Earth observation data, particularly data from the Sentinel satellites. SNAP is part of the Sentinel Toolbox and is freely available to the public. It provides a user-friendly interface and a comprehensive set of tools also for working with a variety of other remote sensing data.

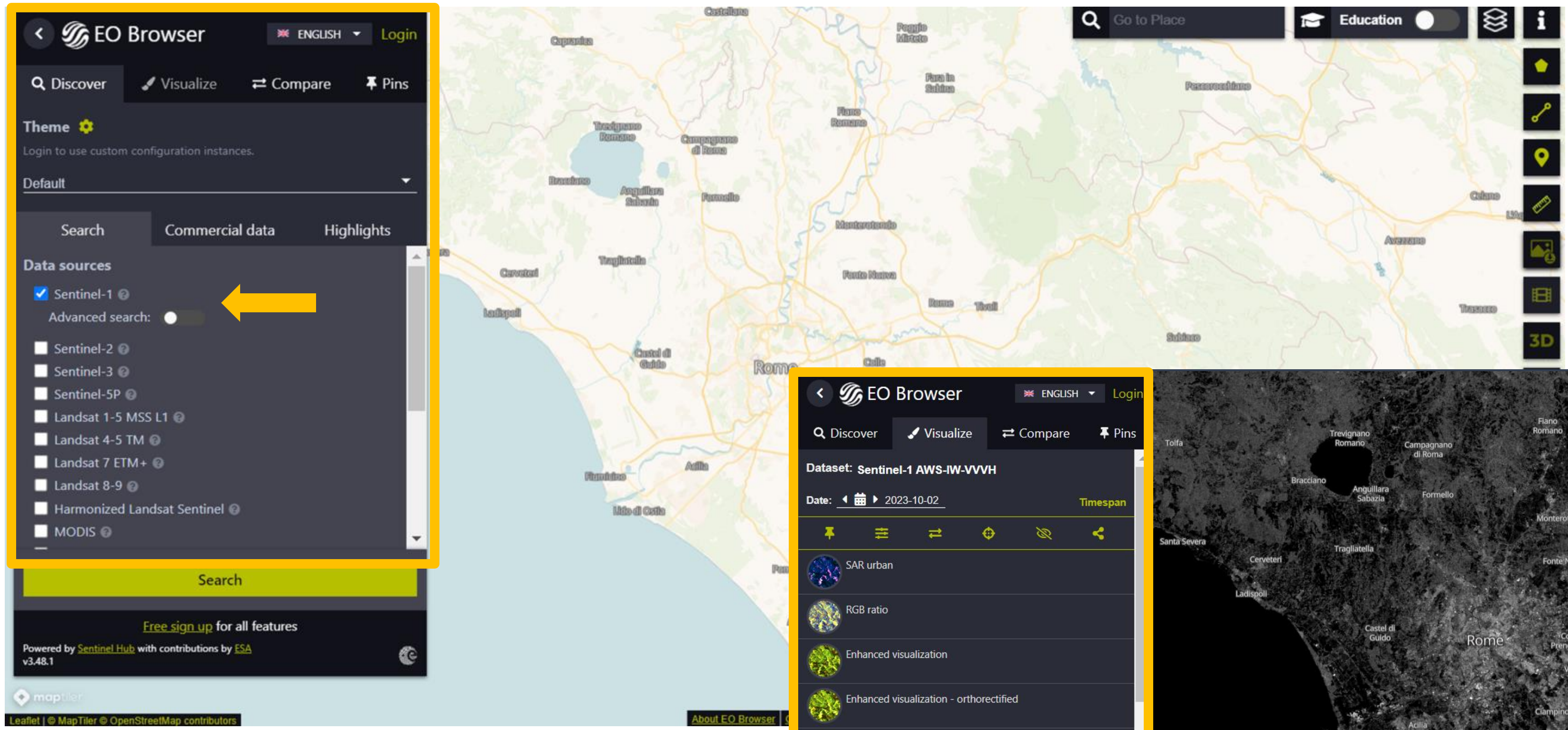
EO data access

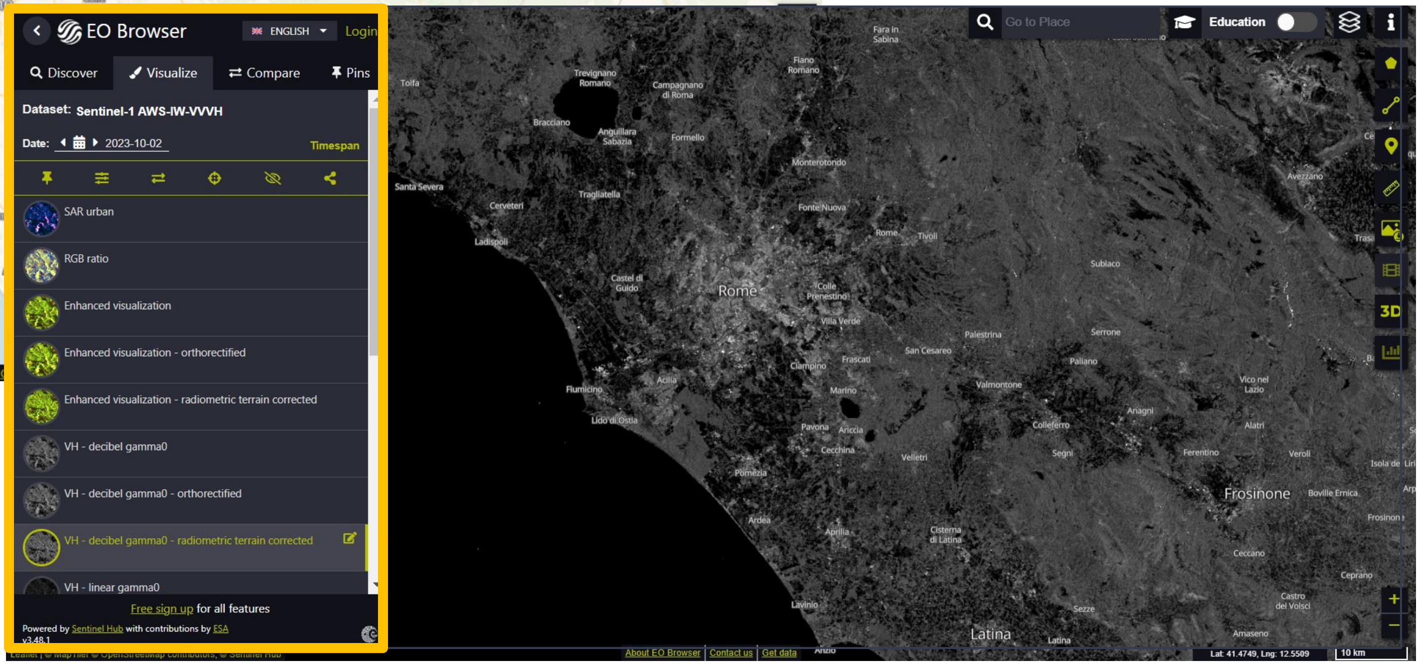
Partially open-source EO platforms

- **EO Browser Sentinel Hub**
- DIAS - Copernicus Data & Information Access Services
- Google Earth Engine
- Earth on AWS

EO Browser - SENTINEL Hub

https://apps.sentinel-hub.com/eo-browser/





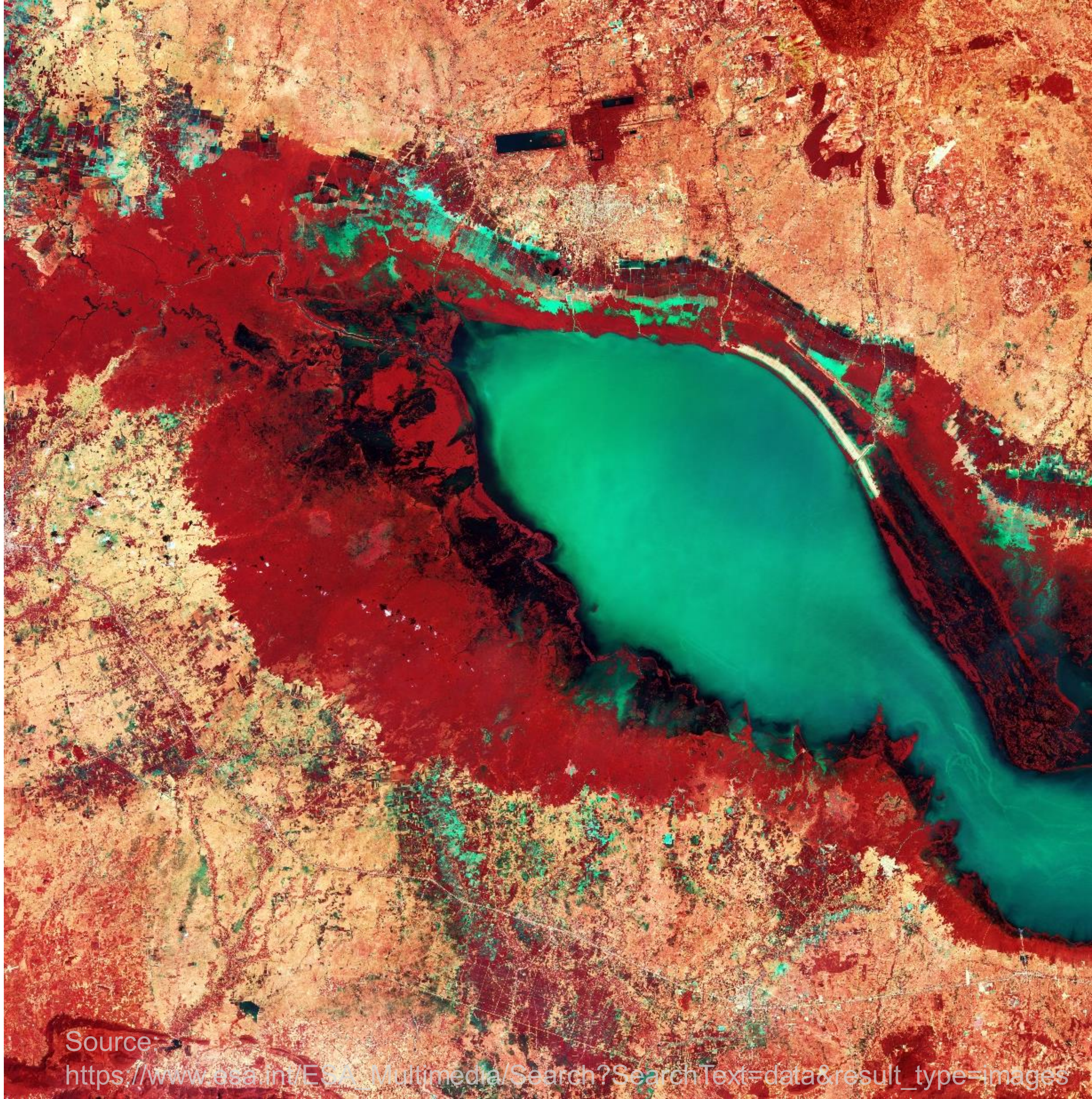
Source: https://apps.sentinel-hub.com/eo-browser

EO data access

Commercial EO platforms

- DigitalGlobe / Maxar
- OneAtlas
- Planet platform
- e-Geos
- Decartes Labs

For more information, see the tutorial: 1. Radar Earth Observation – ESA EO Data Access and resources, applications, Copernicus OA Hub



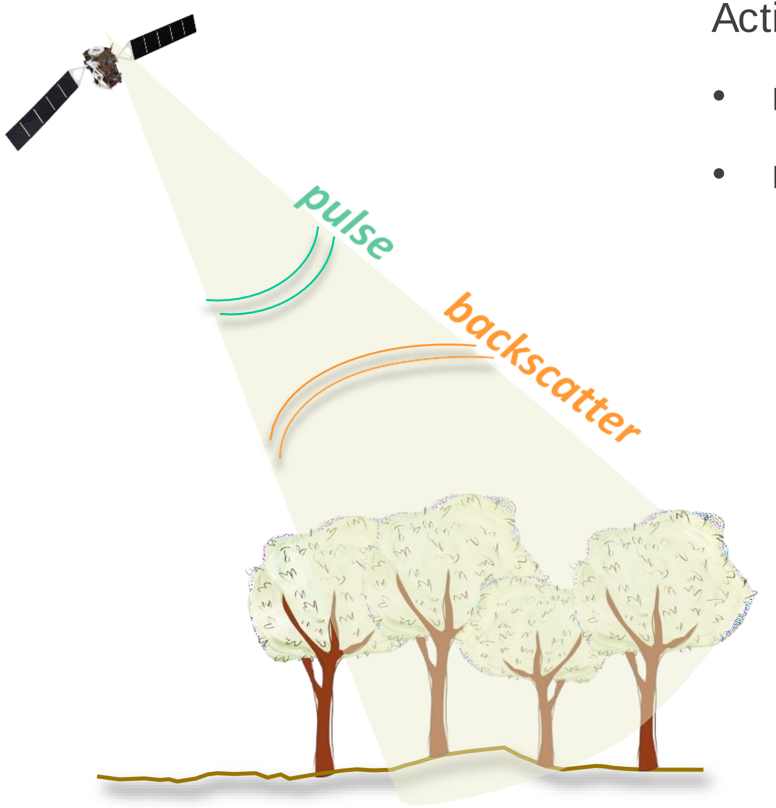
Source: https://www.esa.int/ESA_Multimedia/Search?SearchText=data&result_type=images

2. SAR remote sensing for land applications 1 – SAR basics

Synthetic Aperture Radar (SAR)

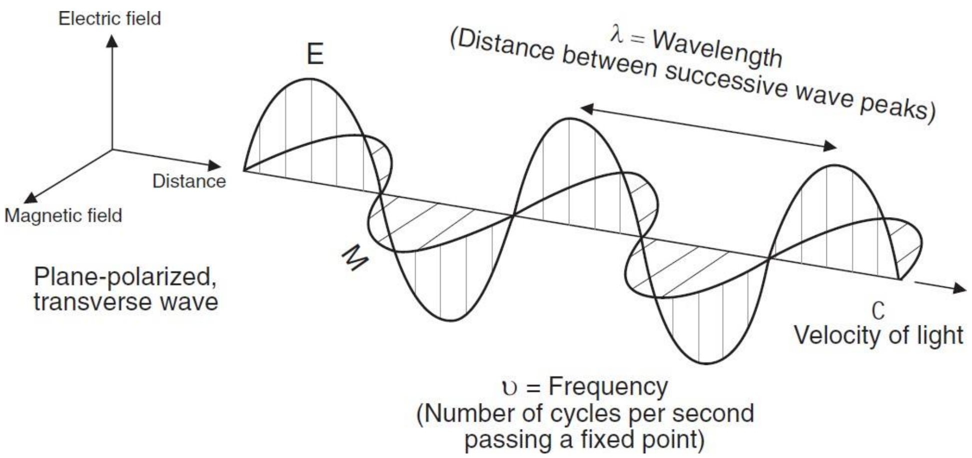
Basic characteristics of SAR (radar) sensors

- **Active → independent of sun illumination**



Active remote sensing sensors generate EM-waves

- no sunlight required night time acquisitions possible
- no problems due to bad illumination



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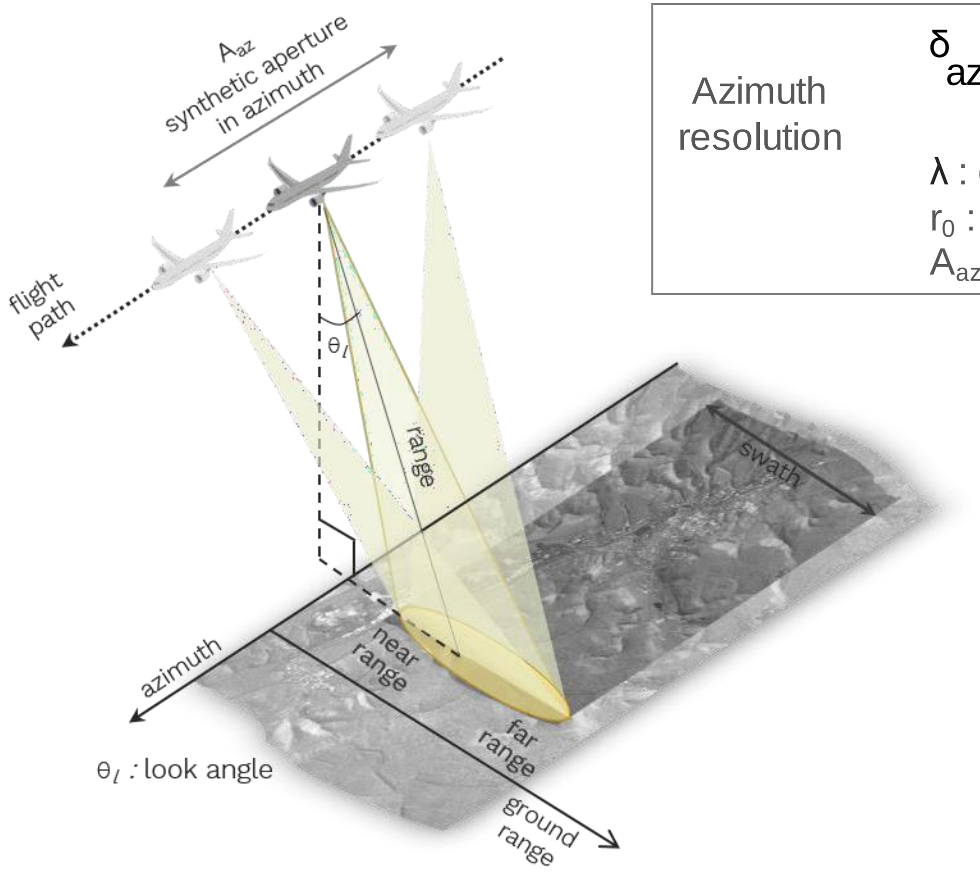
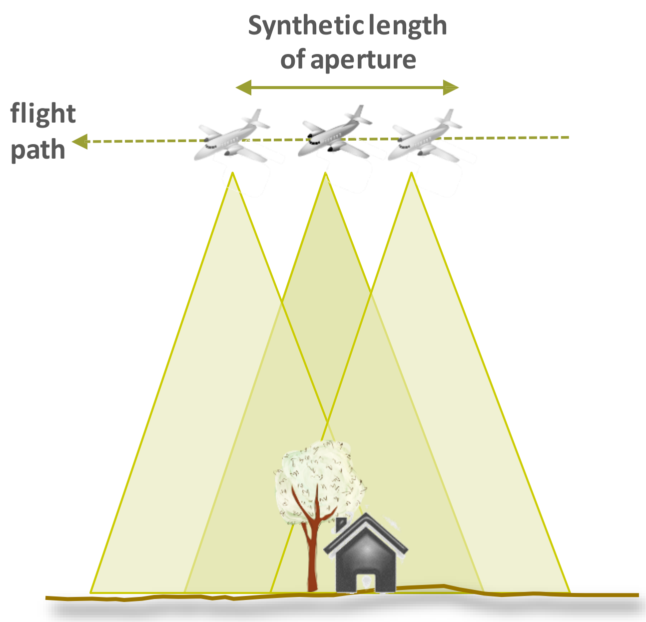
The principle of extending the antenna

The key factor that is utilized in SAR is to synthesize a much longer antenna in azimuth direction by making use of the motion of the SAR sensor in order to achieve finer resolution.



Azimuth resolution	$\delta_{az} = \frac{\lambda r_0}{2A_{az}}$ λ : carrier wavelength r_0 : range distance A_{az} : azimuth aperture

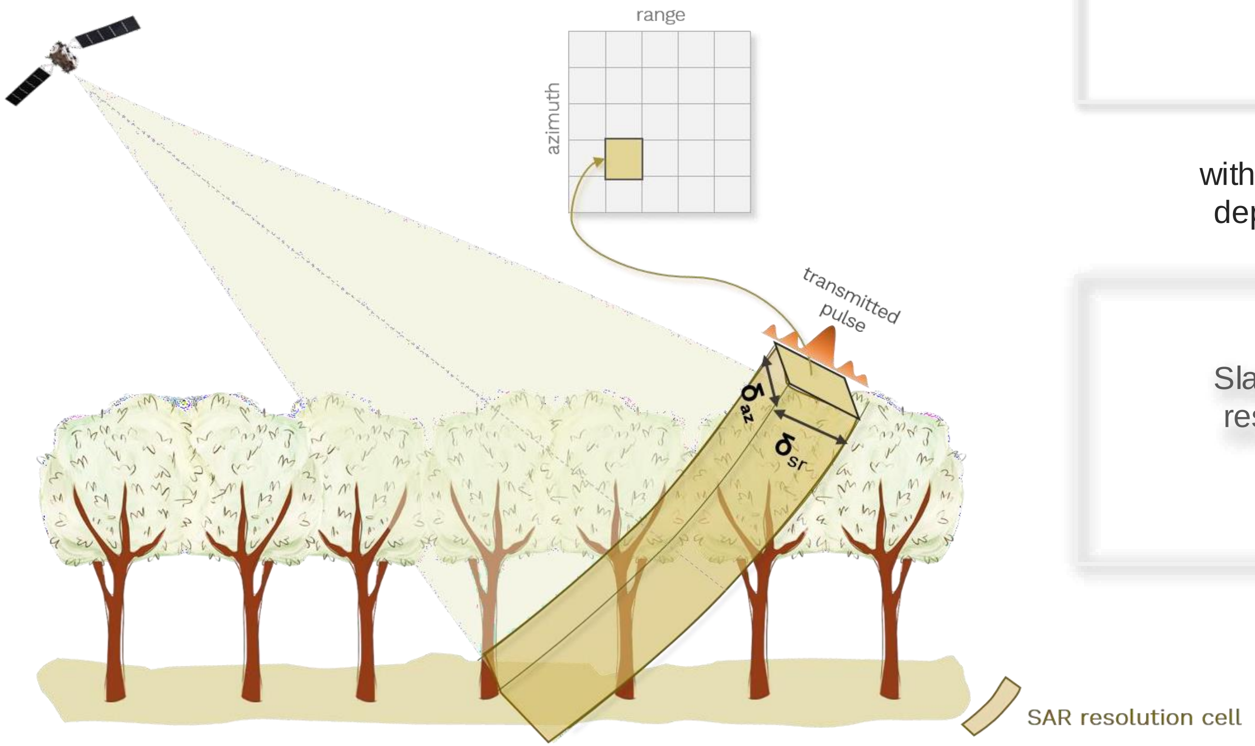


Side view

Synthetic Aperture Radar (SAR)

Cell resolution

A SAR pixel = sum of all contributions within the resolution cell



with the azimuth resolution being a function of the aperture in azimuth

Azimuth resolution

$$\delta_{az} = \frac{\lambda r_0}{2A_{az}}$$

λ : carrier wavelength
r_0 : range distance
A_{az} : azimuth aperture

with the slant-range resolution depending on the bandwidth

Slant-range resolution

$$\delta_{sr} = \frac{c}{2W}$$

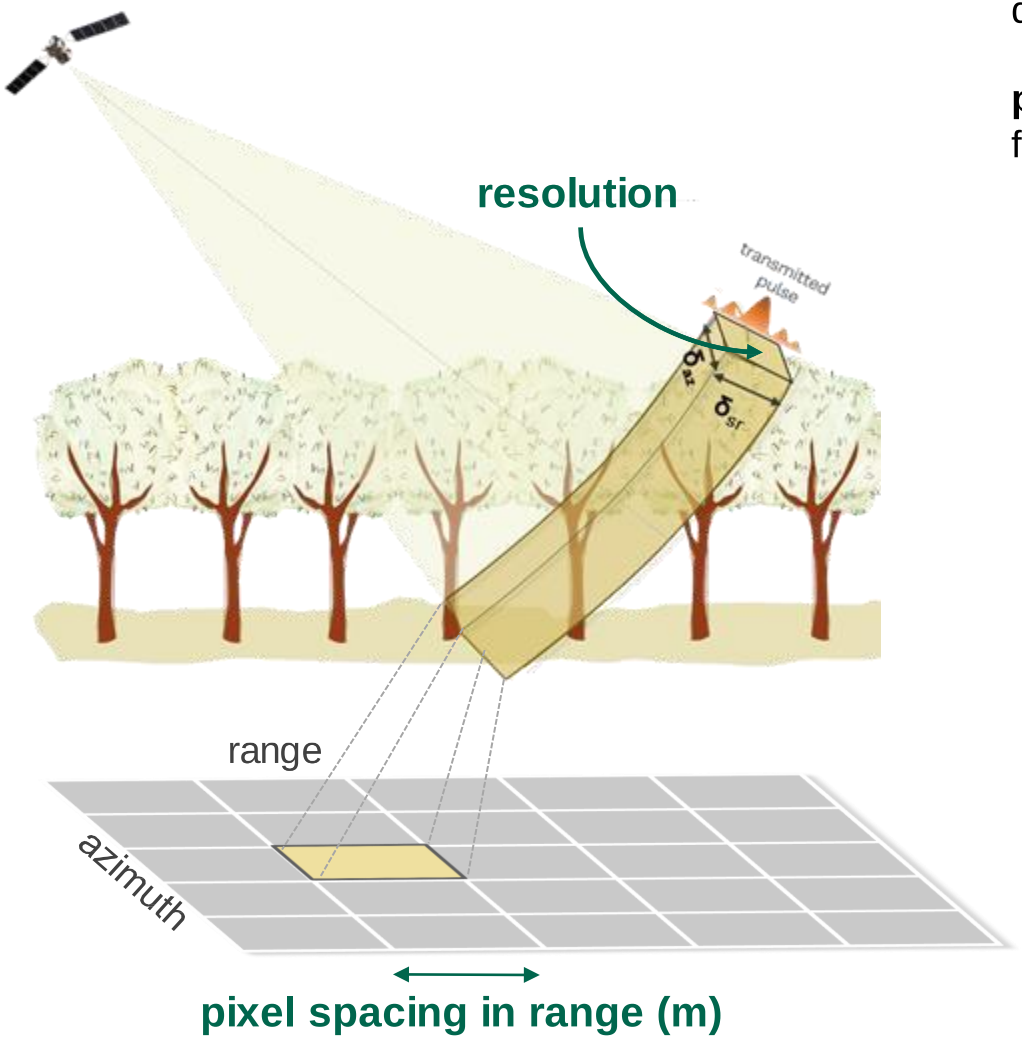
c : speed of light
W : pulse bandwidth

Synthetic Aperture Radar (SAR)

Resolution vs. Pixel spacing

resolution is a measure of the system's ability to distinguish between adjacent targets

pixel spacing represents the distance on the ground for a pixel in the range and azimuth directions



E.g. Acquisition resolution of Sentinel 1 Level-1 SLC

Mode	Resolution rg x az	Pixel spacing rg x az
SM	1.7x4.3 m to 3.6x4.9 m	1.5x3.6 m to 3.1x4.1 m
IW	2.7x22 m to 3.5x22 m	2.3x14.1 m
EW	7.9x43 m to 15x43 m	5.9x19.9 m
WV	2.0x4.8 m and 3.1x4.8 m	1.7x4.1 m and 2.7x4.1 m

Synthetic Aperture Radar (SAR)

Scatterometers vs. SAR

***Scatterometers*:**

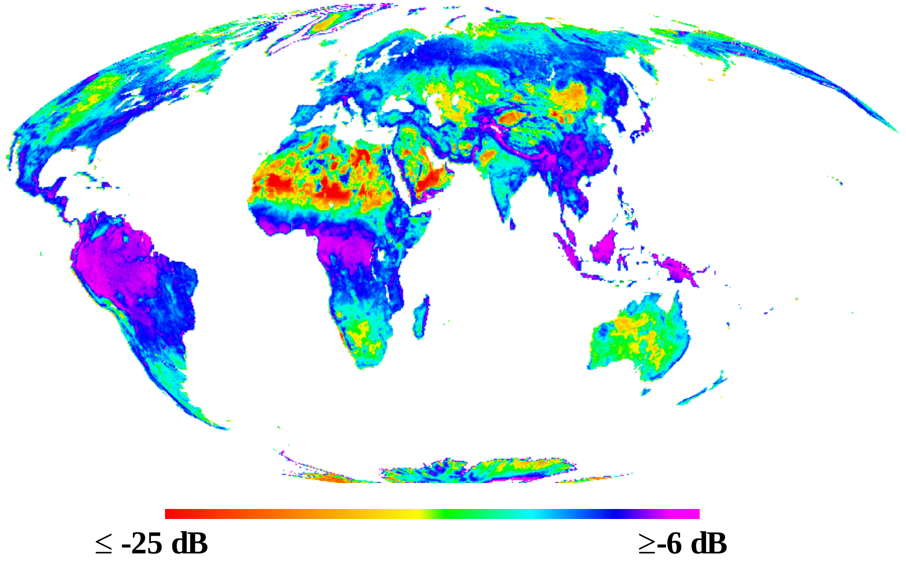
Radar eflectivity estimation (σ°)

- ***low spatial resolution**: ~ 10 – 50 km*
- ***high frequency of acquisitions (~ day)***

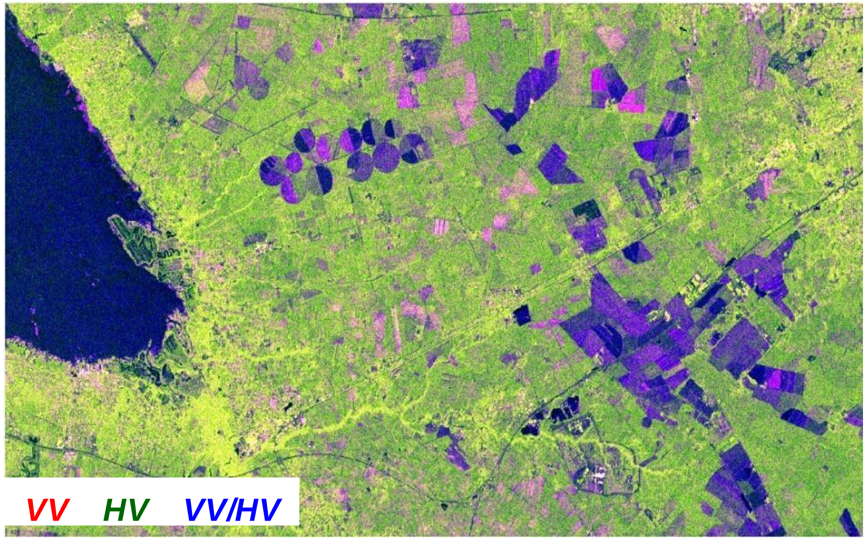
SAR:

Surface imaging

- ***high spatial resolution**: ~ 10 m*
- ***low frequency of acquisition (~ month)***



Scatt. ERS – May 1992

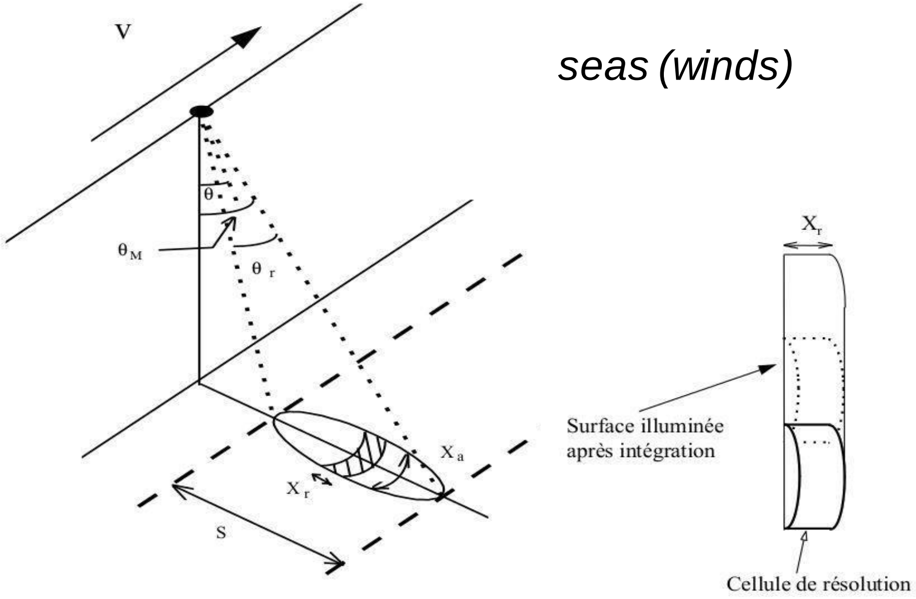


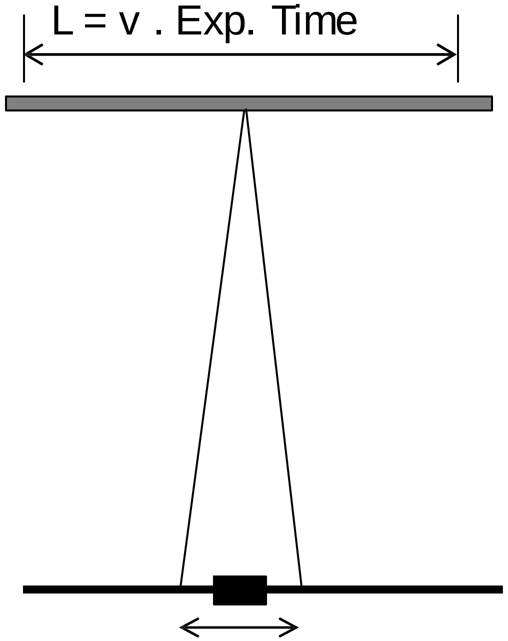
Sentinel-1 – March 2015

Synthetic Aperture Radar (SAR)

Scatterometers vs. SAR

Scatterometers		***SAR***
Incoherent sum *(I)*	**Raw echoes processing**	Coherent sum *(A, ϕ)*
Low (~ 10 – 50 km)	**Spatial resolution**	***Fine*** (1 - 30 m)
High (ENL ~ 400)	**Radiometic resolution**	***Low*** (speckle)
seas (winds)	**Originally designed**	*Land - seas*





Synthetic Aperture Radar (SAR)

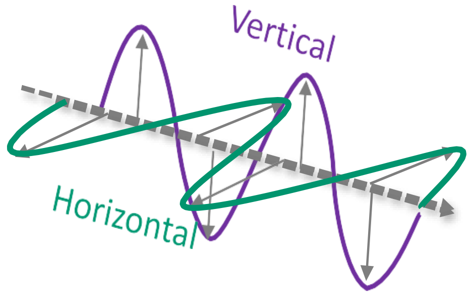
Polarisation

Important characteristics of cohetent EMW: Electromagnetic field evolution is predictable

Radar :

transmits a EMW in a given polarization

measures the backscattered wave contribution in a given polarization



The four combinations of SAR data polarizations:

HH: The emitted and backscattered signals have horizontal polarization

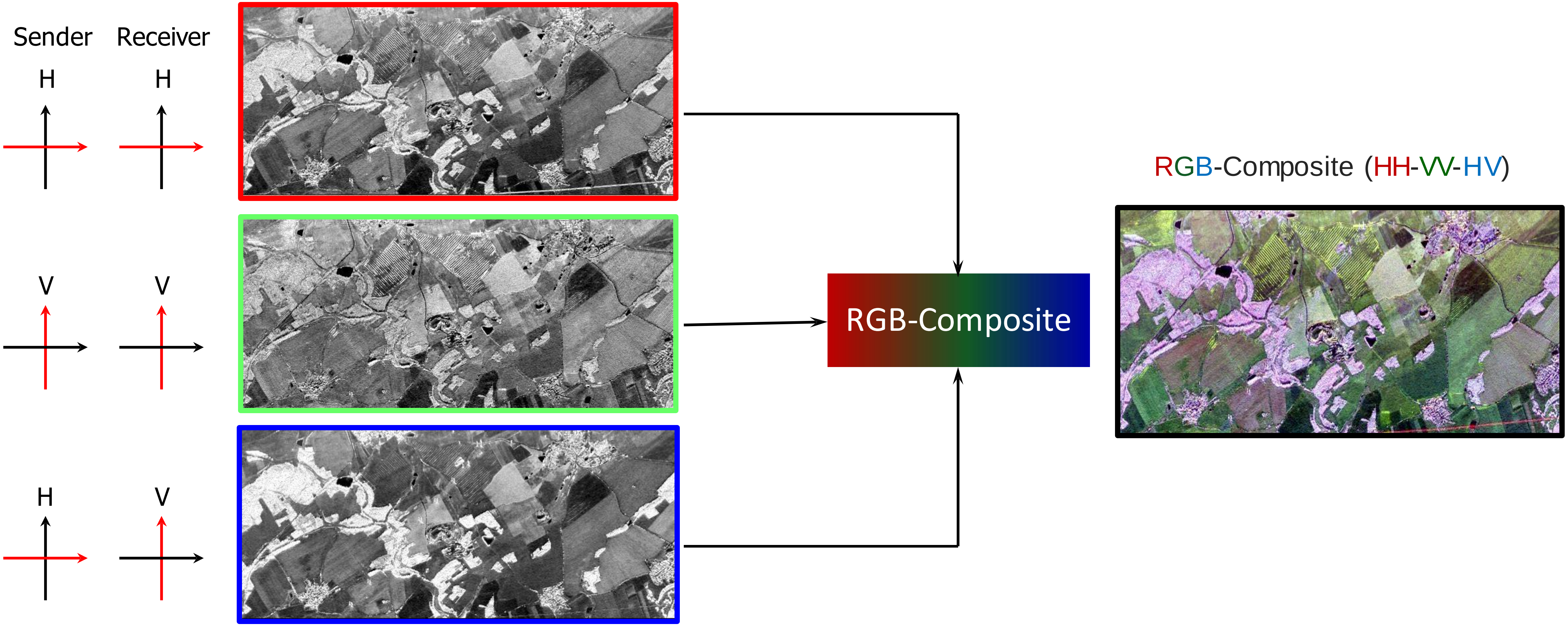
HV: The emitted signal has horizontal polarization, and the backscattered signal has vertical polarization.

VH: The emitted signal has vertical polarization, and the backscattered signal has horizontal polarization.

VV: Both emitted and reflected signals have vertical polarization

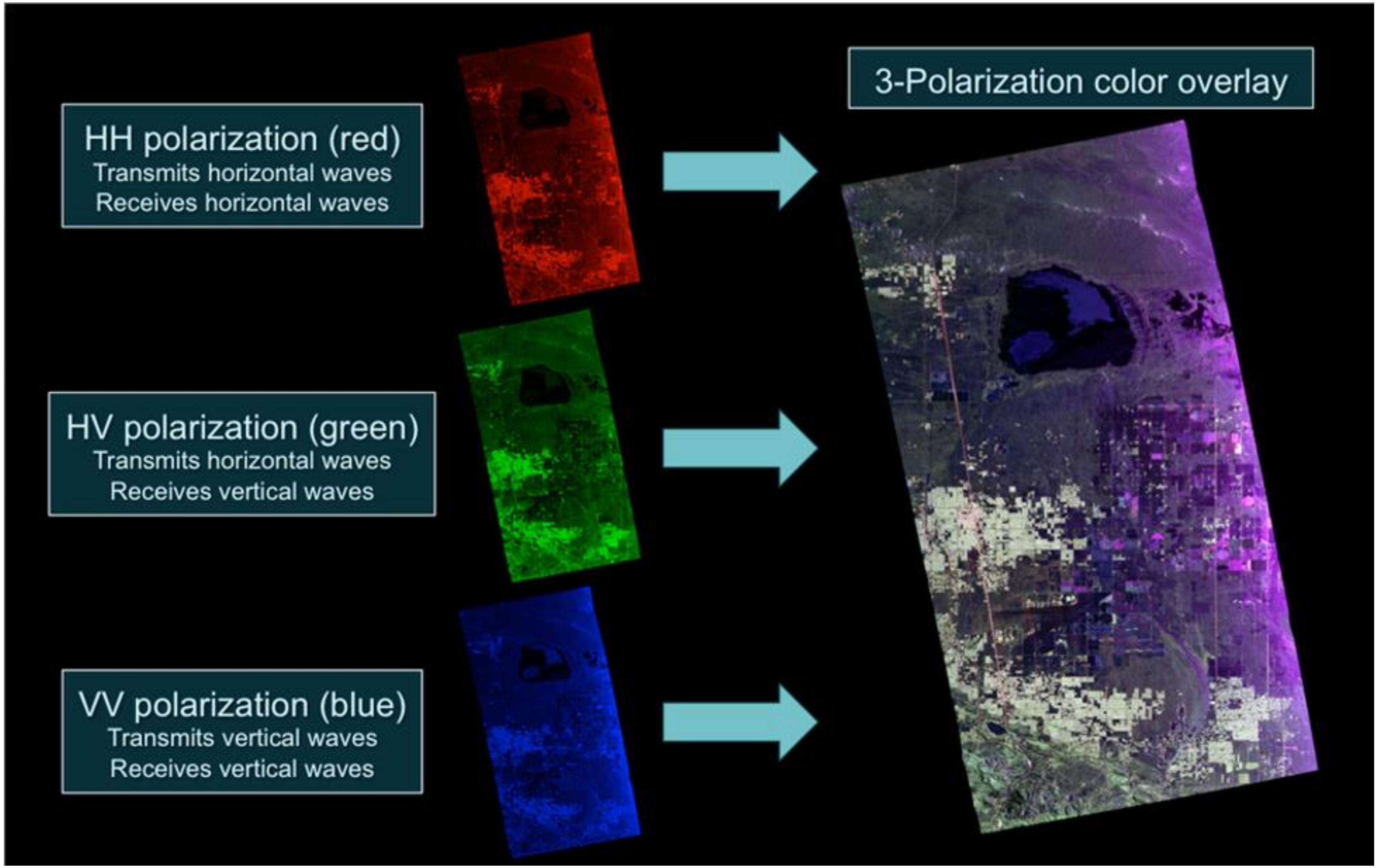
Synthetic Aperture Radar (SAR)

Polarisation



Synthetic Aperture Radar (SAR)

Polarisation



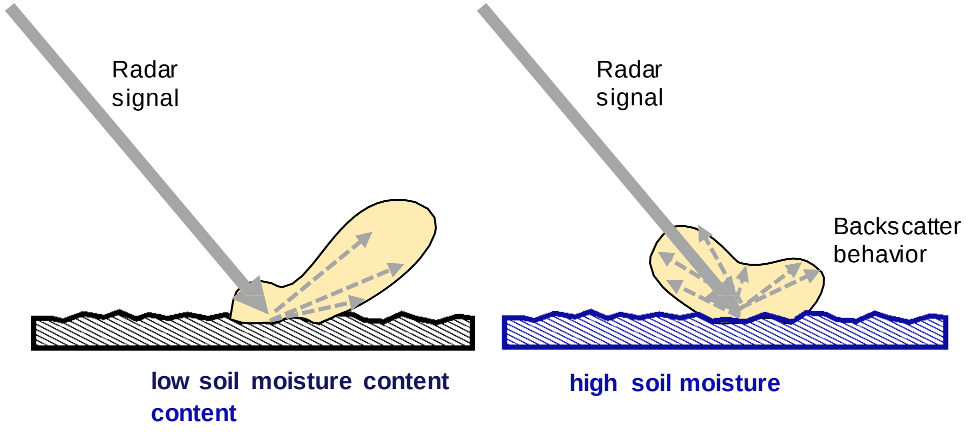
Synthetic Aperture Radar (SAR)

Target parameters : Dielectric Properties

Determined by dielectric constant ε_r :

• Strongly dependent on **water content** of natural media

•Controls reflection properties of natural media and thus the strength of radar backscatter (higher ε_r -> higher backscatter)



Effect of soil moisture on backscattering behavior

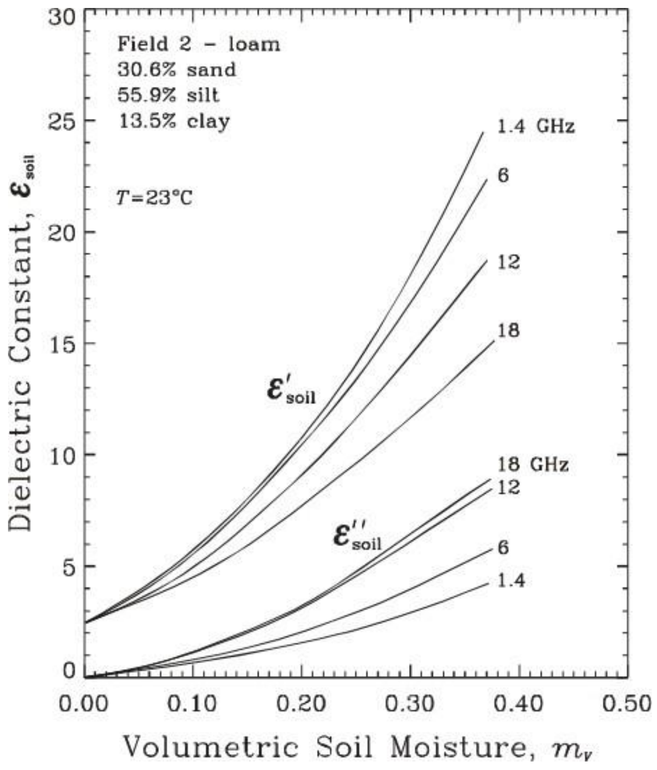
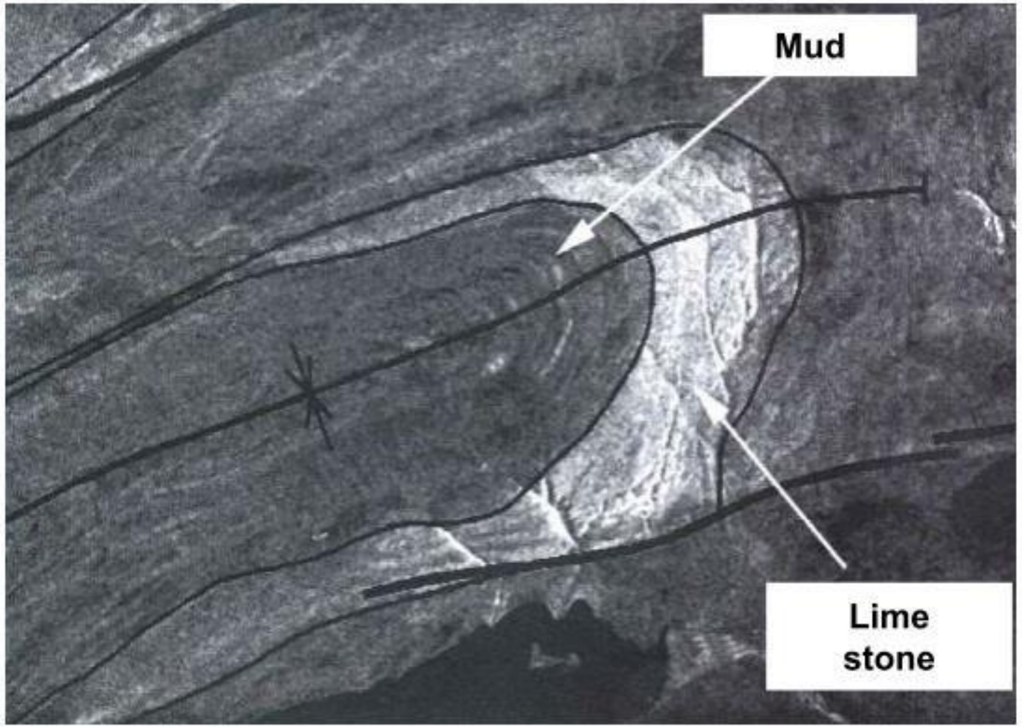


Fig.: Relationship between soil moisture and dielectric constant (Woodhouse, 2006)

Synthetic Aperture Radar (SAR)

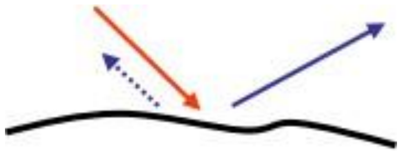
Target parameters : Surface Roughness



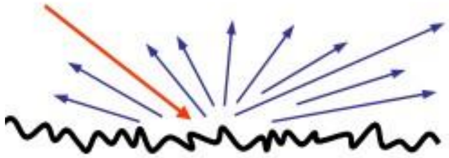
Radarsat, C-band, HH

Bathirst Island, Canada

mud, smooth surface, low radar backscatter



Lime stone, rough surface, high radar backscatter

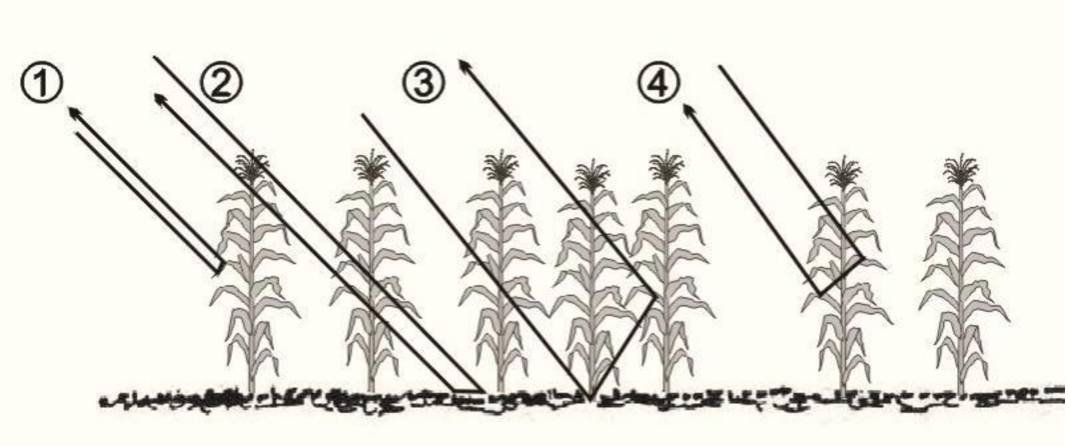


Synthetic Aperture Radar (SAR)

Target parameters : Scattering Mechanisms

The backscattered signal results from:

- surface scattering
- volume scattering
- multiple volume-surface scattering (double-bounce)



1) direct backscattering from plants
2) direct backscattering from underlying soil
3) multiple scattering between plants and soil
4) multiple scattering between plants,
5) leaves, stalks ect.

The relative importance of these contributions depend on

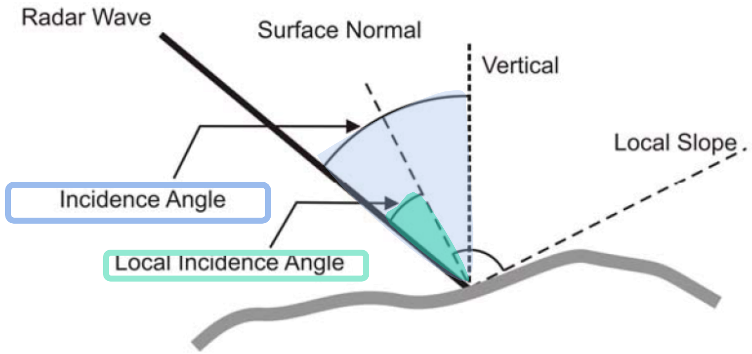
- surface roughness
- dielectric properties of the medium All

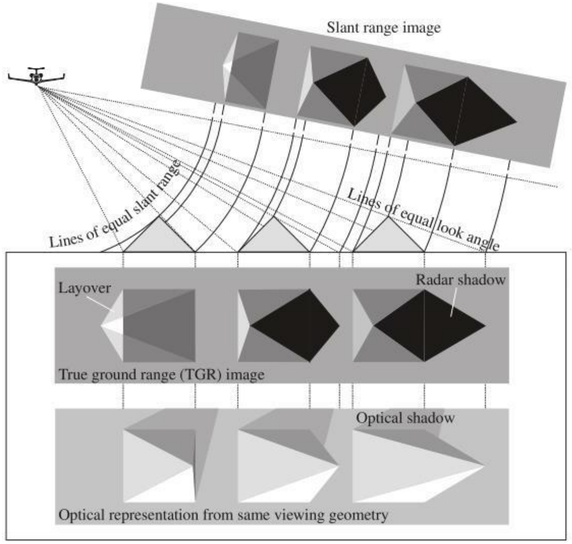
of these factors depend on

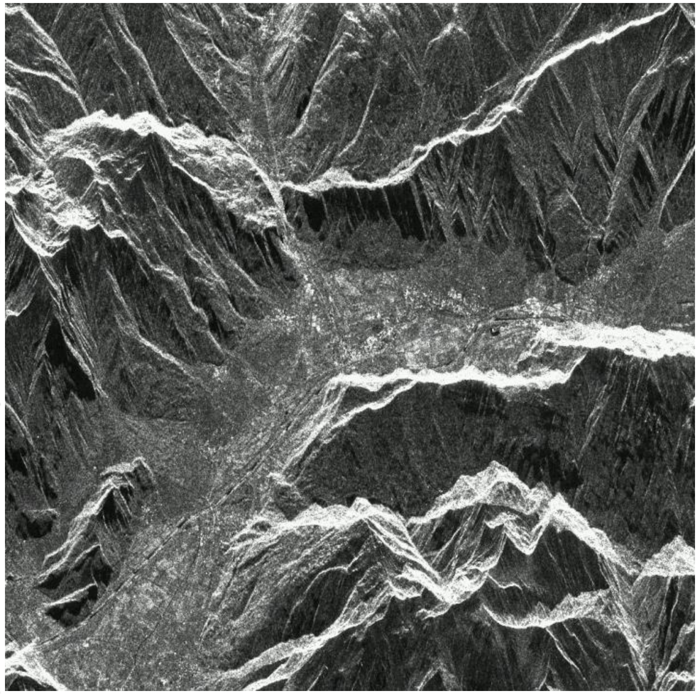
- the radar frequency
- the polarization
- the incidence angle

Synthetic Aperture Radar (SAR)

Target parameters : Local slope & orientation

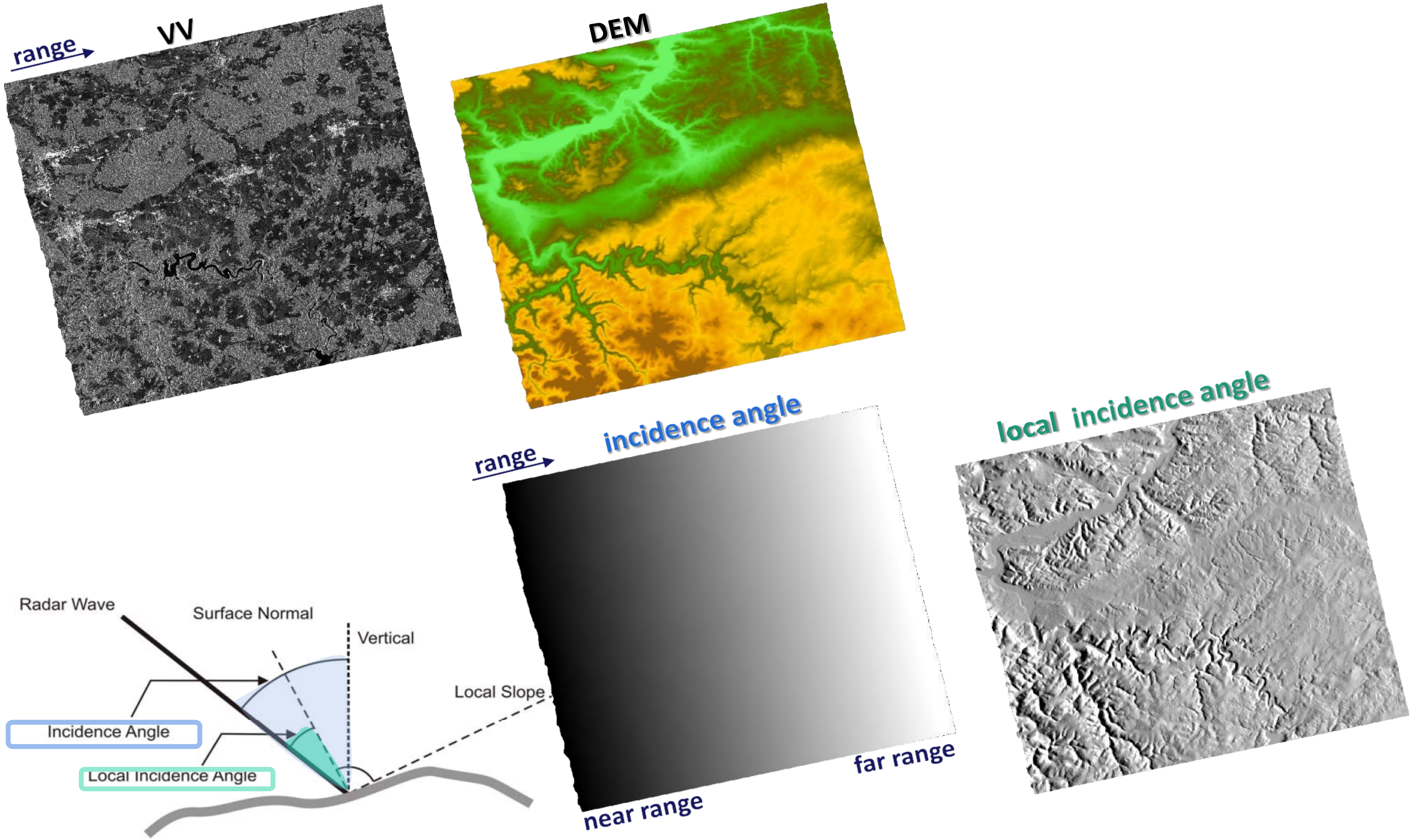






Synthetic Aperture Radar (SAR)

Target parameters : Local slope & orientation



Sentinel-1 – Radar vision

Mission profile:

- C-Band SAR mission at 5.4 GHz
- 4 operation modes
- Spatial resolution: 20 m
- Swath width: 250 km
- Two polarizations over land surfaces: VV and VH

Sentinel-1A: launched the 3rd April 2014
== > SAR data from March 2015

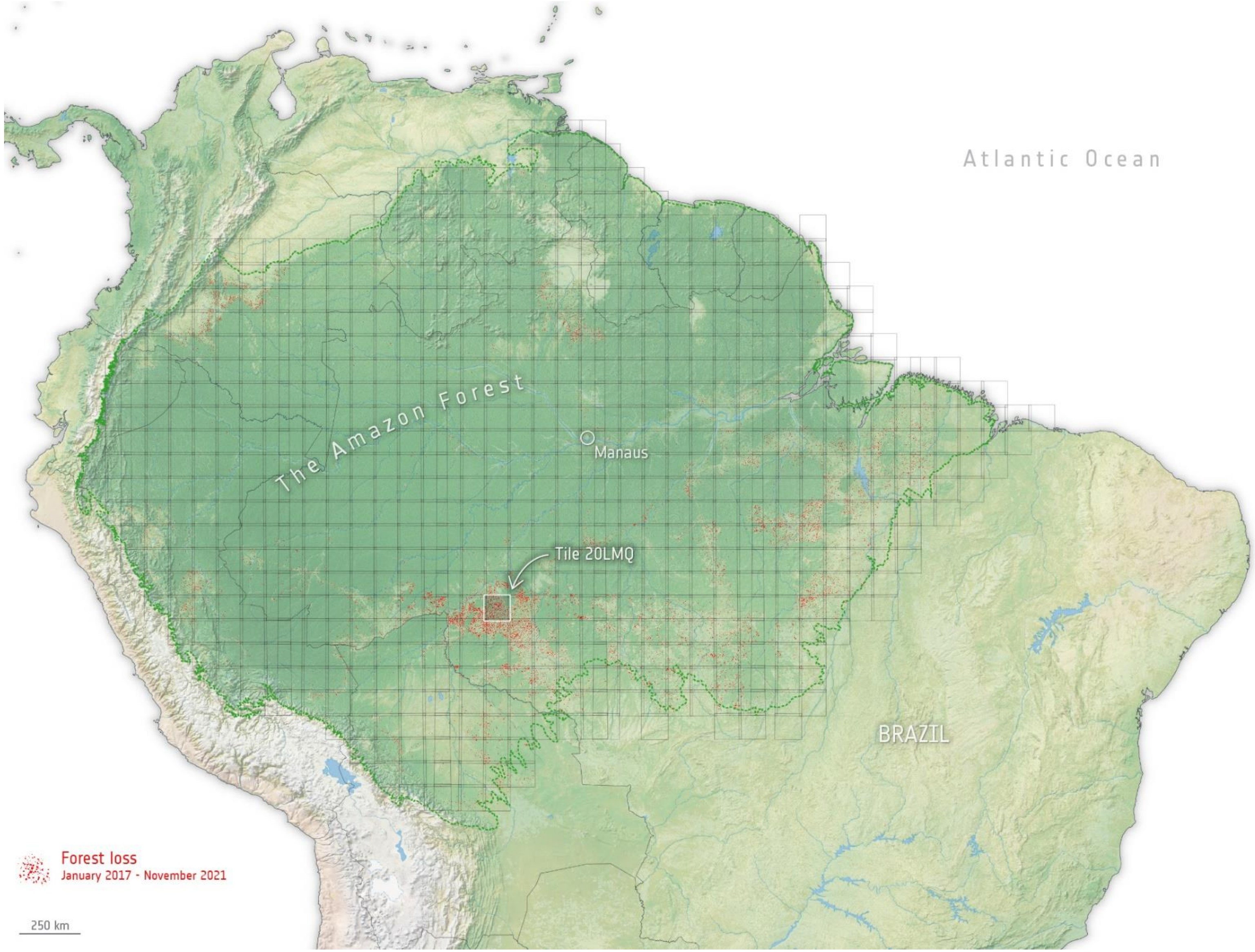
Sentinel-1B: launched the 22th April 2016
== > SAR data from September2016

Revisit time: 12 days
Revisit time: 12 days
6 days

- **High temporal frequency** of acquisition is necessary for seasonal variation of land surfaces
- Accessible now with **Sentinel-1** data at **local** scales

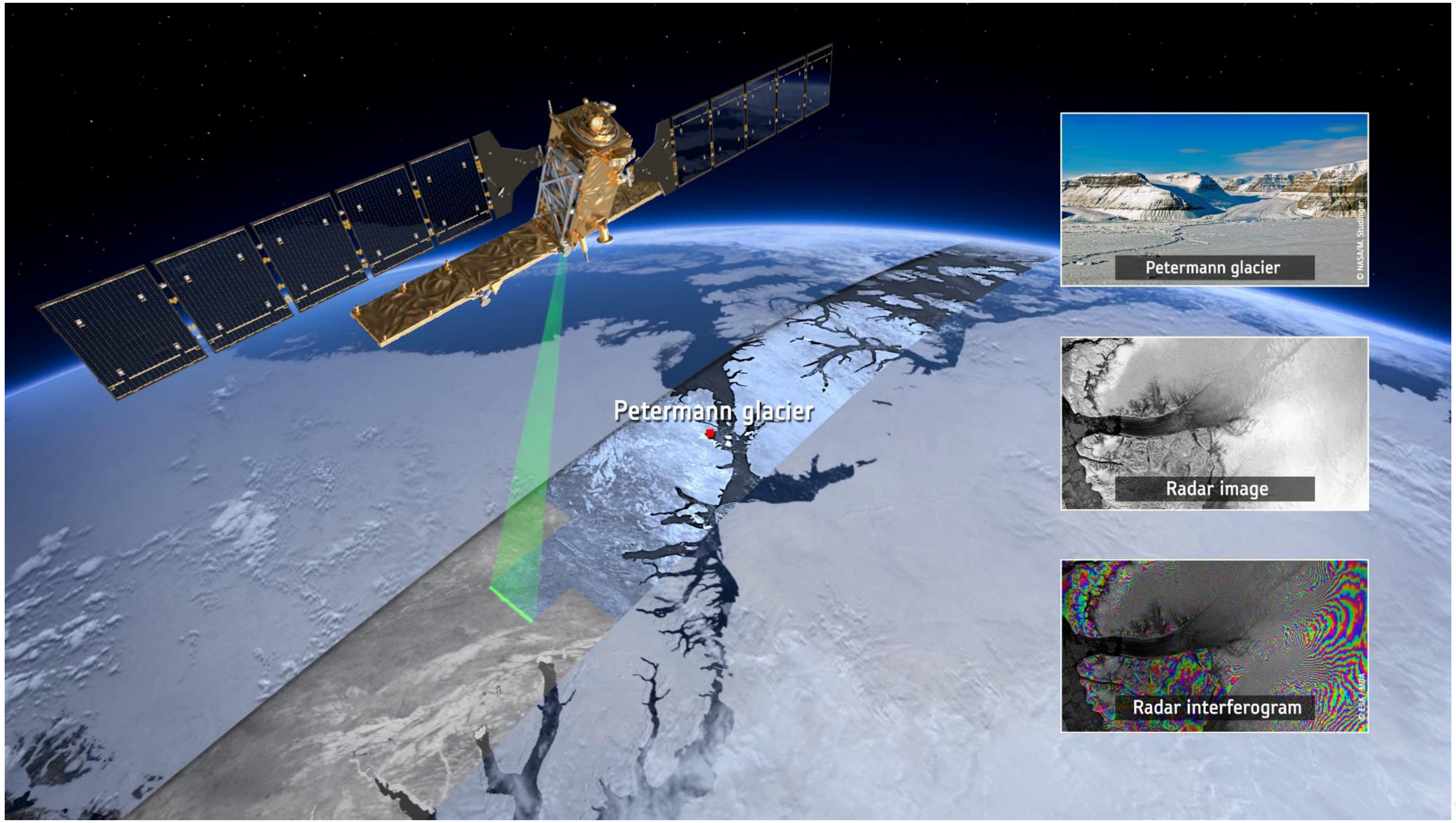
https://sentinels.copernicus.eu

Sentinel-1 - Forestry



Forest loss across the Amazon

Sentinel-1 – Topographic mapping

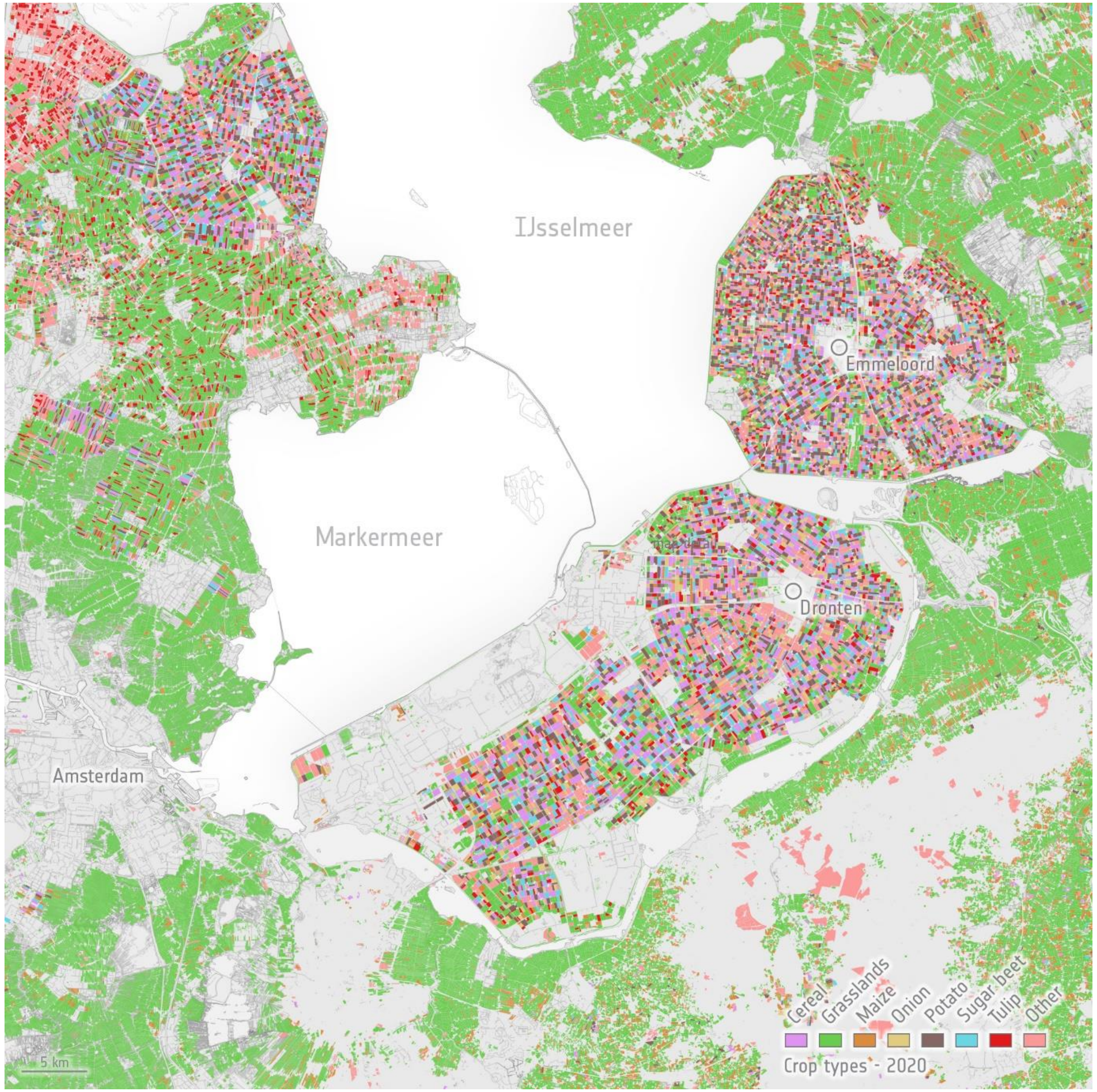


Sentinel-1 monitoring motion

Radar images from Sentinel-1 can be used to generate 3D models of Earth's surface and to closely monitor land and ice surface deformation. Synthetic aperture radar interferometry – or InSAR – is a technique where two or more satellite radar images acquired over the same area are combined to produce an interferogram. Small changes on the ground cause changes in the radar signal phase and lead to rainbow-coloured fringes in the interferogram. These products are important for mapping topography to produce 'digital elevation models' and to monitor surface deformation caused by, for example, mining, earthquakes, volcanic activity, melting permafrost and glacial flow.

Source: https://www.esa.int/ESA_Multimedia/Videos/2014/08/Sentinel1_monitoring_motion

Sentinel-1 - Crop monitoring

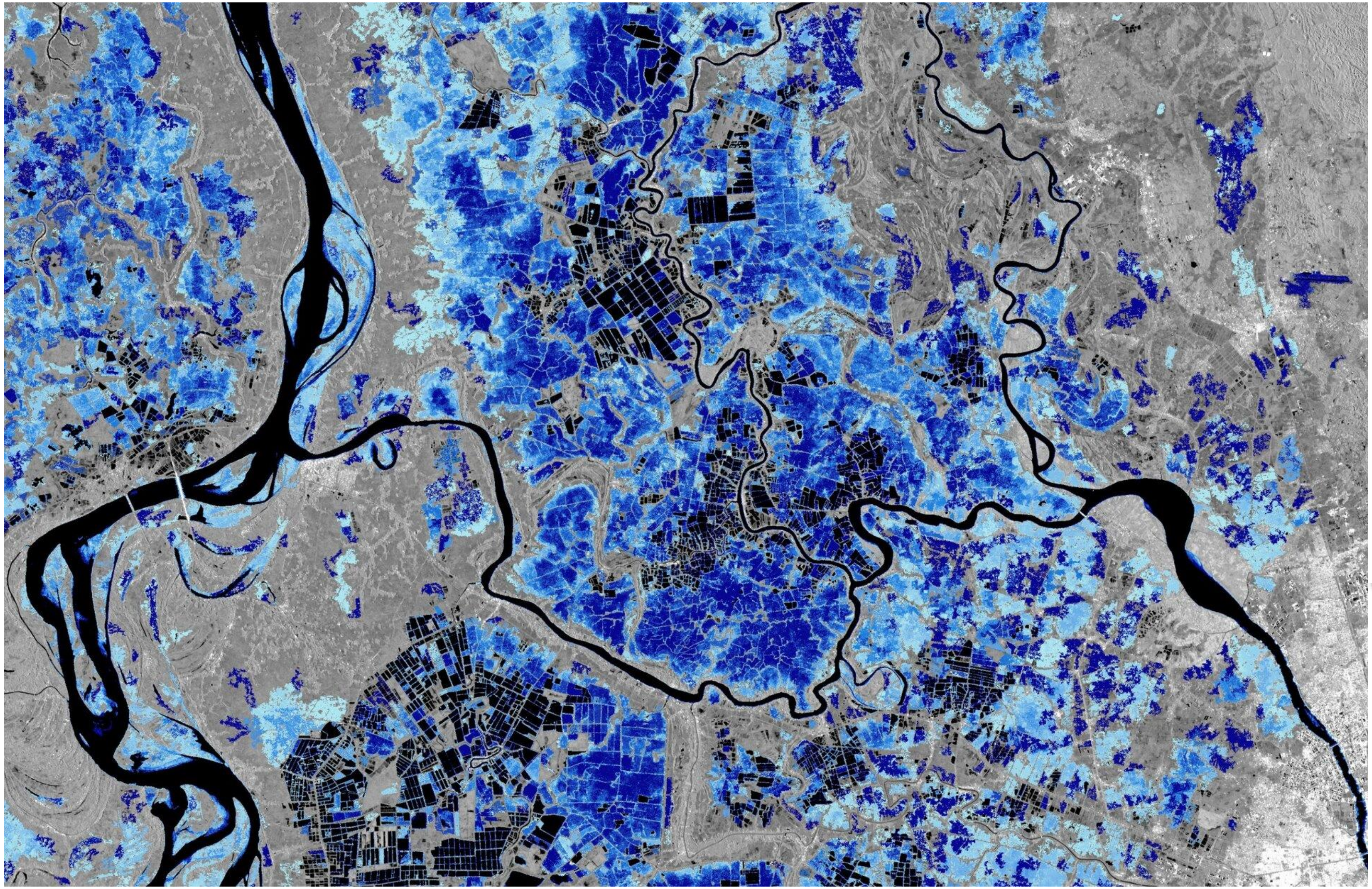


Crop type for all agricultural parcels Flevoland in the Netherlands

This figure zooms in on Flevoland in the Netherland to illustrate individual crop parcels. ESA worked with the Delft University of Technology in the Netherlands to develop Agricultural Sandbox NL, which makes use of radar data from Copernicus Sentinel-1 and optical, or camera-like, data from Copernicus Sentinel-2 and reduces terabytes of satellite data to just 10 gigabytes per year. Importantly, this dataset tool makes these data perfect for non-expert data users in the agriculture sector.

Source:https://www.esa.int/ESA_Multimedia/Images/2022/02/Crop_type_for_all_agricultural_parcels_Flevoland_in_the_Netherlands

Sentinel-1 – Flood mapping



Copernicus Sentinel-1 flood monitoring

Flood frequency mapping in Myanmar, using data from the Copernicus Sentinel-1 mission. Dark areas represent permanent water bodies or fields frequently or always covered by water, for example rice fields. Different shades of blue represent the flood occurrences frequency estimated from Copernicus Sentinel-1 data archive (light blue: less frequent; dark blue: more frequent).

Source:https://www.esa.int/Applicatios/Observing_the_Earth/Using_space_to_foster_development_assistance_for_disaster_resilience

For more information, see the tutorial: 2. SAR for Land Applications 1 – SAR basics for Land monitoring using SNAP software

esa space solutions

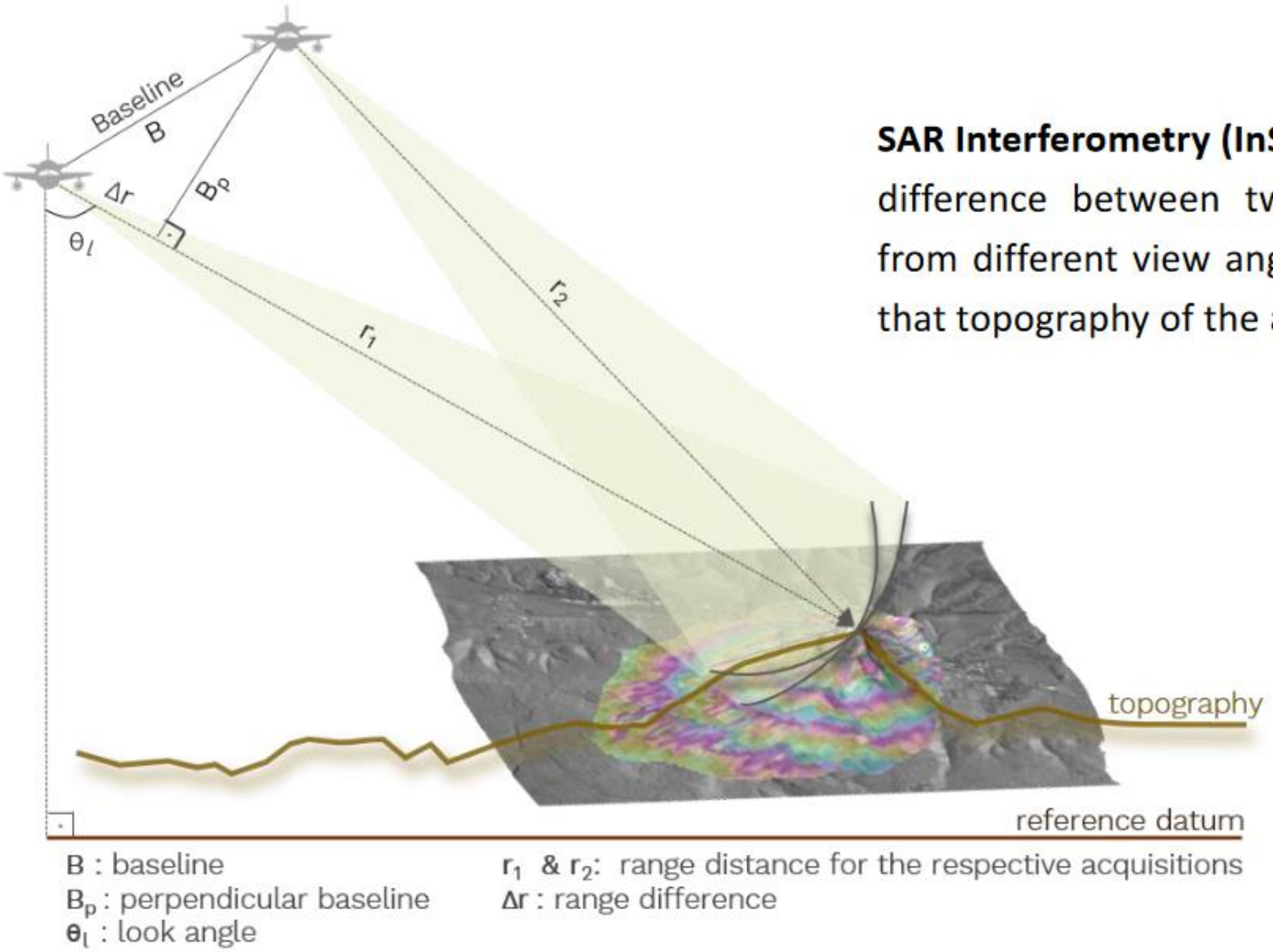
Copernicus Academy

ÚSTAV GEOGRAFIE
Prírodovedecká fakulta UPJŠ v Košiciach

3. SAR remote sensing for land applications 2 – Introduction to Interferometric SAR

Synthetic Aperture Radar Interferometry (InSAR)

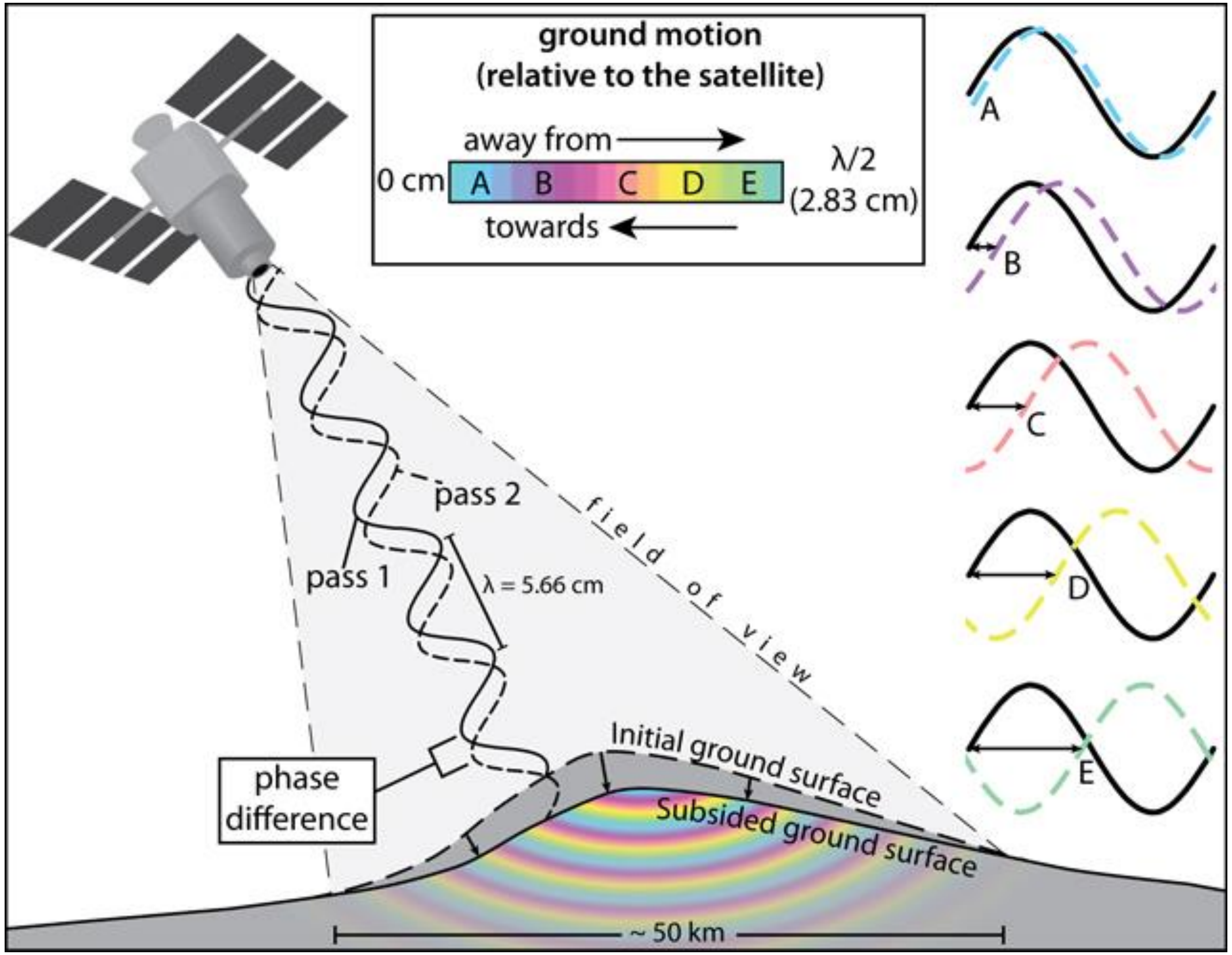
Determining elevation



SAR Interferometry (InSAR) makes use of the phase difference between two complex valued images from different view angle, i.e. forming baseline, so that topography of the area can be imaged.

Synthetic Aperture Radar Interferometry (InSAR)

Determining elevation

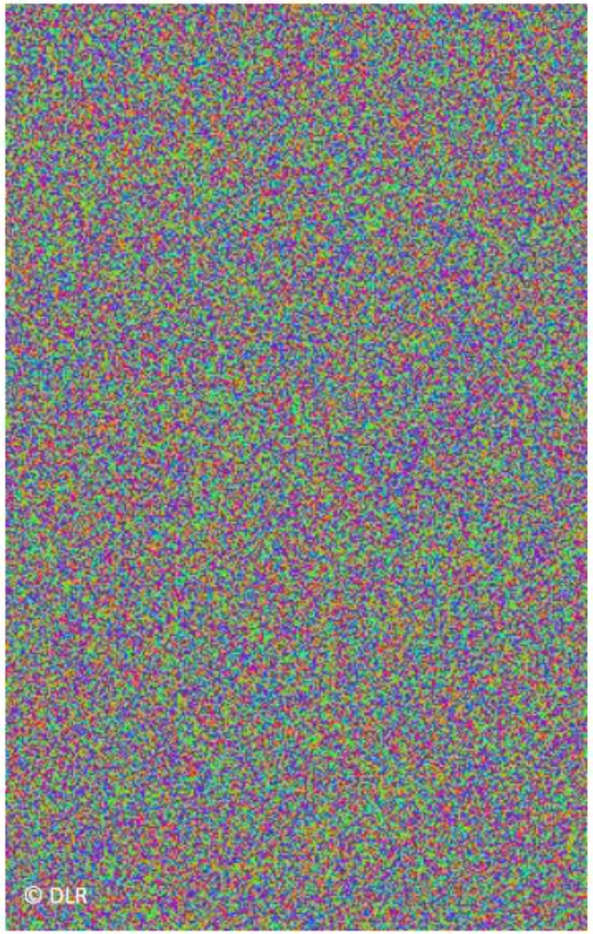


Synthetic Aperture Radar Interferometry (InSAR)

Amplitude and phase

A complex SAR image can be decomposed into …

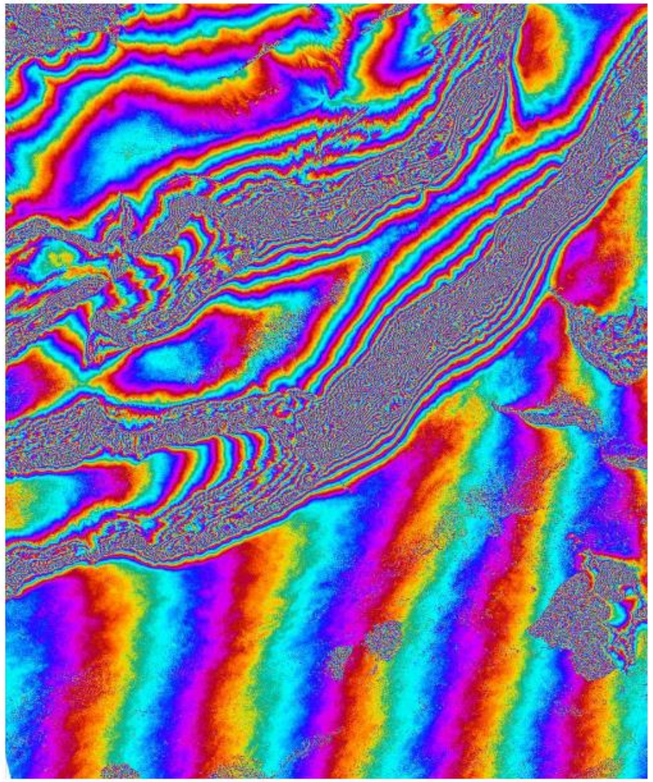
Amplitude & Phase

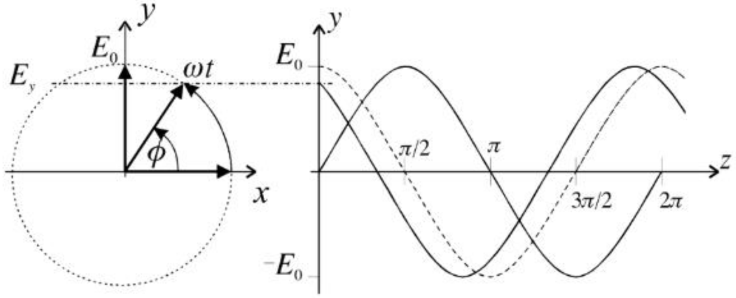


Synthetic Aperture Radar Interferometry (InSAR)

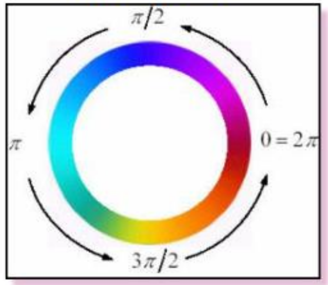
Phase to elevation (DEM)

Interferometric phase
Bachu, China
approx. 100 km × 80 km



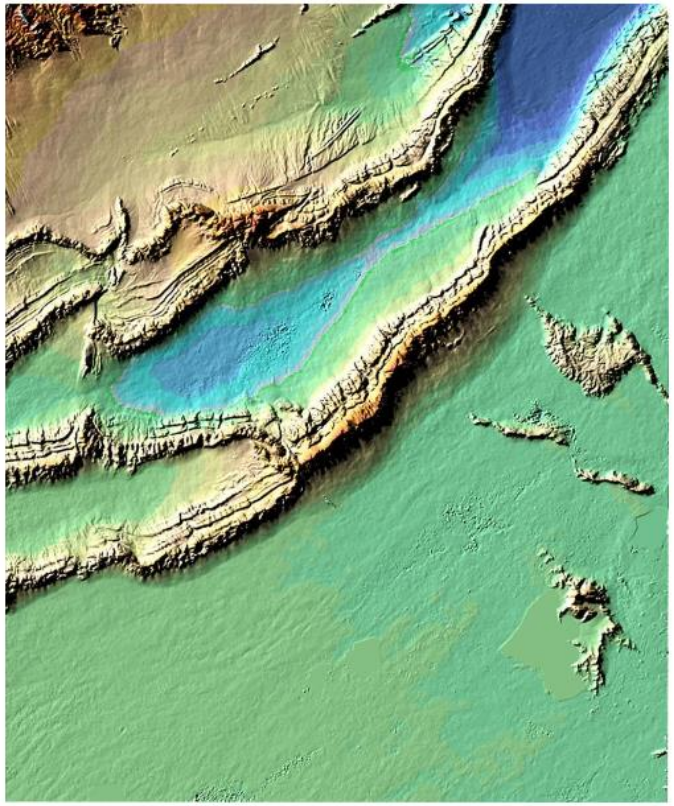


color wheel



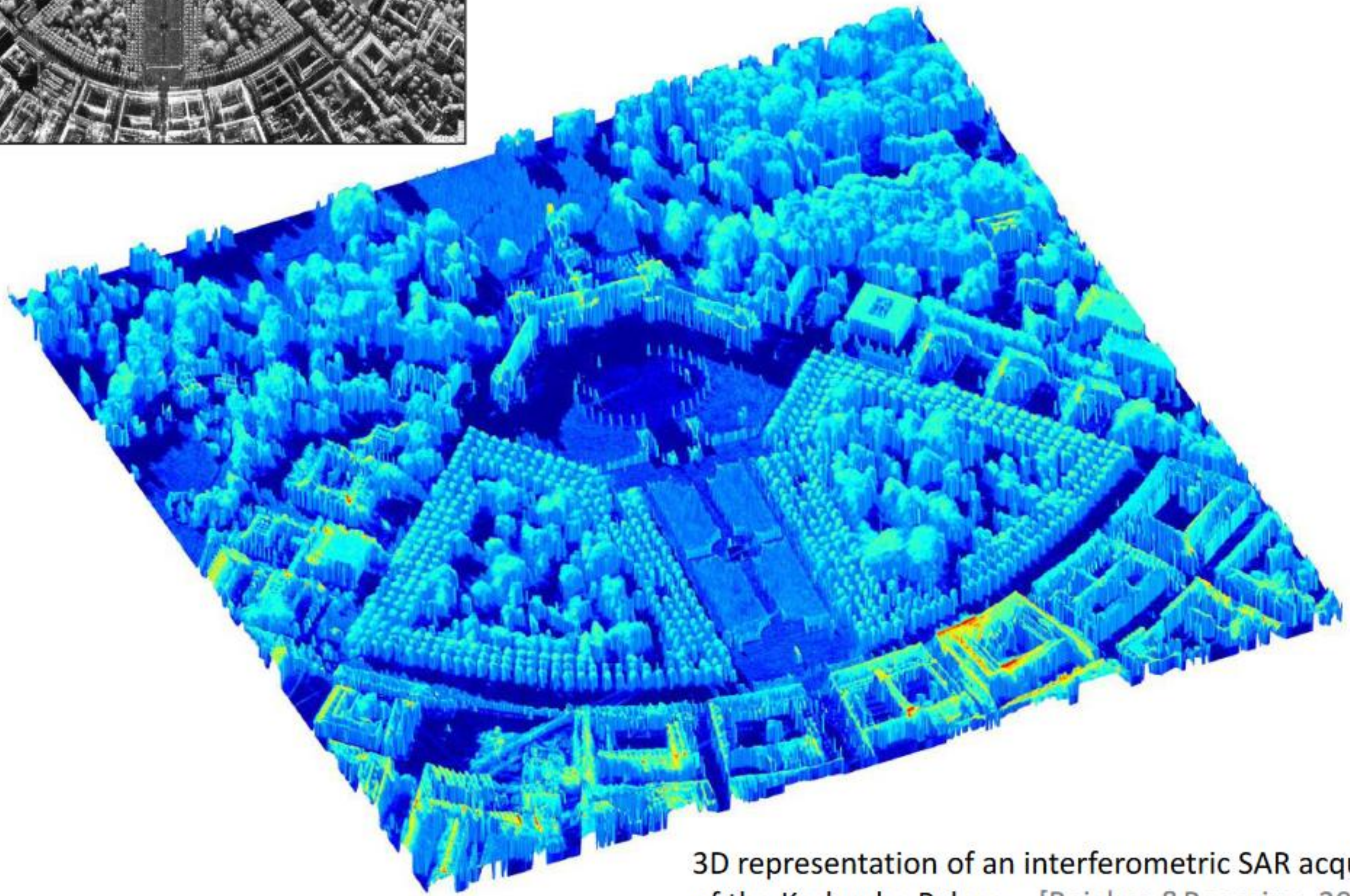
Phase is always ambiguous w.r.t. integer multiples of 2π
→ phase unwrapping required!

Final DEM



Synthetic Aperture Radar Interferometry (InSAR)

Trees acquired at superhigh resolution (X-band)



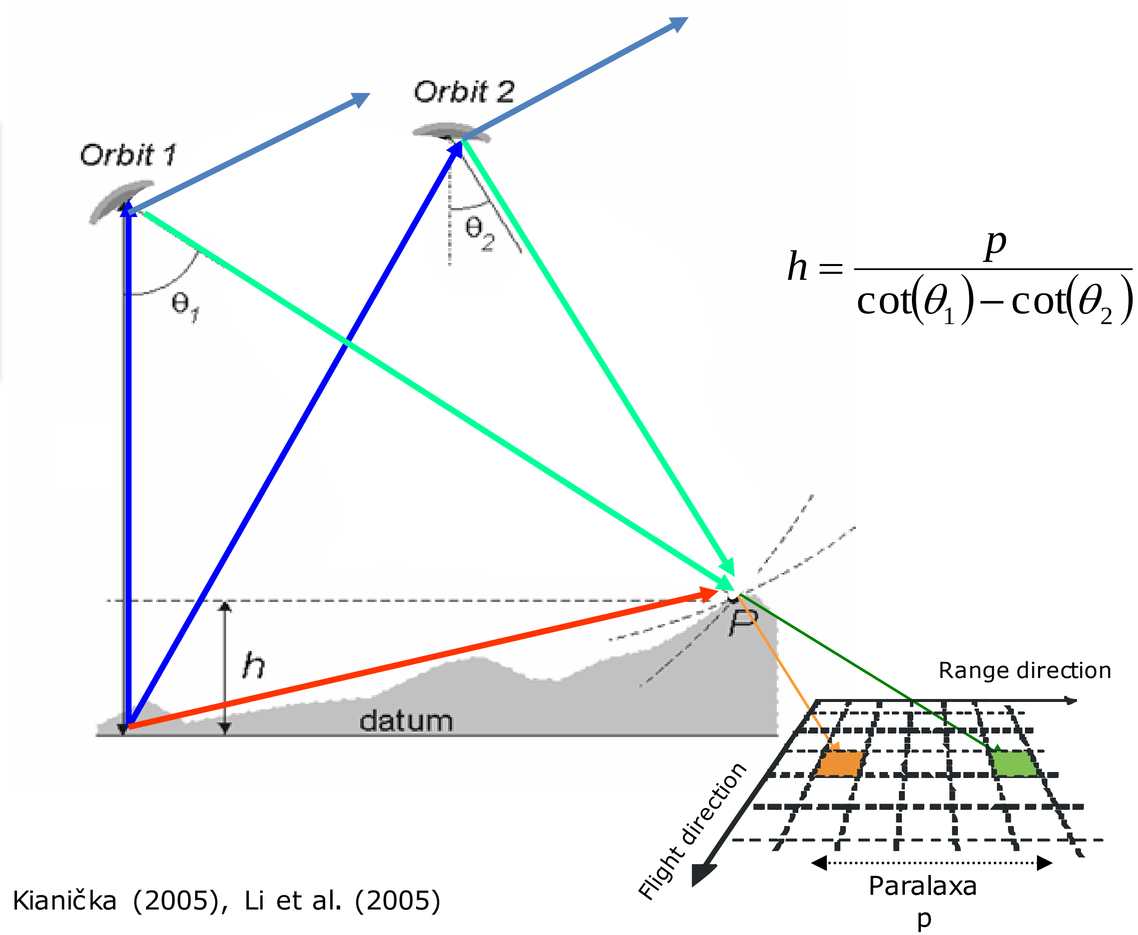
3D representation of an interferometric SAR acquisition of the Karlsruhe Palace [Reigber &Roessing, 2008]

Synthetic Aperture Radar Interferometry (InSAR)

Methods of image analysis

Radargrametry

The principle of **measuring the parallax** of point P using SAR stereo images.



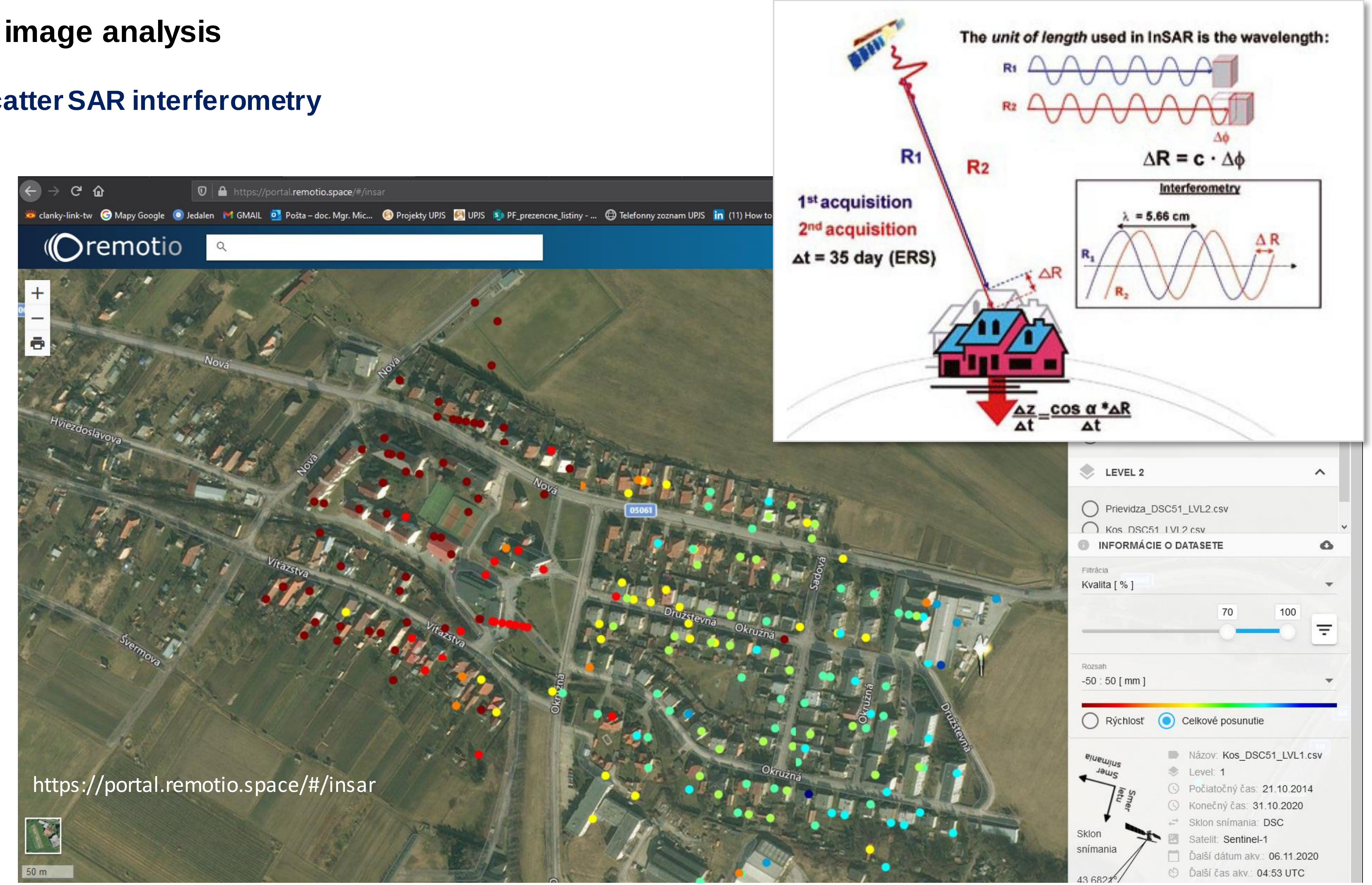
$$h = \frac{p}{\cot(\theta_1) - \cot(\theta_2)}$$

Kianička (2005), Li et al. (2005)

Synthetic Aperture Radar Interferometry (InSAR)

Methods of image analysis

Persistent scatter SAR interferometry

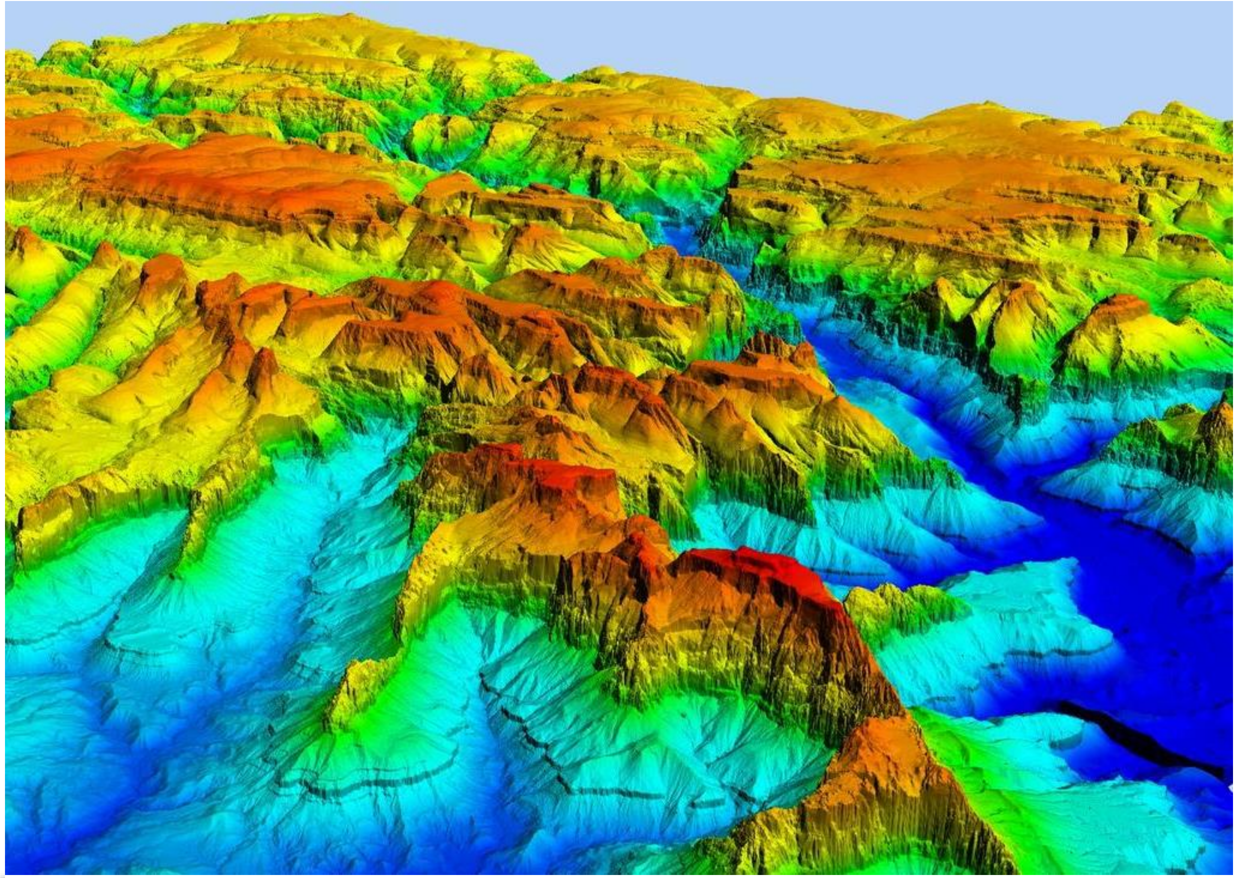


Persistent scatter SAR interferometry PSInSAR

- Measurement of movement on points with intense radar signal reflection does not involve using all pixels of the radar record, as in D-InSAR. Many pixels in D-InSAR may have unstable coherence of reflected radiation over time (reflectivity changes over time) due to variations in moisture and vegetation growth.
- Objects that consistently reflect microwaves well are found naturally (rock outcrops, rocky walls) or artificially (roofs, buildings, building corners, antennas, pipes).
- This method determines the phase change of waves due to slight movement of the signal reflector
- It enables the determination of surface deformation/object movement with millimeter precision.
- Compared to GNSS measurements, PSInSAR offers the advantage of monitoring a large number of points over a larger area at a lower cost.

InSAR for high-resolution DEM generation

- A Digital Elevation Model (DEM), also referred to as the Digital TerrainModel (DTM) is a digital model or three dimensional (3D) representation of the land surface elevation with respect to any reference datum.
- Technically a DEM contains only the elevation information of thesurface, free of vegetation, buildings and other non ground objects with reference to a datum such as Mean Sea Level (MSL).

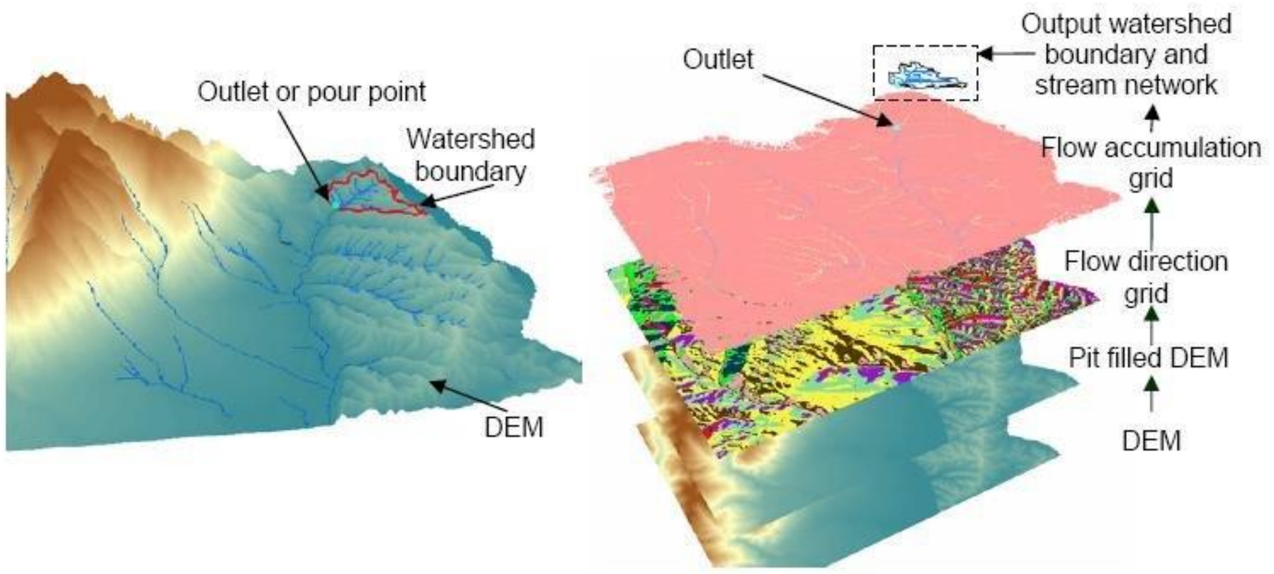


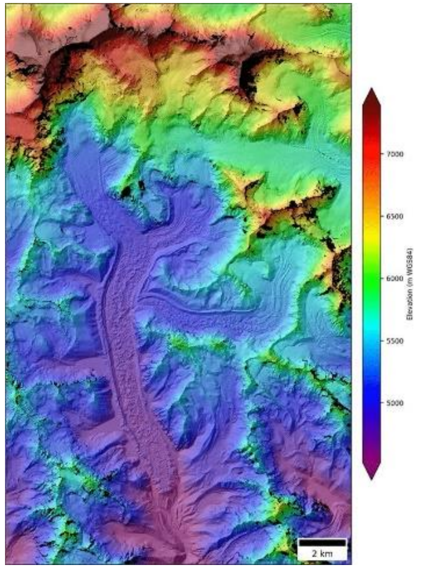
Source: https://www.surveyinggroup.com/dsm-dem-dtm-elevation-models-in-gis/

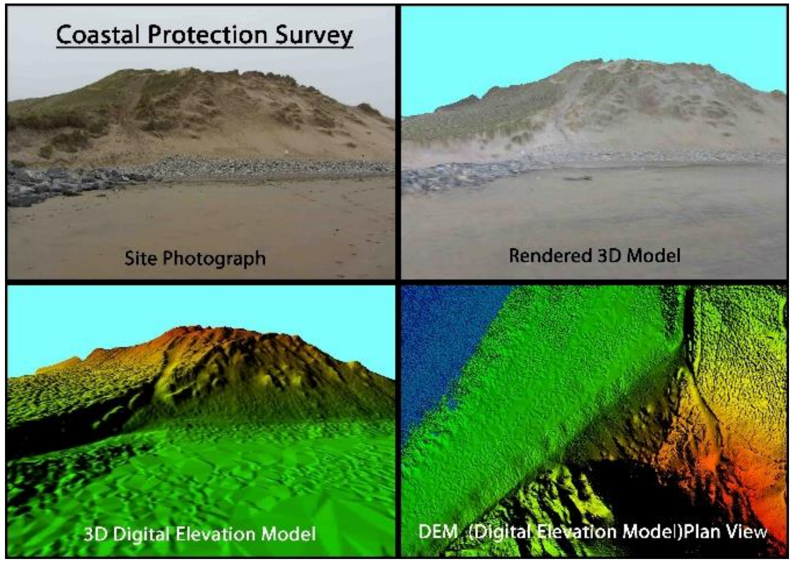
Use of DEM

Digital Elevation Models (DEMs) are used in many applications in the context of earth sciences:

- Topographic mapping
- Environmental modelling
- Rainfall-runoff studies
- Watershed management
- Coastal management
- Landslide hazard zonation
- Seismic source modelling
- etc. ...

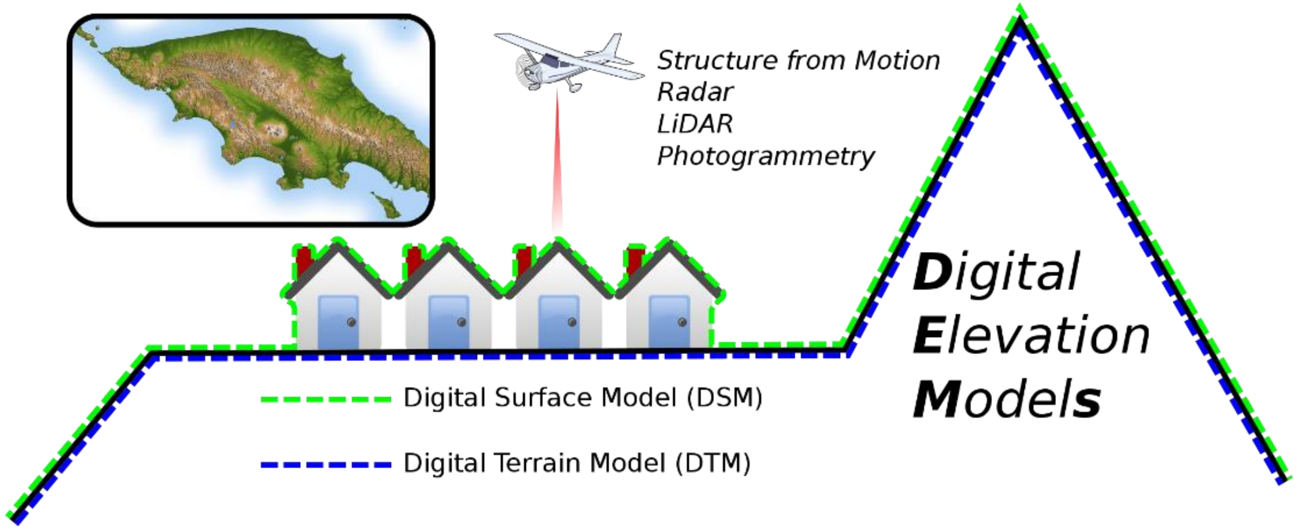






Types of DEM

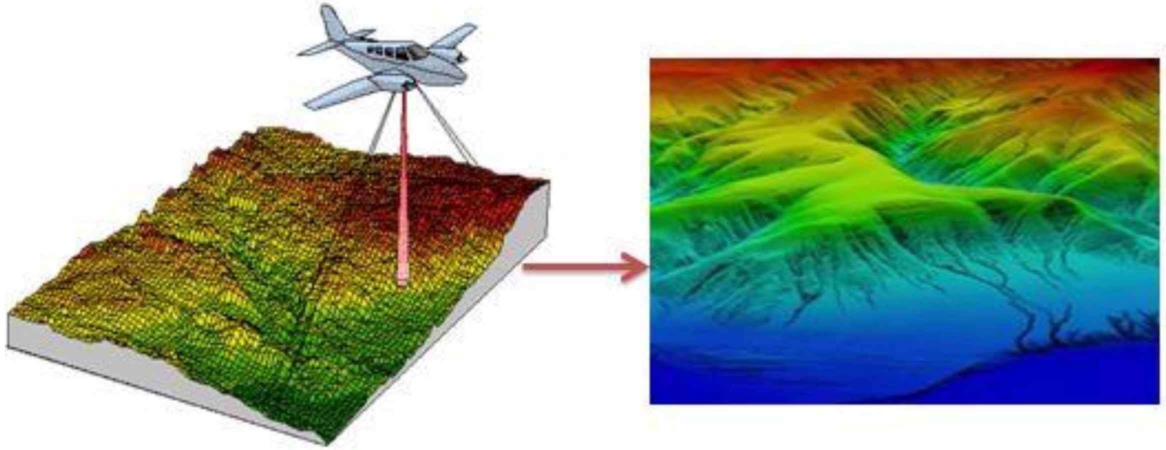
- **Digital Terrain Models (DTM)** - the height of the earth's surface in relation to otherpoints
- **Digital Elevation Models (DEM)** - the height of the earth's surface specifically in relation to a standard global/regional elevation (normally sea level).
- **Digital Surface Models (DSMs)** - the height of the surface including objects (buildings, vegetation, etc).



Source:https://commons.wikimedia.org/wiki/File:The_difference_between_Digital_Surface_Model_%28DSM%29_and_Digital_Terrain_Models_%28DTM%29_when_talking_about_Digital_Elevation_models_%28DEM%29.svg

DEM Retrieval

- DEMs are generated by using the elevation information from several points spaced at regular or irregular intervals.
- DEMs are commonly built using data collected using remote sensing techniques such as SAR, photogrammetry and LIDAR, but they may also be built from land surveying.

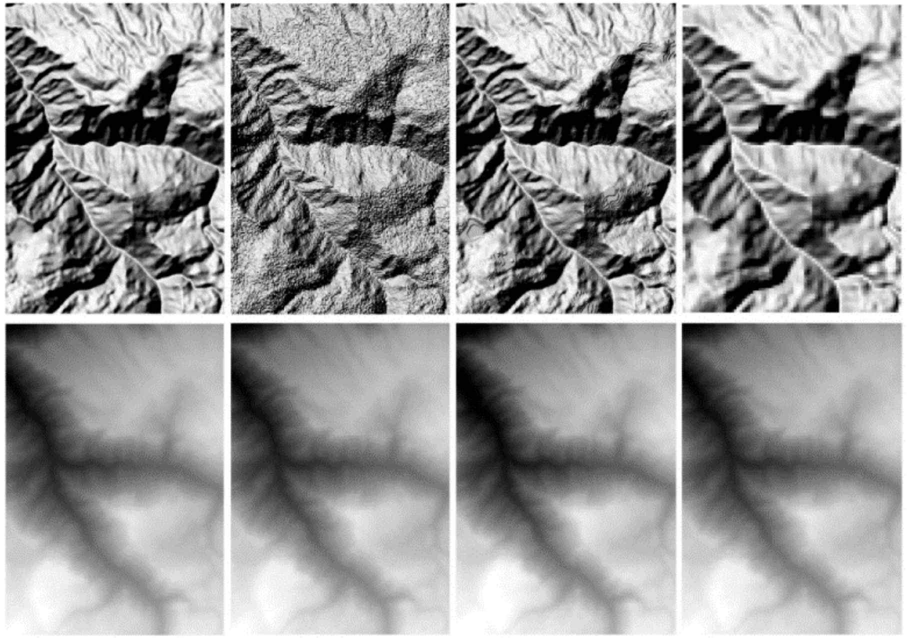


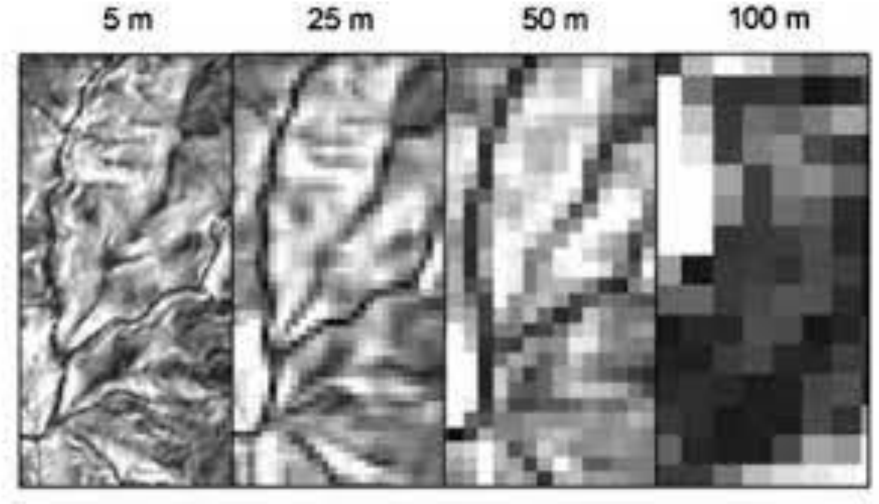
DEM Quality

The quality of a DEM is a measure of how accurate elevation is at each pixel (absolute accuracy) and how accurately is the morphology presented (relative accuracy).

Several factors play an important role for quality of DEM-derived products:

- terrain roughness
- sampling density
- grid resolution or pixel size
- Interpolation algorithm
- vertical resolution
- terrain analysis algorithm
- reference 3D products include quality masks that give information on the coastline, snow, etc.





Free DEM data sources

1. Space Shuttle Radar Topography Mission (SRTM)

- 1-arc second global digital elevation model with a spatial resolution of about 30 meters covering most of the world with absolute vertical height accuracy of less than 16m
- SRTM DEM data is being howsed on the USGS EarthExplorer server

2. ASTER Global Digital Elevation Modal

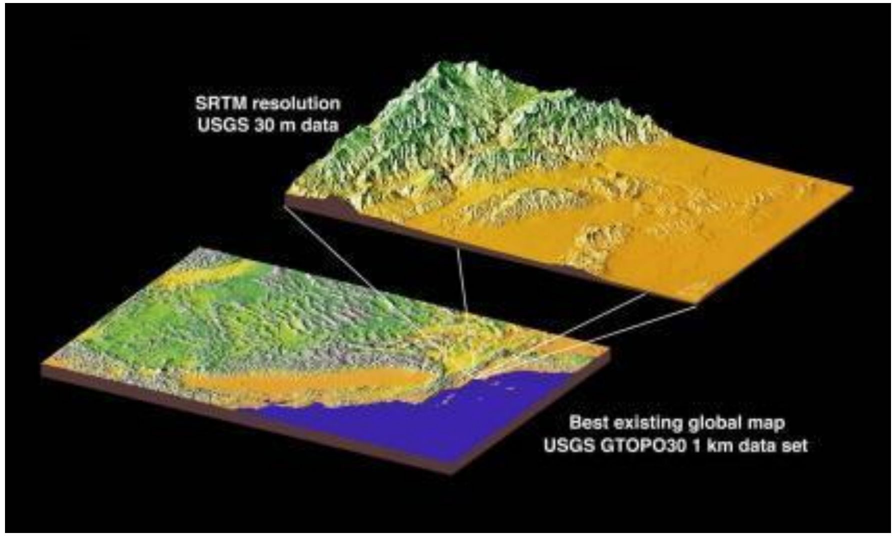
- A joint operation between NASA and Japan was the birth of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
- ASTER GDEM boasted a global resolution of 90 meters with a resolution of 30 meters in the United States
- You can download the ASTER DEM data for free from the USGS EarthExplorer

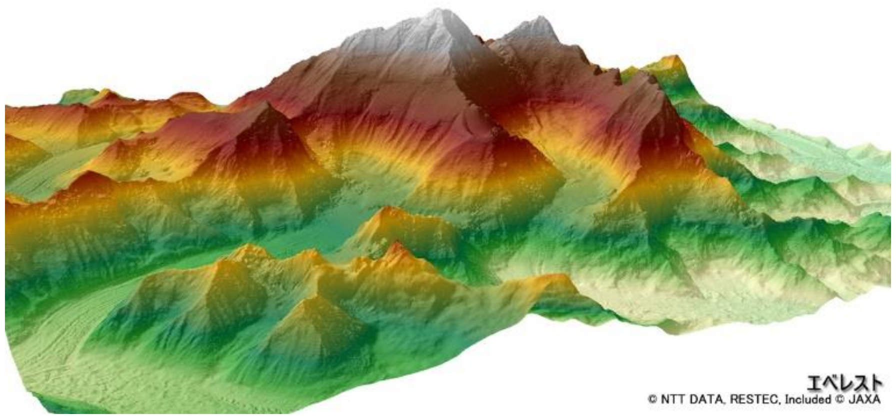
3. JAXA's Global ALOS 3D World

- 30-meter spatial resolution digital surface model (DSM) constructed by the Japan Aerospace Exploration Agency's (JAXA)
- The most precise global-scale elevation data at this time using the Advanced Land Observing Satellite “DAICHI" (ALOS)
- The DSM was generated using stereo mapping (PRISM) for worldwide topographic data with its optical stereoscopic observation
- In order to obtain this highly accurate DSM, you have to register online through the “JAXA Global ALOS portal”

4. Indian Portal Bhuvan

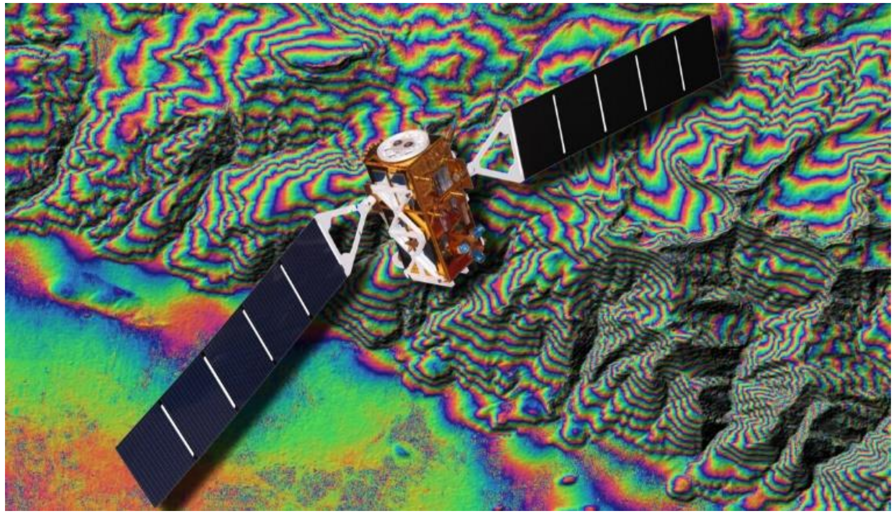
- CARTOSAT 1 and 2 derived stereo DEM, available for entire India freely

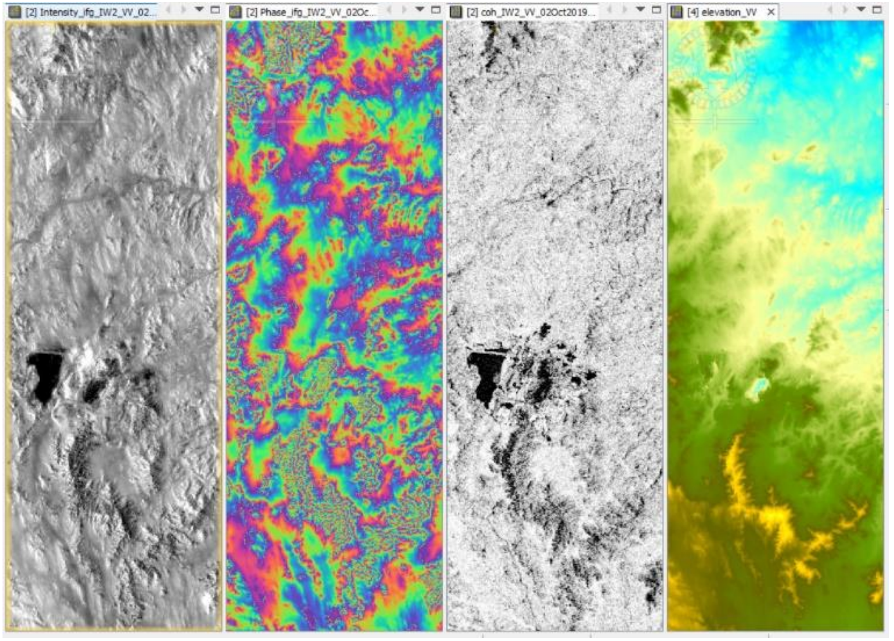




Retrieval of DEM using Sentinel-1 radar data

- The launch of Sentinel-1 by the European Space Agency (ESA) in 2014 marked the beginning of a new era in openly available radar data under the Copernicus Programme.
- This C-band radar mission, comprising Sentinel-1A (S1A) and Sentinel-1B (S1B), provides data at a spatial resolution of 5 × 20 m (single look complex).
- While primarily designed for differential radar interferometry (DInSAR) to measure surface deformations, its capability to derive Digital Elevation Models (DEMs) is limited. Despite this, studies on absolute elevations or object heights are scarce and often associated with exaggerated expectations.

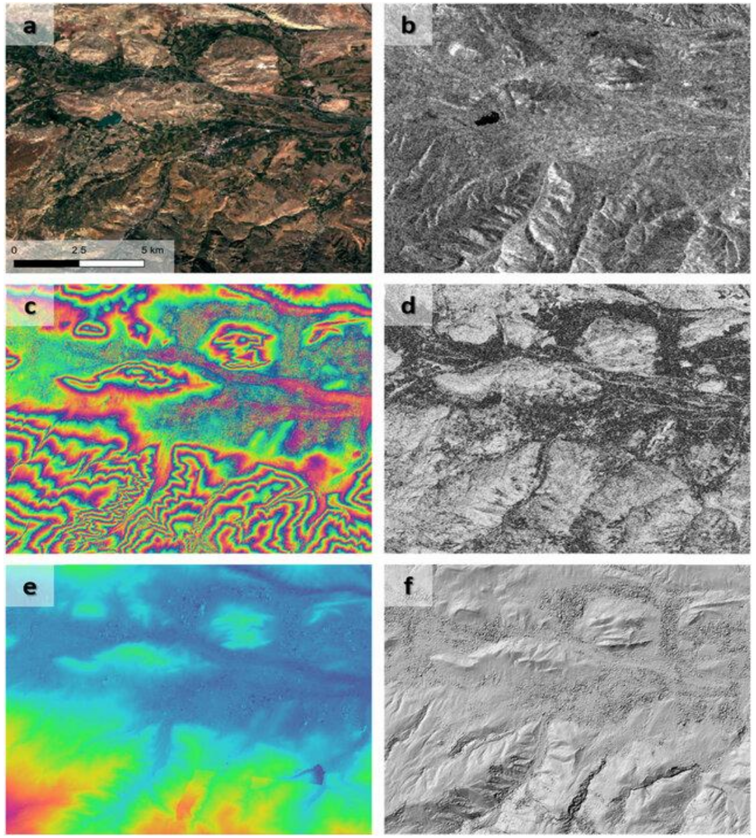




Create a DEM using Sentinel-1 radar data

This steps allow the user to create a DEM product from two Sentinel-1 SLC scenes:

- Data Pre-processing
- Coregistration
- Interferogram Formation and Coherence Estimation
- Visualize Interferometric Phase — TOPS Deburst
- Multi-looking and Phase Filtering
- Phase unwrapping and import
- Create the DEM – Convert Phase to Elevation
- Geocode the DEM



Steps of DEM generation with Sentinel-1: (a) Sentinel 2 image from 02.07.2019 (for visual reference), (b) Sentinel-1 image from 02.07.2019, (c) interferogram from 26.06.19 and 02.07.2019, (d) coherence image, (e) unwrapped interferogram, and (f) hillshade of the derived DEM.

Create a DEM using Sentinel-1 radar data

Preparation

Choosing appropriate image pairs is essential for successful DEM generation. Key considerations include:

1. **Minimizing Temporal Decorrelation:** Select image pairs with a short temporal baseline to reduce the risk of phase decorrelation. Longer time gaps between acquisitions can lead to out-of-phase signals, particularly over vegetation, water, or areas with changing moisture conditions.

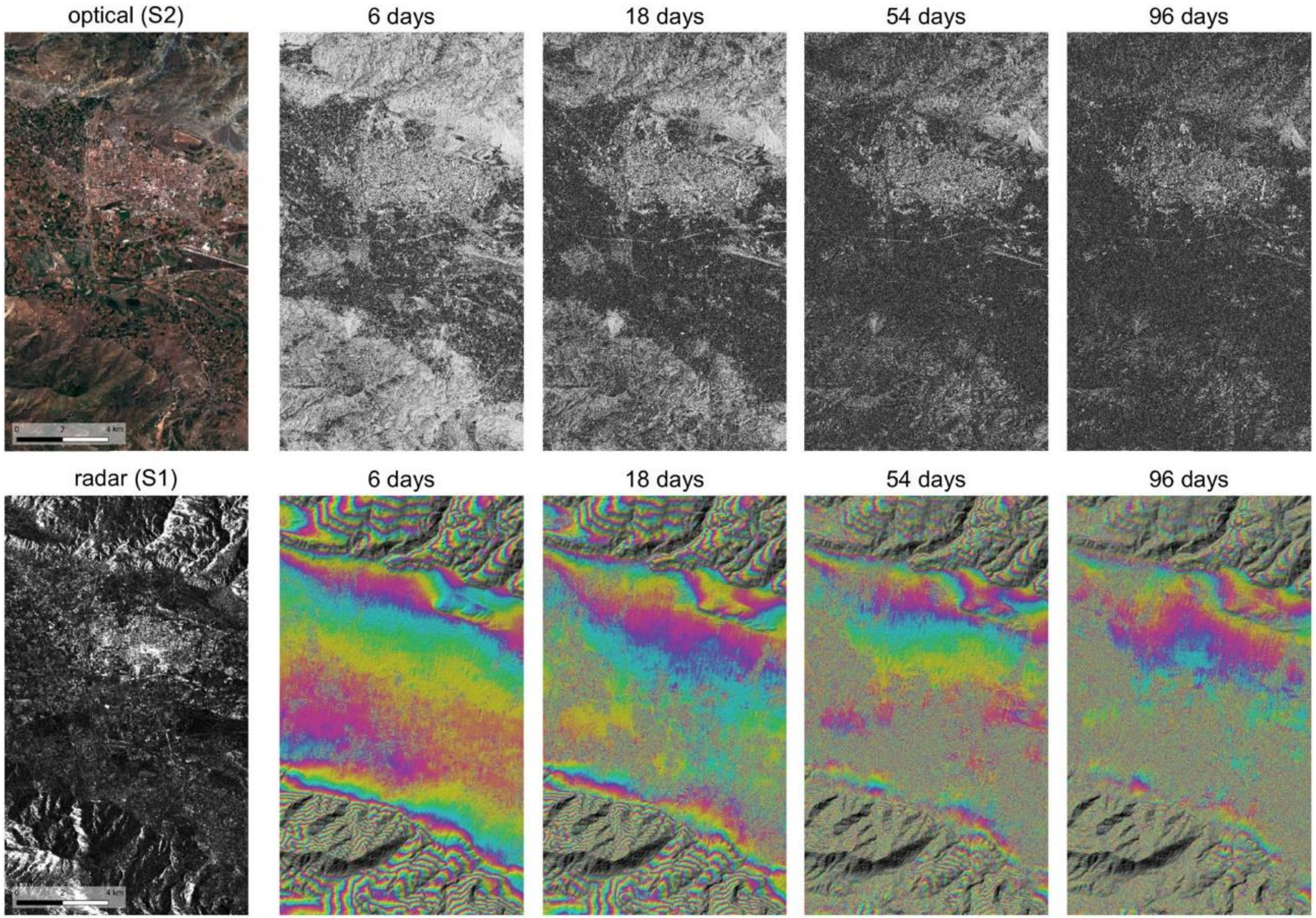
2. **Optimal Perpendicular Baseline:** The distance between satellite positions during image acquisition should ideally be between 150 and 300 meters. This ensures sufficient angle between acquisitions, allowing for the retrieval of topographic variations through parallax-like effects.

3. **Considerations for Sentinel-1:** Sentinel-1 was primarily designed for deformation retrieval (DInSAR) rather than DEM generation, resulting in predominantly short baselines, often below 30 meters. Finding image pairs with short temporal baselines and large perpendicular baselines can be challenging.

4. **Monitoring Atmospheric Conditions:** Select images acquired during dry periods to minimize phase delays caused by atmospheric water vapor. Avoid selecting images acquired during rainfall events, as they may decrease measurement quality.

Create a DEM using Sentinel-1 radar data

Preparation



Coherence (top) and interferograms (bottom) for selected temporal baselines. For reasons of visualization, the interferograms are combined with a hillshade representation retrieved from the SRTM data.

Create a DEM using Sentinel-1 radar data

Coregistration

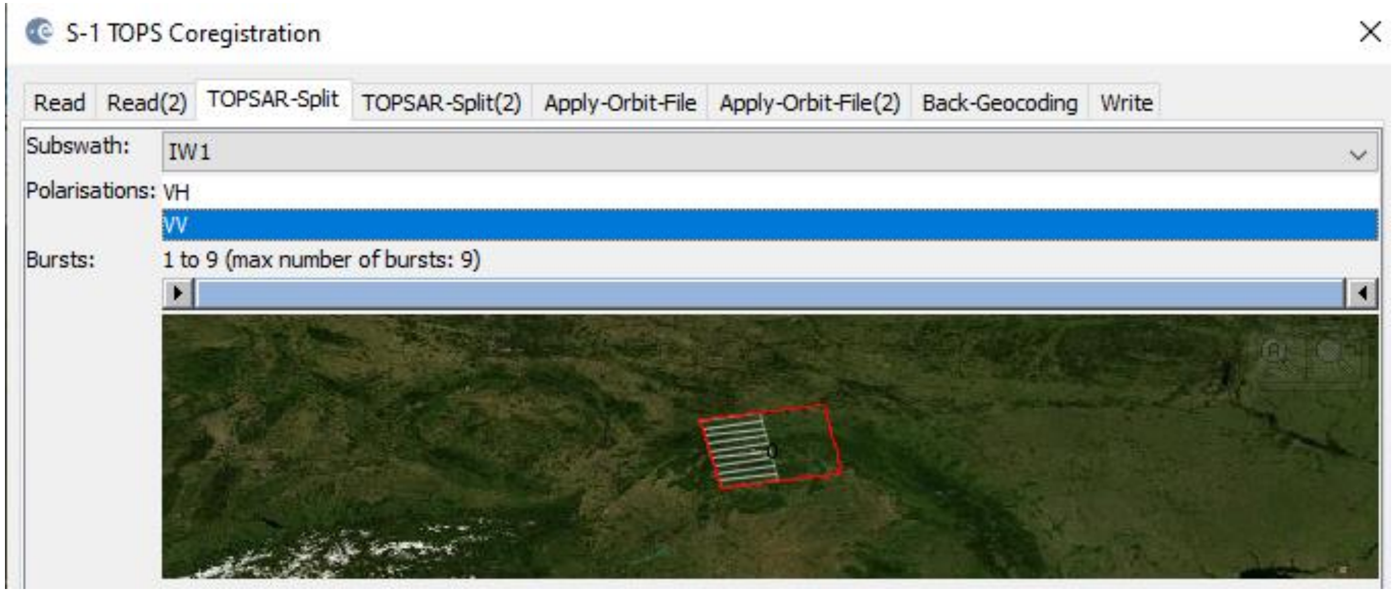
In order to utilize the phase difference between the acquisitions, it is necessary to first create a stack containing both products. Coregistration involves aligning both products with sub-pixel accuracy using image statistics.

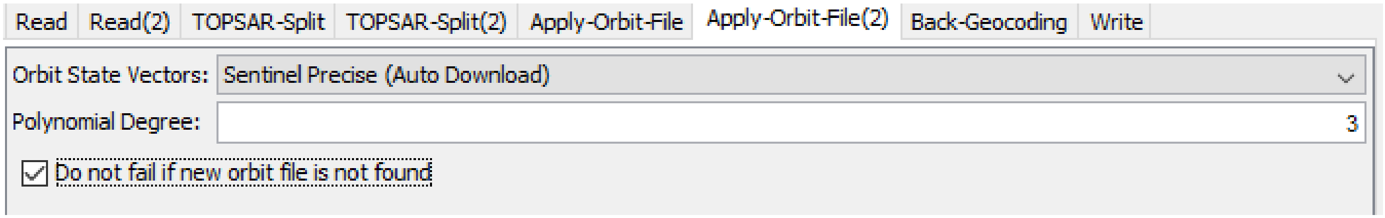
TOPS Split

The S-1 TOPS Split function is utilized to filter and select specific bursts required for analysis.

Applying Orbit Information

Orbit auxiliary data comprises details regarding the satellite's position at the time of data acquisition. SNAP automatically incorporates it into the metadata using the Apply Orbit File operator.





Create a DEM using Sentinel-1 radar data

Coregistration

Back Geocoding and Enhanced Spectral Diversity

- The S-1 Back Geocoding operator, aligns the two split products utilizing orbit details included in the preceding step and data from a digital elevation model (DEM) obtained through SNAP.

- To enhance the coregistration quality, the S-1 Enhanced Spectal Diversity (ESD) operator is utilized. It implements range and azimuth shift corrections to the secondary image.

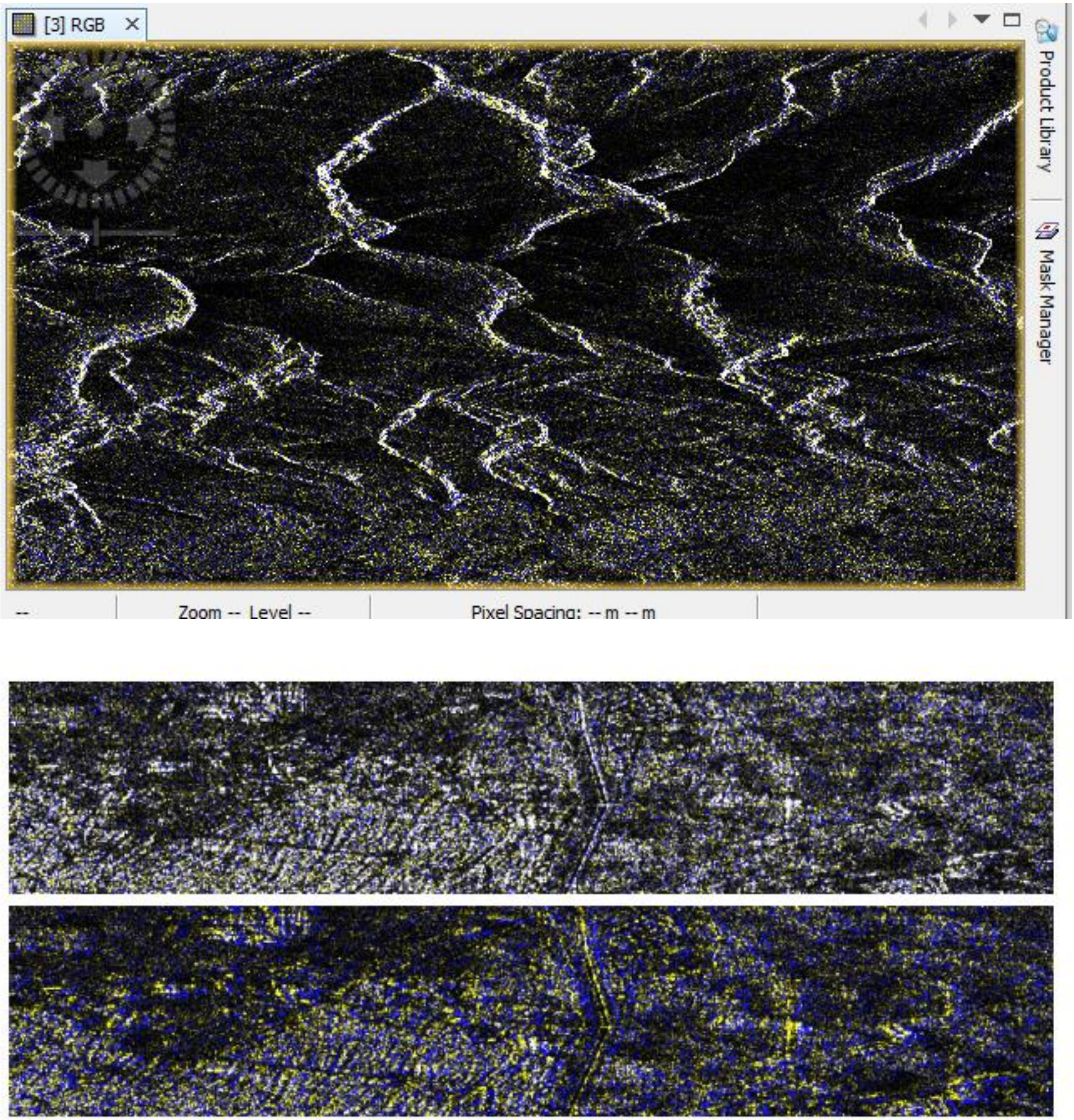


Figure 15: Successful (top) vs. failed (bottom) coregistration in an RGB image

Create a DEM using Sentinel-1 radar data

Forming an Interferogram

Forming a raw interferogram

An interferogram is created by multiplying the reference image by the complex conjugate of the secondary image. The amplitude of both images is multiplied, while the phase indicates the phase difference between them. The interferometric phase of each SAR image pixel is determined solely by the variance in travel paths from the two SARs to the resolution cell being considered. Thus, the resulting interferogram displays phase fluctuations.

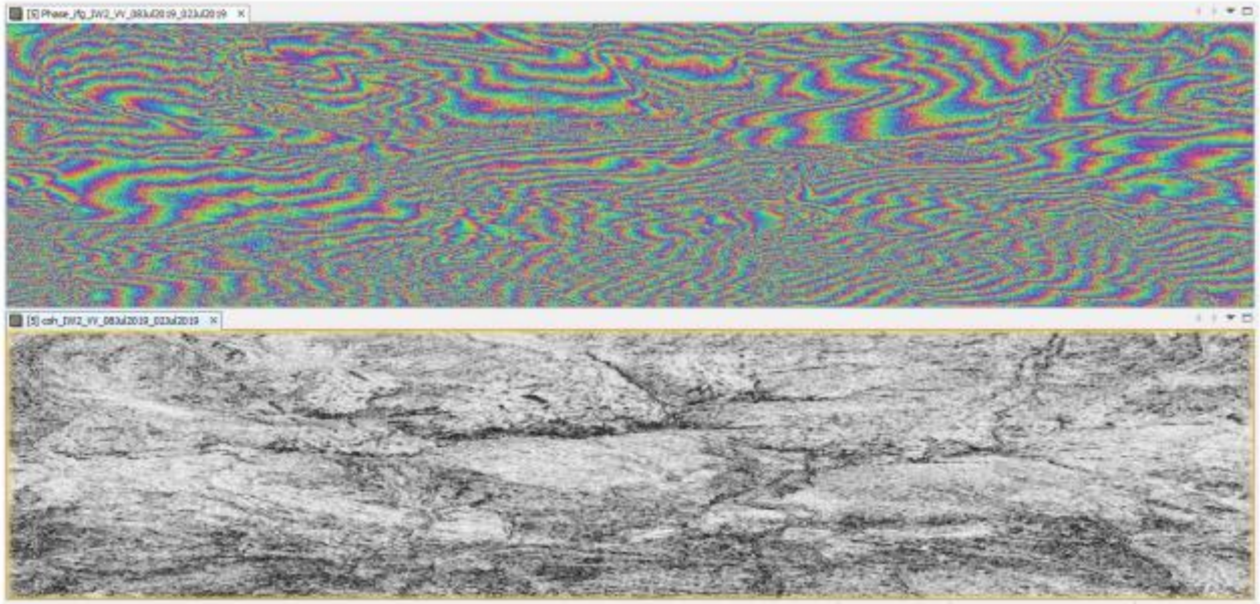


Figure 18: Interferogram (top) and coherence (bottom)

Create a DEM using Sentinel-1 radar data

Tops Debursting

The next stage in interferometry using Sentinel-1 TOPS mode (IWS) data involves "debursting" or merging the bursts to remove the seamlines, a step not required with Sentinel-1 or other stripmap SAR data.

Goldstein Phase Filtering

Interferometric phase can be corrupted by various sources - noise from temporal and geometric decorrelation, volume scattering, processing errors, etc. However, the quality of fringes present in the interferogram can be improved by employing specialized phase filters like the Goldstein filter. This filter utilizes Fast Fourier Transformation (FFT) to enhance the signal-to-noise ratio of the image.

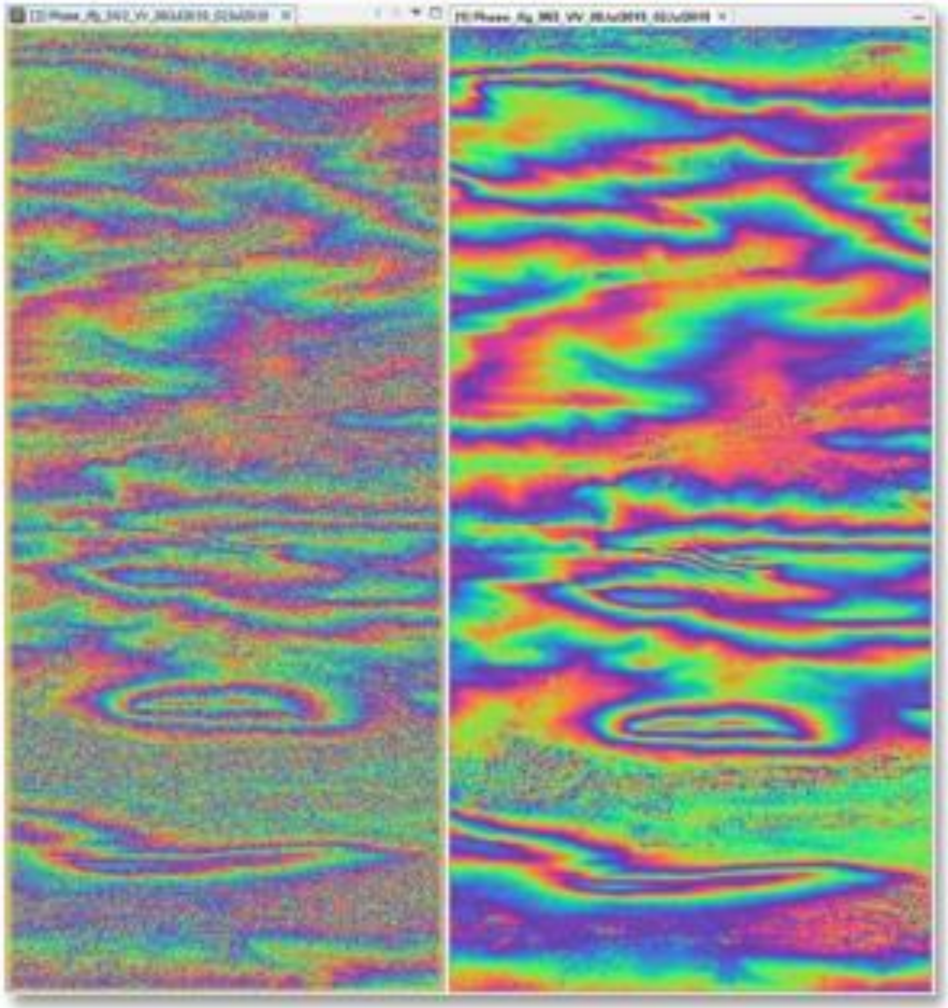


Figure 21: Interferogram before (left) and after (right) Goldstein phase filtering

Create a DEM using Sentinel-1 radar data

Create subset

In the earlier stages of processing, empty pixels along the interferogram's perimeter may have been created, particularly in regions not overlapped by both input images. To remove these sections, employ the Subset function found under Raster. This approach will also decrease processing time in subsequent stages, especially when the analysis is concentrated on a specific area rather than the entire scene.

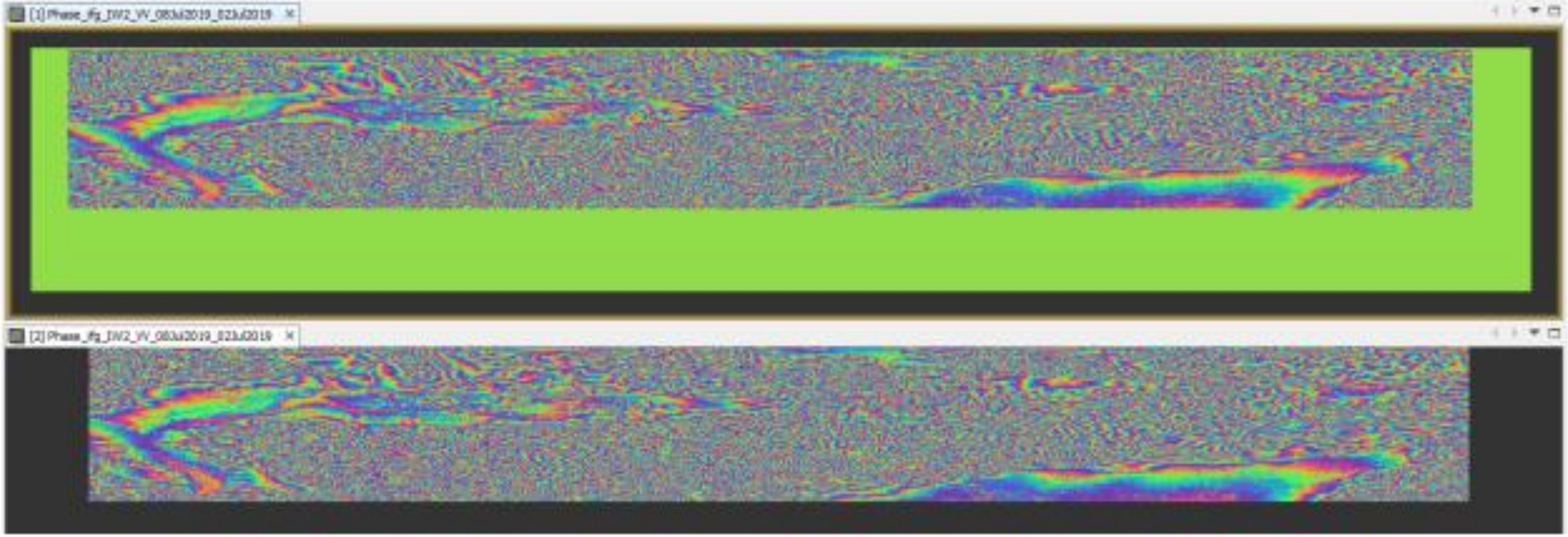


Figure 23: Interferogram before (top) and after (bottom) creating the subset

Create a DEM using Sentinel-1 radar data

Phase unwrapping

- In order to correlate the interferometric phase with topographic height, the phase must undergo an unwrapping process.
- The altitude of ambiguity refers to the altitude difference that causes a change in the interferometric phase
- Phase unwrapping resolves this ambiguity by integrating the phase difference between adjacent pixels
- Once unwrapped, the phase variation between two points on the flattened interferogram provides a measurement of the actual altitude variation
- Consequently, unwrapped results should be interpreted as relative height or displacement between pixels in two images.

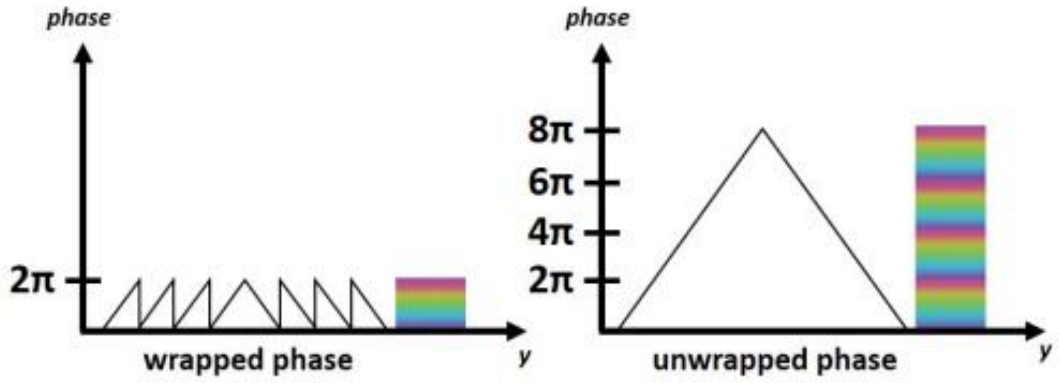


Figure 24: Principle of phase unwrapping

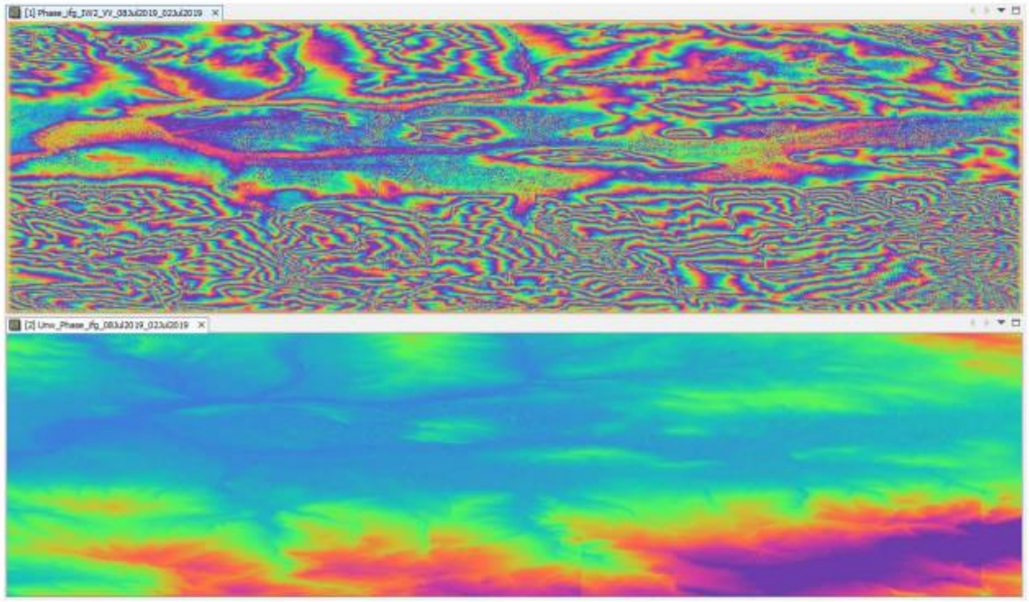
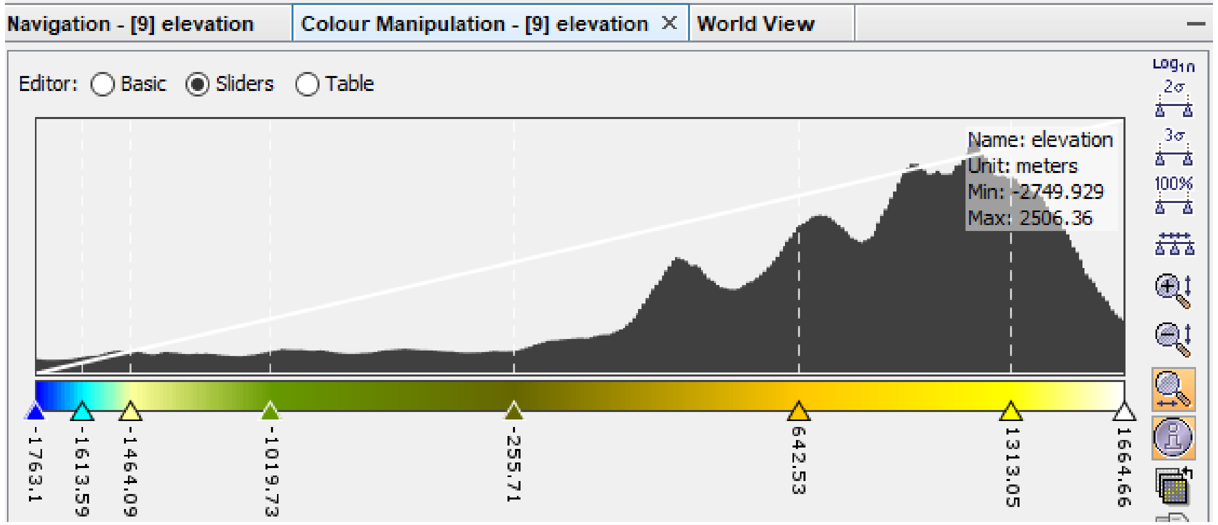


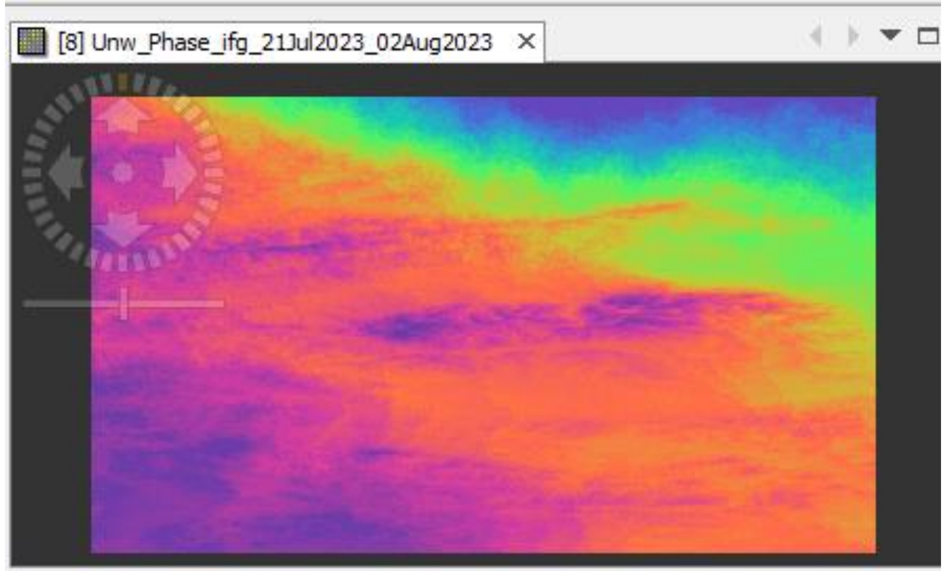
Figure 28: Phase before (top) and after (bottom) unwrapping

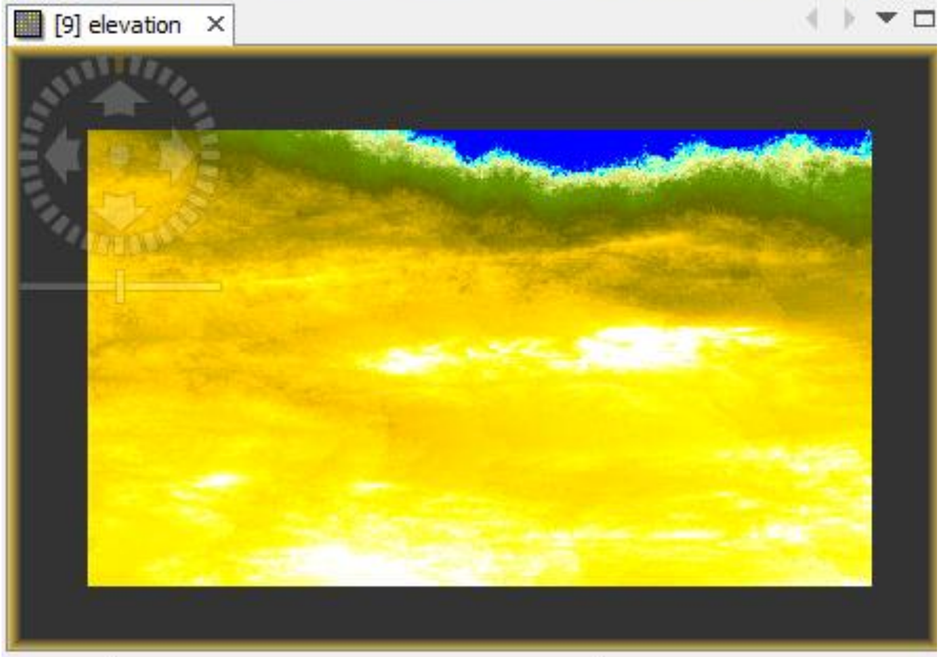
Create a DEM using Sentinel-1 radar data

Phase to elevation

- The unwrapped phase data is now a continuous raster that has to be converted into a metric measure - to achieve this conversion from radian units to absolute heights is employed
- This operation translates the phase values into surface elevations along the line-of-sight (LOS) in meters. To ensure accuracy, a Digital Elevation Model (DEM) is utilized to align the elevation values correctly.







Create a DEM using Sentinel-1 radar data

Terrain correction

- Involves geocoding the image by rectifying SAR geometric distortions, such as foreshortening, layover, and shadow, with the aid of a digital elevation model (DEM), resulting in a map-projected product

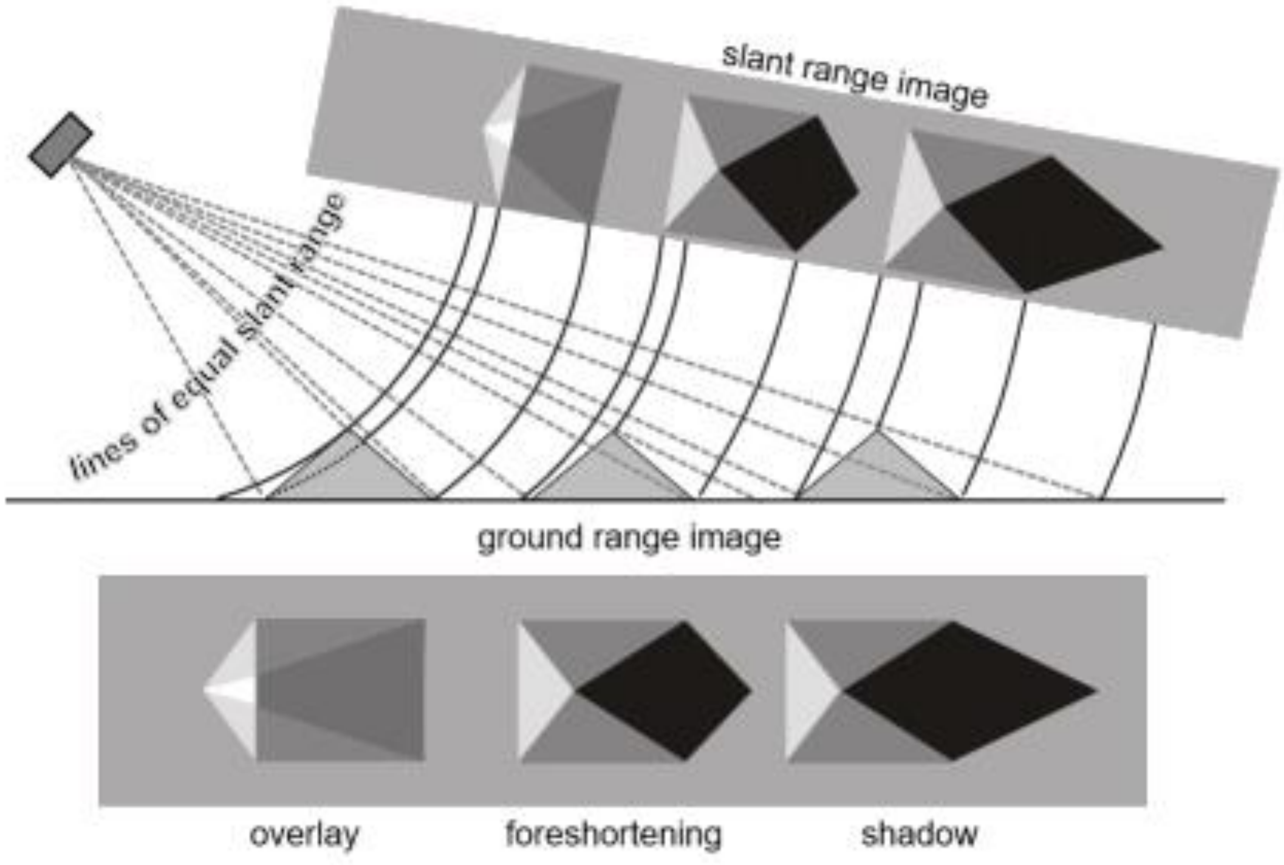
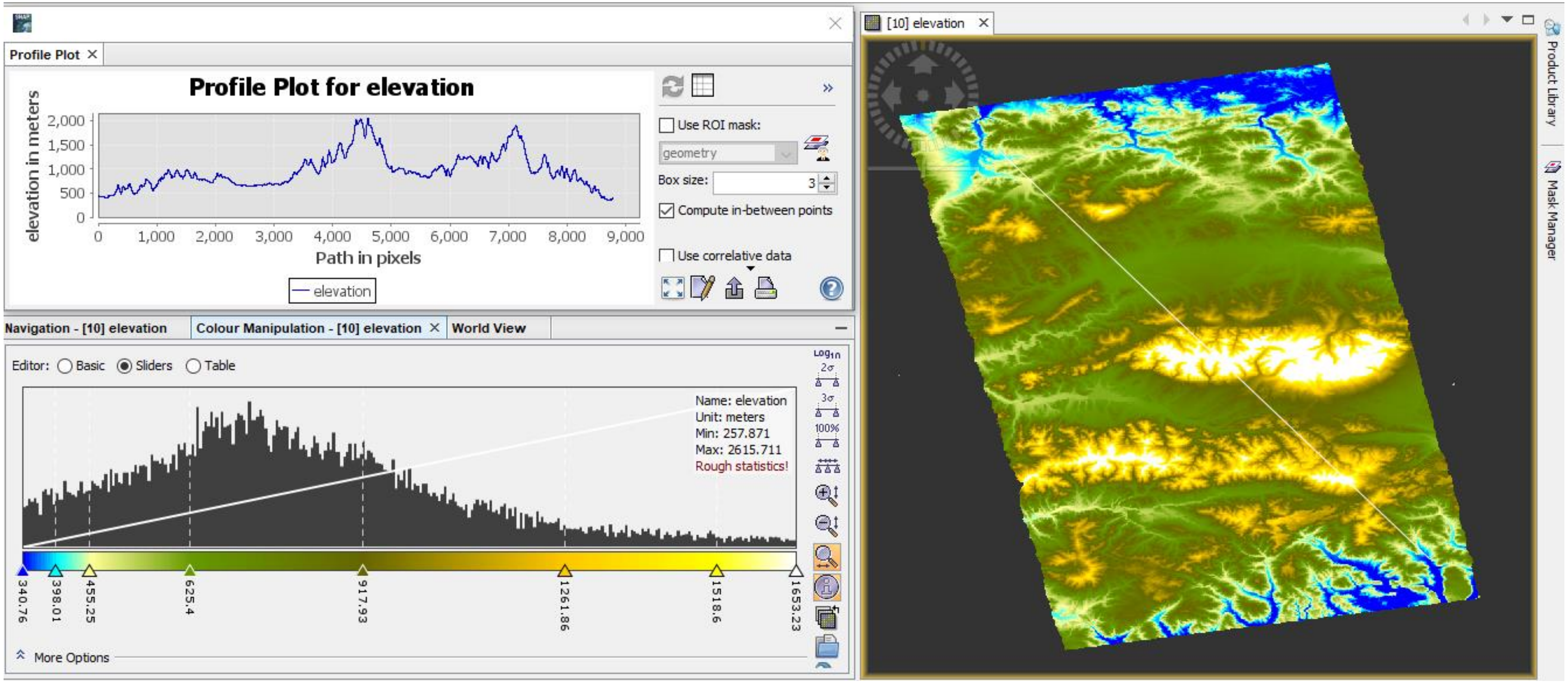


Figure 33: Geometric distortions in radar images (Braun 2019)

Create a DEM using Sentinel-1 radar data

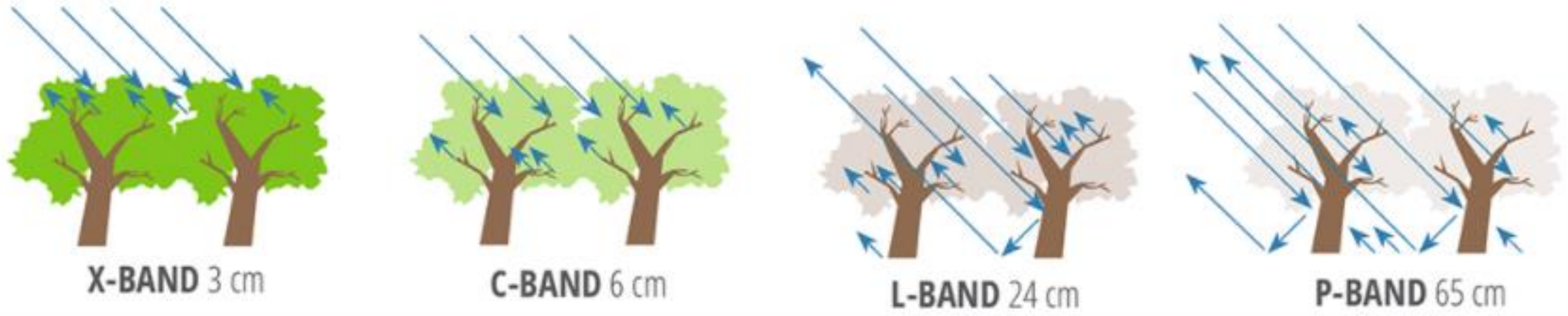
Final DEM

- A digital elevation model (DEM) that can be exported to other GIS softwares



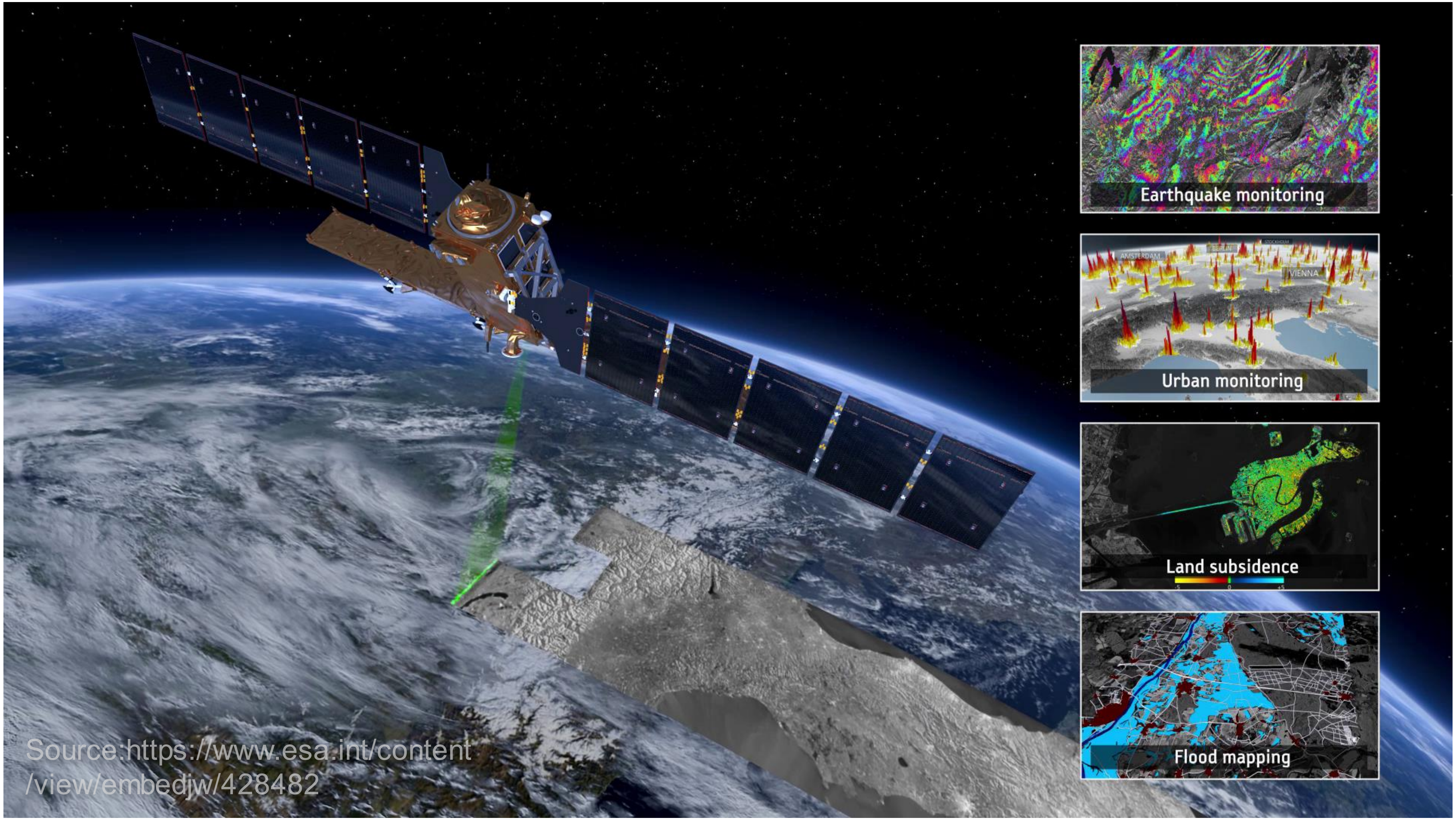
Tradeoffs of DEMs created with Sentinel-1 C-band

- Unfortunately, the C-band used by Sentinel-1 doesn't penetrate through vegetation. Consequently, DEMs derived from C-band radar don't directly measure the Earth's surface but instead depict the top of the canopy. However, Sentinel-1 offers excellent temporal coverage, resulting in lower temporal decorrelation compared to previous sensors.
- L-band radar exhibits higher coherence compared to C-band radar due to less decorrelation from vegetation. Consequently, creating accurate DEMs from Sentinel-1's C-band radar is more challenging than from ALOS's L-band radar.

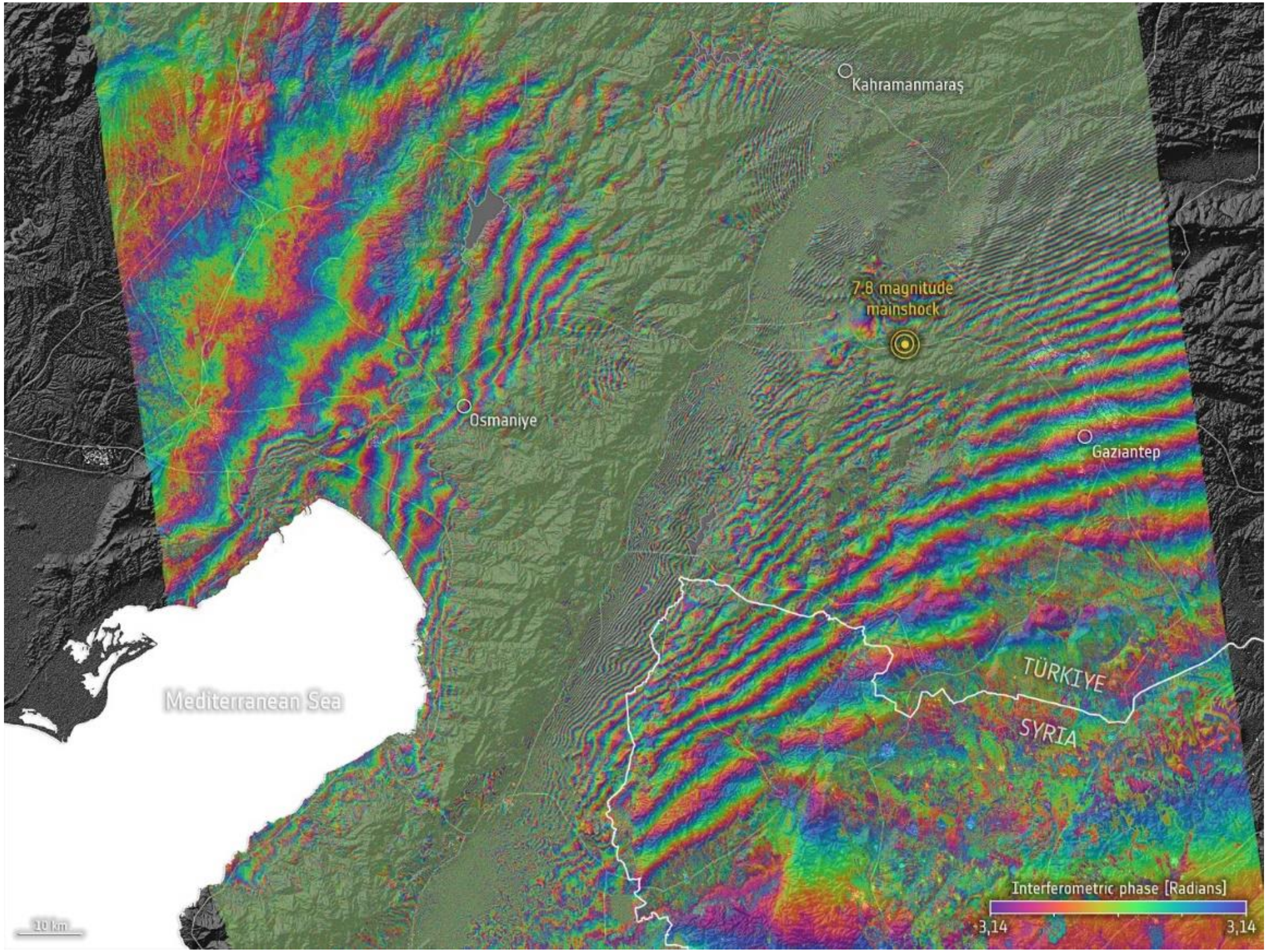


Sensitivity of SAR measurements to forest structure and penetration into the canopy at different wavelengths used for airborne or spaceborne remote sensing observations of the land surface. Credit: NASA SAR Handbook.

InSAR Applications



InSAR Applications

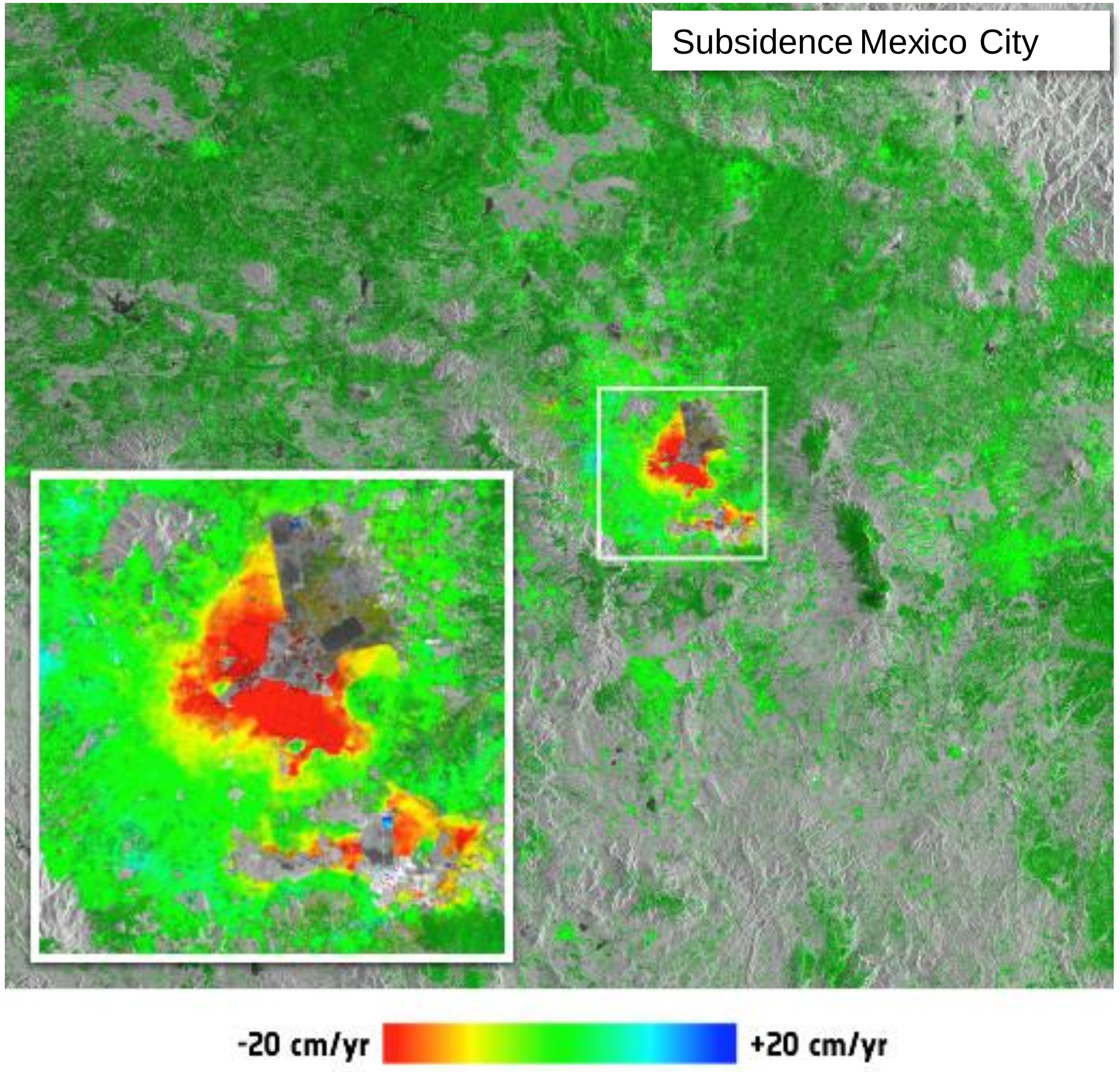


Türkiye–Syria interferogram

Interferogram showing the coseismic surface displacement in the area near Gaziantep, generated from multiple Copernicus Sentinel-1 scans – before and after the earthquakes.

Source:https://www.esa.int/ESA_Multimedia/Images/2023/02/Tuerkiye_Syria_interferogram

InSAR Applications



Subsidence Mexico City
This image, showing surface deformation in Mexico City, was generated using a 'stack' of 11 images aquired between 4 April and 30 November 2013. The images are from Radarsat-2, which was programmed to work in an experimental imaging mode called Terrain Observation by Progressive Scans in azimuth (TOPS) to mimic Sentinel-1A's interferometric wide-swath mode. Images such as this are helping users prepare for Sentinel-1A.
Source:https://www.esa.int/ESA_Multimedia/Images/2014/03/Subsidence_Mexico_City

For more information, see the tutorial: 3. SAR for Land Applications 2 – Interferometric SAR data processing, using SNAP software

4. SAR remote sensing for forestry

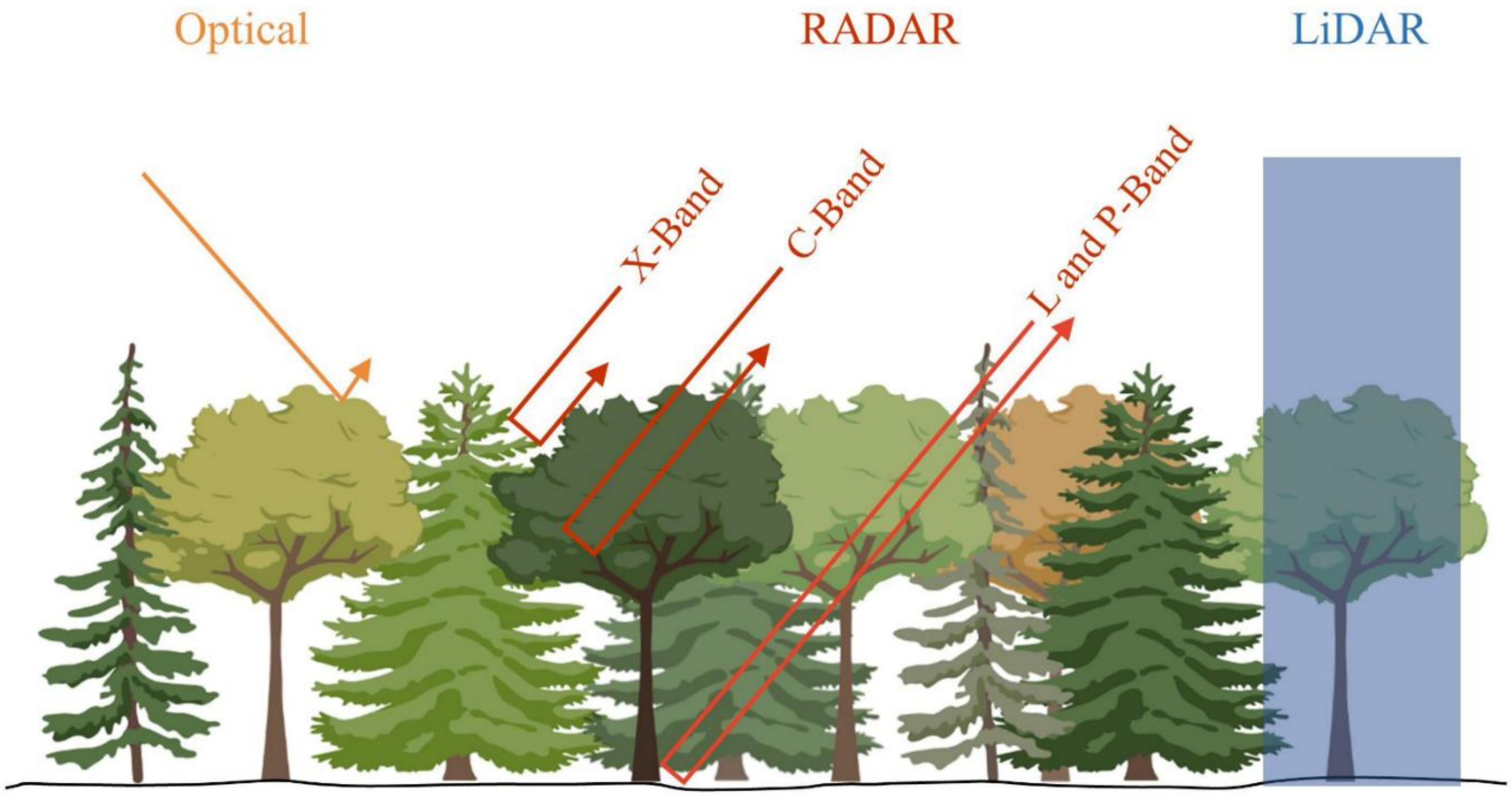
Parameters to Consider for a Forestry Mapping

Radar Parameters

- Wavelength
- Polarizations
- Incidence Angle

Surface Parameters

- Structure
- Dielectric



https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part1.pdf, https://www.mdpi.com/1999-4907/14/6/1086

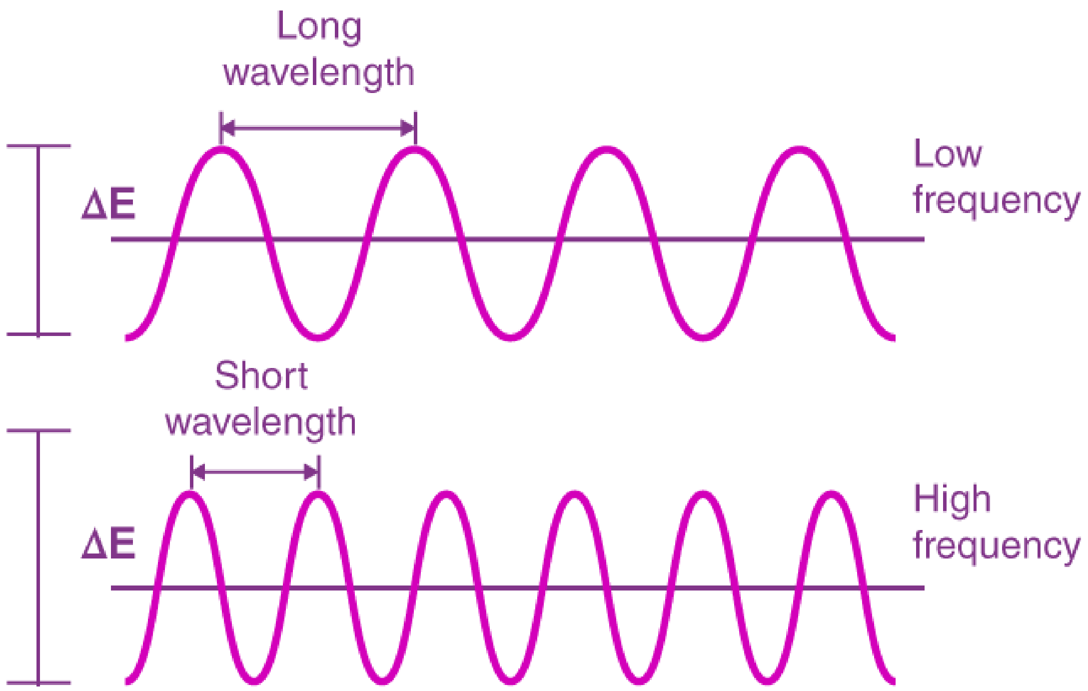
Radar Parameters to Consider for a Forestry Mapping

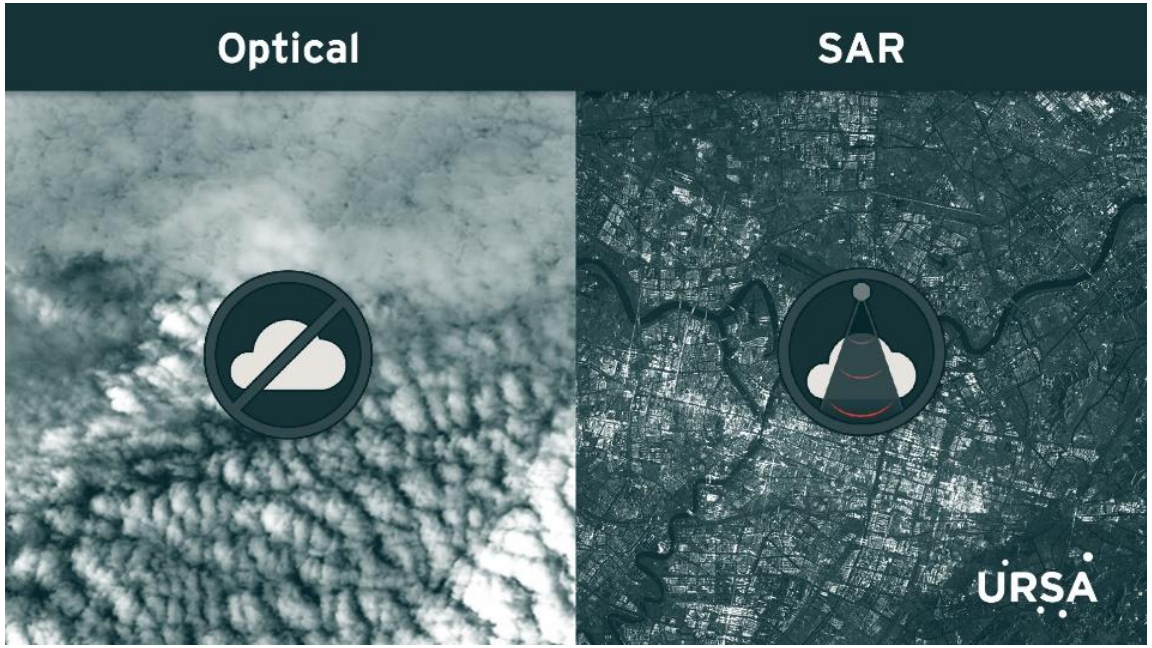
Frequency and Wavelenght

$$\text{Wavelength} = \frac{\text{speed of light}}{\text{frequency}}$$

Active remote sensing sensors generate EM-waves

- no sunlight required night time acquisitions possible
- no problems due to bad illumination





Source: https://cdn1.byjus.com/wp-content/uploads/2023/03/Relation-Between-Frequency-And-Wavelength.png

Radar Parameters to Consider for a Forestry Mapping

Frequency and Wavelenght

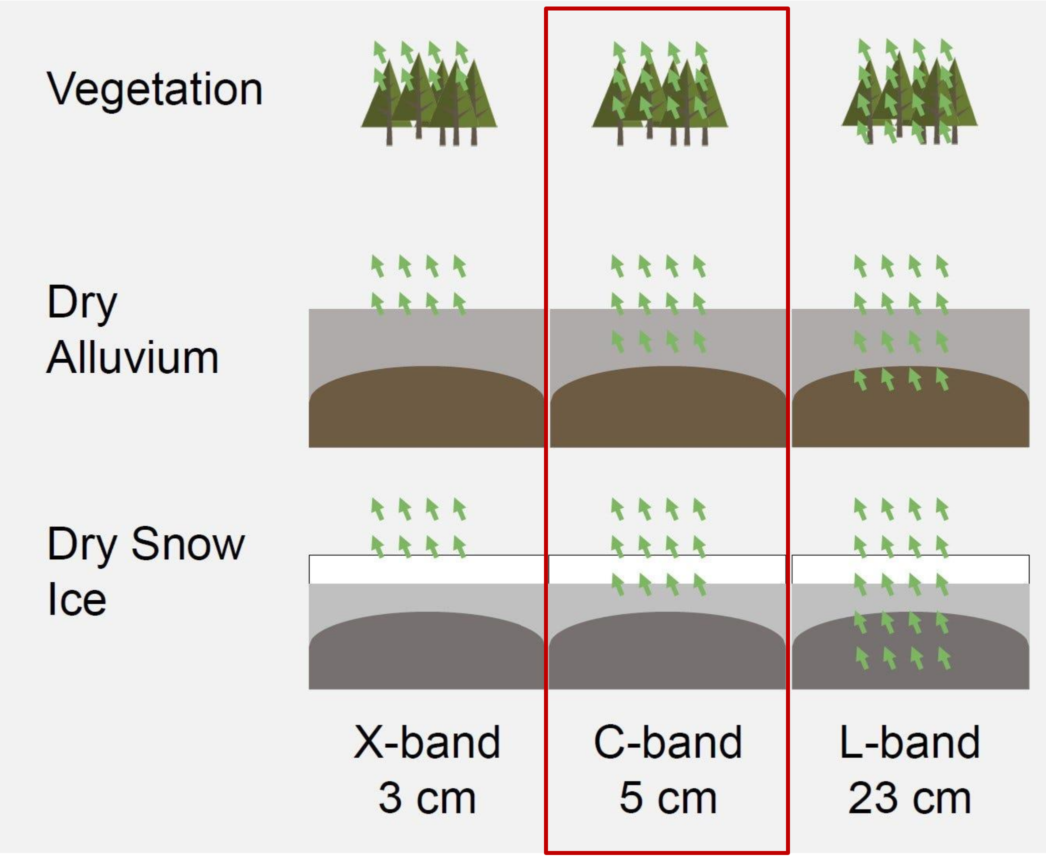
Band	Frequency	Wavelength	Typical Application
Ka	27–40 GHz	1.1–0.8 cm	Rarely used for SAR (airport surveillance)
K	18–27 GHz	1.7–1.1 cm	rarely used (H_2O absorption)
Ku	12–18 GHz	2.4–1.7 cm	rarely used for SAR (satellite altimetry)
X	8–12 GHz	3.8–2.4 cm	High resolution SAR (urban monitoring,; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4–8 GHz	7.5–3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2–4 GHz	15–7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1–2 GHz	30–15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3–1 GHz	100–30 cm	Biomass. First p-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

Source: https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar

Radar Parameters to Consider for a Forestry Mapping

Penetration through vegetation as a Function of Wavelength and dielectric characteristics

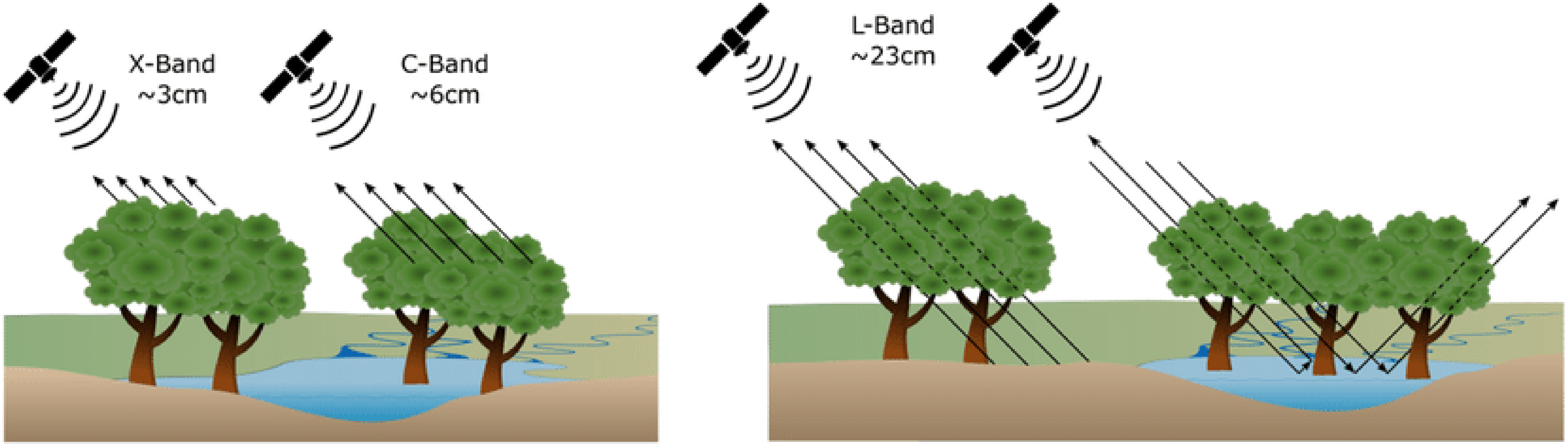
- The penetration depth is depending on **wavelength** and **dielectric characteristics** of objects
- Penetration is the predominant consideration when selecting a wavelength
- Typically, longer wavelengths result in greater penetration into the target



Source:https://medium.com/@preet.balaji20/decoding-synthetic-aperture-radar-sar-remote-sensing-sar-series-part-1-getting-started-d3409eb3b2e3

Radar Parameters to Consider for a Forestry Mapping

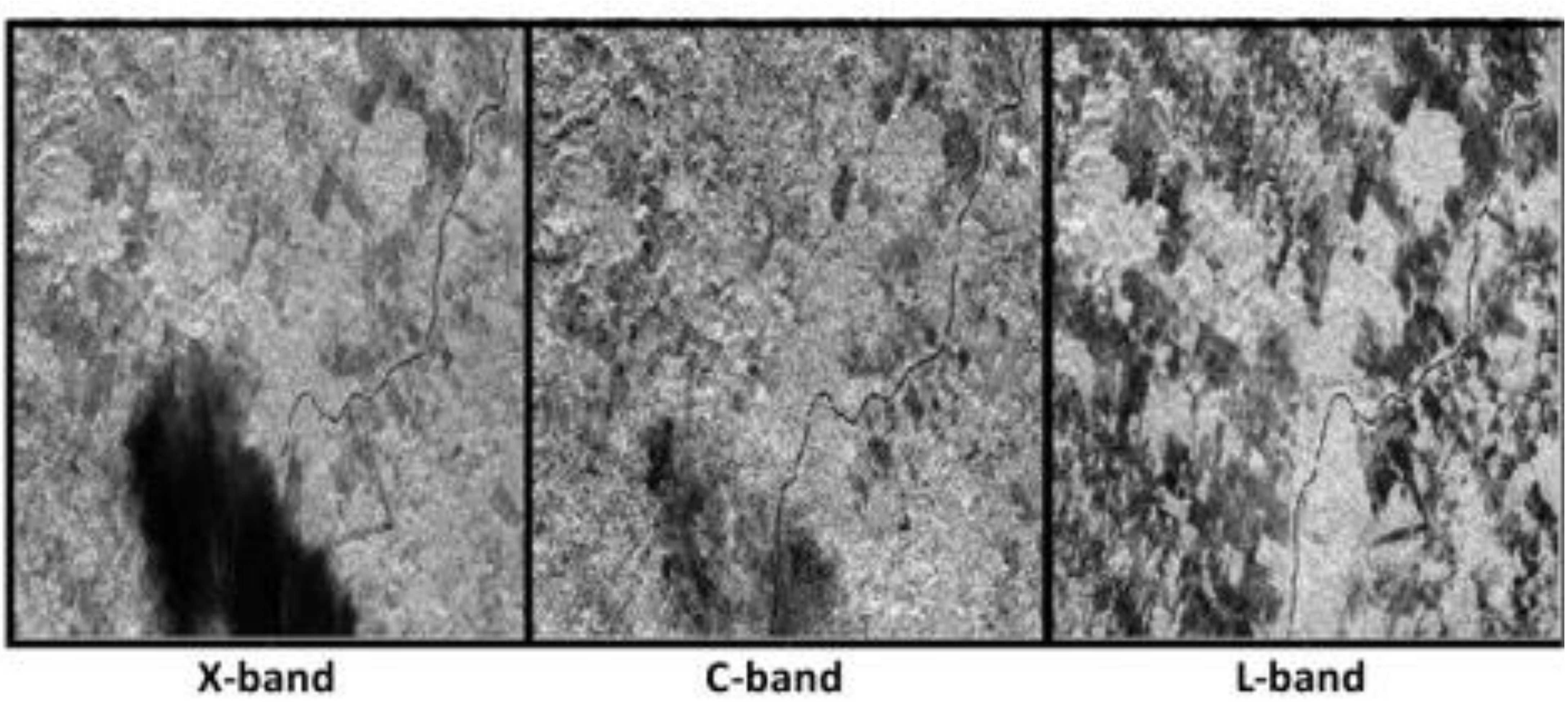
Penetration through vegetation as a Function of Wavelength and dielectric characteristics



Source:https://medium.com/@preet.balaji20/decoding-synthetic-aperture-radar-sar-remote-sensing-sar-series-part-1-getting-started-d3409eb3b2e3

Radar Parameters to Consider for a Forestry Mapping

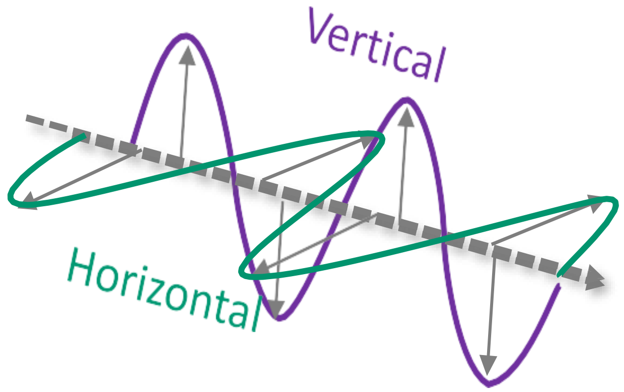
Penetration through vegetation as a Function of Wavelength and dielectric characteristics



Source: https://ars.els-cdn.com/content/image/3-s2.0-B9781785481598500013-f01-25-9781785481598.jpg

Radar Parameters to Consider for a Forestry Mapping

Polarisation



The radar signal is polarised:

Radar: ***transmits*** a EMW in a given polarization
measures the backscattered wave contribution in a given polarization

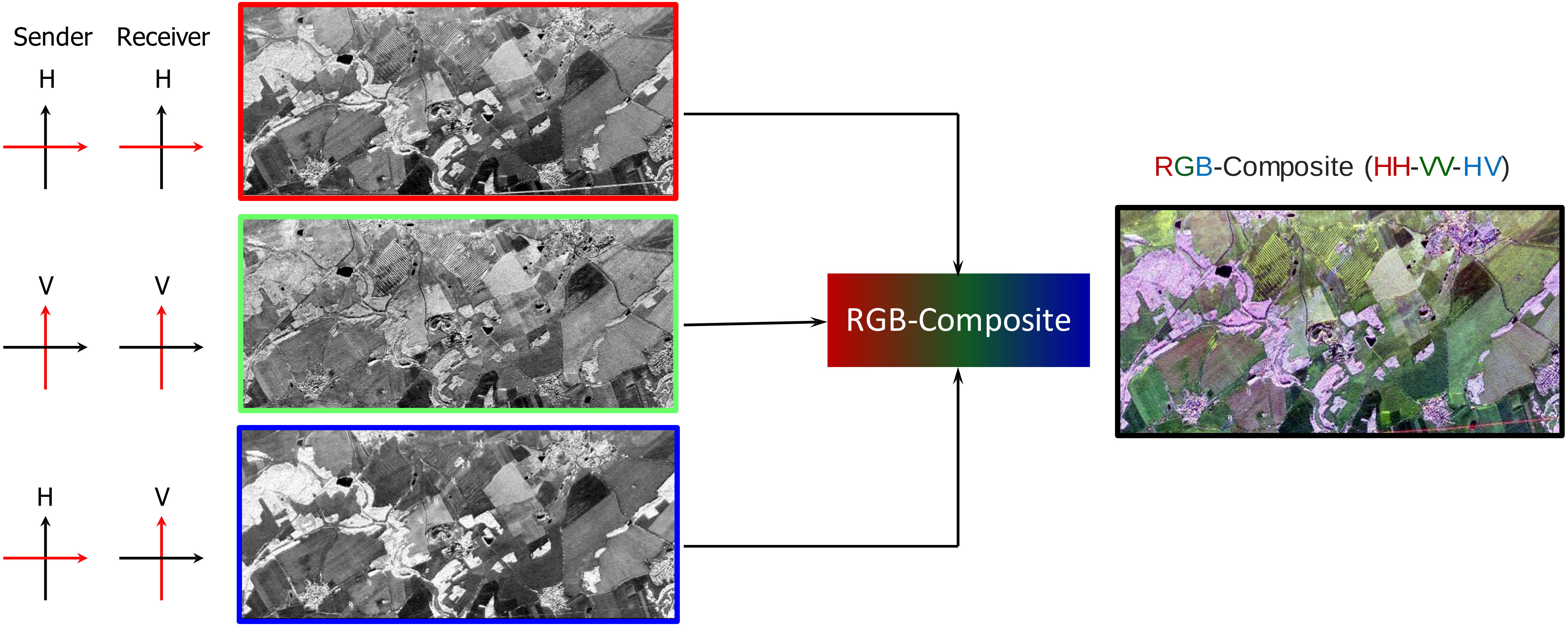
The four combinations of SAR data polarizations:

- **HH**: Horizontal Transmit, HorizontalReceive
- **HV**: Horizontal Transmit, Vertical Receive
- **VH**: Vertical Transmit, Horizontal Receive
- **VV**: Vertical Transmit, Vertical Receive

- Quad-Pol Mode: When all four polarizations are measured
- Different polarizations can determine physical properties of the observed object.

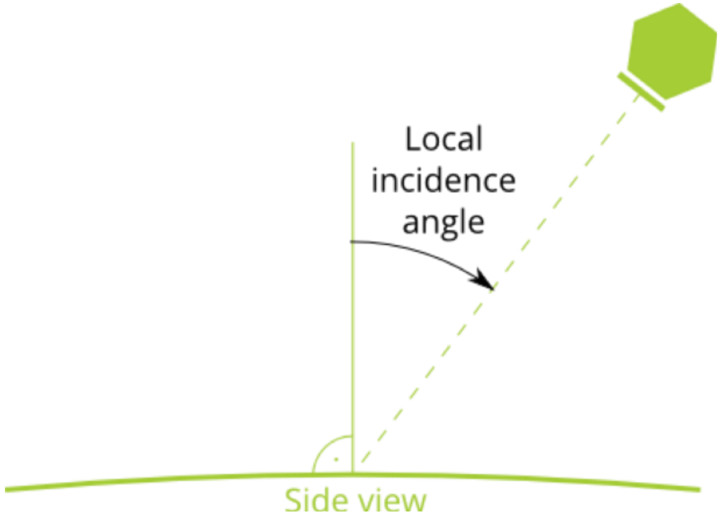
Radar Parameters to Consider for a Forestry Mapping

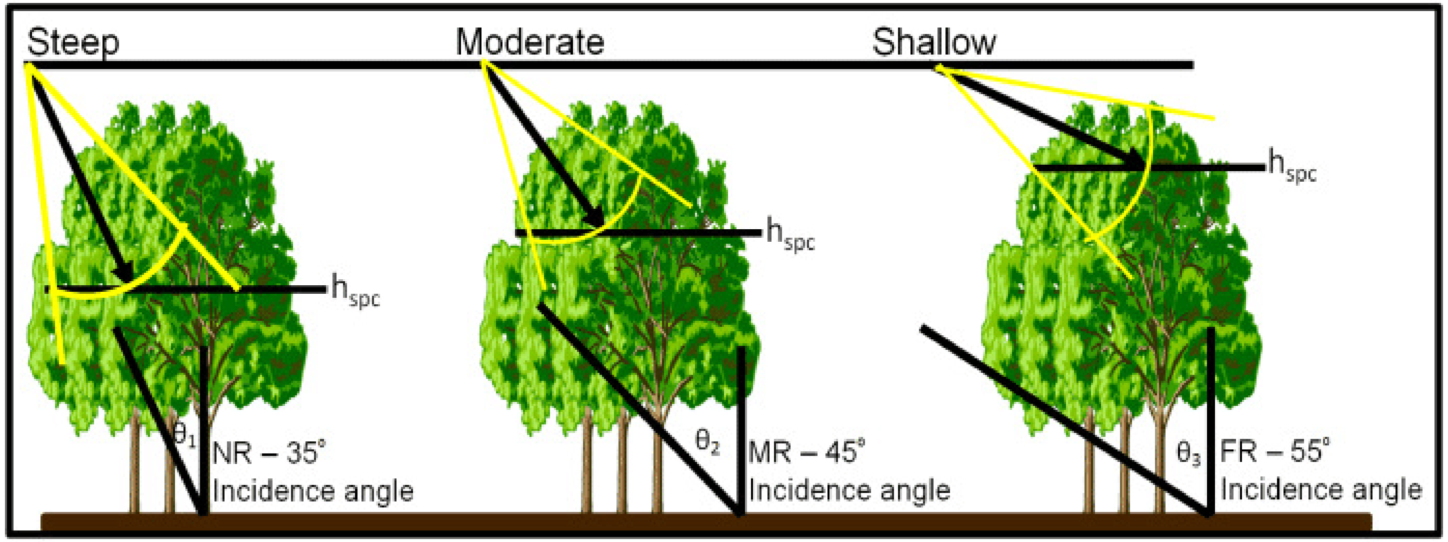
Polarisation – Example of multiple polarisations for vegetation studies



Radar Parameters to Consider for a Forestry Mapping

Incidence angle





Local Incidence Angle:

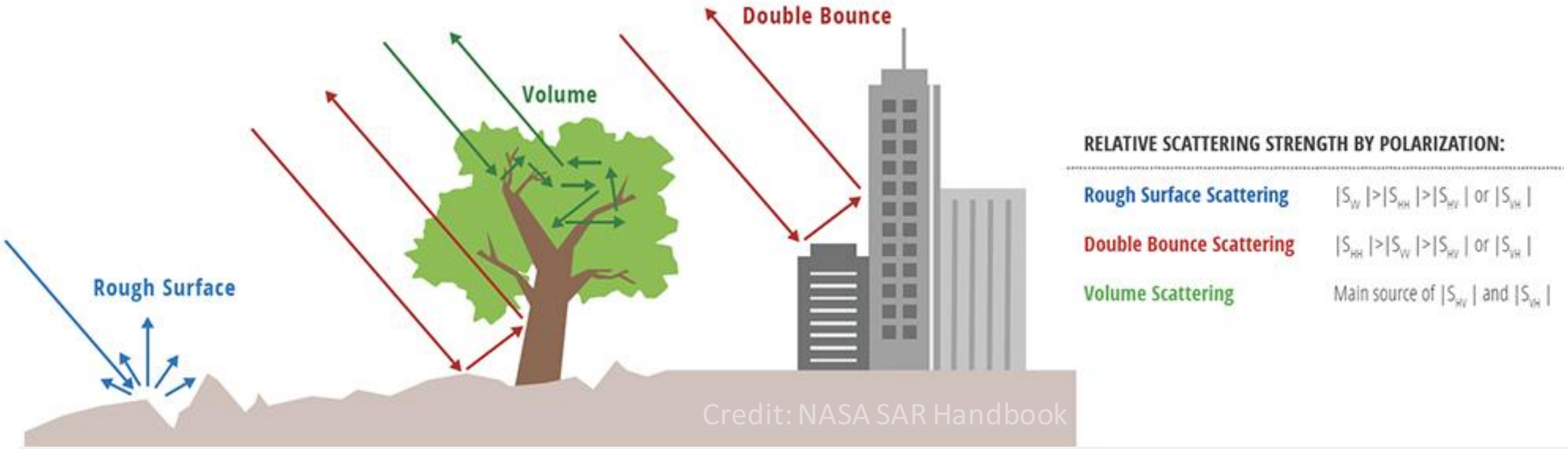
- Refers to the angle formed between the radar illumination direction and the Earth's surface
- Takes into consideration the local slope of the terrain
- Affects the brightness of the image
- Determined by the sensor's altitude
- Results in varying geometric configurations across different points in the image's range direction

Source: https://isprs-archives.copernicus.org/articles/XXXIX-B7/91/2012/

Radar Parameters to Consider for a Forestry Mapping

Signal interacton

Analyzing the signal intensity from these various polarizations provides insights into the composition of the observed surface, as it relates to the following types of scattering:

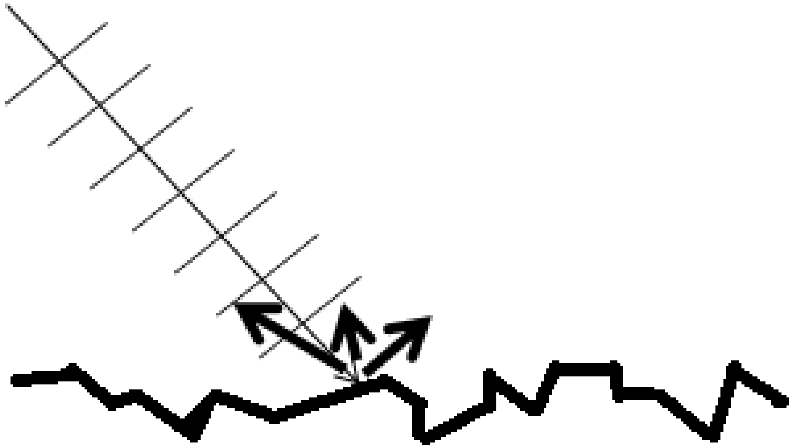


Rough surface scattering	• most sensitive to VV scattering • caused f.e. by bare soil or water
Volume scattering	• most sensitive to cross-polarized data like VH or HV • scattering by the leaves and branches
Double bounce	• most sensitive to an HH polarized signal • caused by buildings, tree trunks, or inundated vegetation

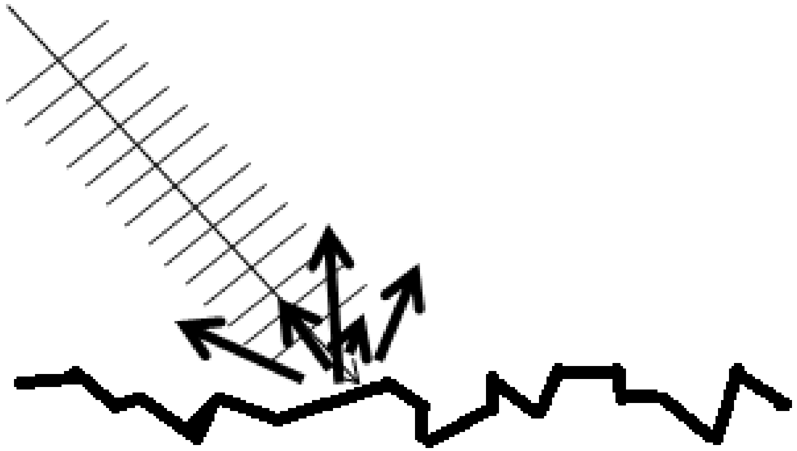
Radar Parameters to Consider for a Forestry Mapping

Radar backscaterring

- The intensity of backscattered energy typically increases with surface roughness



The surface appears smooth to long wavelength
=> Backscattering is low

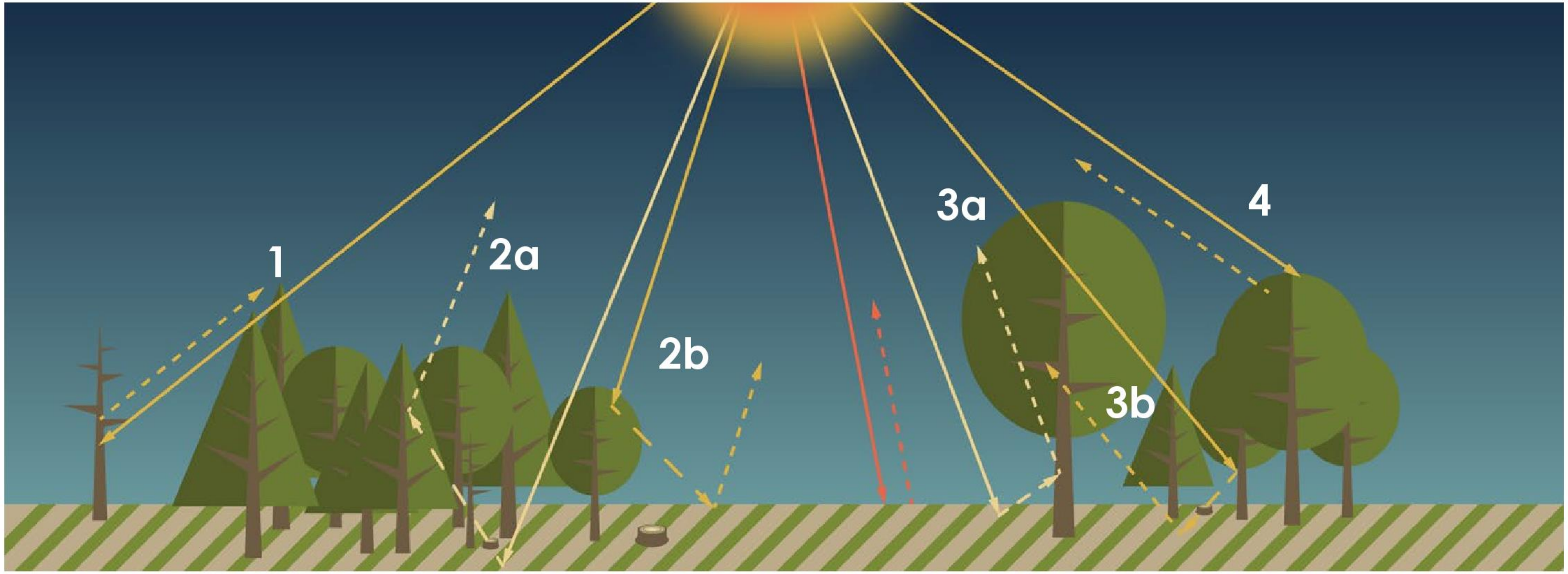


The surface appears rough to shorter wavelength
=> Backscattering increases

https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part3.pdf

Radar Parameters to Consider for a Forestry Mapping

Radar backscaterring in Forests

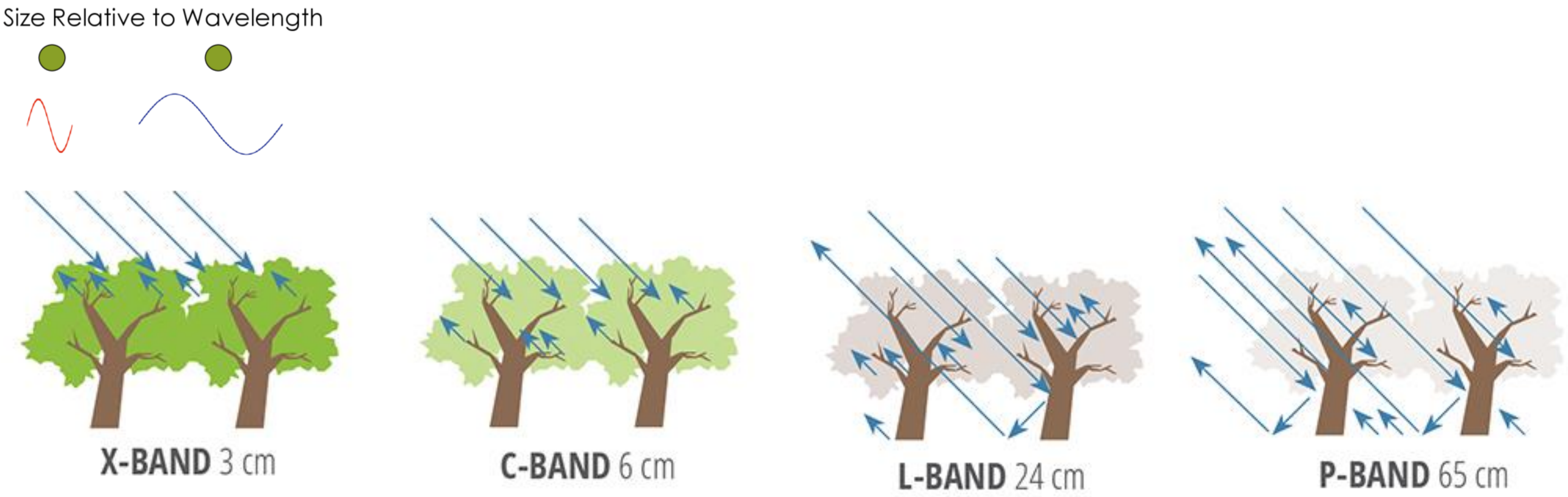


Dominant backscattering sources in forests: (1) direct scattering from tree trunks, (2a) ground-crown scattering, (2b) crown-ground scattering, (3a) ground-trunk scattering, (3b) trunk-ground scattering, (4) crown volume scattering.

https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part3.pdf

Surface Parameters to Consider for a Forestry Mapping

Structure

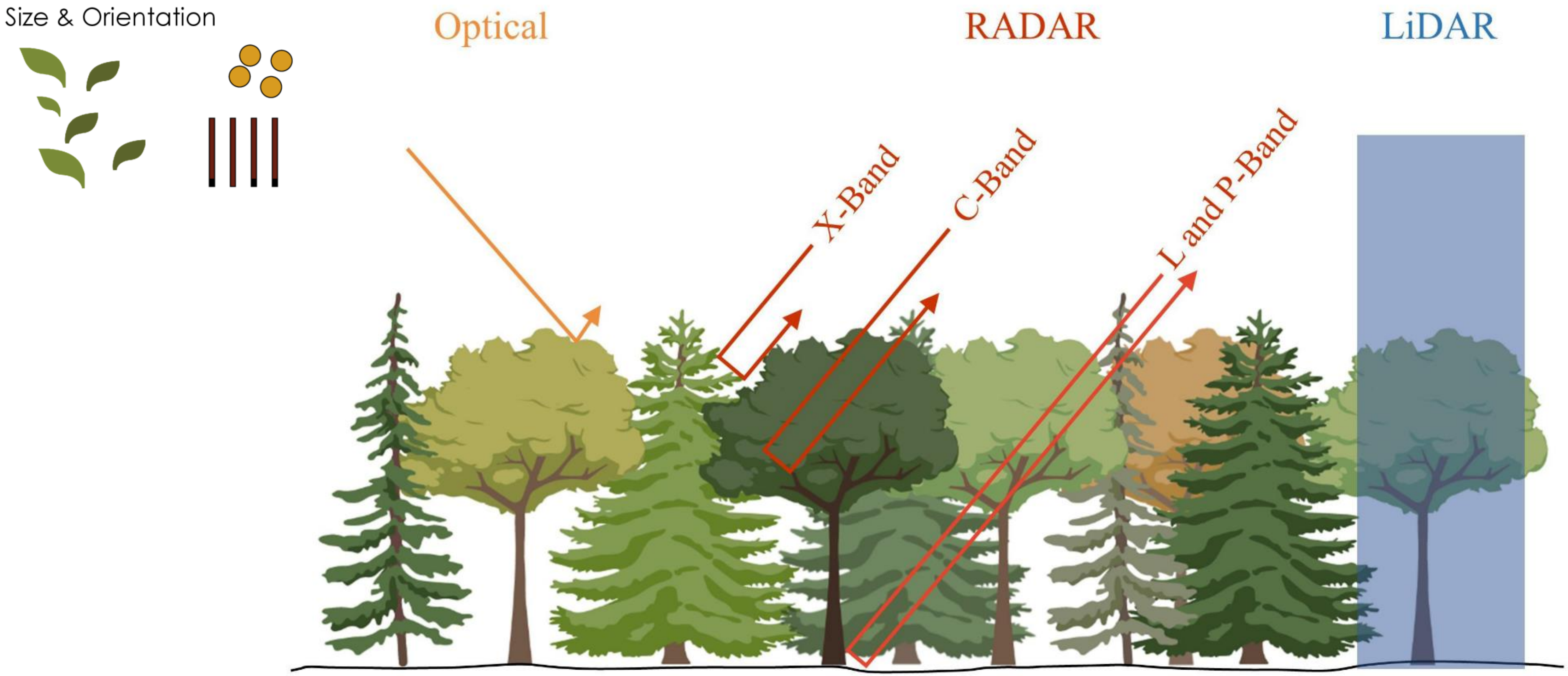


- **P-band SAR**: provide information for forest biomass and height estimations
- **L-band SAR**: forest cover and change monitoring using dual polarization (cross-pol most sensitive to forest structure (e.g. JERS-1, ALOS PALSAR)
- **C-band**: dense time-series for accurate detection of forest cover change
- **X-band**: application in forest degradation assessment and forest height estimation (e.g. using TanDEM-X)

https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part1.pdf

Surface Parameters to Consider for a Forestry Mapping

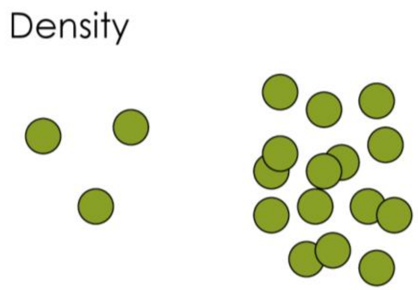
Structure



https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part1.pdf, https://www.mdpi.com/1999-4907/14/6/1086

Surface Parameters to Consider for a Forestry Mapping

Structure



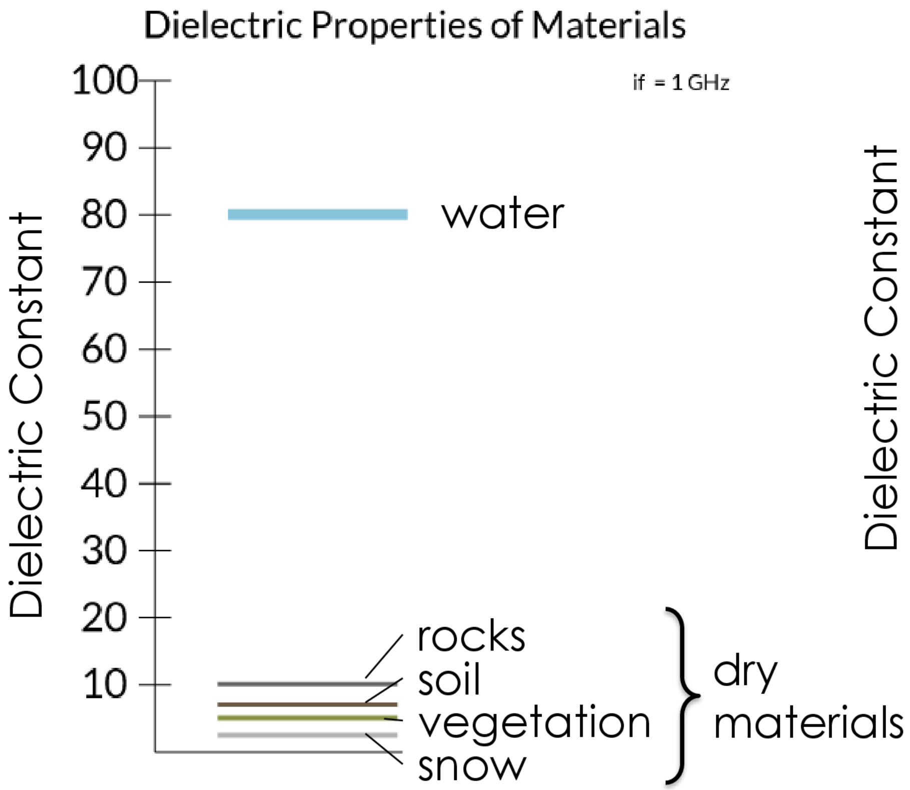
- The more dense the vegetation, the lower the probability of signal penetration through the canopy (influenced by wavelength)
- Saturation issue - the signal reaches a maximum level at a specific biomass threshold, which varies according to wavelength:
  - C-band ≈ 20 tons/ha (2 kg/m2)
  - L-band ≈ 40 tons/ha (4 kg/m2)
  - P-band ≈ 100 tons/ha (10 kg/m2)

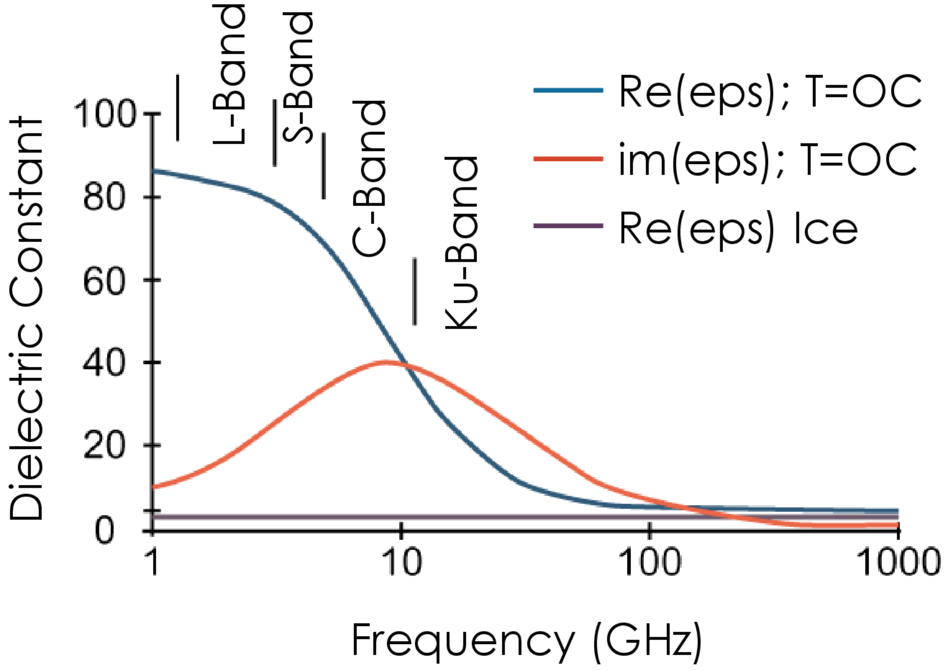
→ Combination of different polarizations can improve biomass estimates

https://www.civilsdaily.com/wp-content/uploads/2017/01/classification-dense.png

Surface Parameters to Consider for a Forestry Mapping

Dielectric constant



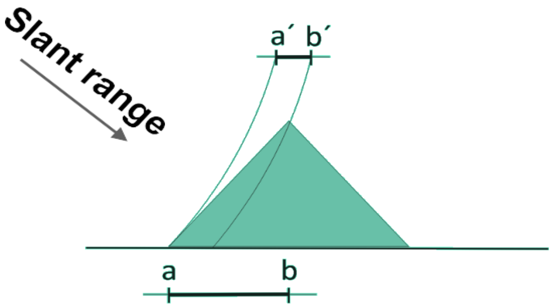


Source: https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part1.pdf

Surface Parameters to Consider for a Forestry Mapping

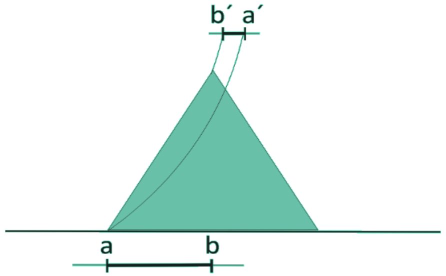
Geometric Effects

Foreshortening



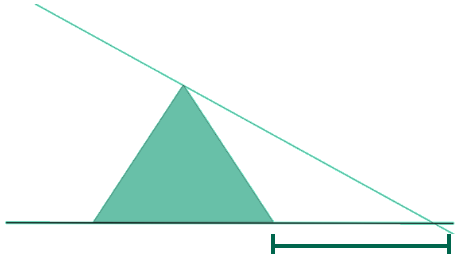
- Slopes oriented to the SAR appear compressed (Distance between a and b is shortened)
- Appears as very bright area
- More pronounced in near range (small incidence angle) than in far range (high incidence angles)

Layover



- Steep slopes oriented to the SAR lead to ghost images
- When radar beam reaches the top of a high feature (b) before it reaches the base (a)

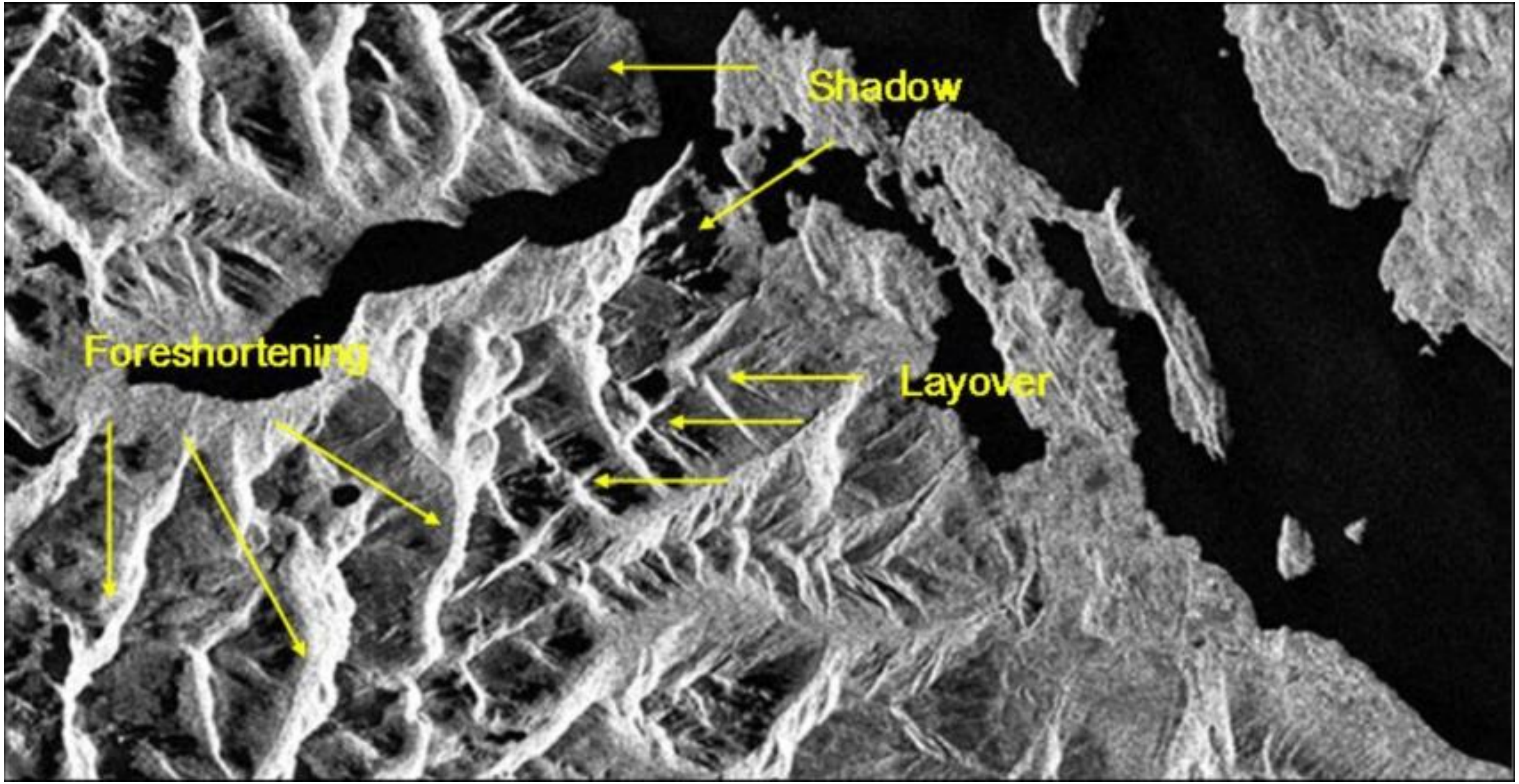
Radar shadow



- Steep slopes oriented away from the SAR return no signal
- No signals can be transmitted to this area (as it is blocked by the slope), thus no signals can be scattered back from these areas
- Appears as black area in the image

Surface Parameters to Consider for a Forestry Mapping

Geometric Effects

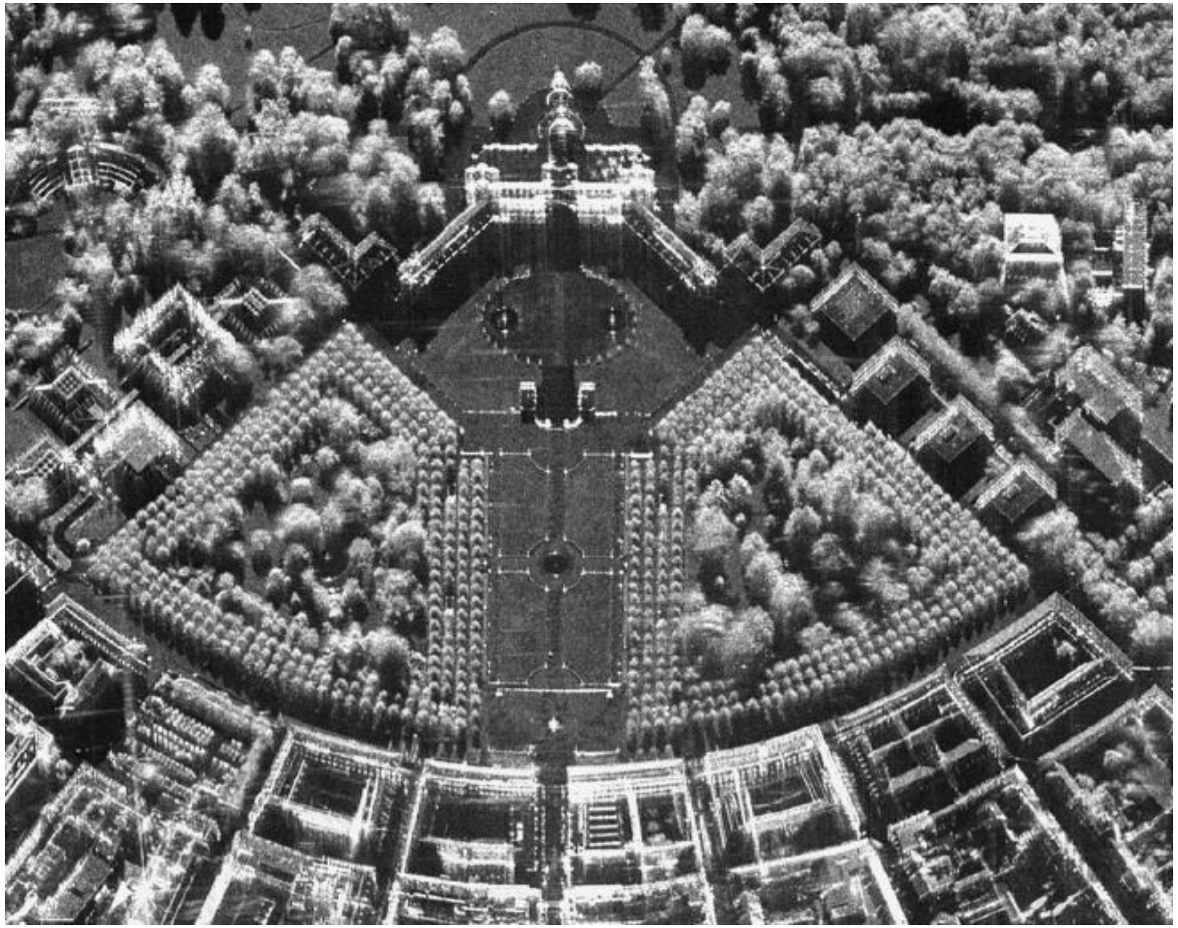


Source: https://www.researchgate.net/profile/M-Lenzano/publication/263124688/figure/fig23/AS:614356547039256@1523485423960/Figura-9-Efectos-de-shadowi-ng-foreshortening-y-layover-en-una-imagen-SAR-de-RADARSAT-1.png

Surface Parameters to Consider for a Forestry Mapping

Geometric effects – side looking

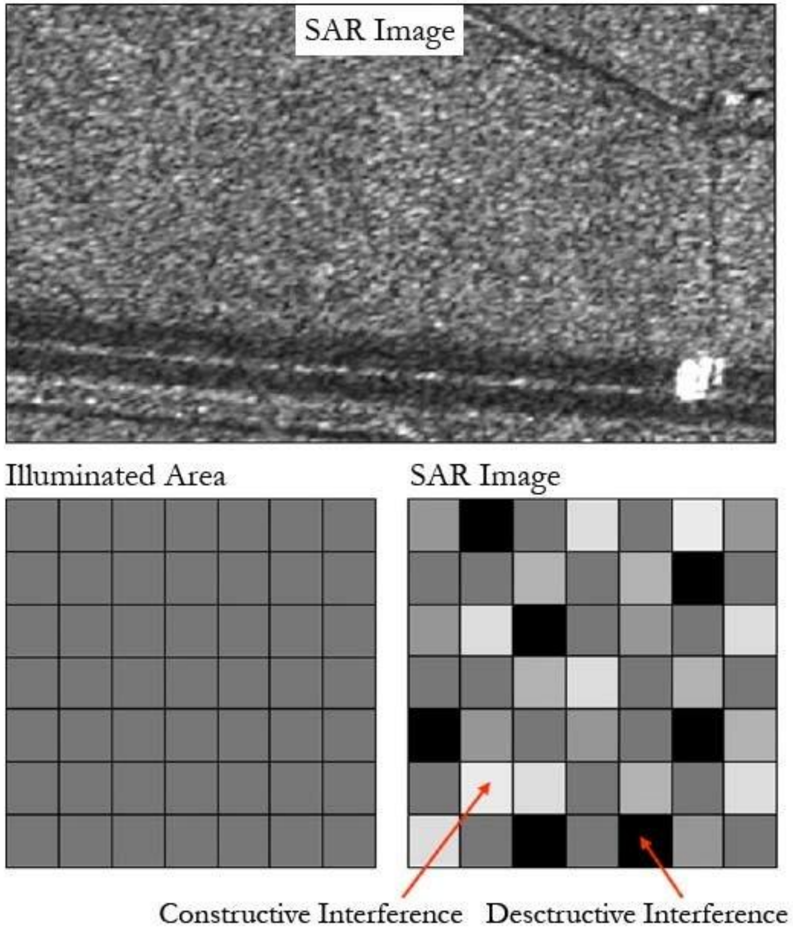
Google maps



Andreas R. Brenner and Ludwig Roessing, Radar Imaging of Urban Areas by Means of Very High-Resolution SAR and Interferometric SAR, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 46, NO. 10, OCTOBER 2008 (X-band)

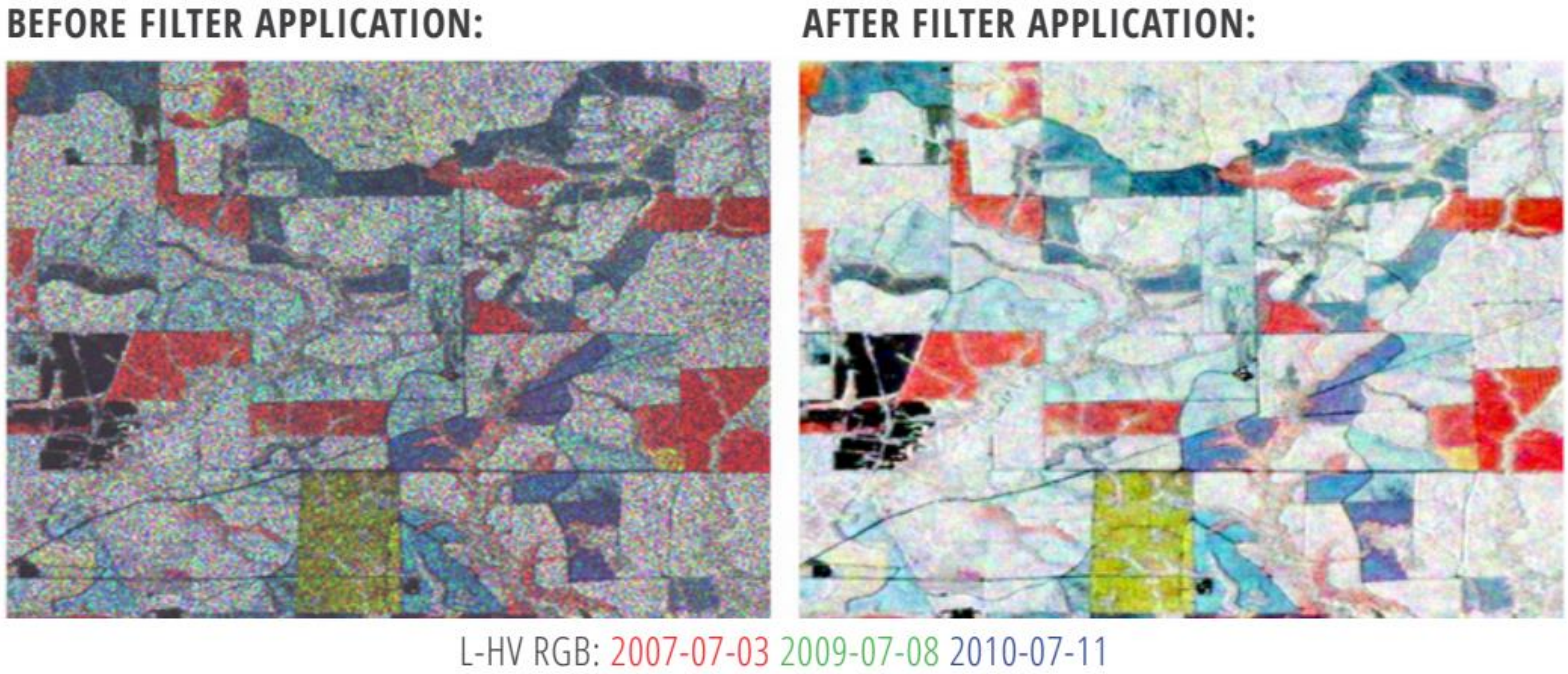
Speckle

- Granular noise that affects radar images, reducing class spectral seperability
- Degrades the quality of SAR image
- Results from random fluctuations in the return signal from an object
- Preprocessing is necessary to filter the images, aiming to minimize information loss - using of moving windows filters



Source:https://www.researchgate.net/publication/225006983_The_Combined_Use_of_Optical_and_SAR_Data_for_Large_Area_Impervious_Surface_Mapping/figures?lo=1

Speckle



Multitemporal speckle flter application on a perfectly co-registered time series data stack of ALOS L-band data over Louisiana, U.S.

Source:https://gis1.servirglobal.net/TrainingMaterials/SAR/Ch3-Content.pdf

SAR for forestry - Applications

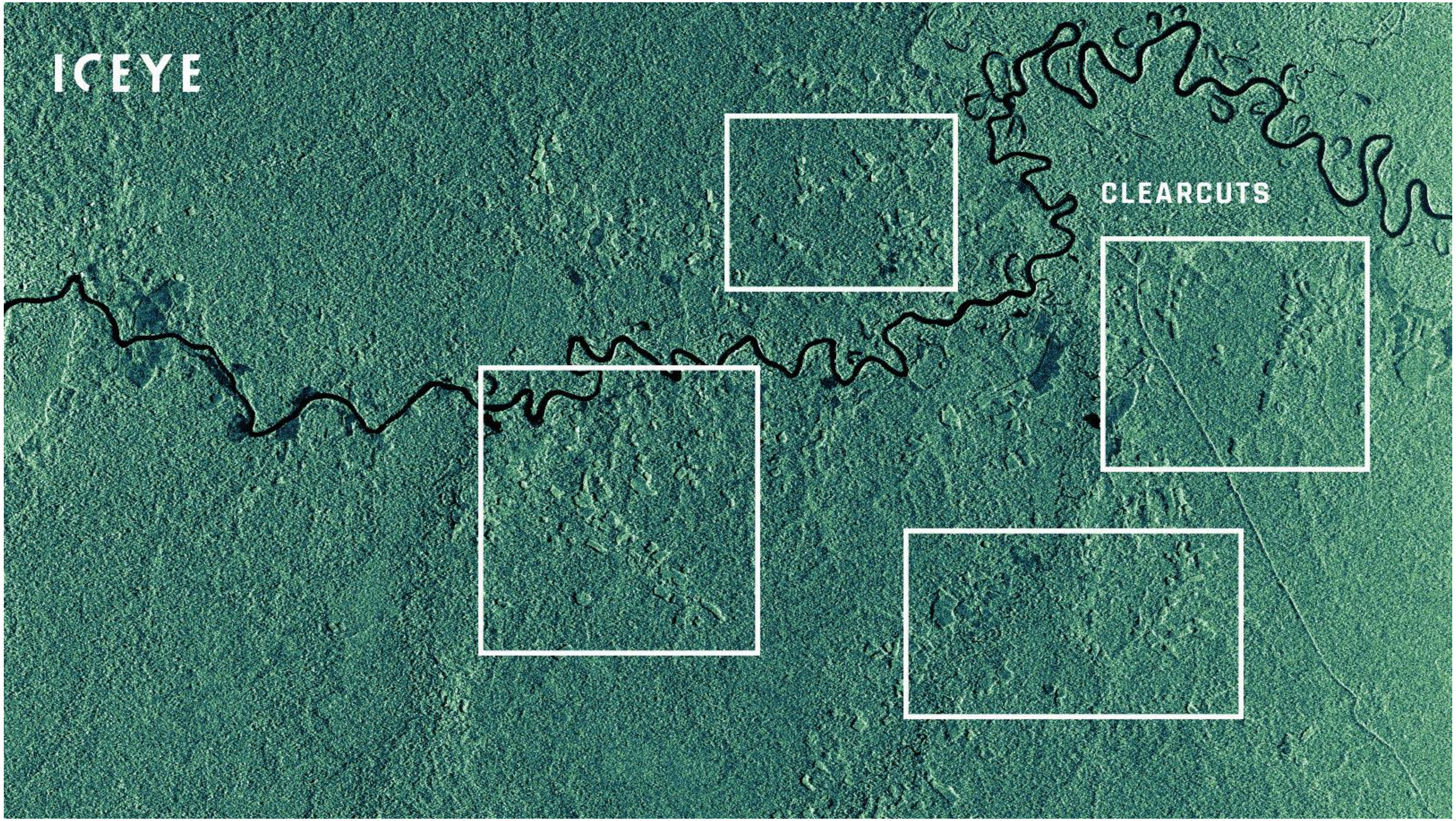
Expected backscatter characteristics for diferent vegetation transition

WAVELENGTH	POLARIZATION	RESPONSE BY FOREST TYPE					
		Sparse Forest (dry)	Sparse Forest (flooded)	Degraded Forest (dry)	Degraded Forest (flooded)	Dense Forest (dry)	Dense Forest (flooded)
C-band backscatter (g0)	VV	Medium to high; Depending on the roughness of the forest floor and moisture, there is lots of variation in this category	Low to medium; Depending on forest density, lots of forward scattering	Medium to high; most scattering from crown	Medium to high; most scattering from crown	Medium to high; most scattering from crown (Can be low in scenarios where absorption dominates and diminishes backscatter)	Medium to high; most scattering from crown (Can be low in scenarios where absorption dominates and diminishes backscatter)
	VH	Medium to high; Depending on the roughness of the forest floor and moisture, there is lots of variation in this category	Low to medium; Depending on forest density, lots of forward scattering	Medium to high; most scattering from crown	Medium to high; most scattering from crown	Medium to high; most scattering from crown (Can be low in scenarios where absorption dominates and diminishes backscatter)	Medium to high; most scattering from crown (Can be low in scenarios where absorption dominates and diminishes backscatter)
	VV/VH Ratio	Medium to high	Medium to high	Medium	Medium	Medium	Medium
L-band backscatter (g0)	HH	Low to medium; lower than dense forest and flooded sparse forest. At steep incidence angles, backscatter can be medium to high	Medium to high, depending on how much double bounce is contributing to the signal	Medium to high	High to very high, double bounce contributes to high backscatter	High to very high; higher than degraded forest, however at very high biomass levels we see saturation and no distinction with degraded forests	High to very high, double bounce contributes to high backscatter
	HV	Low to very low, depending on how dry the soils are	Low to very low. Most scattering is in the forward direction due to specular reflection	Medium to high	Medium to high, no seasonal variation with flooded forest floor	High to very high; volume scattering is dominant – best senstivity to biomass	Medium to high, no seasonal variation with flooded forest floor
	HH/HV Ratio	Medium	High	Medium	High	Medium	High

Source:https://gis1.servirglobal.net/TrainingMaterials/SAR/Ch3-Content.pdf

SAR for forestry - Applications

Detecting clearcuts



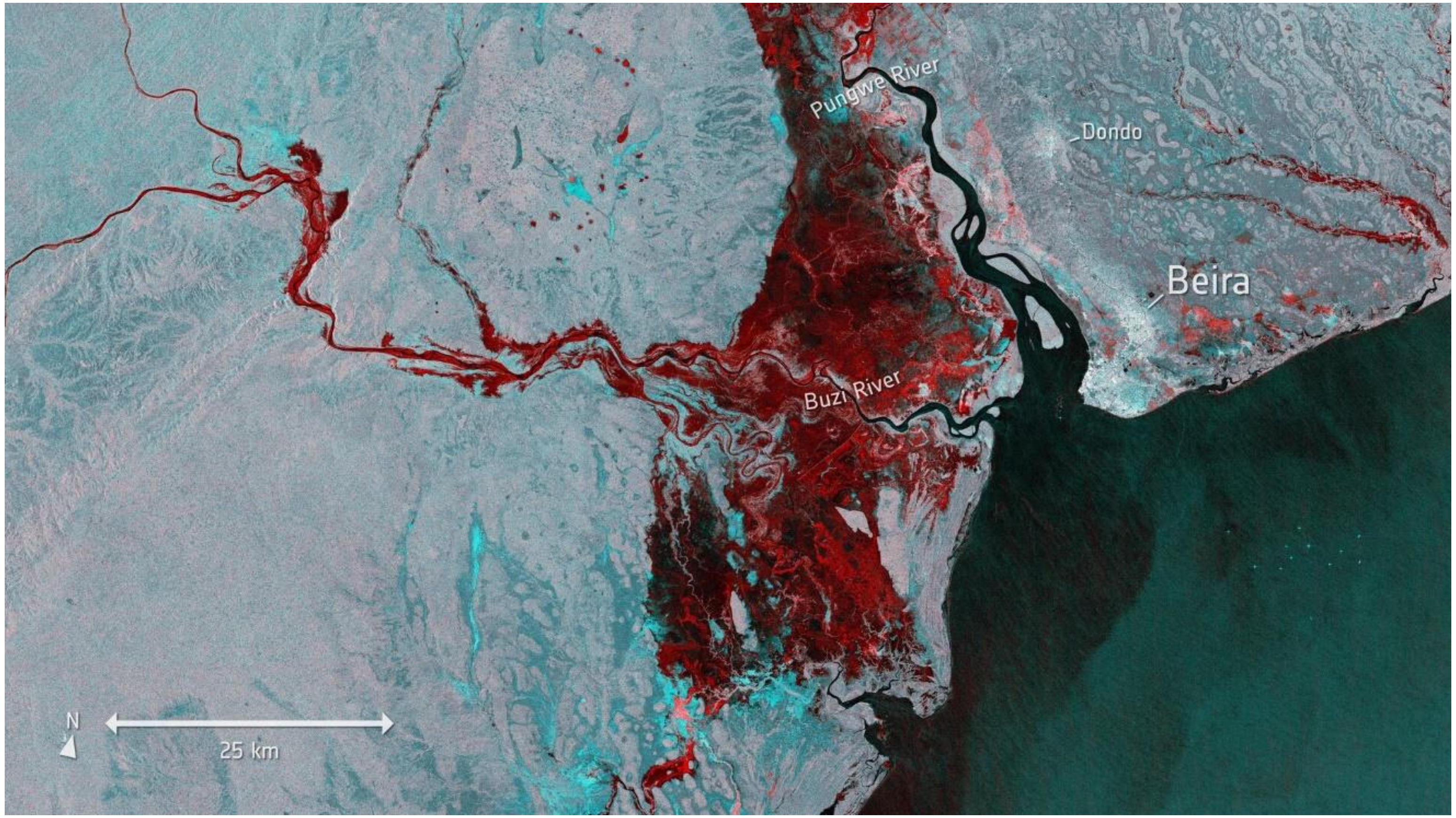
ICEYE SAR satellite Strip image of Masisea District, Peru, west of Area de Conservación Regional Imiría. The image was taken on 9th of April 2020.

For more information, see the tutorial: [4. Forestry with Sentinel-1: Single Image Analysis and Time Se ries to detect forest change using SNAP software]

Source: https://www.iceye.com/hubfs/26618_20200409-Masisea-Peru-deforestation.jpg:

SAR for forestry - Applications

Detecting inundated forests and floods



Floods imaged by Copernicus Sentinel-1
Millions of people in Mozambique, Malawi and Zimbabwe are struggling to cope with the aftermath of what could be the southern hemisphere's worst storm: Cyclone Idai. This image is from Copernicus Sentinel-1 and shows the extent of flooding, depicted in red, around the port town of Beira in Mozambique on 19 March. This mission is also supplying imagery through the Copernicus Emergency Mapping Service to aid relief efforts.

CREDIT: contains modified Copernicus Sentinel data (2019), processed by ESA

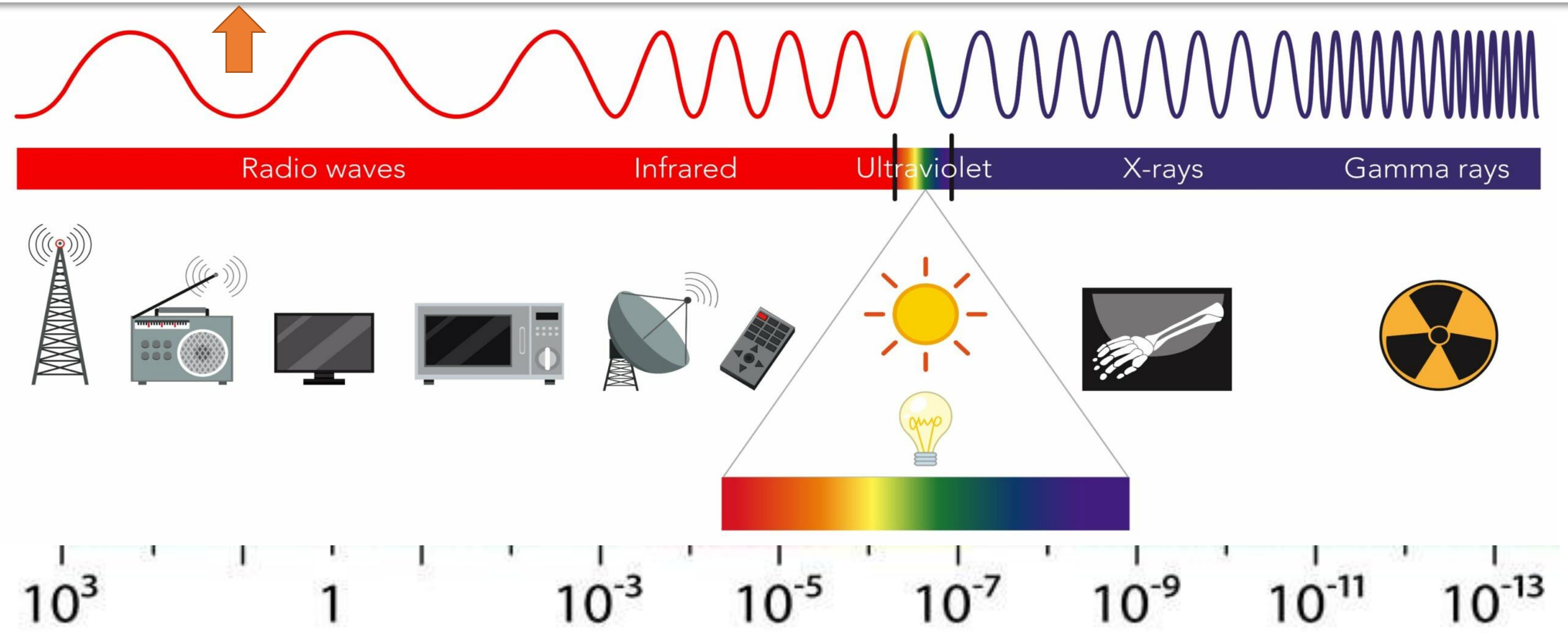
Source: https://www.esa.int/ESA_Multimedia/Images/2019/03/Floods_imaged_by_Copernicus_Sentinel-1 esa space solutions | Copernicus Academy | ÚSTAV GEOGRAFIE Prírodovedecká fakulta UPJŠ v Košiciach

5. SAR and optical remote sensing for precision agriculture 1

SAR and optical for precise agriculture

RADAR SATELLITES
Weather & illumination independence
Penetration through cloud cover

Use: information about the vegetation structure and moisture content

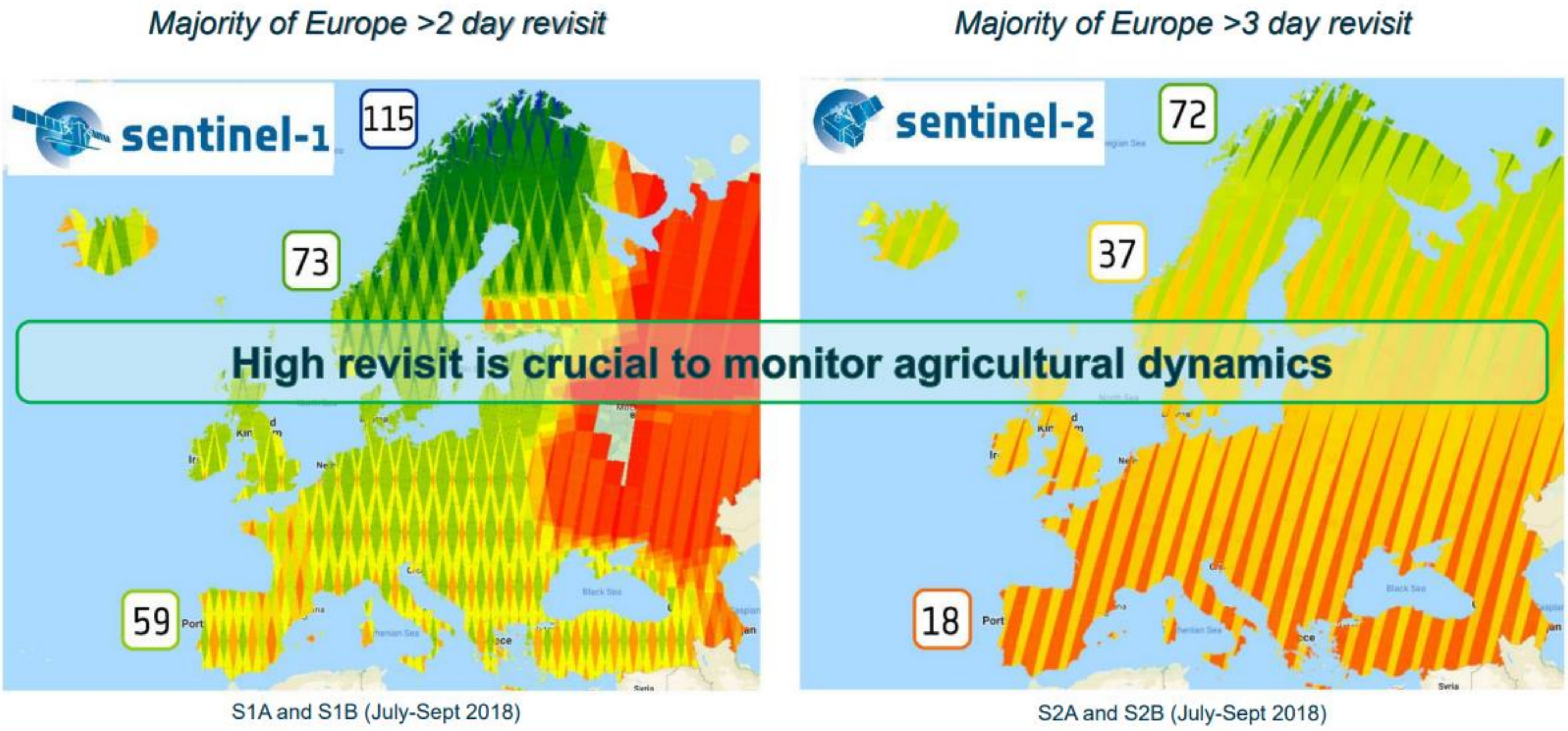


OPTICAL SATELLITES
Weather & illumination dependence
No penetration through cloud cover

Use: spectral (and chemical) properties of vegetation

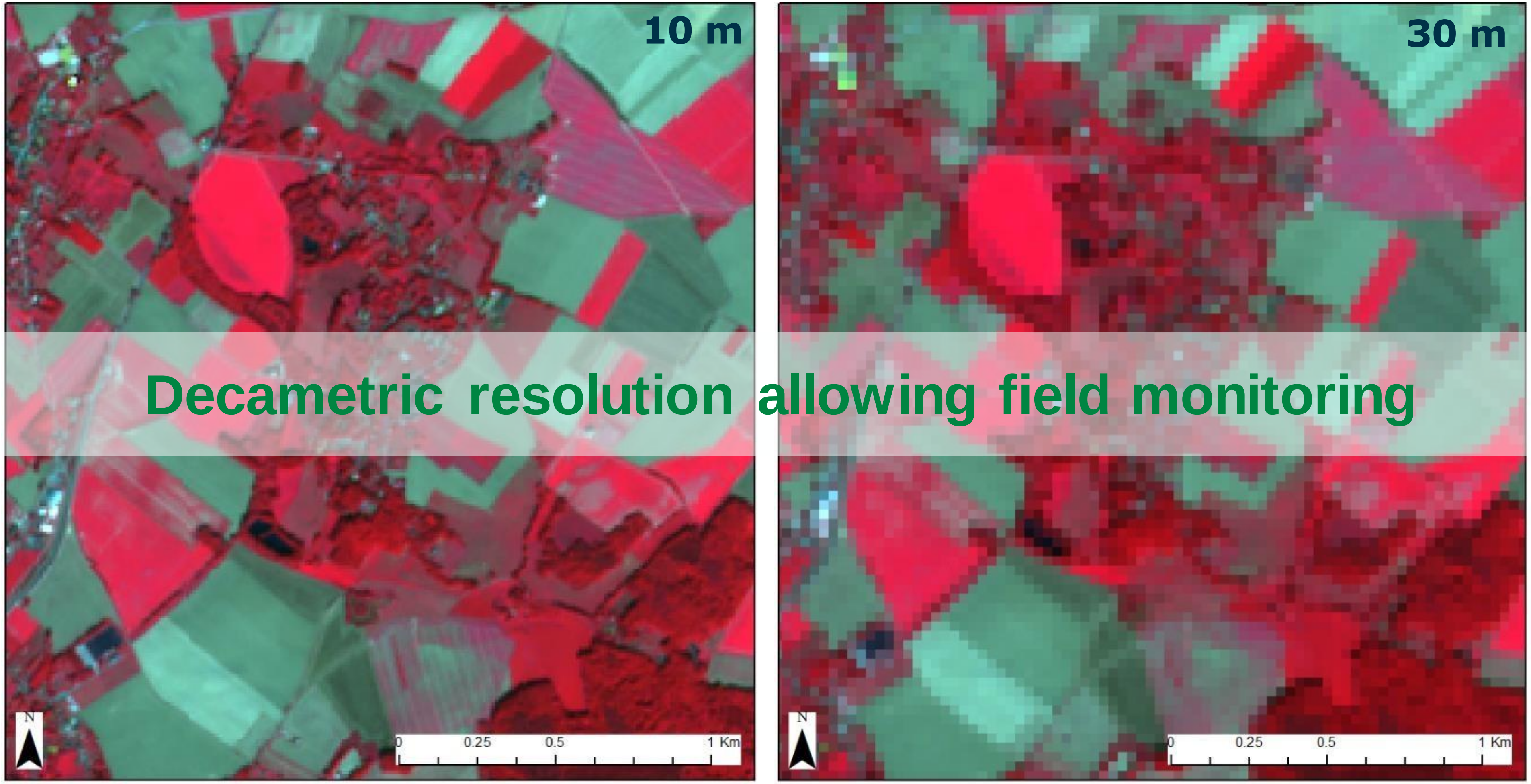
Source:https://cthrumetals.com/emi-shielding/

Sentinels – game changer for precision agriculture

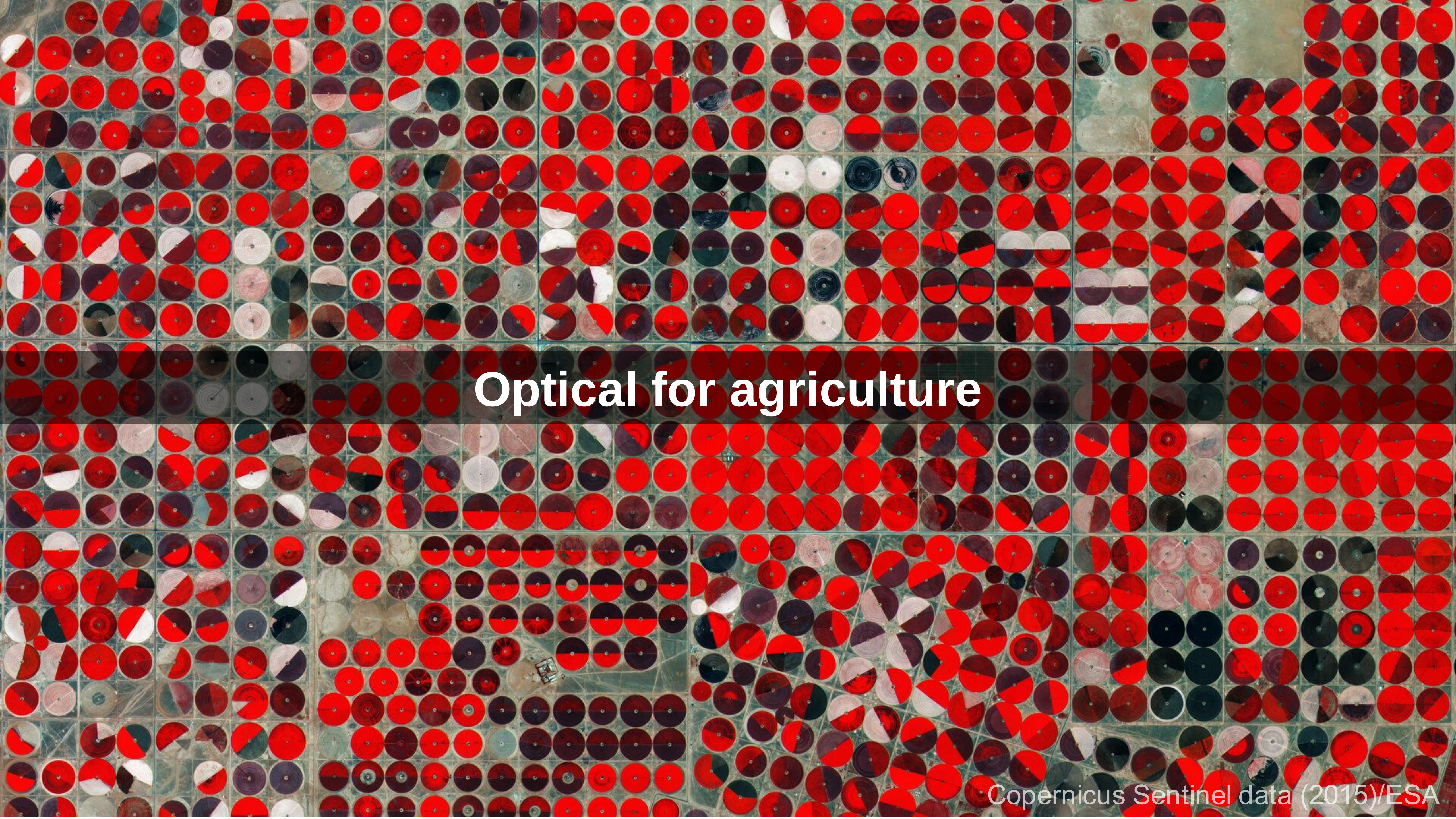


https://eo4society.esa.int/training_uploads/LTC2022/2_Tuesday/13_LTC22_ppt_CropType_DianeH.pdf

Sentinels – game changer for precision agriculture



https://eo4society.esa.int/training_uploads/LTC2022/2_Tuesday/13_LTC22_ppt_CropType_DianeH.pdf



Optical for agriculture
Copernicus Sentinel data (2015)/ESA

From EO signal to agriculture information content

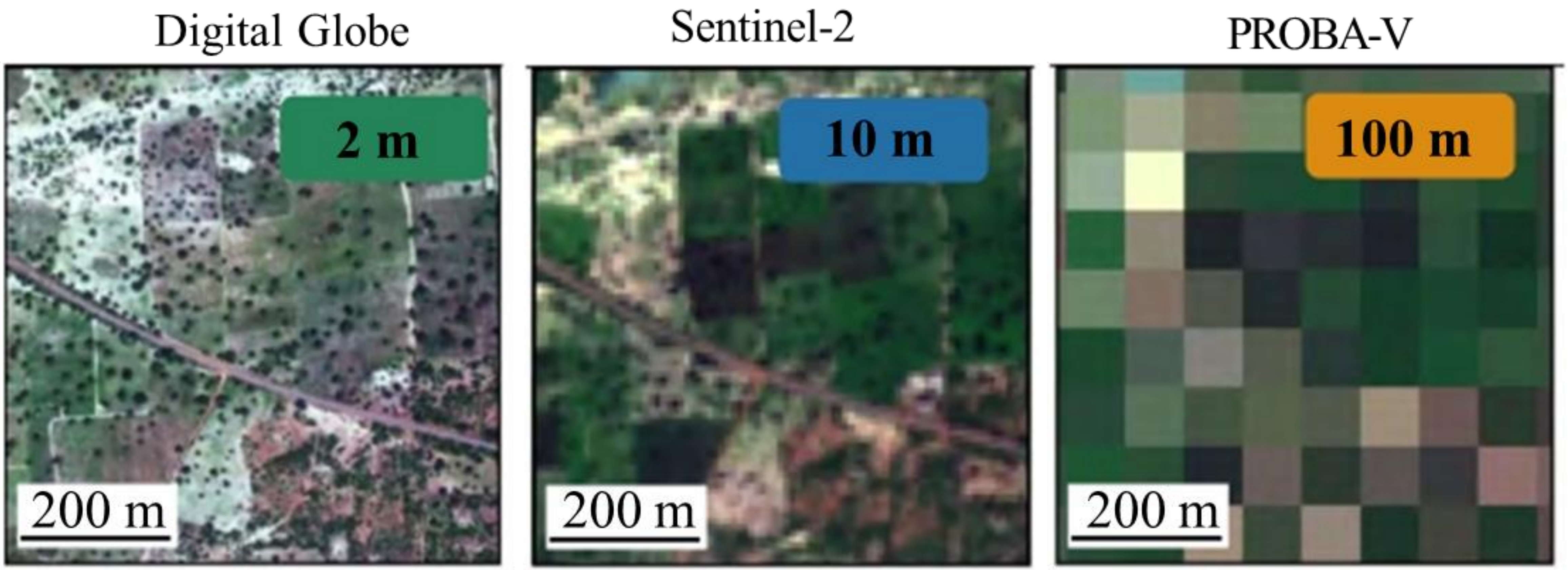
Spatial + spectral + temporal information content + Machine learning for classification

Satellite Service Provider	Type	Resolution		
		Spatial	Spectral	Temporal
Landsat (NASA)	Public	15m, 30m, 60m, 100m, 120m	Natural colour (Visible, NIR), Coastal aerosol, SWIR 1/2, Panchromatic, Cirrus, TIRS 1/2[63]	16-18 days
Sentinel (ESA)	**Public**	**5m, 10m, 20m, 60m**	**C-band, Natural colour (Visible, NIR, SWIR)**	**1-5 days**
Planet	Private	0.72m, 3m, 4.77m, 6.5m	Natural colour: Blue, Green, Red, Red-Edge, NIR	12 hours - 5 days
Maxar	Private	0.3m, 0.4m, 0.5cm, 0.6m, 1.2m, 2.0m	Panchromatic, 8 NIR bands (RGB, near-IR1/2, coast, yellow, red-edge), 8 SWIR bands, 12 CAVIS bands (for clouds, ice, and snow)	1-2 days

Resolutions offered by popular satellite imagery providers

From EO signal to agriculture information content

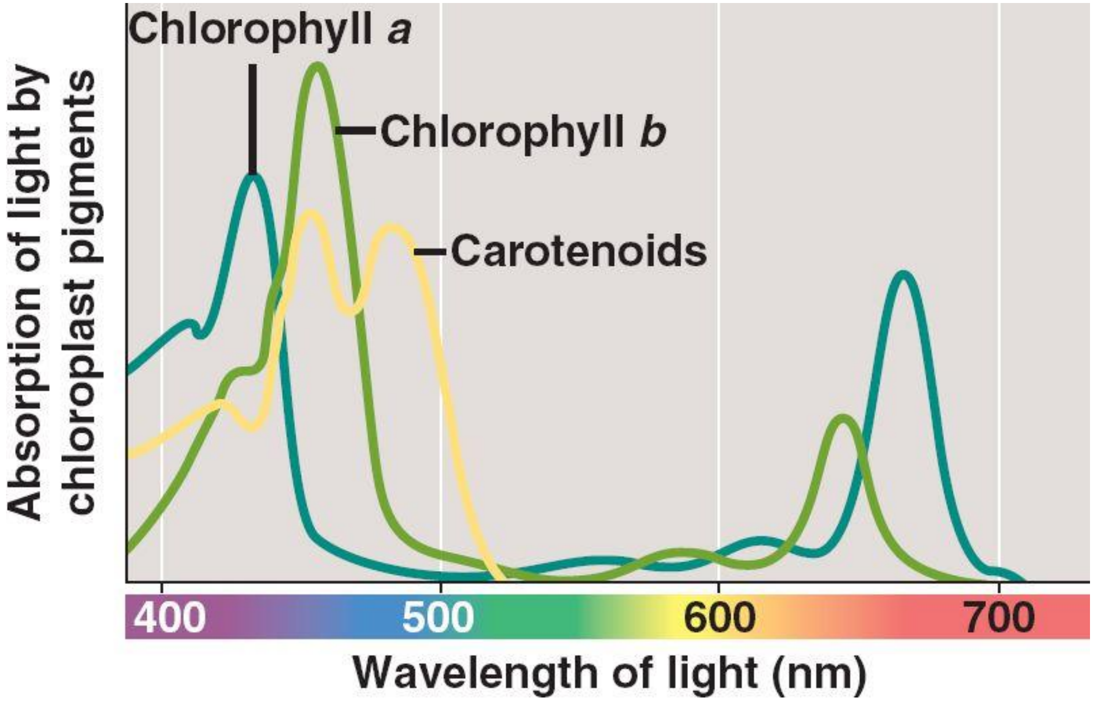
Spatial resolution



From EO signal to agriculture information content

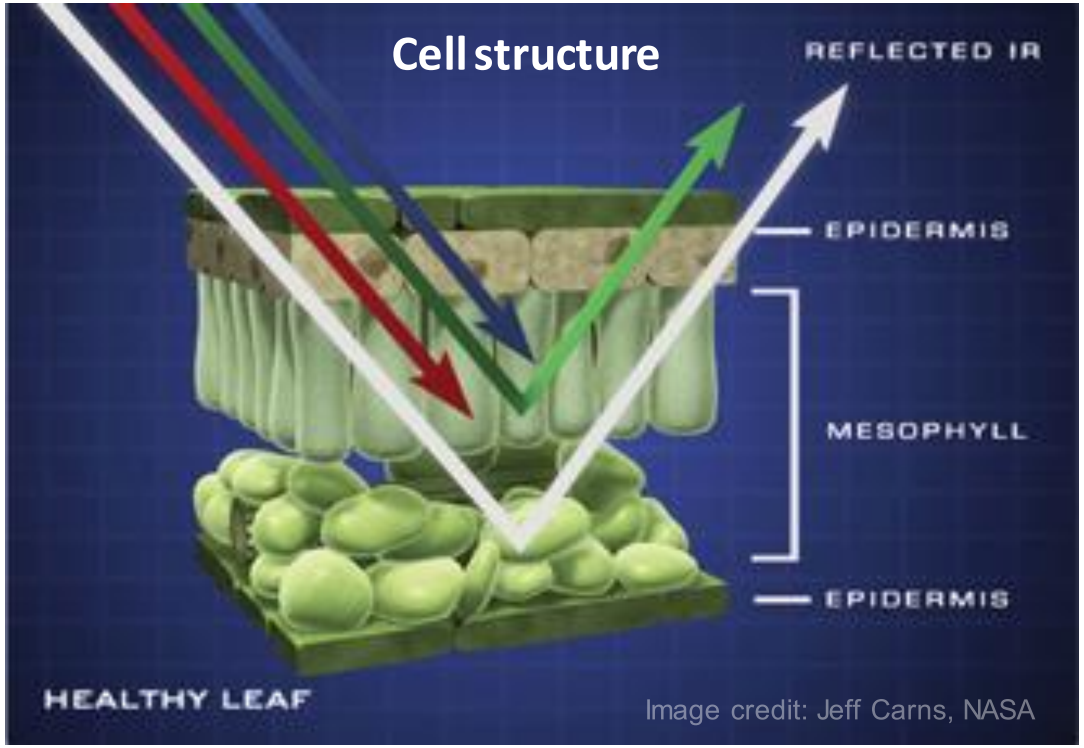
Spectral signature of the plants

Plant pigments

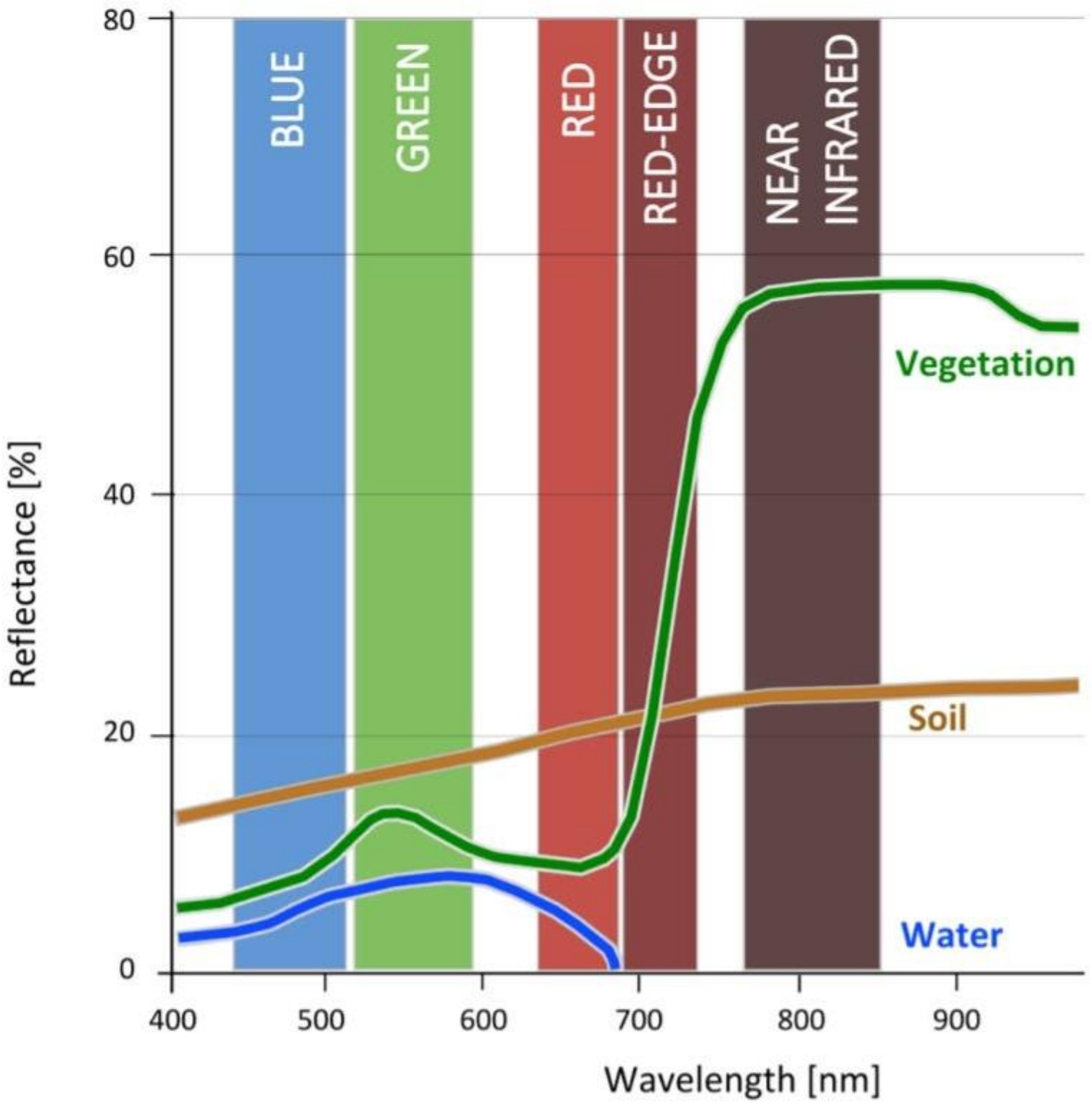


Chlorophyll predominately absorbs blue wavelengths (400-500 nm) and red (600-700 nm). Note that carotenoids absorb blue light as well as some green.

- Chlorophyll in the leaf preferentially absorbs blue and red light
- Green light is reflected (that's why healthy vegetation with lots of chlorophyll is green to our eyes)
- A healthy leaf cellular structure strongly reflects near-infrared light (to prevent cell demage)

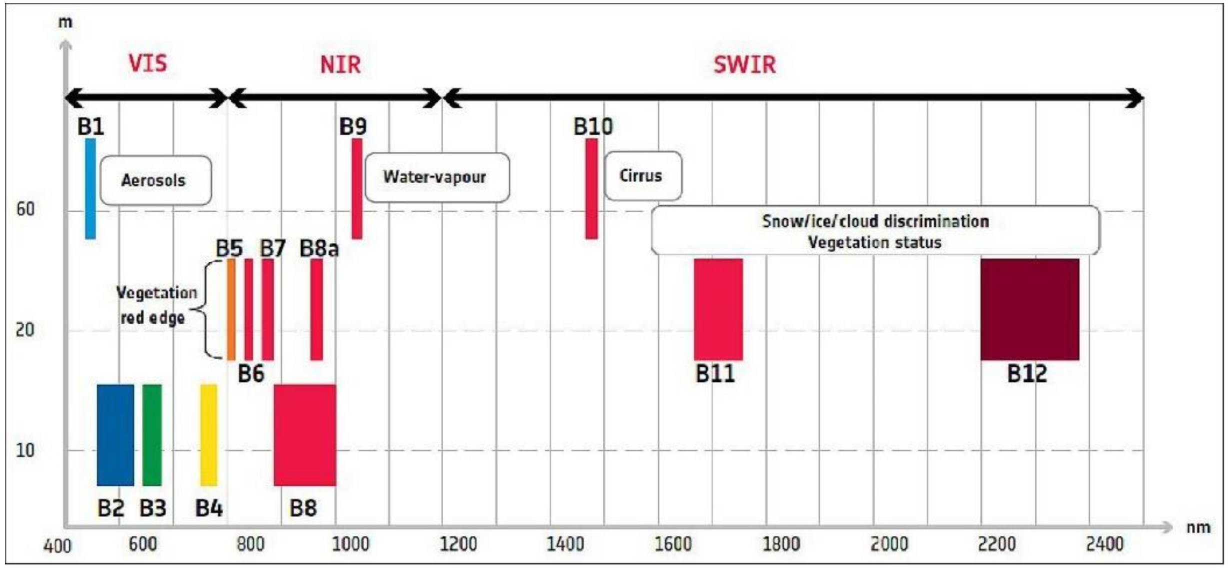


From EO signal to agriculture information content



RED EDGE

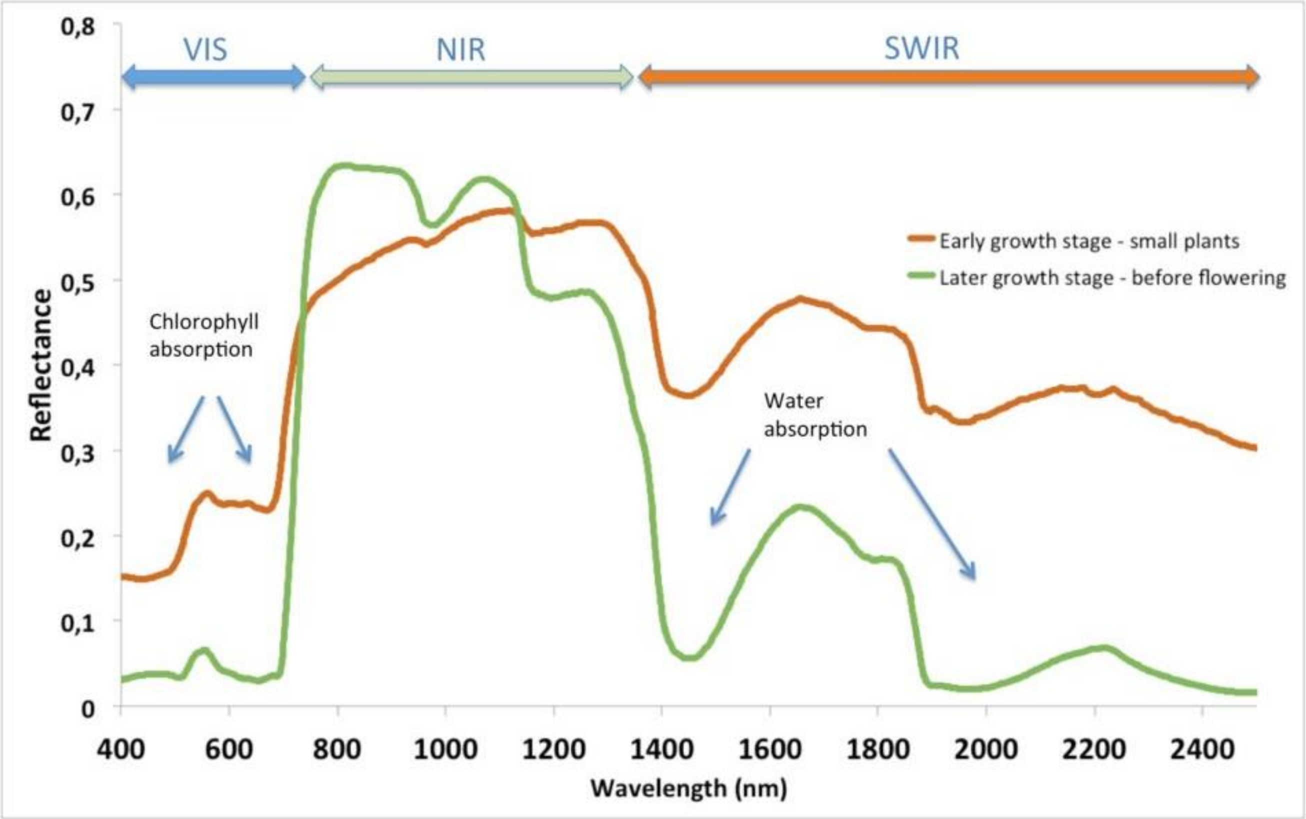
- The three 20m 'red edge' bands of Sentinel-2 provide key information on the state of vegetation
- Very narrow band (700 – 730 nm) corresponding to the red NIR transition zone
- Very sensitive to plant stress – provides information on the canopy chlorophyll and nitrogen content



From EO signal to agriculture information content

Spectral indices - to extract specific signal from spectral signature

- Particular wavelengths are sensitive to particular chemicals and compounds
- Indices take advantage of these wavelength features



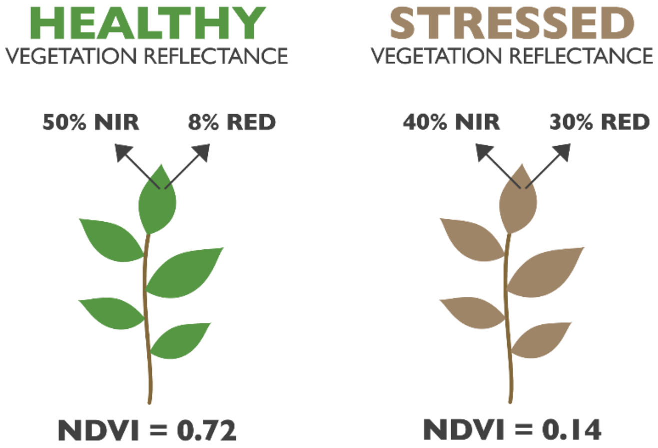
Vegetation indices:

- VI - Vegetation Index
- NDVI - Normalized Difference Vegetation Index
- EVI - Enhanced Vegetation Index
- SAVI - Soil Adjusted NDVI
- AVI - Advanced Vegetation Index
- NDMI - Normalized Difference Moisture Index
- …

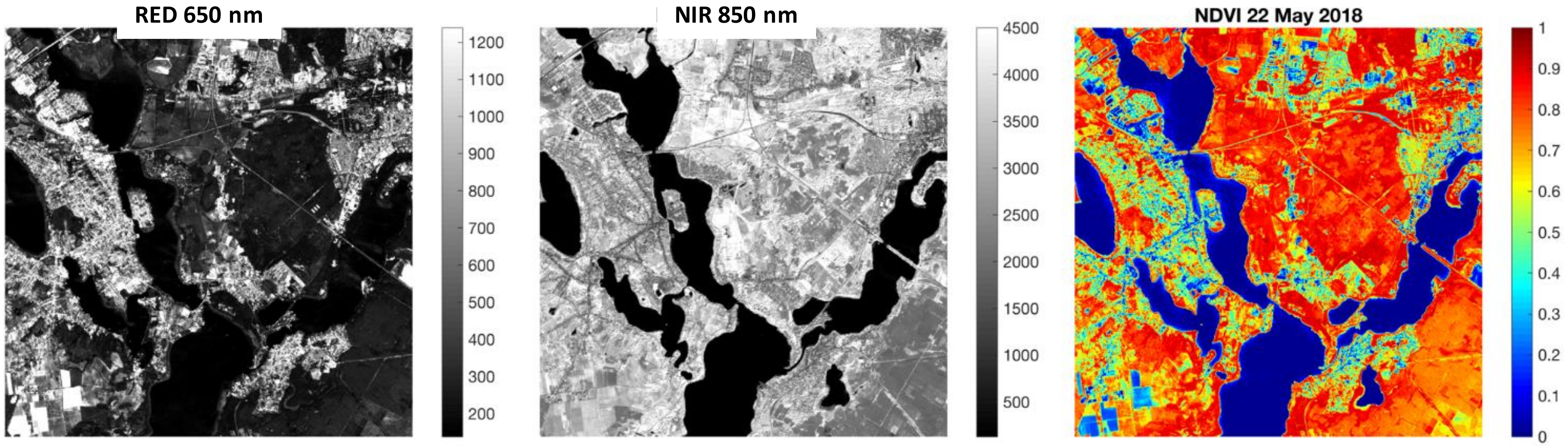
From EO signal to agriculture information content

NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

- Very popular in eco/geosciences
- Output values between -1.0 and 1.0
- Very low values (0.1 and below) = barren areas of rock, sand, snow
- Moderate values (0.2 to 0.3) = shrub and grassland
- High values (0.6 to 0.8) = temperate and tropical rainforests

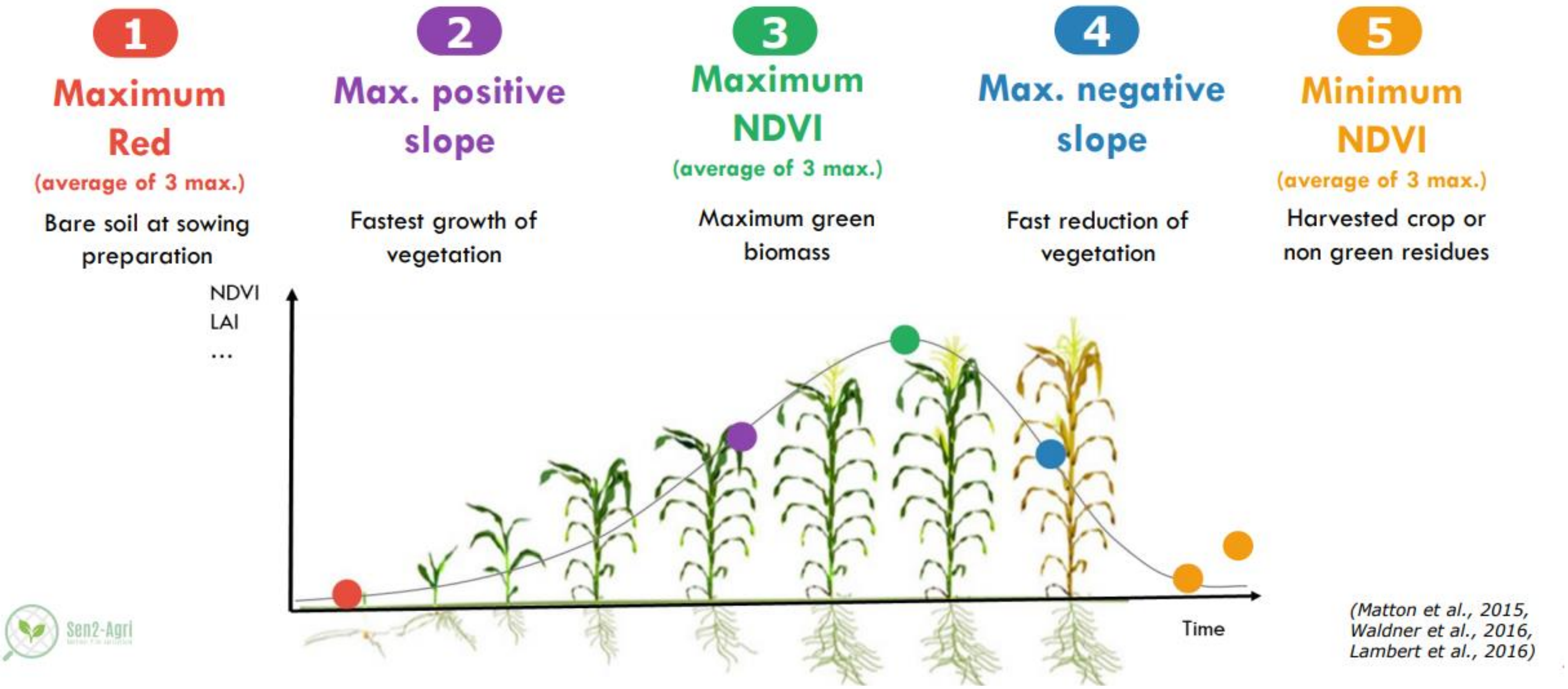


$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$



From EO signal to agriculture information content

NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI)

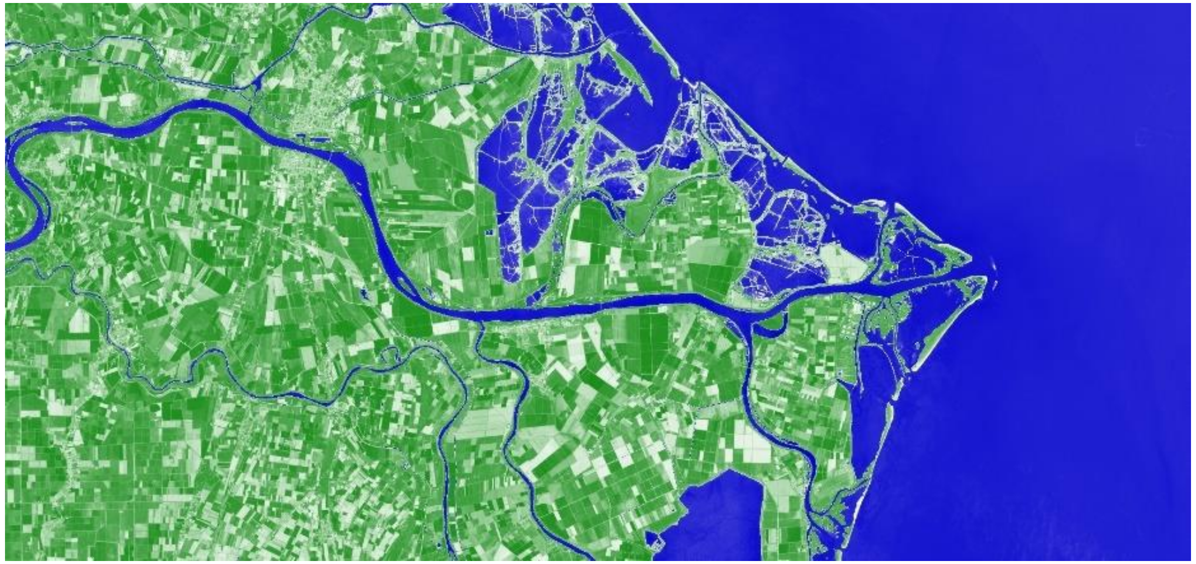


https://eo4society.esa.int/training_uploads/LTC2022/2_Tuesday/13_LTC22_ppt_CropType_DianeH.pdf

From EO signal to agriculture information content

NORMALIZED DIFFERENCE WATER INDEX (NDWI)

- Highly correlated with canopy water content and more closely tracked changes in plant biomass than the NDVI
- Used to monitor changes related to water content in water/plant bodies
- As water bodies strongly absorb light in visible to infrared electromagnetic spectrum, NDWI uses green and near infrared bands to highlight water bodies
- Index values greater than 0.5 usually correspond to water bodies. Vegetation usually corresponds to much smaller values and built-up areas to values between 0 - 0.2



NDWI of Italy. Acquired on 2020-08-01.

$$NDWI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$

From EO signal to agriculture information content

LIST OF INDICES FOR AGRICULTURE MONITORING USING SENTINEL-2 DATA

Vegetation indices

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

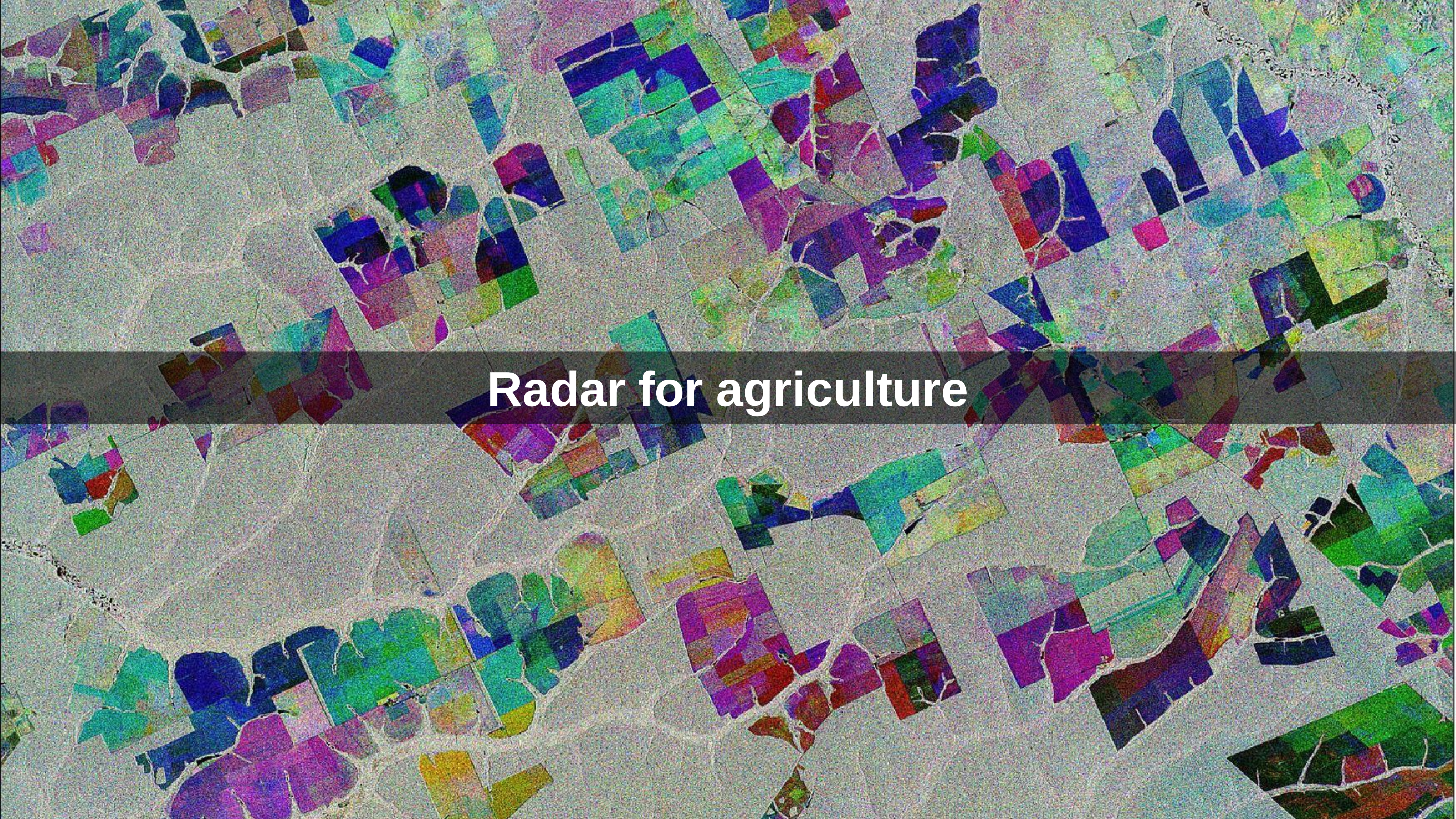
Soil indices

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

Water indices

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

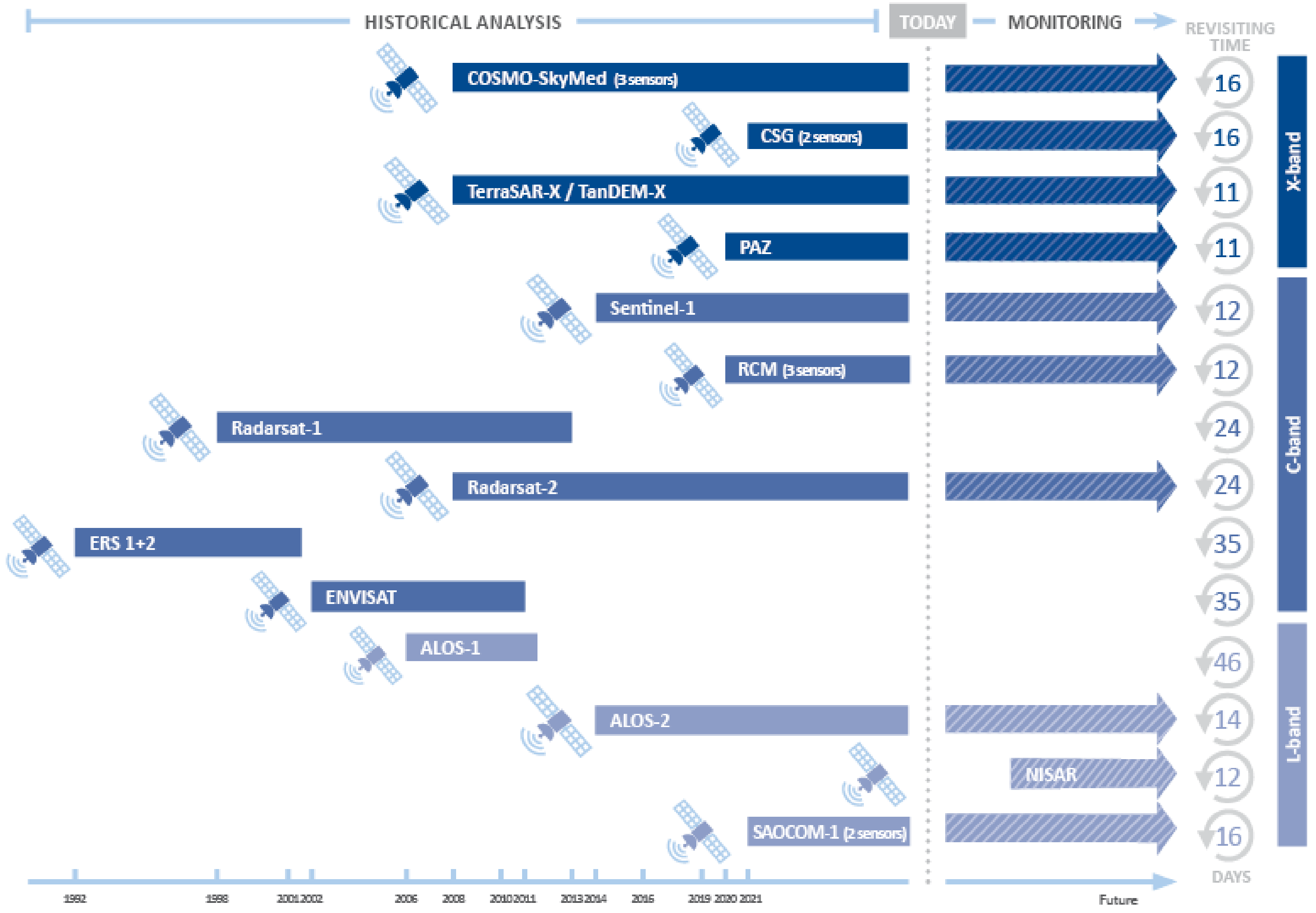
https://eo4society.esa.int/training_uploads/LTC2022/2_Tuesday/13_LTC22_ppt_CropType_DianeH.pdf


Radar for agriculture

SAR sensors for agriculture

Main satellites carrying SAR sensors:

- ENVISAT ASAR - spaceborne SAR operated by the ESA
- ERS-1, ERS-2 SAR - operated by ESA
- SENTINEL-1A -B (ESA, Copernicus program)
- RADARSAT-1, 2- spaceborne SAR operated by the Canadian Space Agency (CSA).
- ALOS-PALSAR 2 - SAR L- band operated by the Japanese Space Agency
- COSMO SKY_MED - X band operated by Italian Space Agency for civil protection purposes
- TERRASAR-X - X band operated by DLR



https://site.tre-altamira.com/company/our-technology/

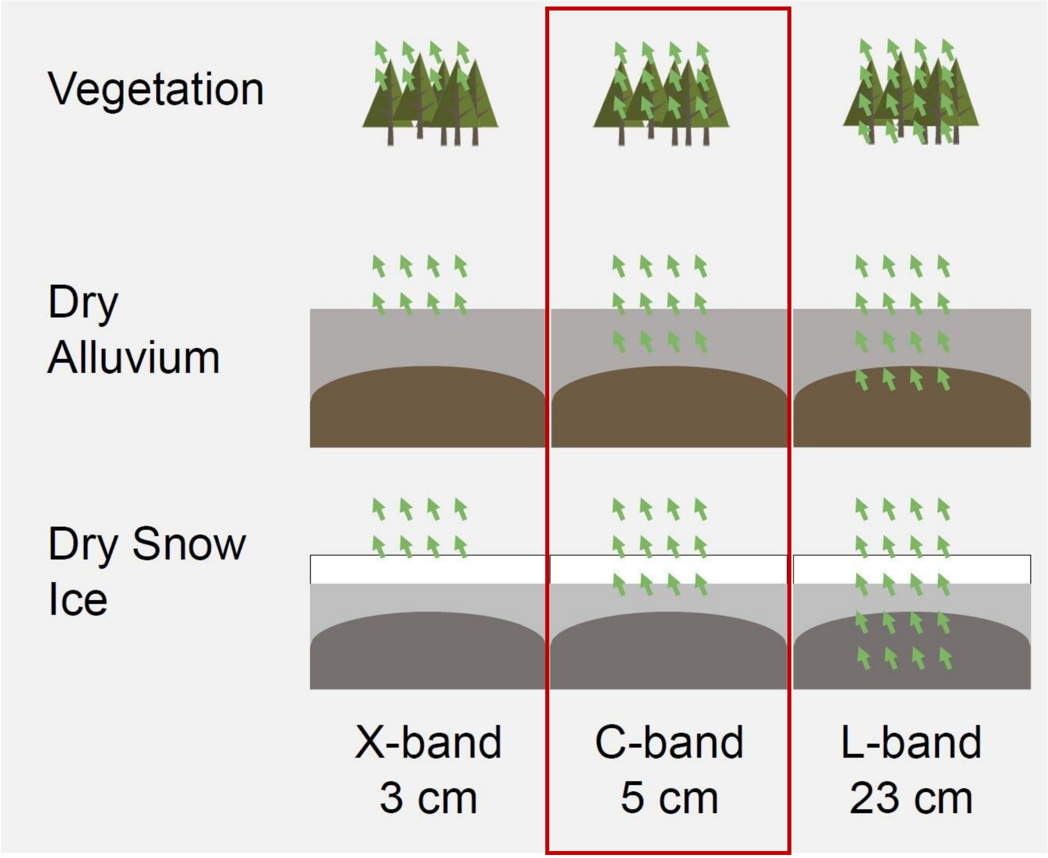
Radar Parameters to Consider in Precise Agriculture

Penetration through vegetation as a Function of Wavelength and dielectric characteristics

- The penetration depth is depending on **wavelength** and **dielectric characteristics** of objects
- Penetration is the predominant consideration when selecting a wavelength
- Typically, longer wavelengths result in greater penetration into the target

Agricultural monitoring

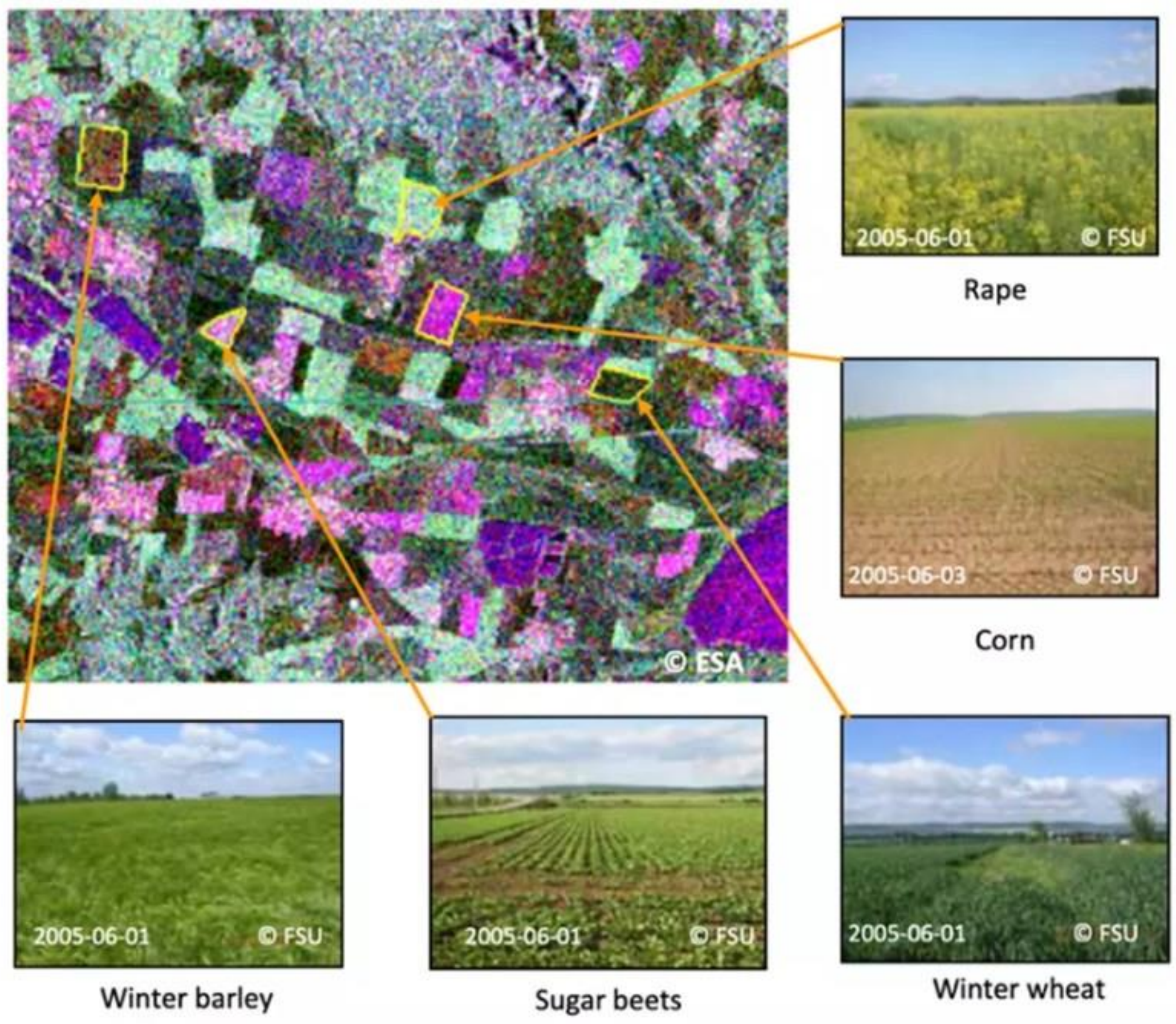
- For agricultural monitoring we need enough penetration into canopy (L- or C-band), but not to deep so that we have soil interference (C- or X-band for lower biomass)



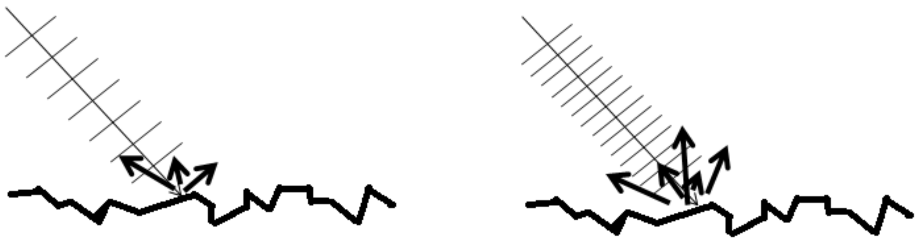
Source:https://medium.com/@preet.balaji20/decoding-synthetic-aperture-radar-sar-remote-sensing-sar-series-part-1-getting-started-d3409eb3b2e3

Radar Parameters to Consider in Precise Agriculture

Radar backscaterring



- The intensity of backscattered energy typically increases with surface roughness



The surface appears smooth to long wavelength
=> Backscattering is low

The surface appears rough to shorter wavelength
=> Backscattering increases

- SAR responds to changes in structure and moisture

https://appliedsciences.nasa.gov/sites/default/files/2020-11/SAR_Part3.pdf,
https://www.groundstation.space/tech/sar-satellites-for-agriculture/

Radar – Multiple frequencies

- **Classification is best with higher frequencies (shorter wavelengths**) as this provides best opportunity for multiple scattering within the canopy
- X-Band provides excellent classification results

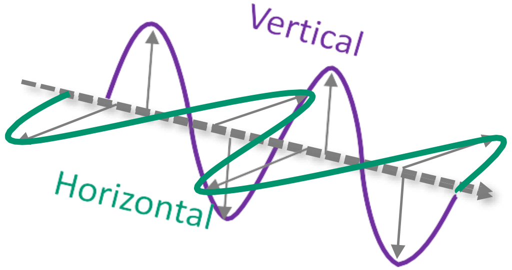
X (3.1 cm)
C (5.5 cm)

RADARSAT-2 VH - July 10, 2016
TerraSAR-X VV - July 10, 2016
ALOS VH - July 9, 2016

Integration of Data from RADARSAT-2, ALOS, and TerraSAR-X, Manitoba (Canada)

Radar Parameters to Consider in Precise Agriculture

Polarisation

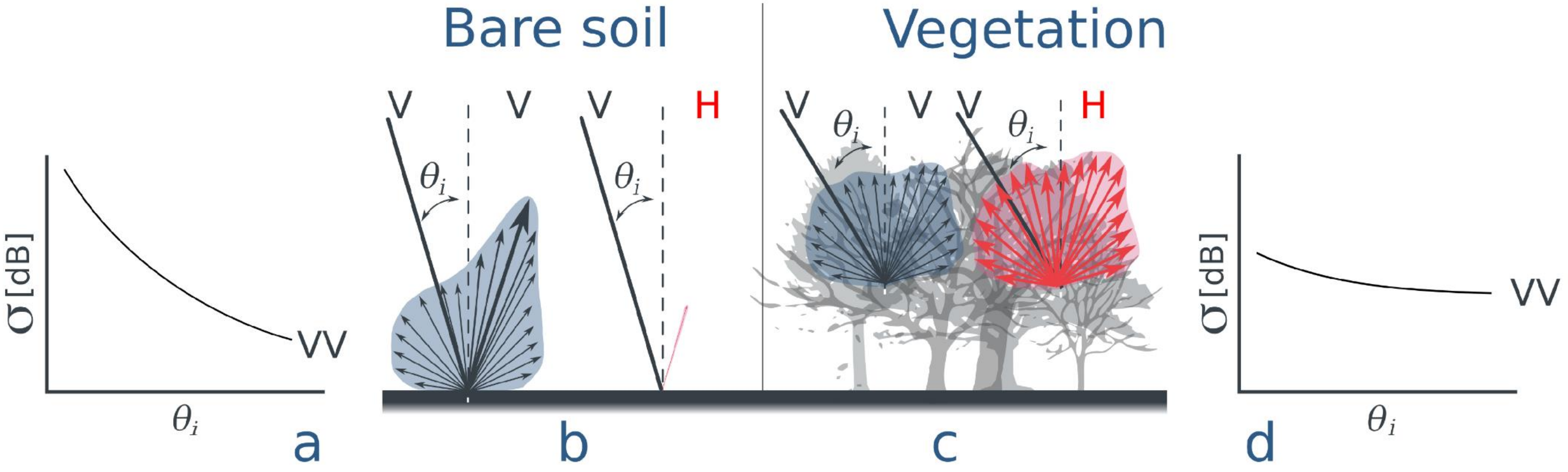


The radar signal is polarised:

Radar: ***transmits*** a EMW in a given polarization
measures the backscattered wave contribution in a given polarization

Vegetation has a predominant vertical structure:

- V-polarized waves align closely with this structure - increased scattering
- H-polarized waves encounter less interaction with the vertically oriented target, allowing more energy to penetrate through the canopy and reach the ground



Scattering mechanisms of VV and VH polarized backscatter, where (**a**,**b**) show the relation between backscatter and incidence angle and scattering mechanisms for bare soils, and (**c**,**d**) the relation between backscatter and incidence angle and scattering mechanisms for vegetation.
https://www.mdpi.com/2072-4292/12/20/3404

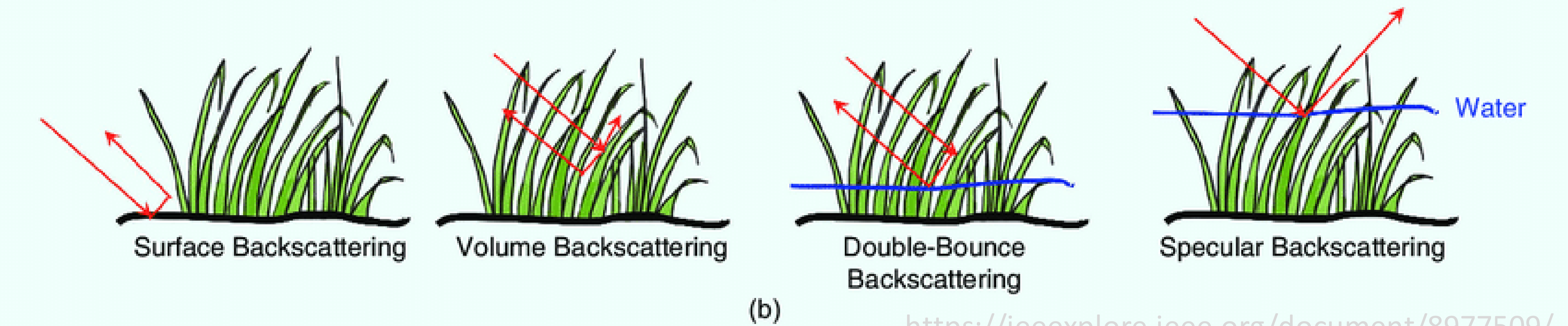
Radar Parameters to Consider in Precise Agriculture

Vegetation effects

Scattering of longer-wavelength microwaves is driven by:
- orientation of leaves, stems
- the volume of water in the vegetation

These scattering effects determine how much of the energy will return back to the SAR sensor and how the phase between e.g. H and V components will change

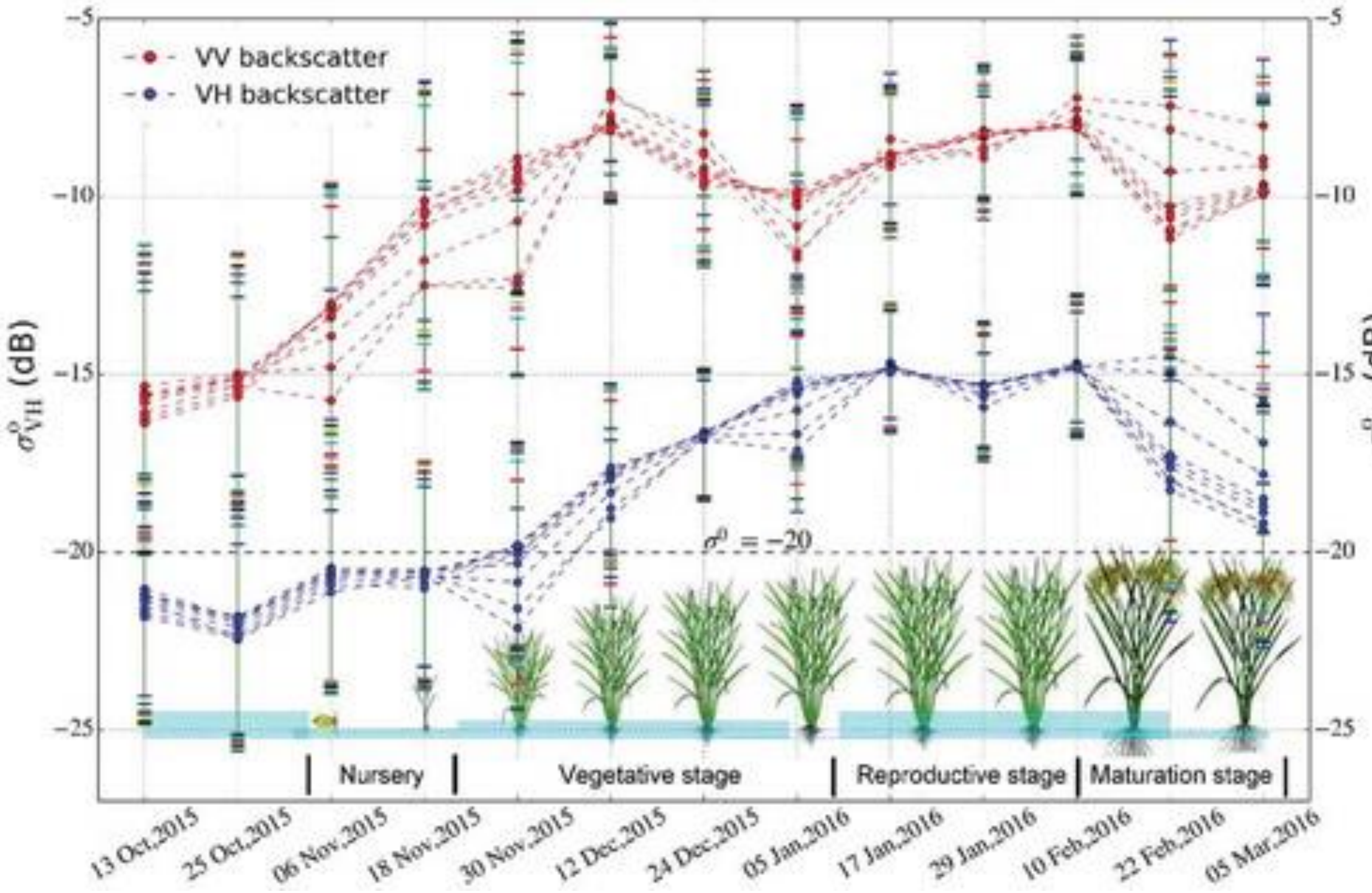
Following a wave into a canopy, it may scatter as below:



https://ieeexplore.ieee.org/document/8977509/

Radar Parameters to Consider in Precise Agriculture

Density of SAR time series

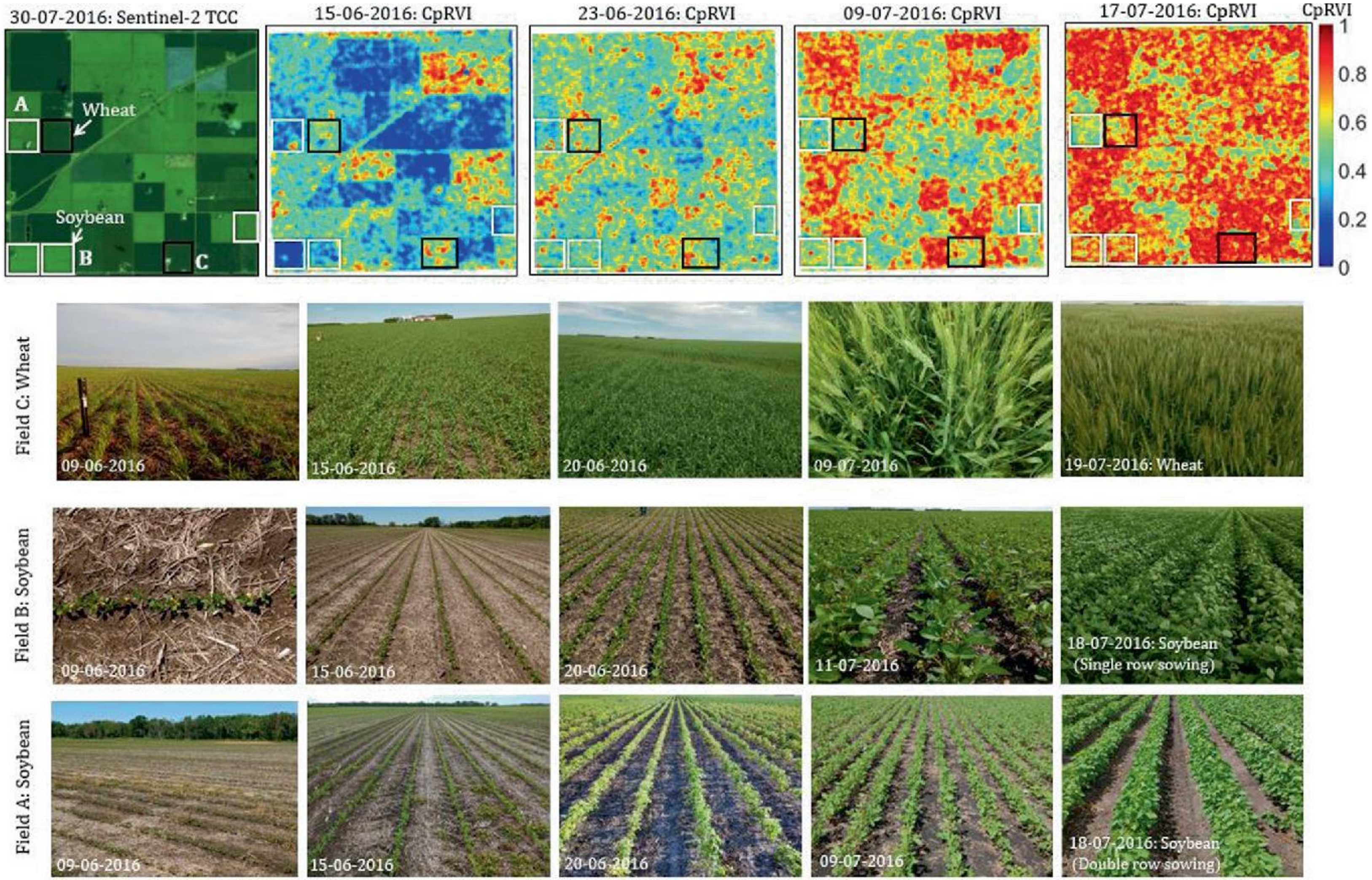


- SAR backscattering
- SAR coherence

https://www.tandfonline.com/doi/full/10.1080/2150704X.2016.1225172

Radar and Optical in Precise Agriculture - Applications

Spatio-temporal variations

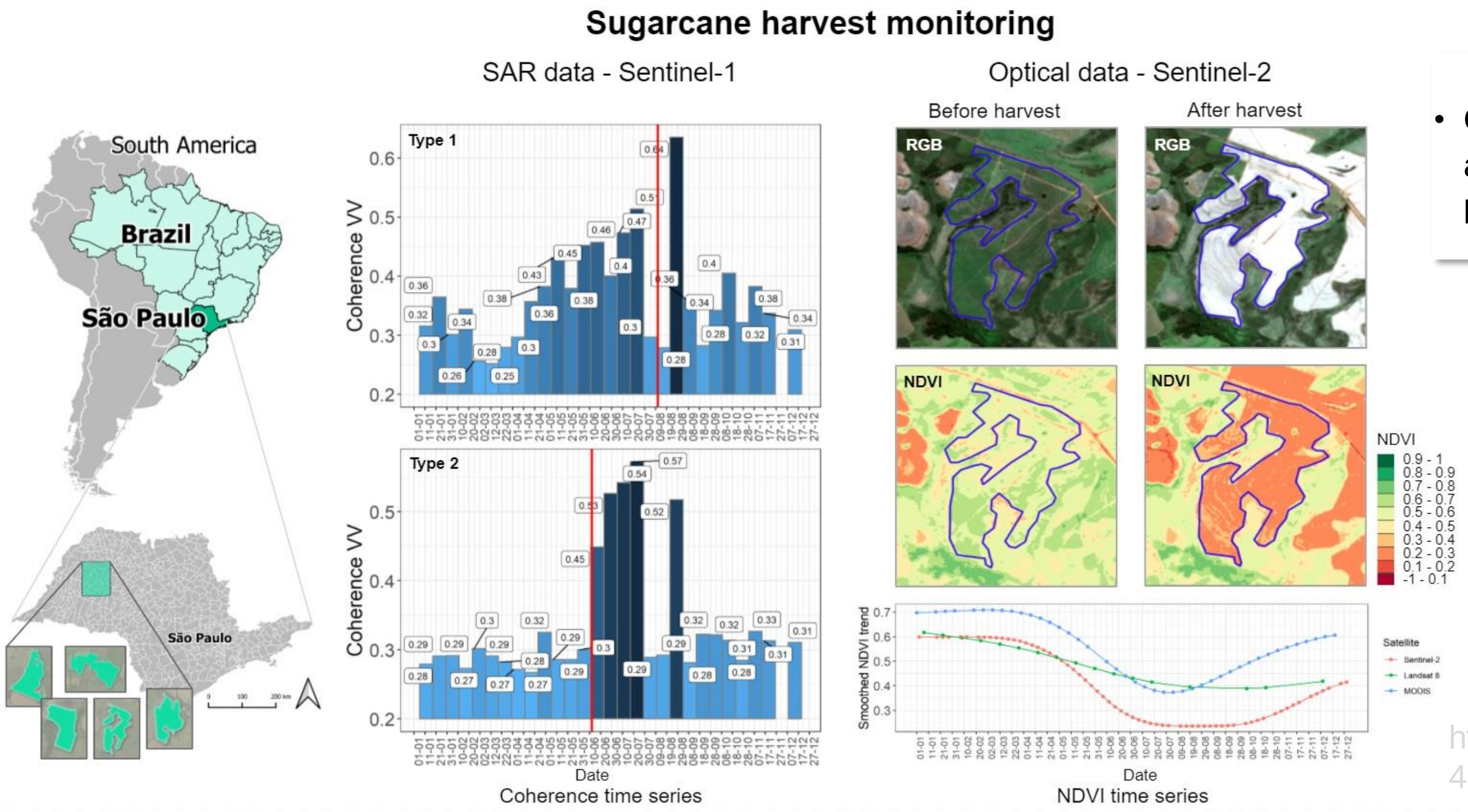


- Combined use of SAR and Optical data
- Spatio-temporal variations of CpRVI within the wheat and soybean fields. The black and white polygons show the sampling fields of wheat and soybean, respectively. The field photos during the campaign at specific instances are presented for wheat and soybean.

https://link.springer.com/chapter/10.1007/978-981-16-4424-5_7/figures/18

Radar and Optical in Precise Agriculture - Applications

Harvest monitoring

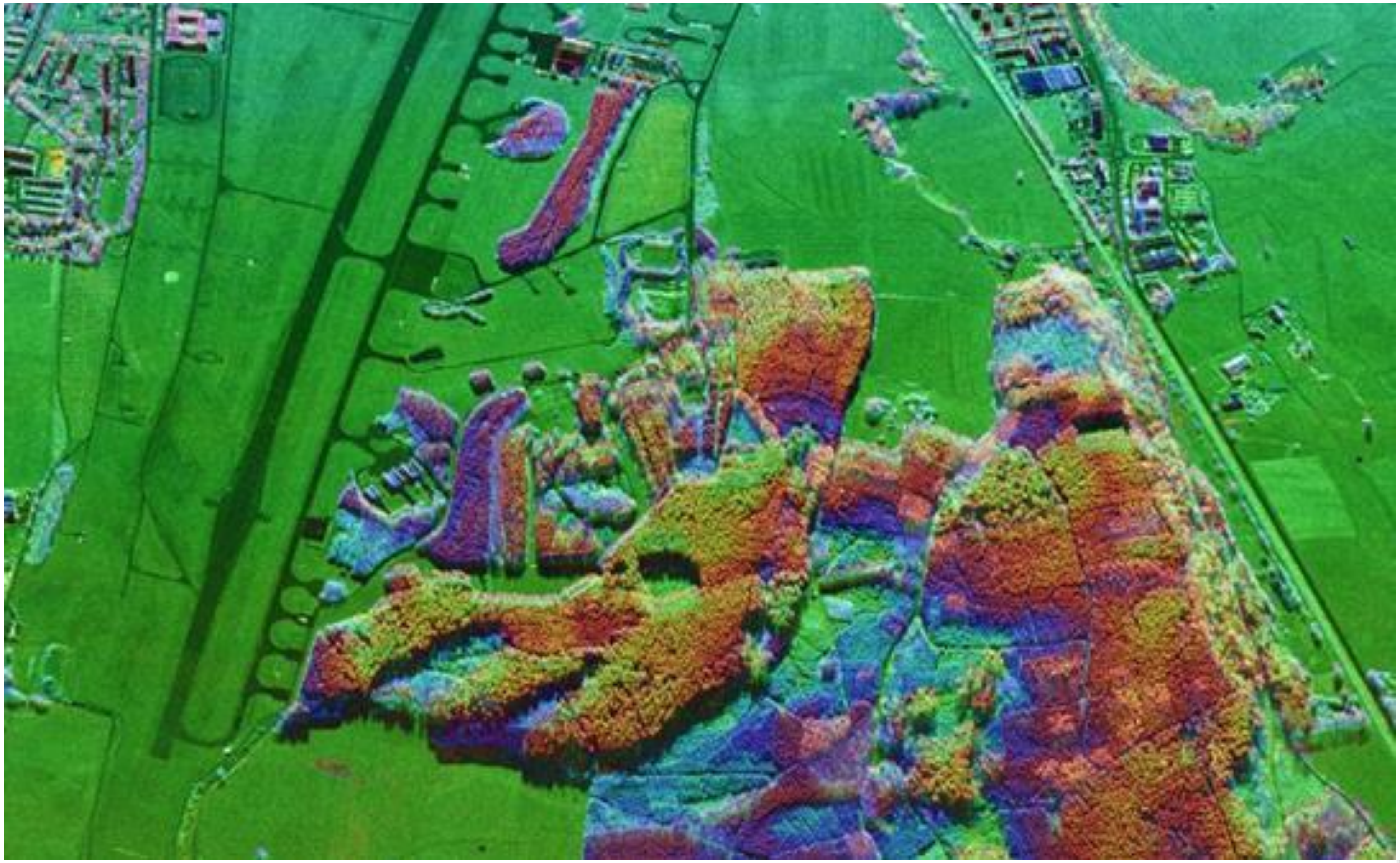


- Combined use of SAR and Optical data for harvest monitoring

https://www.mdpi.com/2072-4292/12/24/4080#

Radar and Optical in Precise Agriculture - Applications

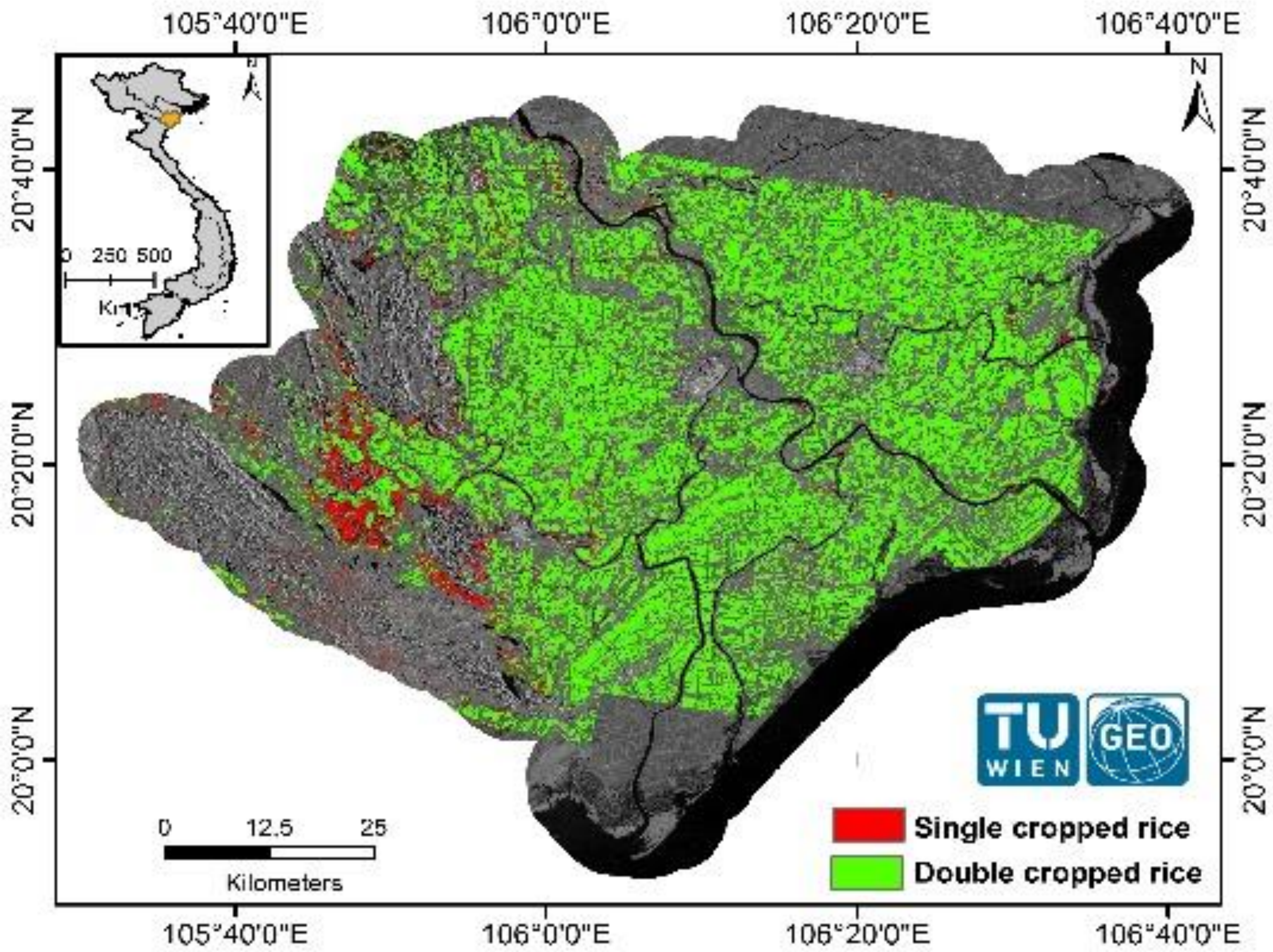
Estimation of crop condition using POLinSAR



POLinSAR, a technique that combines polarimetry, involving varying the orientation of radar signals, with interferometry, which analyzes phase differences in the signal, to generate differential range and range-change measurements from two or more images captured by synthetic aperture radars (SARs). This combined approach enables the visualization of the Earth in three dimensions. CREDIT: ESA

Radar and Optical in Precise Agriculture - Applications

Cropping systems

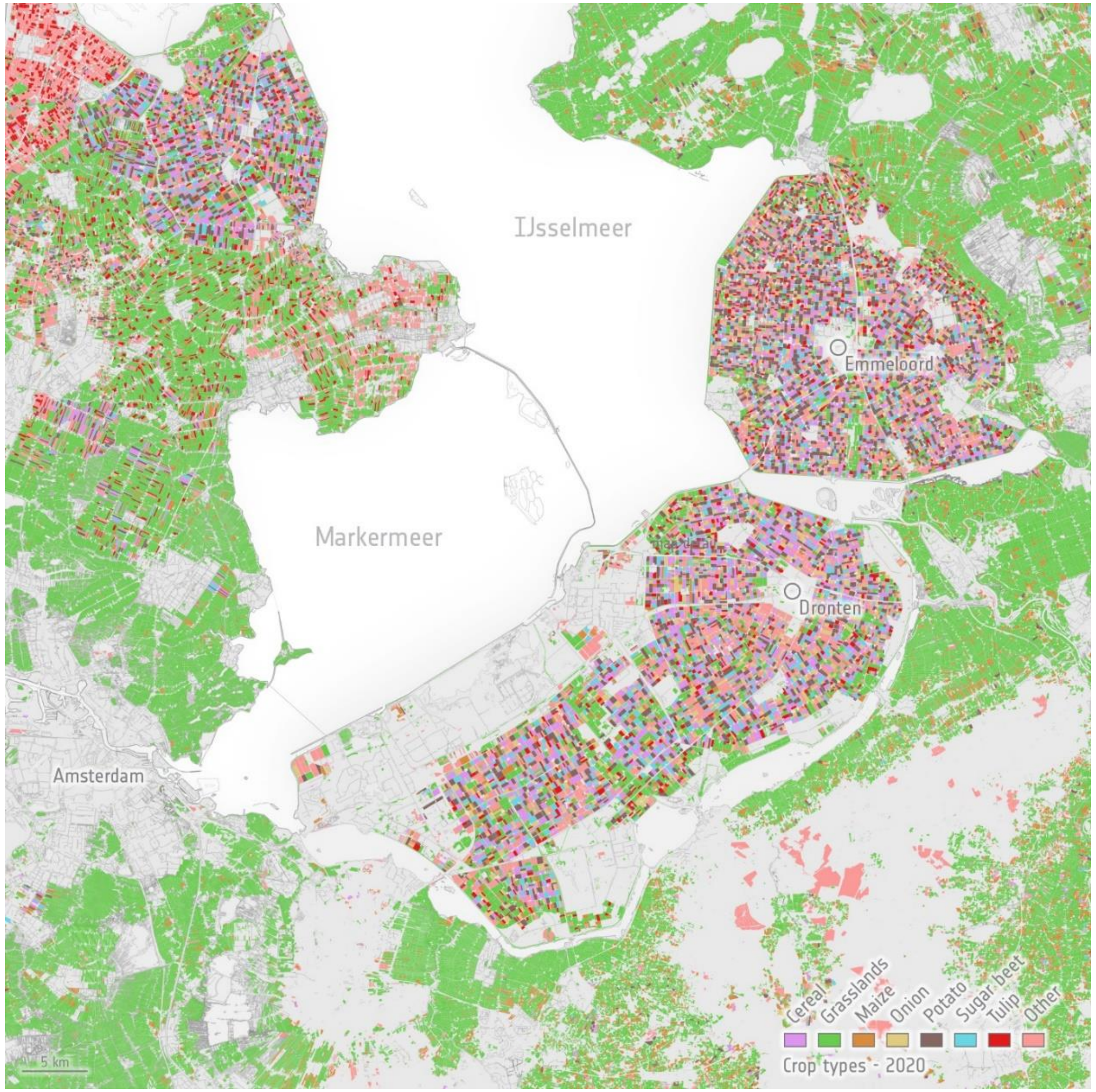


Rice-cropping systems in Vietnam's Red River Delta

Intra-annual Sentinel-1 data from January 2015 to December 2015 were used to produce rice-cropping systems map in the Red River Delta, Vietnam. In this case study, a significant area of rice paddies grows two crops per year (green). The remaining areas, in mountainous and riverine regions (red), are where the long-term flooded or saturated soil conditions permitted only one crop of rice per year.

Radar and Optical in Precise Agriculture - Applications

Monitoring of crop types



Crop type for all agricultural parcels Flevoland in the Netherlands

This figure zooms in on Flevoland in the Netherland to illustrate individual crop parcels. ESA worked with the Delft University of Technology in the Netherlands to develop Agricultural Sandbox NL, which makes use of radar data from Copernicus Sentinel-1 and optical, or camera-like, data from Copernicus Sentinel-2 and reduces terabytes of satellite data to just 10 gigabytes per year. Importantly, this dataset tool makes these data perfect for non-expert data users in the agriculture sector.

CREDIT
ESA/Crop Parcel Base Register, Dutch Ministry of Economic Affairs and Climate Policy

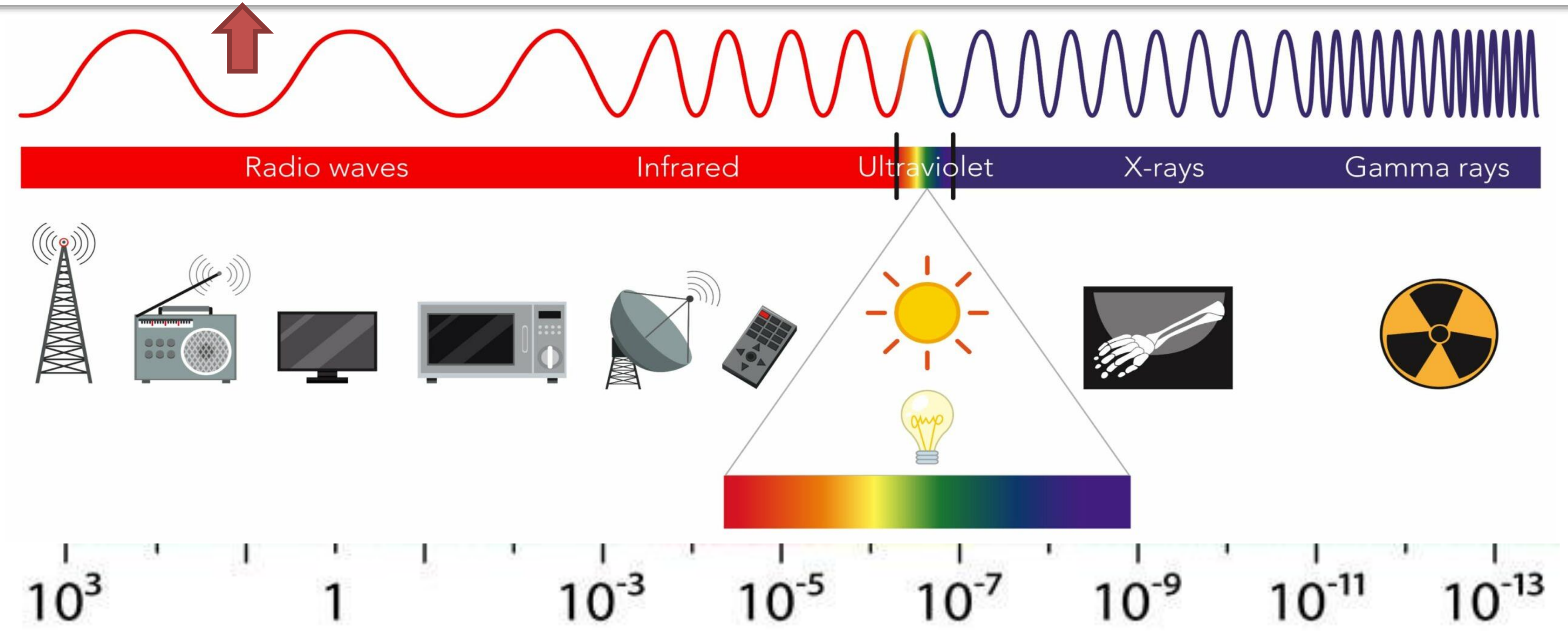
For more information, see the tutorial:
5. Crop Classification with S1 and S2 data using the SNAP software

6. SAR and optical remote sensing for precision agriculture 2

SAR and optical for precise agriculture

RADAR SATELLITES
Weather & illumination independence
Penetration through cloud cover

Use: information about the vegetation structure and moisture content



OPTICAL SATELLITES
Weather & illumination dependence
No penetration through cloud cover

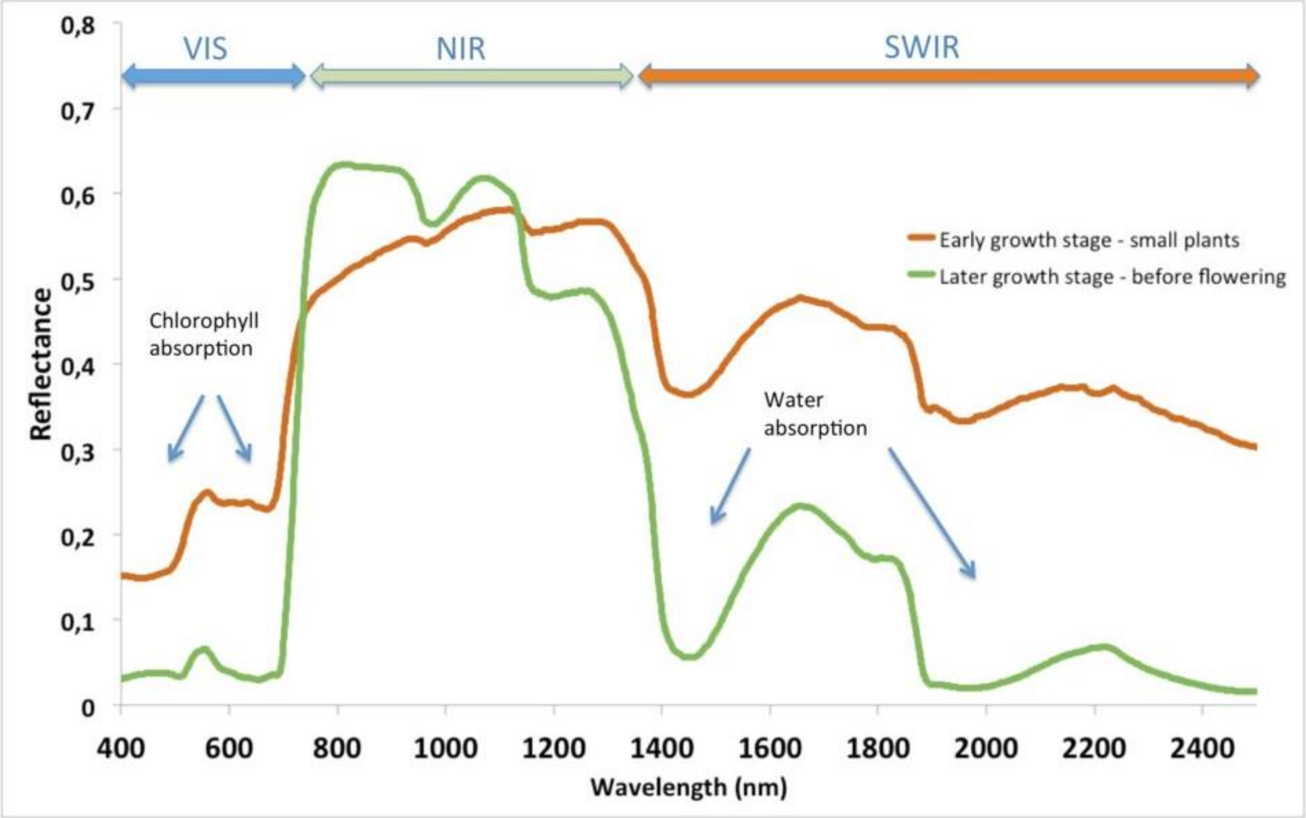
Use: spectral (and chemical) properties of vegetation

Source:https://cthrumetals.com/emi-shielding/

From EO signal to agriculture information content

Optical Sensors: Spectral indices - to extract specific signal from spectral signature

- Particular wavelengths are sensitive to particular chemicals and compounds
- Indices take advantage of these wavelength features



Vegetation indices:

- VI - Vegetation Index
- NDVI - Normalized Difference Vegetation Index
- EVI - Enhanced Vegetation Index
- SAVI - Soil Adjusted NDVI
- AVI - Advanced Vegetation Index
- NDMI - Normalized Difference Moisture Index
- …

From EO signal to agriculture information content

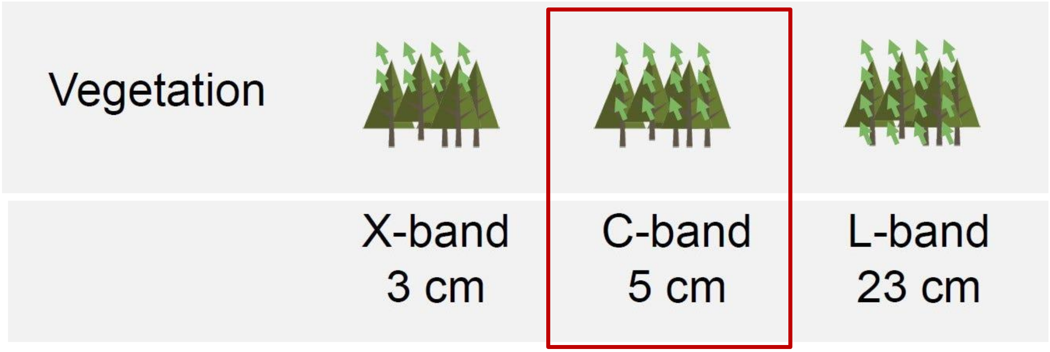
Penetration through vegetation as a Function of Wavelength and dielectric characteristics

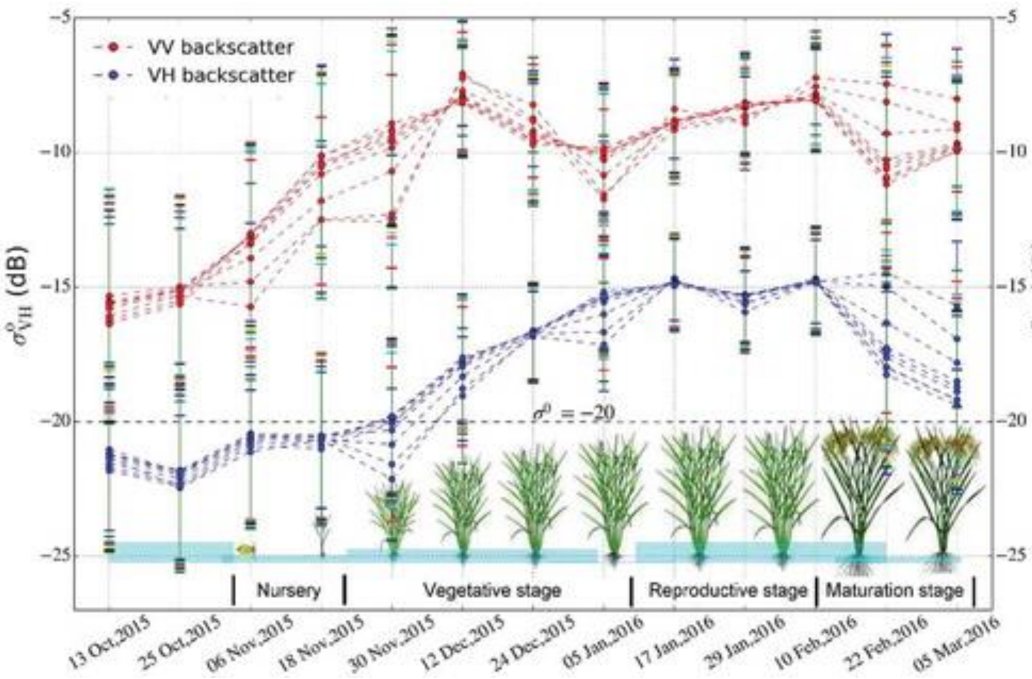
- The penetration depth is depending on **wavelength** and **dielectric characteristics** of objects

Agricultural monitoring

- For agricultural monitoring we need enough penetration into canopy (L- or C-band), but not to deep so that we have soil interference (C- or X-band for lower biomass)
- information about the vegetation structure, moisture content, spatio-temporal changes, harvest time

Source:https://medium.com/@preet.balaji20/decoding-synthetic-aperture-radar-sar-remote-sensing-sar-series-part-1-getting-started-d3409eb3b2e3





From EO signal to agriculture information content

Biophysical variables estimation for agriculture applications

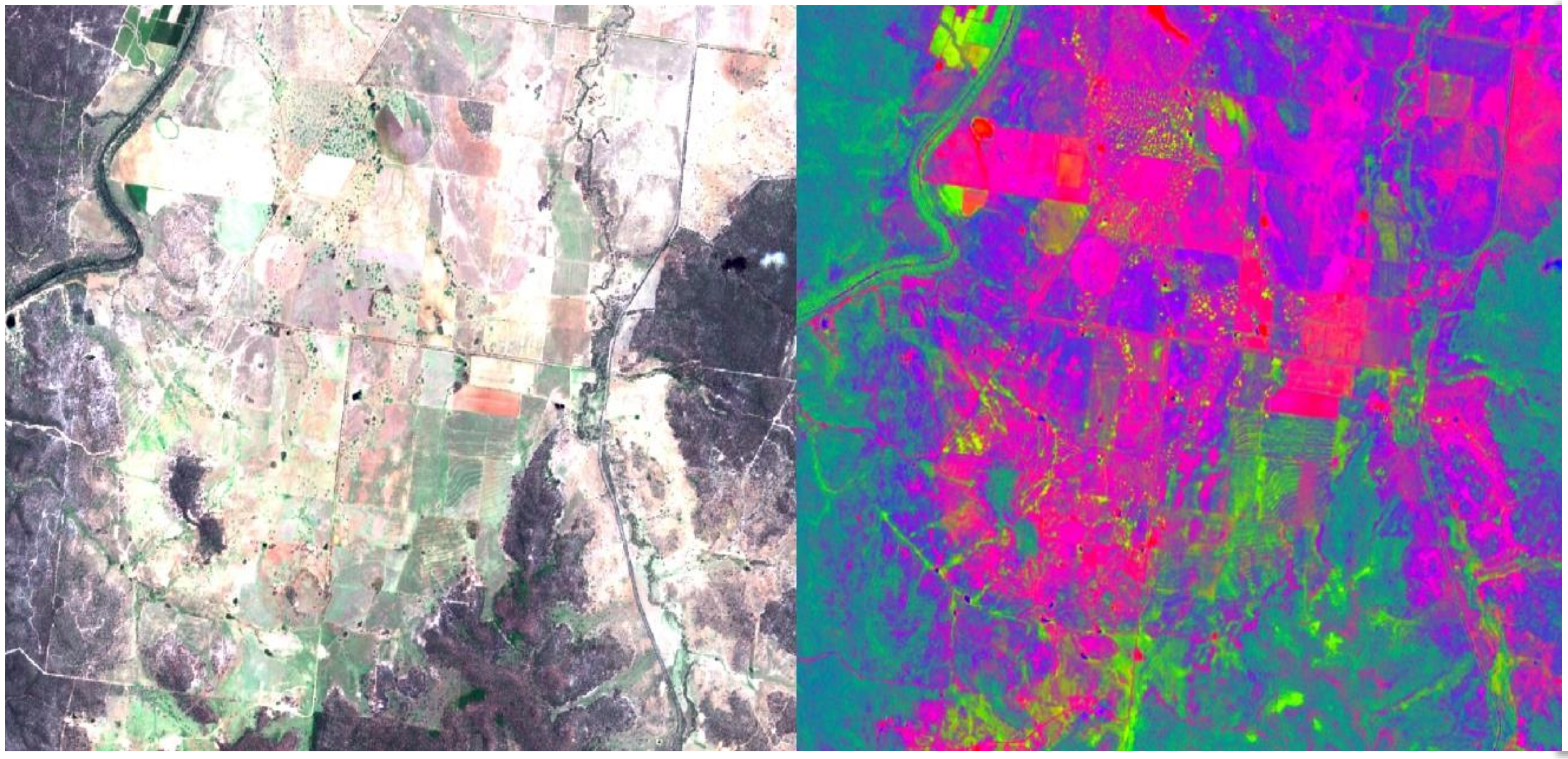
Biophysical variables are plant traits or characteristics of interest which can be measured on the ground and possibly estimate by remote sensing at various scales depending of the sensor spatial resolution

Crop processes	LAI	FAPAR	FCOVER	Albedo	Chlorophyll	Water-content	SLA	soil brightness	Temperature
Photosynthesis	+++	+++			+++		++		
Evapotranspiration	++	+++	+++	++		++			+++
Respiration	++								
Nitrogen	+++				+++				
Phenology	+++	++	++						
Lodging									
Impact of pests	+++								
Soil permanent charac.								+++	
Residues									

From EO signal to agriculture information content

Fraction of green Vegetation Cover – FCover

- Corresponds to the fraction of ground covered by green vegetation
- Quantifies the spatial extent of the vegetation
- Independent of the geometry of illumination (unlike FAPAR)



The image on the left is a true-colour (red, green, blue) Sentinel-2 reflectance image. The darker areas are woodlands. The image on the right shows the same imagery, transformed using a model originally developed for Landsat which estimates fractional vegetation cover from the reflectance values. On each pixel, the proportions of red, green and blue represent the proportion of bare ground, live vegetation and dead vegetation respectively.

From EO signal to agriculture information content

Fraction of Absorbed Photosynthetically Active Radiation - FAPAR

- Quantifies the fraction of the solar radiation absorbed by live leaves for the photosynthesis activity.
- It refers only to the green and alive elements of the canopy
- Depends on the canopy structure, vegetation element optical properties, atmospheric conditions, and angular configuration

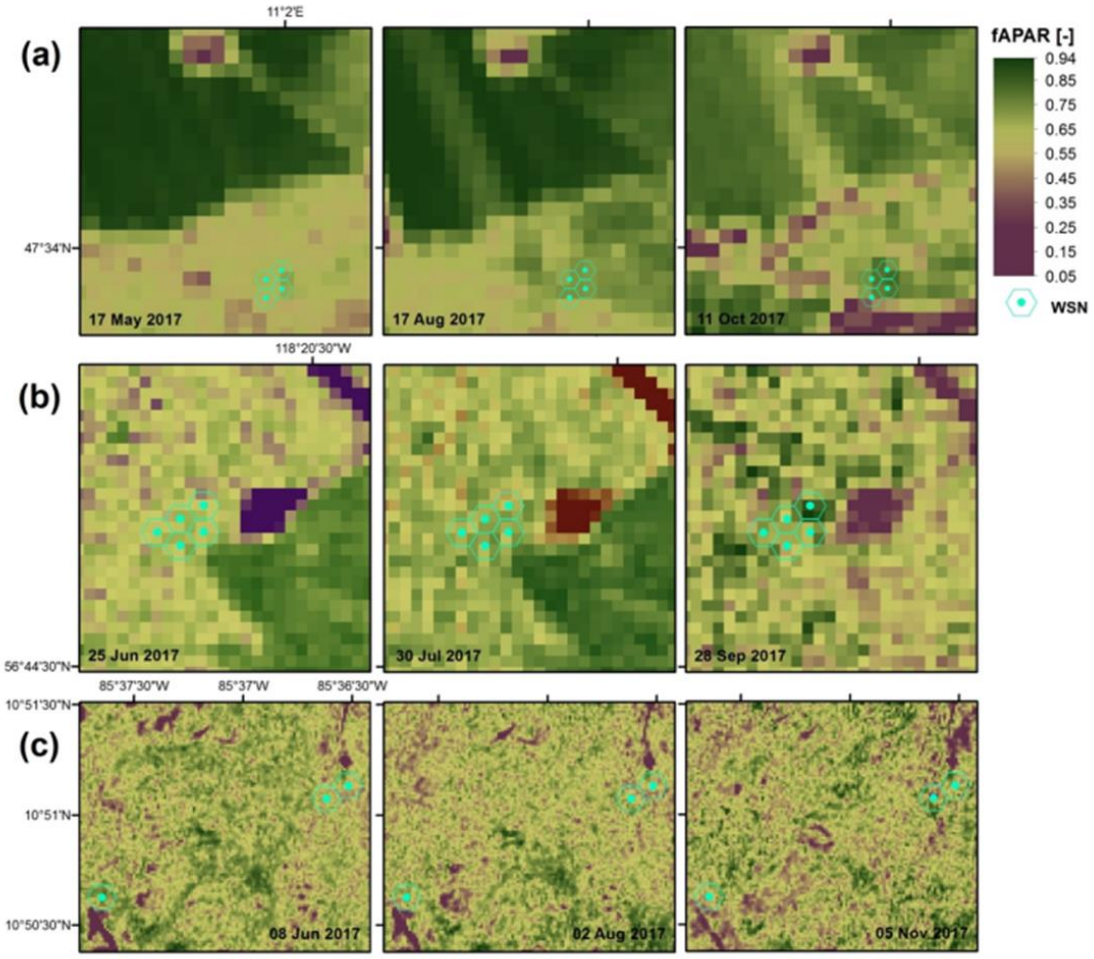


Fig. 7. The S2 fAPAR products at (a) Graswang, (b) Peace River and (c) Santa Rosa for several dates, representing early, peak and end of vegetation periods.

From EO signal to agriculture information content

Canopy Chlorophyll Content (CCC)

The **total amount of chlorophyll a and b pigments** in a contiguous group of plants per unit ground area (in g/m²)

- Closely related to the plant nitrogen content (fertilization)
- Absorption at 675 nm very sensitive to changes in chlorophyll content but only for low CCC values
- Lower chlorophyll absorption at 550 nm, sensitive to a greater range of CCC , not easily saturated but less sensitive to chlorophyll changes

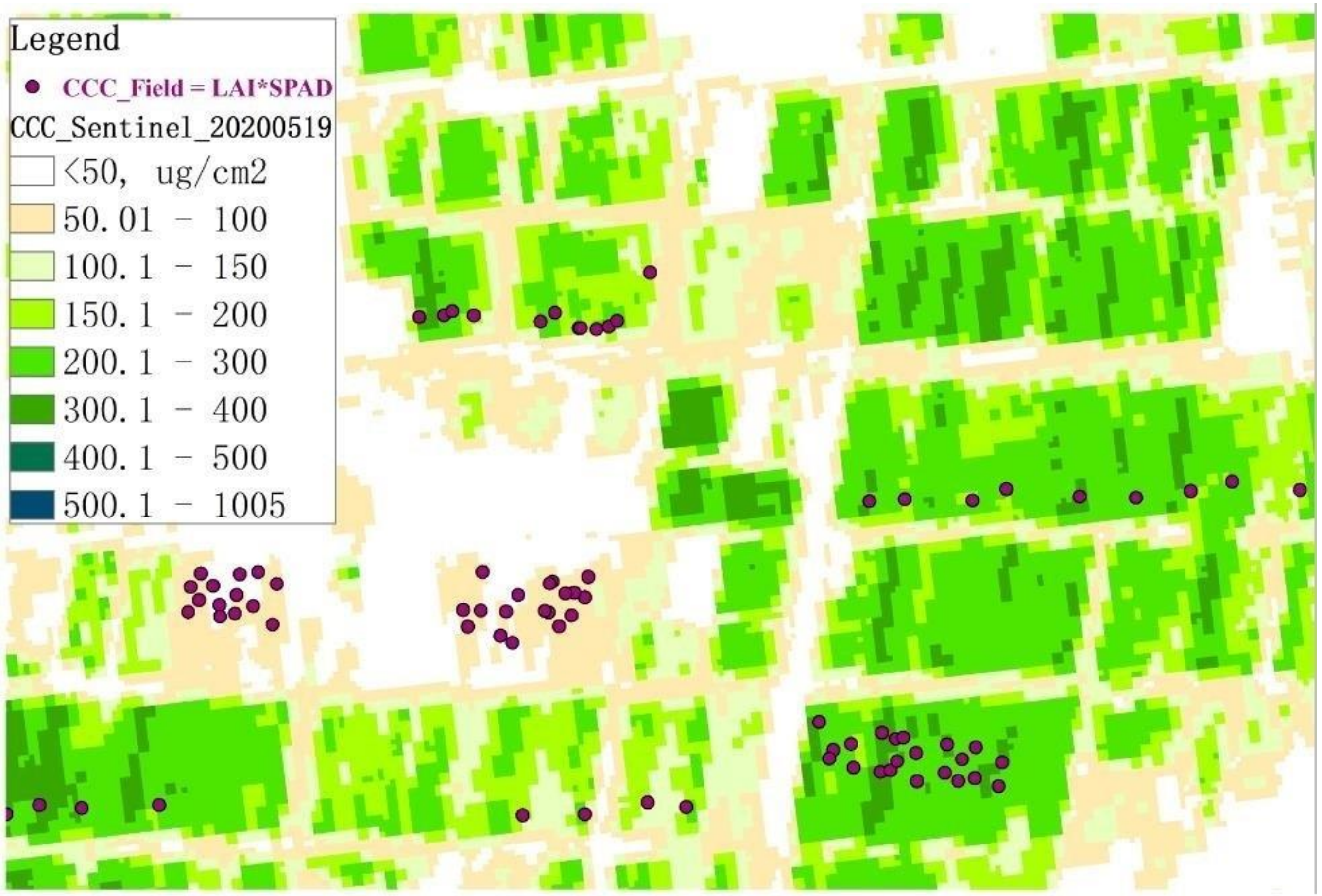
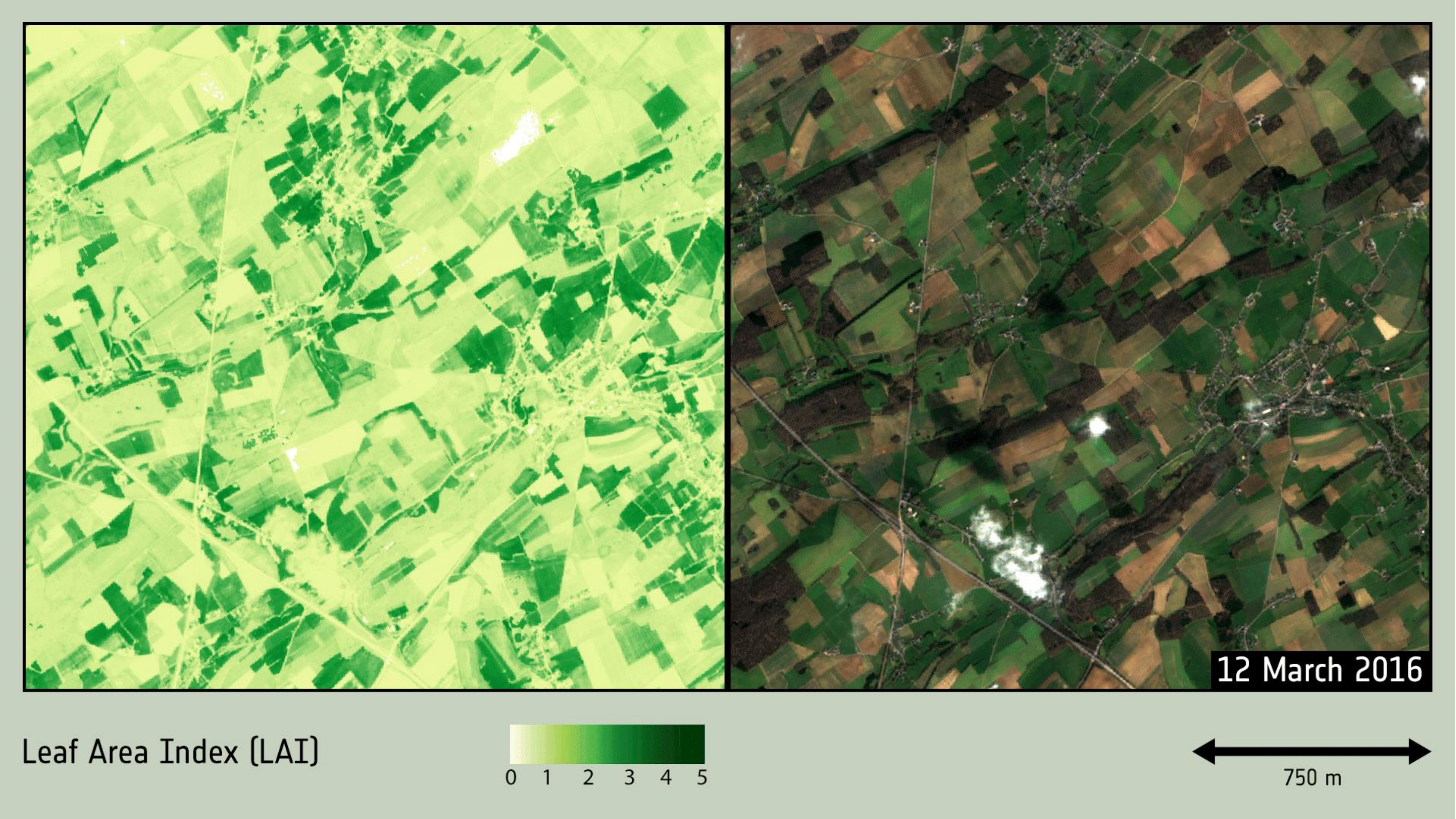


Figure 1 Winter wheat Crown Chlorophyll Content and sample sites in Yucheng, Shandong Province

From EO signal to agriculture information content

LEAF AREA INDEX (LAI)

LAI is a dimensionless index measuring the one-sided green leaf area over a unit of land (m^2 / m^2).

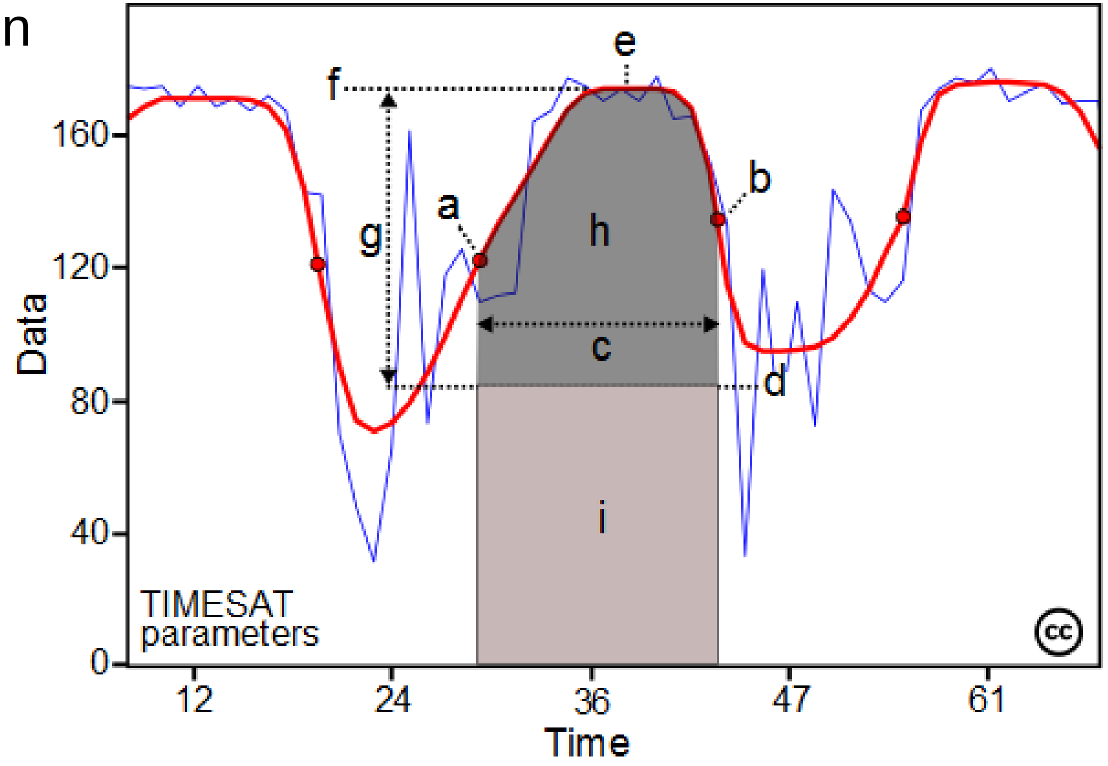


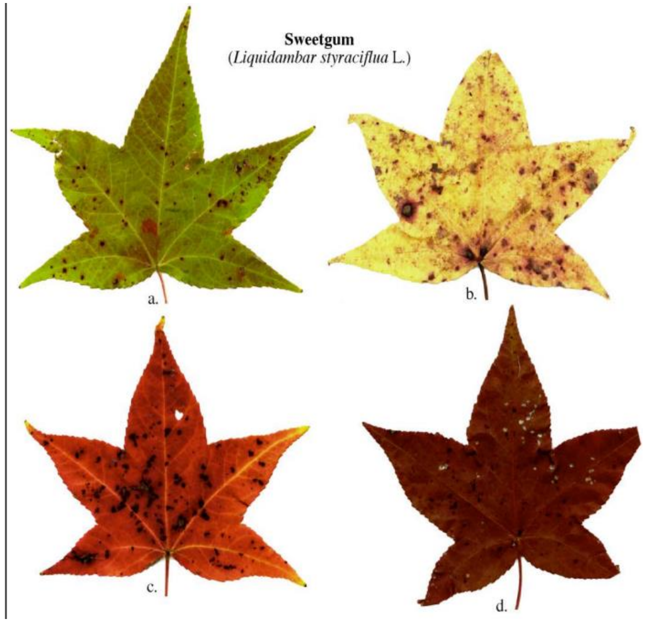
Data from the Copernicus Sentinel-2 mission can be used to measure the ‘leaf area index’ of vegetation (left). This information can, in turn, be used to monitor crop growth and agricultural practices like harvesting. The animation shows the development of crop fields in Belgium between March and October 2016.

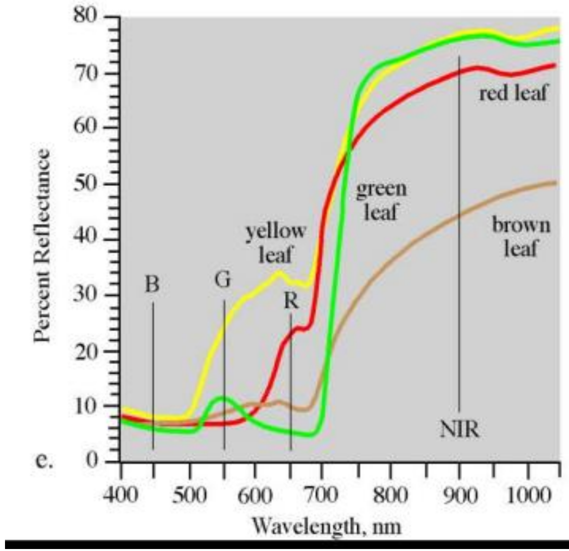
From EO signal to agriculture information content

Temporal development of vegetation

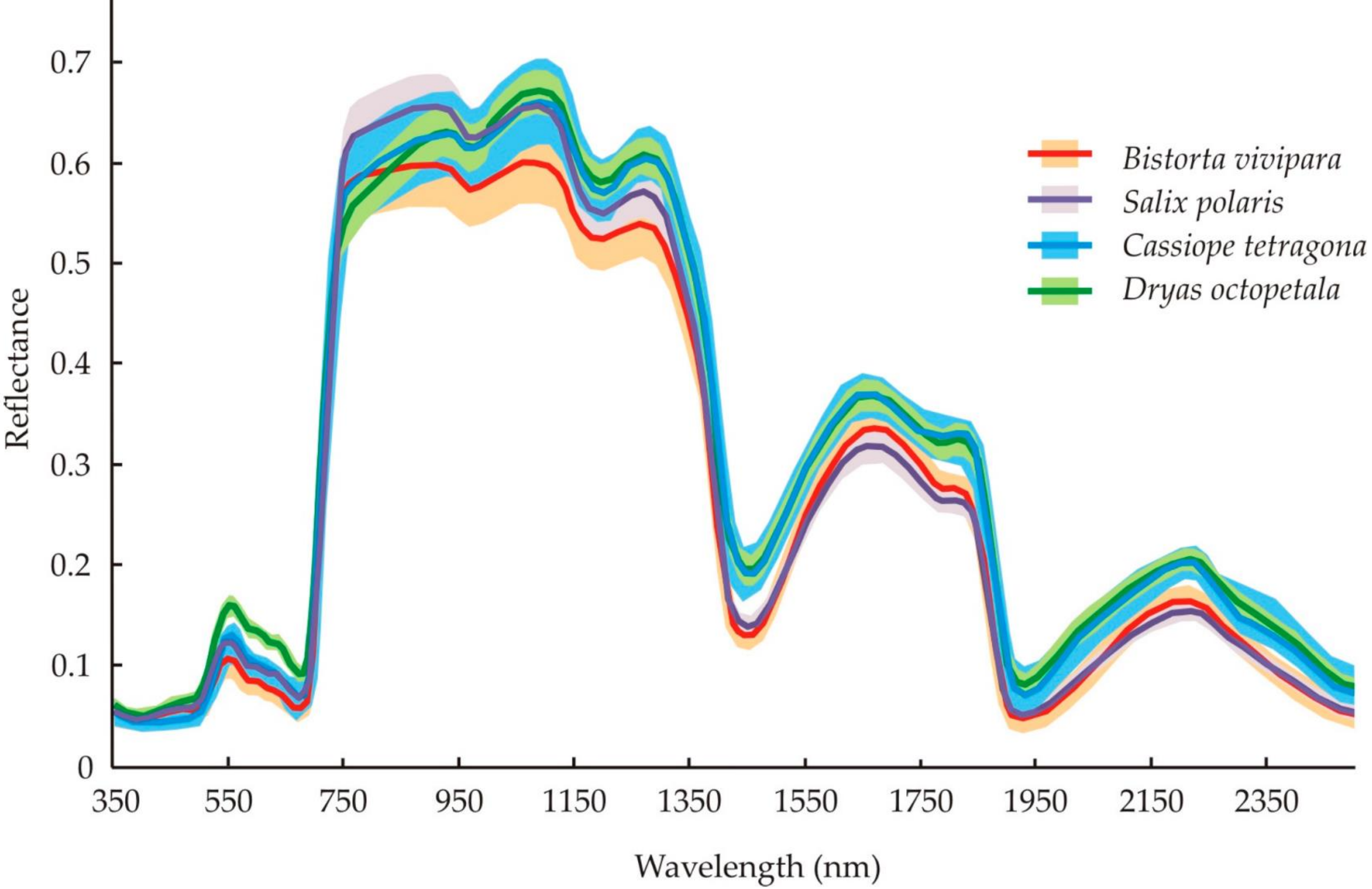
(a) beginning of season
(b) end of season
(c) length of season
(d) base value
(e) middle of season
(f) maximum value
(g) amplitude



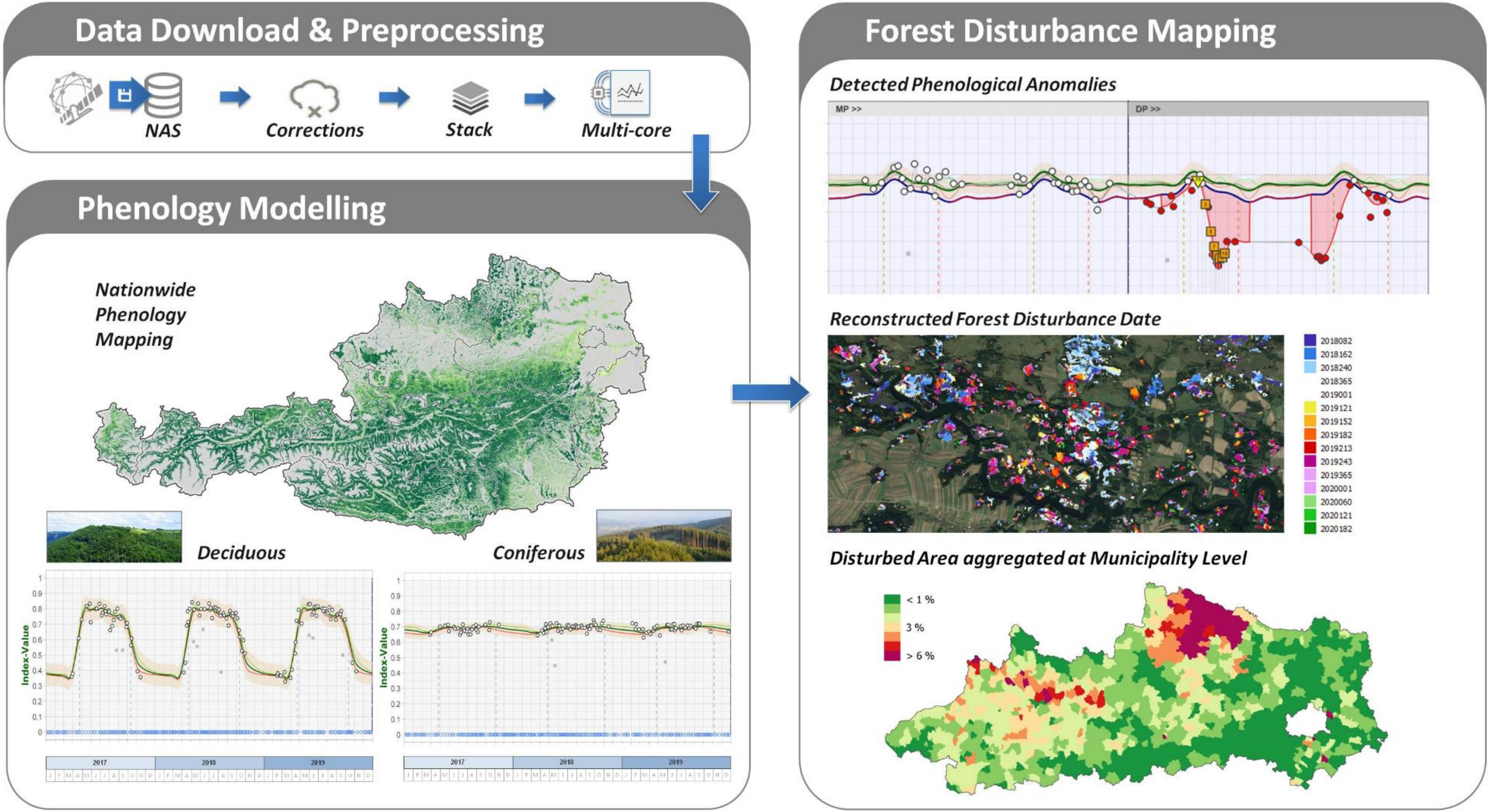




Different vegetation types



Phenology and disturbances



Sentinel-based markers for CAP Monitoring

https://dataspace.copernicus.eu/news/2023-10-19-cap-monitoring-national-scale-slovenia-based-copernicus-data

sen4cap common agricultural policy

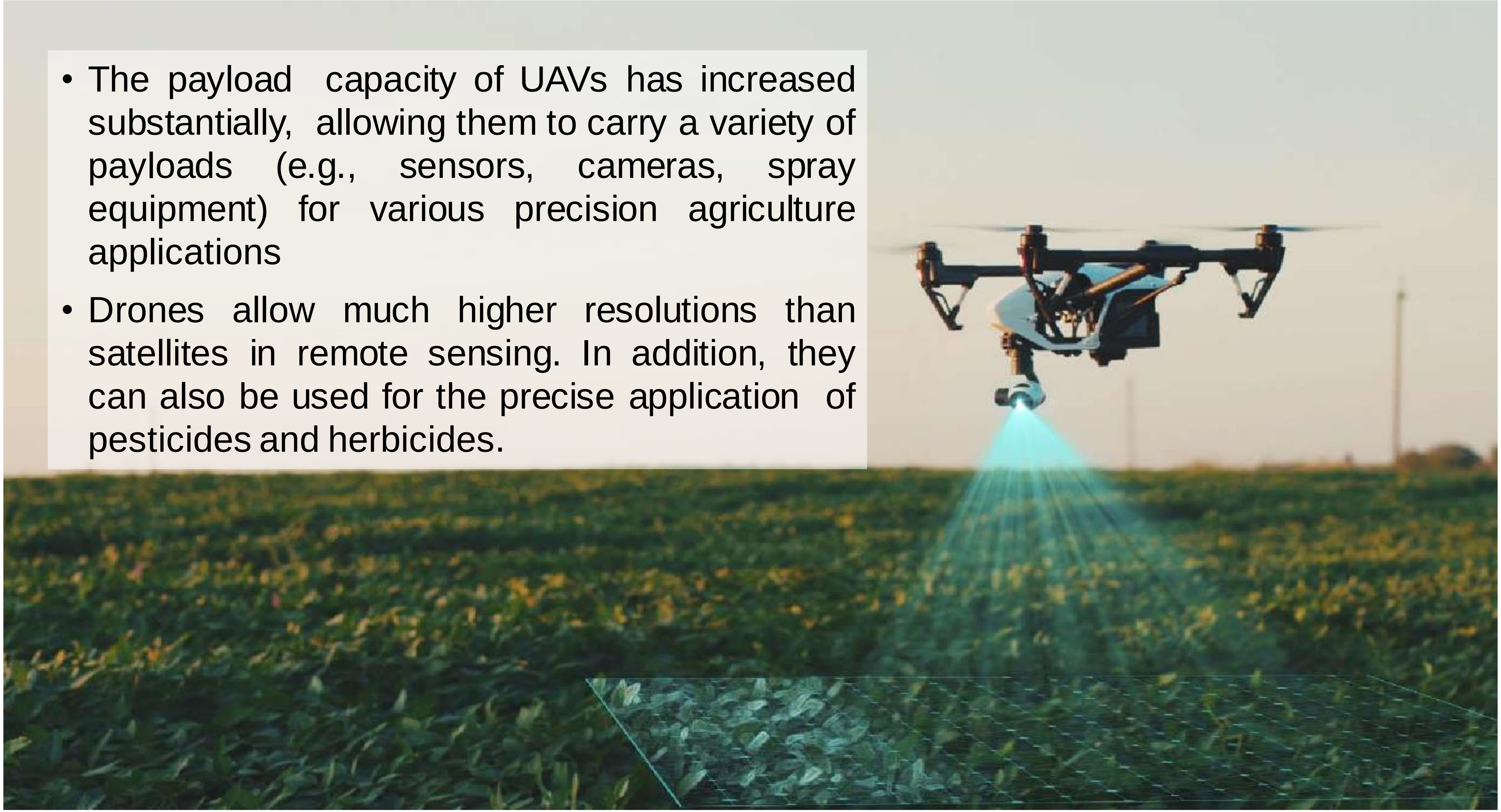
Sen2-Agri Sentinel-2 for Agriculture

Sen4Stat Sentinels for Agricultural Statistics

UAV sensors and platforms

Unmanned Aerial Vehicles (UAVs)

- The payload capacity of UAVs has increased substantially, allowing them to carry a variety of payloads (e.g., sensors, cameras, spray equipment) for various precision agriculture applications
- Drones allow much higher resolutions than satellites in remote sensing. In addition, they can also be used for the precise application of pesticides and herbicides.



Various Drone Payloads and Their Applications[69]

RGB Camera

Only able to capture the wavelengths of the visible spectrum.

- Monitoring plants outer defects, greenness and growth
- Calculating a range of vegetation indices
- Creating high-resolution digital elevation models (DEMs)
- Mapping vegetation height

Multispectral Camera

Able to capture wavelengths beyond the visible spectral range, usually through 3-15 bands.[70]

- Monitoring and mapping crop diseases and weeds
- Estimating the vegetation state
- Detecting nutrient deficiency
- Mapping vegetation height

Hyperspectral Camera

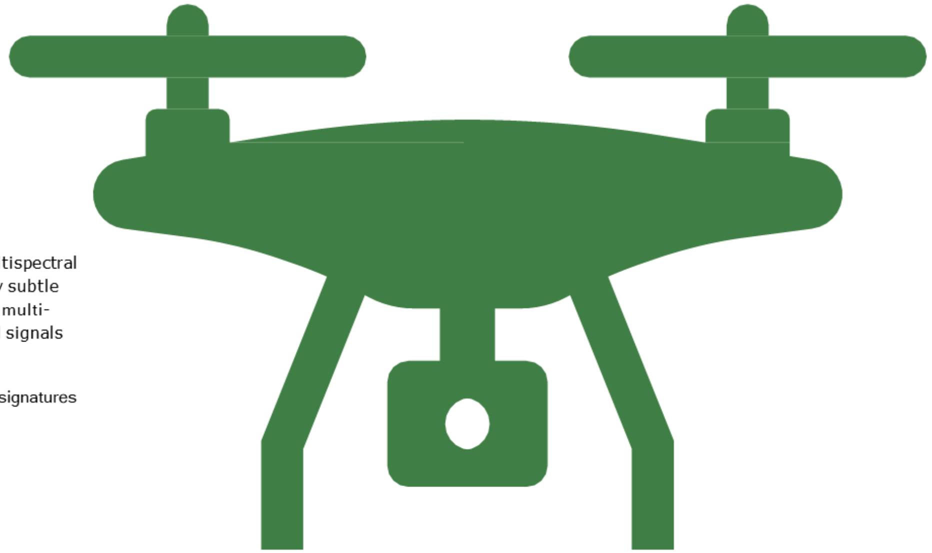
Has more and narrower spectral bands compared to multispectral (They are most suitable when there is a need to identify subtle differences in signal along a continuous spectrum. Since multi-spectral cameras sample larger wavebands, these small signals may not be detected)[71]

- Distinguishing different plant species with similar spectral signatures
- Identifying plant biochemical composition
- Quantifying soil vegetation
- Calculating chemical attributes

Thermal Camera

Infrared radiation to form a heat zone image, operating at wavelengths of ~14,000 nm

- Evaluating water stress and assessing irrigation uniformity
- Calculating vegetation indices
- Calculating chemical attributes



Lidar (Light Detection and Ranging)

Uses laser beams to create a 3D representation of the surveyed environment

- Creating high-resolution digital surface models of terrain and elevation
- Measuring canopy heights, coverage, tree density, location and height of individual trees

Position Sensors

Includes inertial navigation systems, GPS, magnetometer

- Finding the physical location of the UAV

Chemical Sensors

- Measuring and detecting quantities of various chemical agents

Biological Sensors

- Identifying various forms of microorganisms

Meteorological Sensors

- Measuring weather-related indicators such as wind speed, temperature and humidity

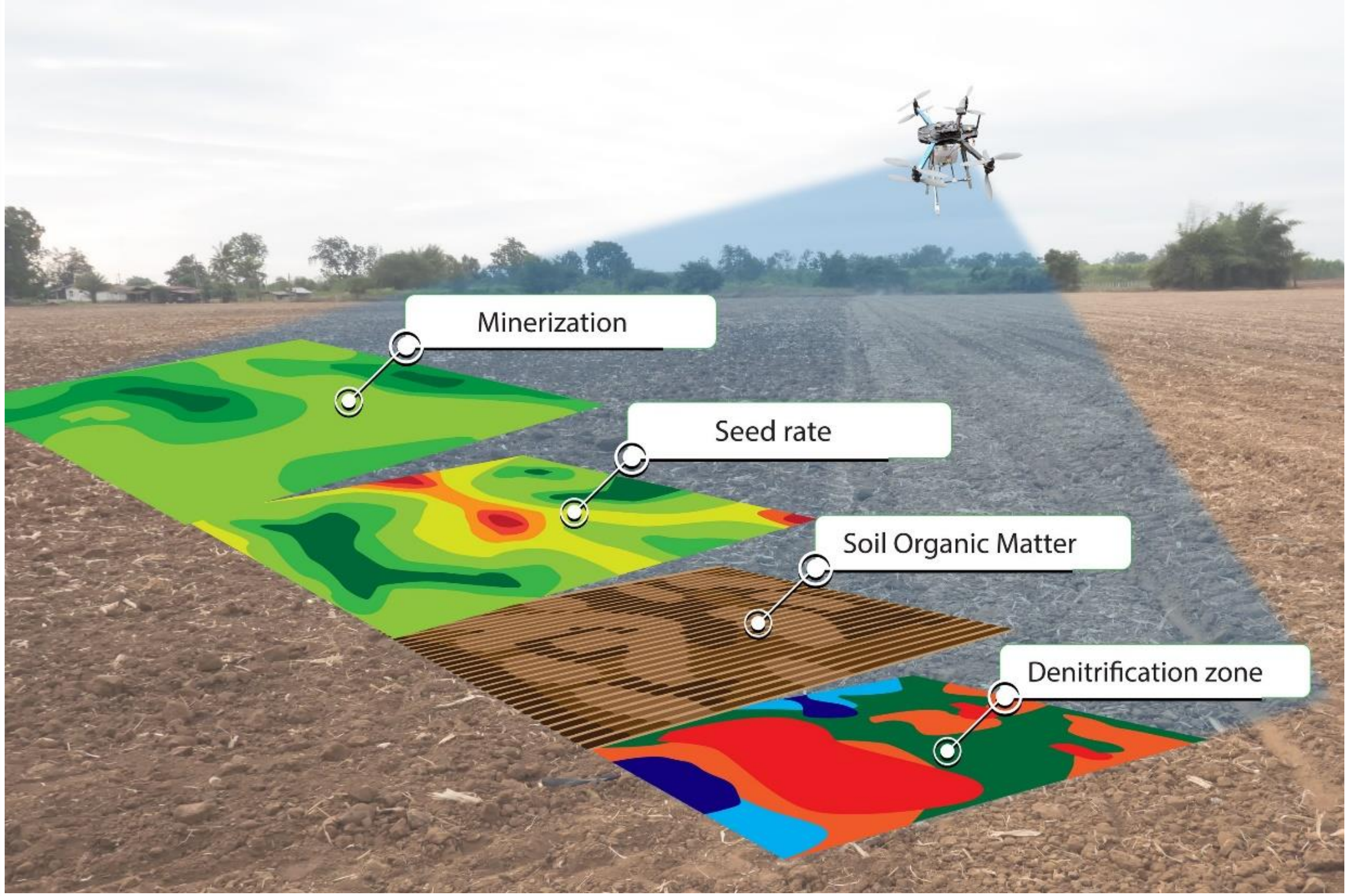
Spraying System or Similarpayloads

- System consisting of pumps and sprinklers for spraying chemical inputs

Common Benefits Of Using UAVs In Agriculture

- Increased Mapping Accuracy
- Reduced Crop Survey Cost
- Increased Efficiency
- Reduced CO_2 Emissions
- Increased Crop Yields
- 3D mapping of land
- Save money on crop surveys
- Save money on insurance

https://www.skydatausa.com/skydata-s-fleet/mavic-3m-crops-and-natural-resources-hide-no-secrets



On-site sensors

On-site sensors measure field and crop characteristics with high accuracy, which growers can use to make farming decisions. Sensors are used in pest monitoring, soil monitoring, smart irrigation, yield monitoring, weather monitoring, and precision planting and spraying applications. The most commonly used sensors are listed in the table below.

Table 4: Types of on-site sensors for precision agriculture

Group	Sensors
Soil	Moisture, temperature, nitrogen, phosphorous, potassium, carbon, pH
Plants	NDVI, chlorophyll, plant health, plant water demands, sugar content
Atmospheric	Temperature, humidity, wind speed, rainfall, pressure, precipitation
Water	pH, temperature, turbidity, water depth, conductivity, dissolved O_2

Satellites and UAVs in Precise Agriculture - Applications

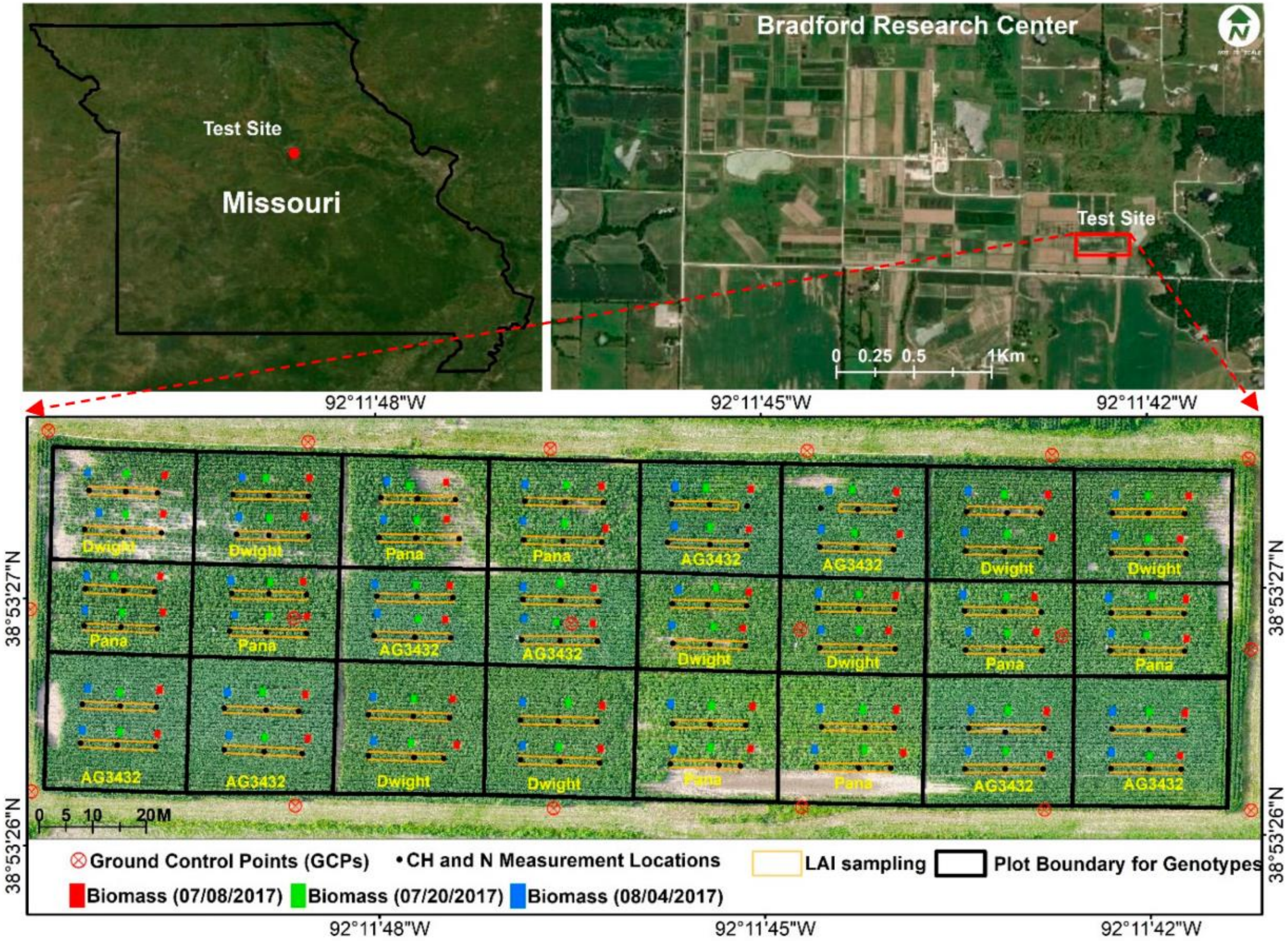
Comparing Satellite Imagery To UAV Data

Feature	Drone	Satellites
Autonomy	Needs an operator	Fully autonomous
Accessibility	Suits for flat and easy-to-reach areas	Doesn't depend on relief specifics
Scalability	Typically used for small fields	Covers large and small areas
Limitations	Prohibited in certain areas	No field data restrictions*
Dependence on weather conditions	Can't be operated in heavy rains and strong winds	Partial data loss due to cloud cover
Price of use	Correlates with operating time	Correlates with the captured territory
Complexity of interpretation	Requires additional analysis by a GIS specialist	Usually processed on online farming platforms

https://eos.com/blog/drones-vs-satellites/

Satellites and UAVs in Precise Agriculture - Applications

Crop Monitoring Using Satellite/UAV Data Fusion



https://www.mdpi.com/2072-4292/12/9/1357

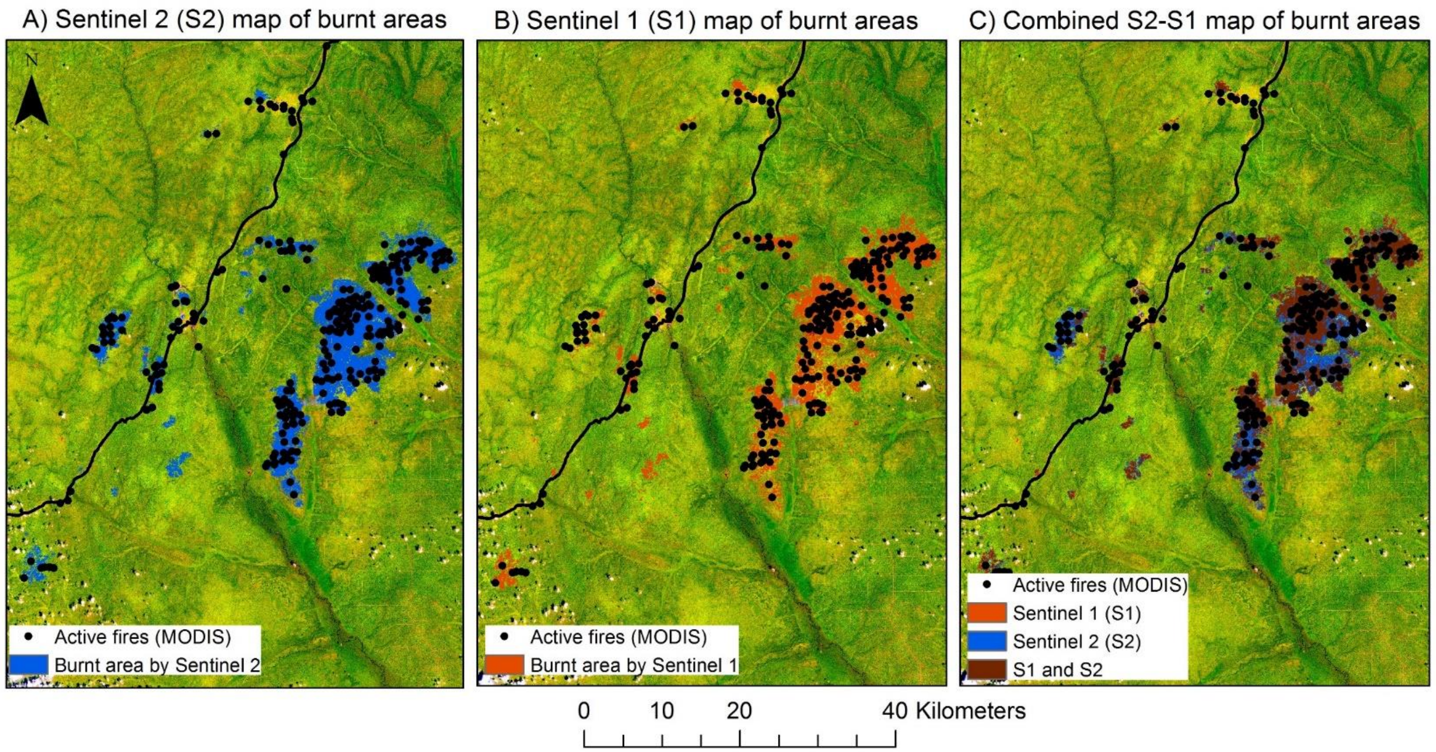
For more information, see the tutorial:
[6. Crop Classification with S1 time series data using the SNAP software]

7. SAR and optical remote sensing for mapping wildfires

Wildfires

Research Objectives

- To develop innovative and globally applicable methods for *early detection, near real-time monitoring of wildfires and rapid damage assessment* using Earth Observation (EO) big data and deep learning
- Combining SAR and optical Remote Sensing

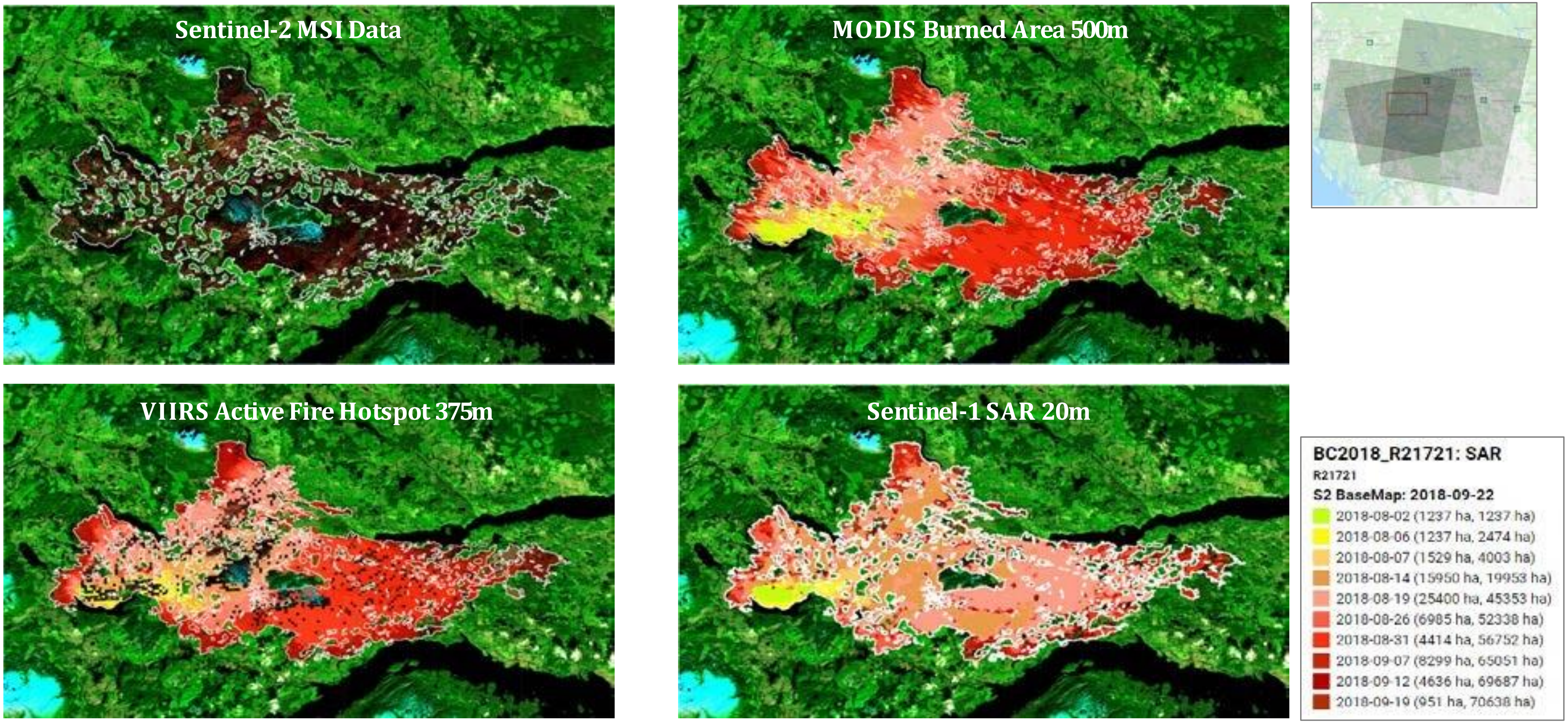


Spatial coherence in the location of the burnt areas as detected by Sentinel-2A (A) and Sentinel-1A (B) and MODIS active fire product (black dots). The map on the right (C) combines Sentinel-2 and Sentinel-1 based maps. Sentinel-2 data are in the background.

Comparison of different ESA satellites for detection of wildfires

Comparison of different satellites for detection of wildfires

Comparisons



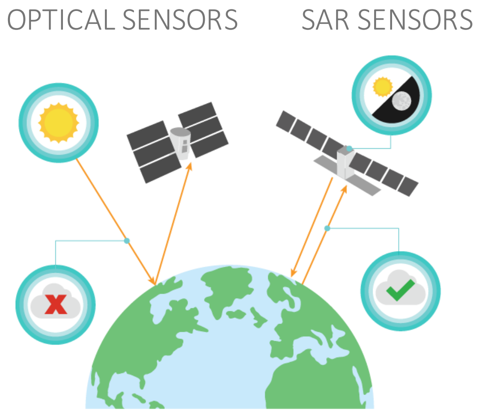
Sentinel-1 C-Band SAR for Detection of Wildfires

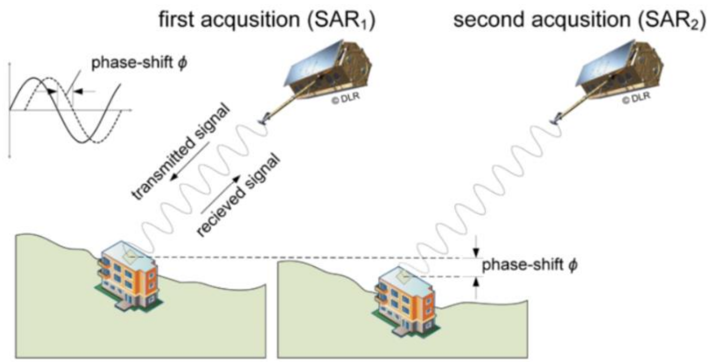
Physical Basis: SAR Data for Wildfire

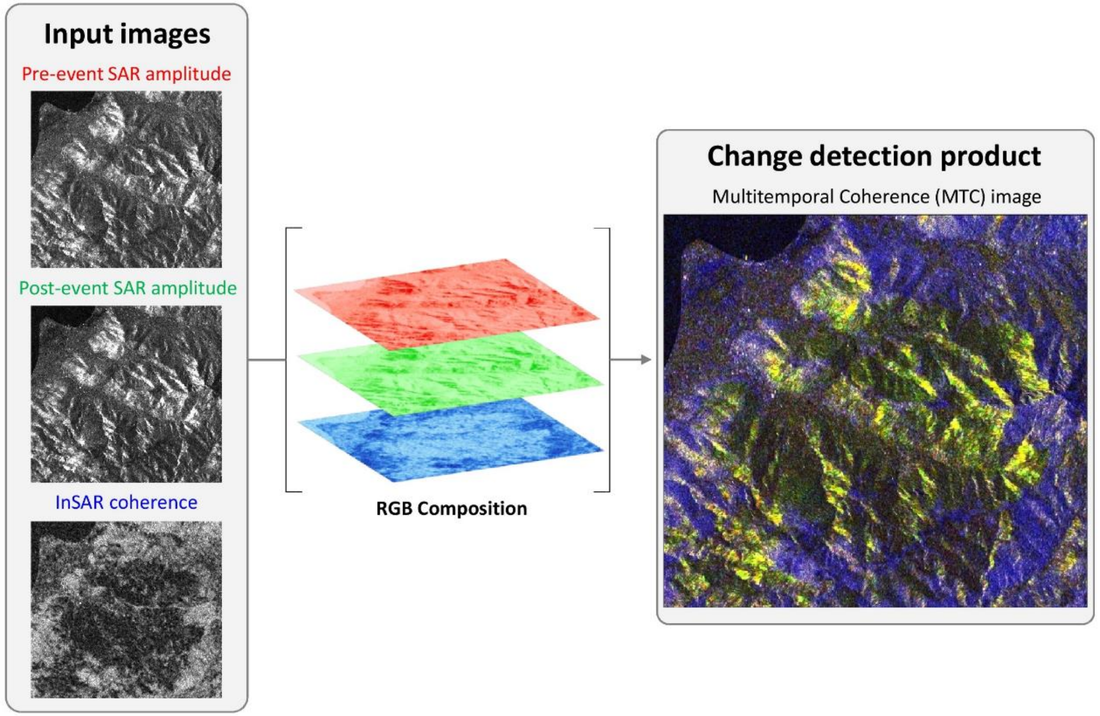
• Synthetic Aperture Radar (SAR) is an active imaging system, it is able to see through smoke and clouds to view changes on the earth's surface → track the fire burn areas while the fire is occurring, even with covering smoke

• SAR collects both intensity and phase, allowing us to track minor surface changes that you can not see with remote sensing data otherwise. In particular, phase can easily pick out areas that were once urban or vegetated that a major change has occurred in.

• Coherence Change Detection is a technique that uses both the intensity and phase to track changes between images.







Sentinel-1 C-Band SAR for Detection of Wildfires

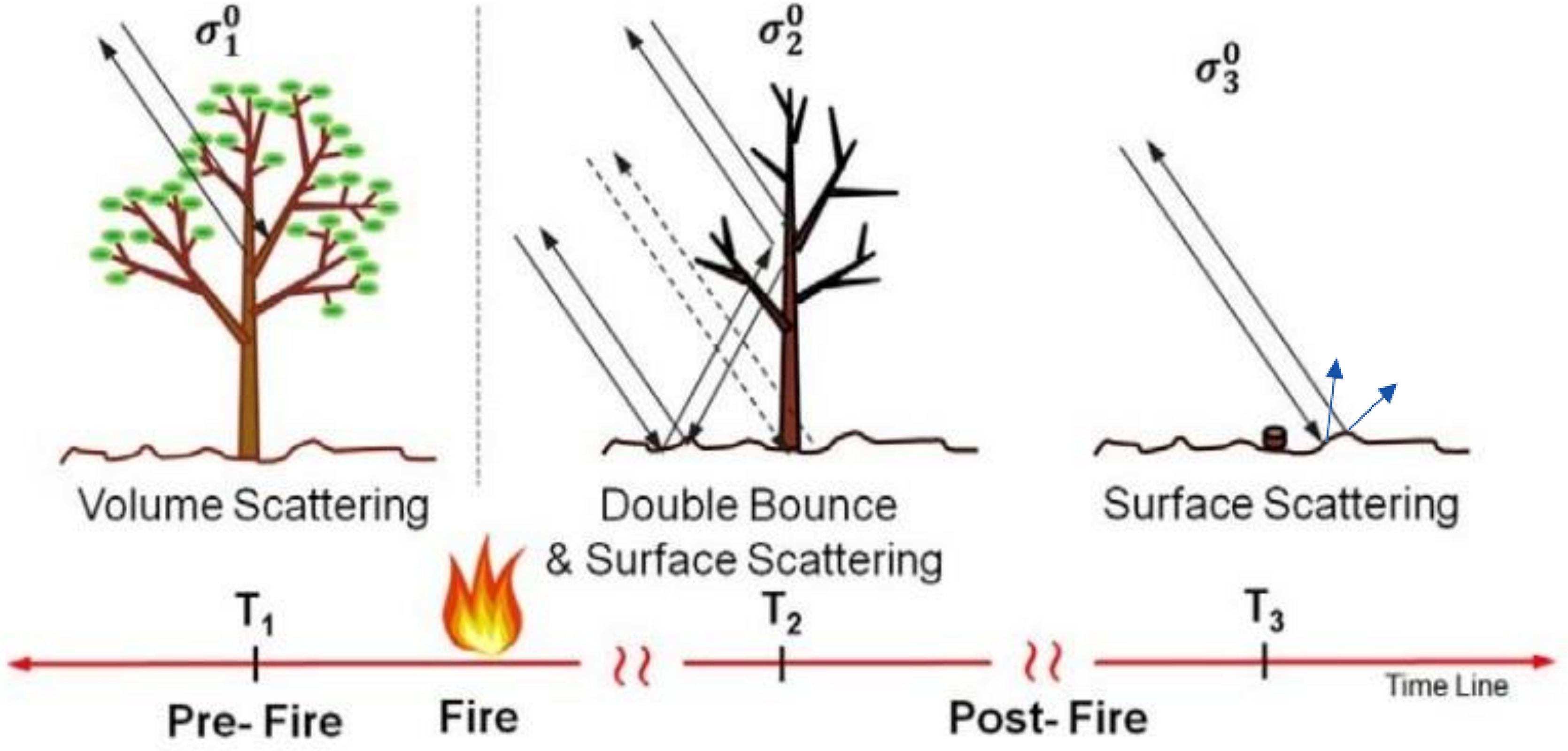
Physical Basis: SAR Data for Wildfire

Scene Properties

- Roughness
- Surface Geometry
- Moisture
- Burn Severity

Sensor Properties

- Wavelength
- Polarization
- Incidence Angle
- Imaging Geometry



$$RBR_{xy} = \frac{\gamma^0 \text{postfire}_{\ xy}}{\gamma^0 \text{prefire}_{\ xy}}$$

Sentinel-1 C-Band SAR for Detection of Wildfires

Physical Basis: SAR Data for Wildfire

Examples of SAR imagery supporting BLM wetlands monitoring and wildfire management, respectively.

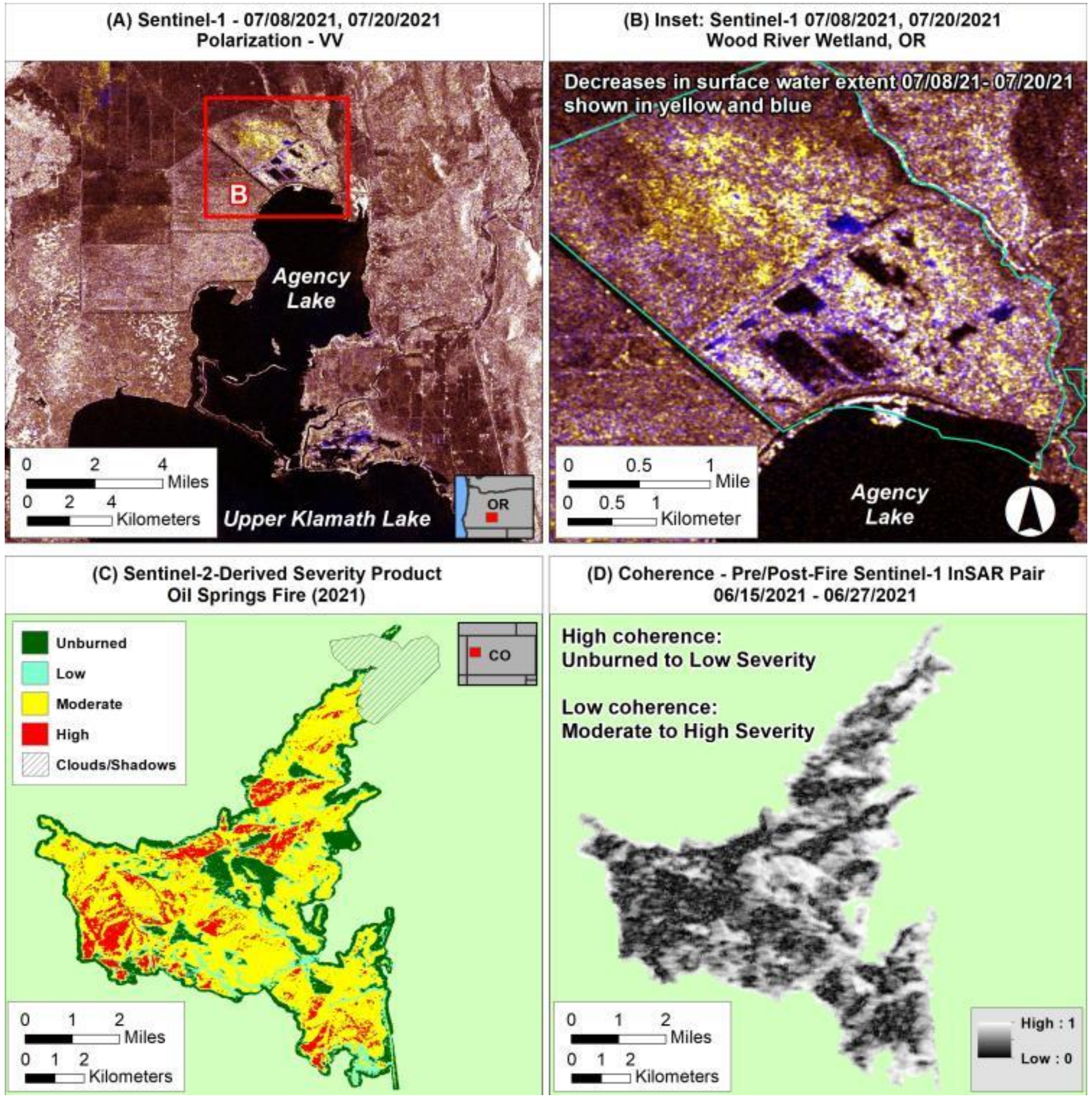
(A) Sentinel-1 image composite of data collected over southern Oregon on July 8 and July 20, 2021.

(B) Inset showing water decreases at BLM-administered Wood River Wetland between these dates at full image resolution. These decreases are identified in water cover with and without inundated vegetation, shown as yellow and blue pixels, respectively.

(C) Severity product for Oil Springs Fire in Colorado, derived from Sentinel-2 electro-optical imagery.

(D) Coherence product derived from pre- and post-event Sentinel-1 imagery using InSAR techniques.

→ SAR products can be useful for post-fire management when electro-optical imagery is unavailable

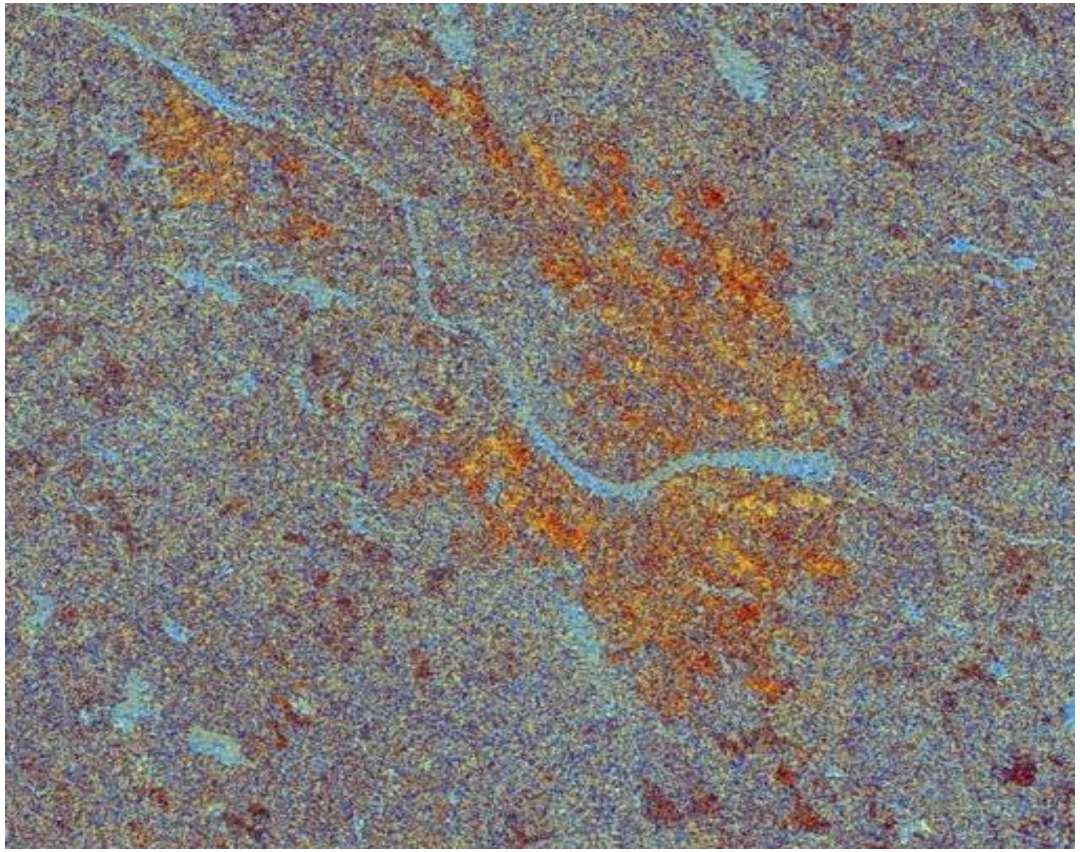


Sentinel-1 C-Band SAR for Detection of Wildfires

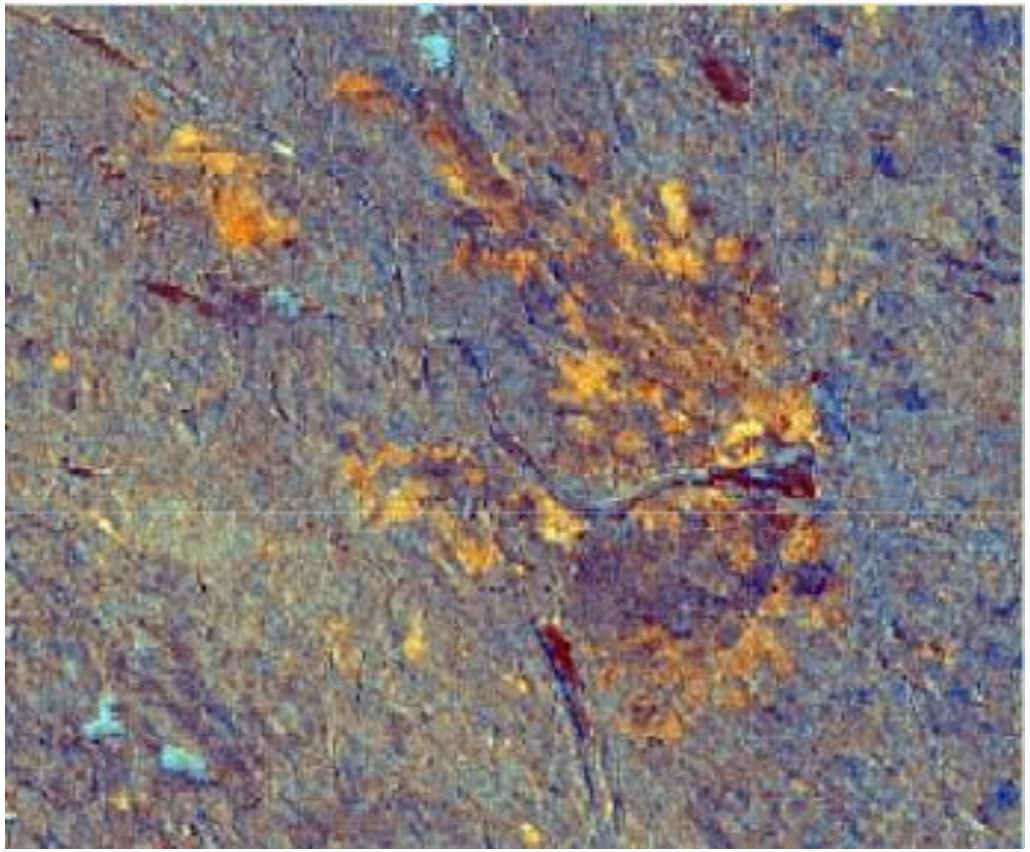
Physical Basis: SAR Data for Wildfire

SAR Detection of Ljusdals-komplexet in 2018

Sentinel-1 C-Band SAR



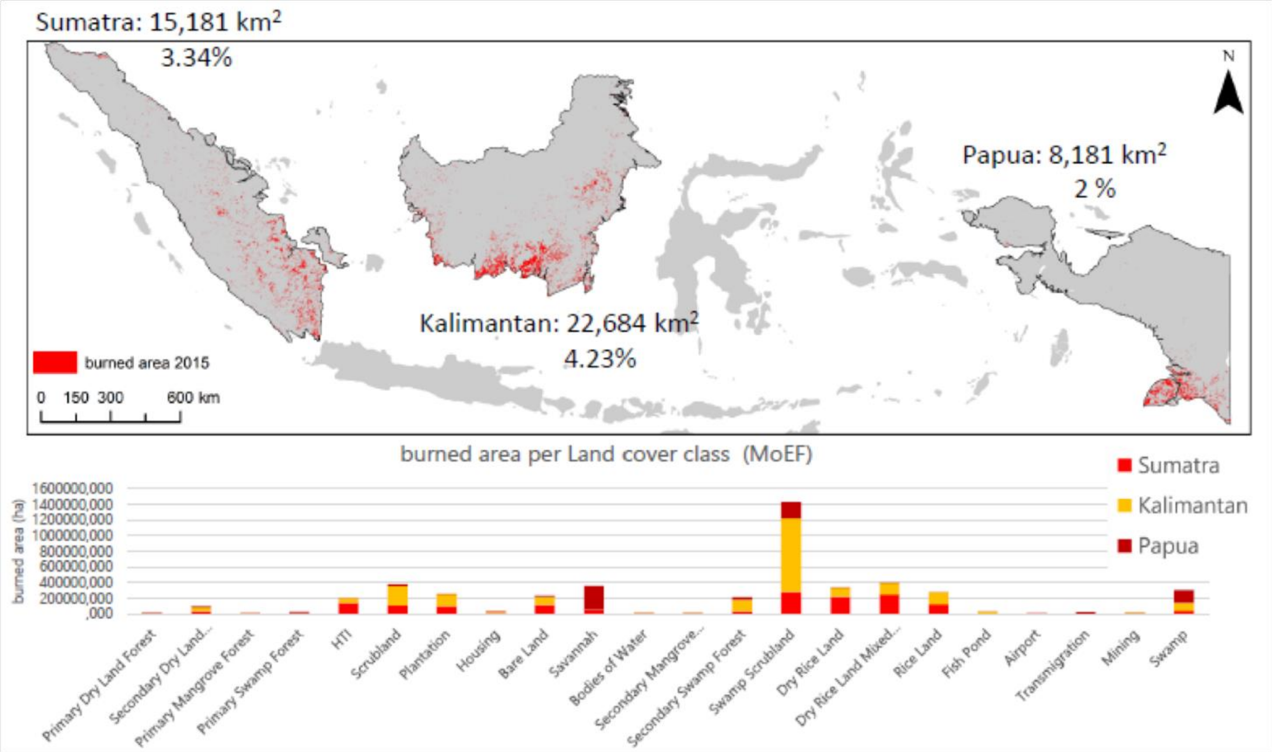
ALOS L-Band PalSAR



Sentinel-1 C-Band SAR for Detection of Wildfires

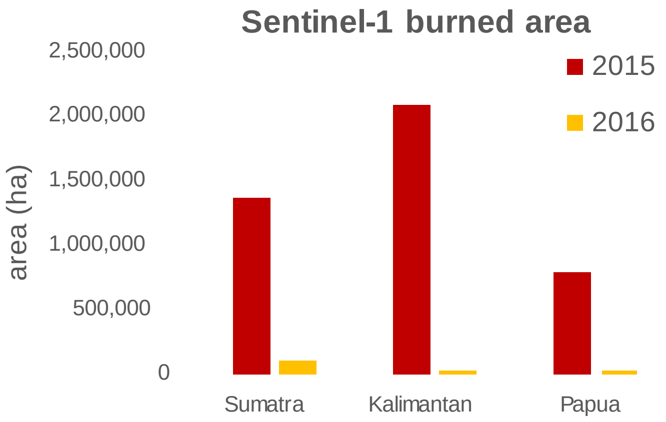
Indonesia SAR analysis for 2015-2016

Sumatra 480,000 km^2 Kalimantan 536,000 km^2 Papua 320,000 km^2



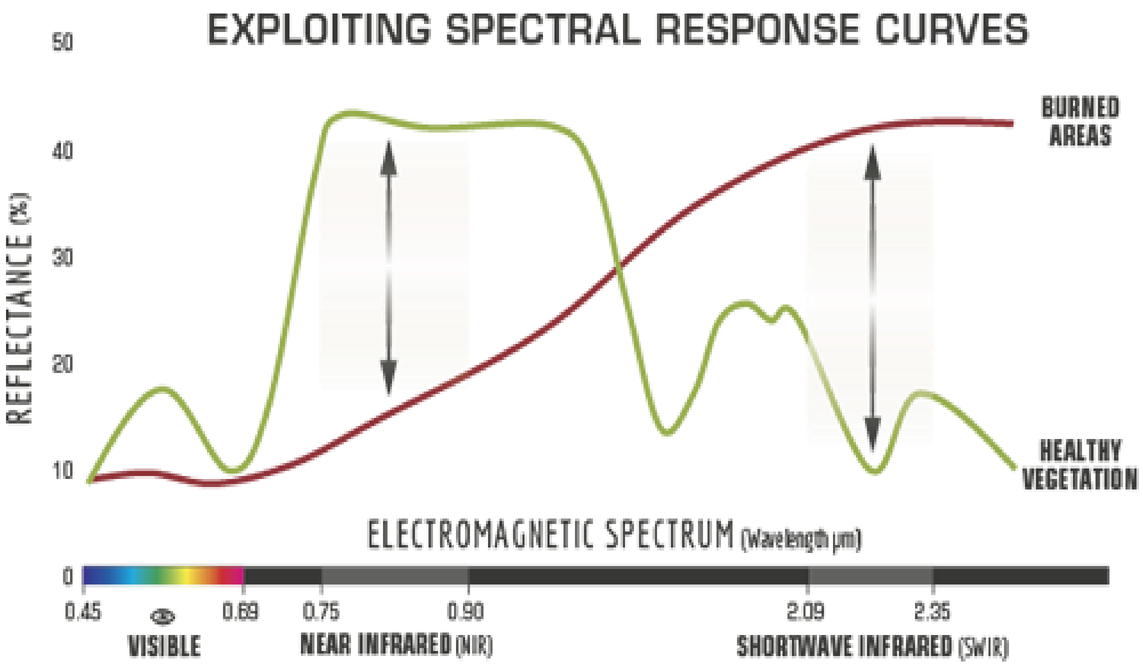
Burning in Indonesia often begins as farmers clear land for crops or grazing animals. Fire that escapes control in Borneo and Sumatra can become difficult to extinguish because of the islands' large deposits of peat—a soil-like mixture of partly decayed plant material that can fuel smoldering fires for months

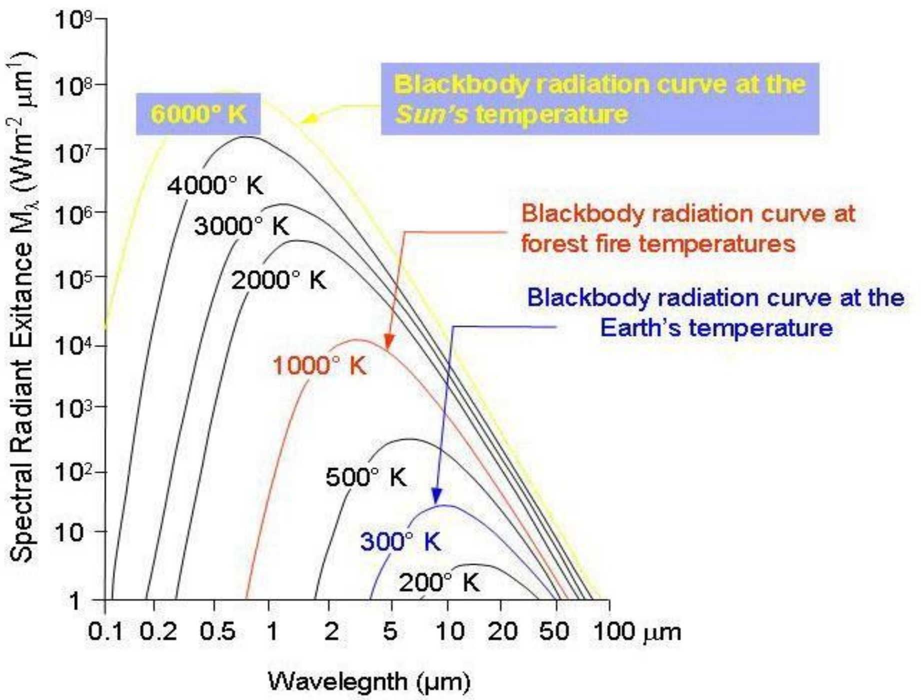
Lohberger et al., 2017



Burned area in ha	Sumatra	Kalimantan	Papua	Total
Year 2015	1,518,127	2,268,352	818,090	4,604,569
Total	1,830,342	2,412,763	865,861	5,108,965

Sentinel-2 MSI for Detection of Wildfires

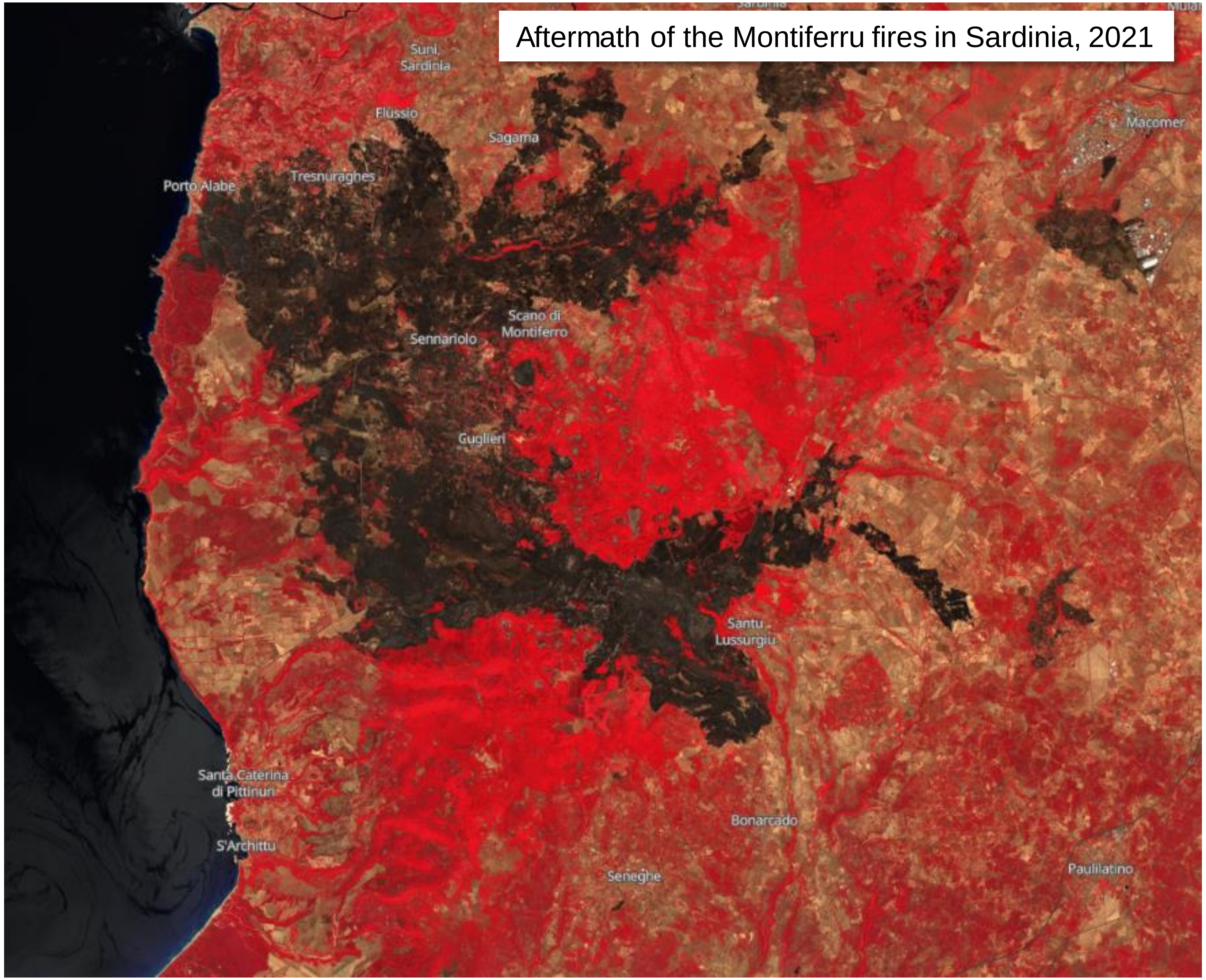




Healthy plant species reflect more energy in NIR but weakly in SWIR. This spectral characteristic is useful for detecting burned areas such as dead soil/plant material on forest floor.

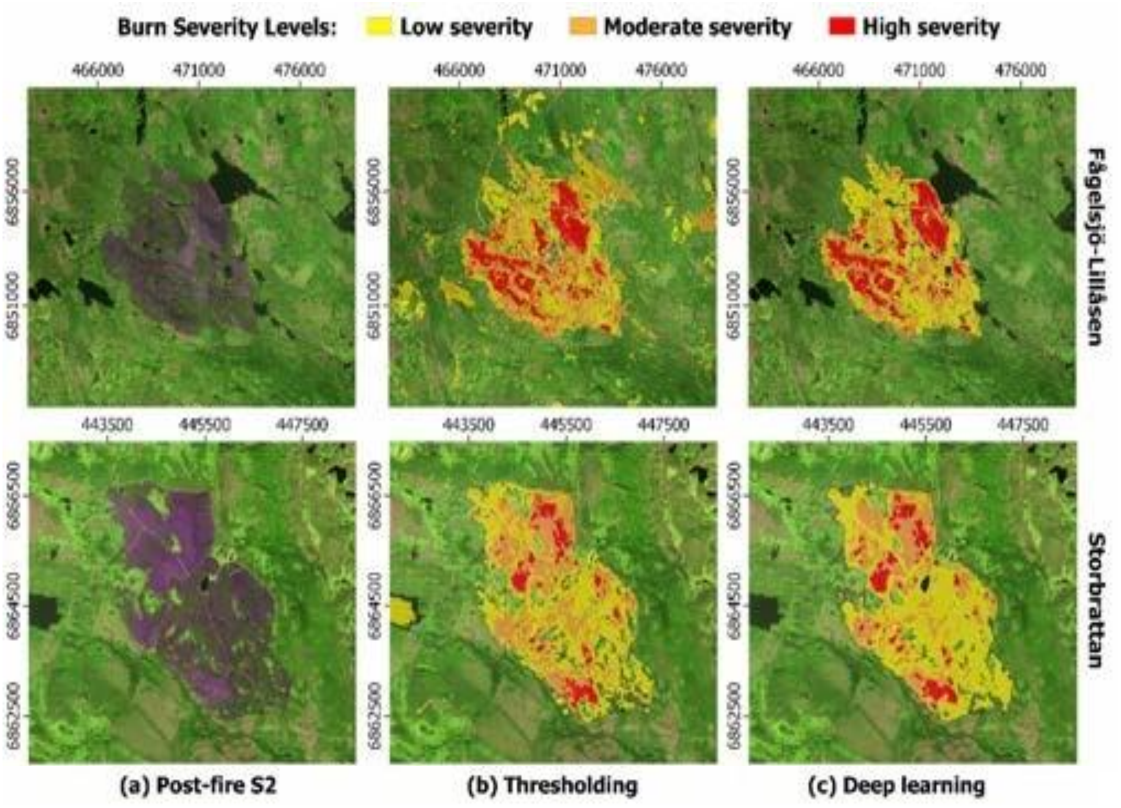
Source: US Forest Service

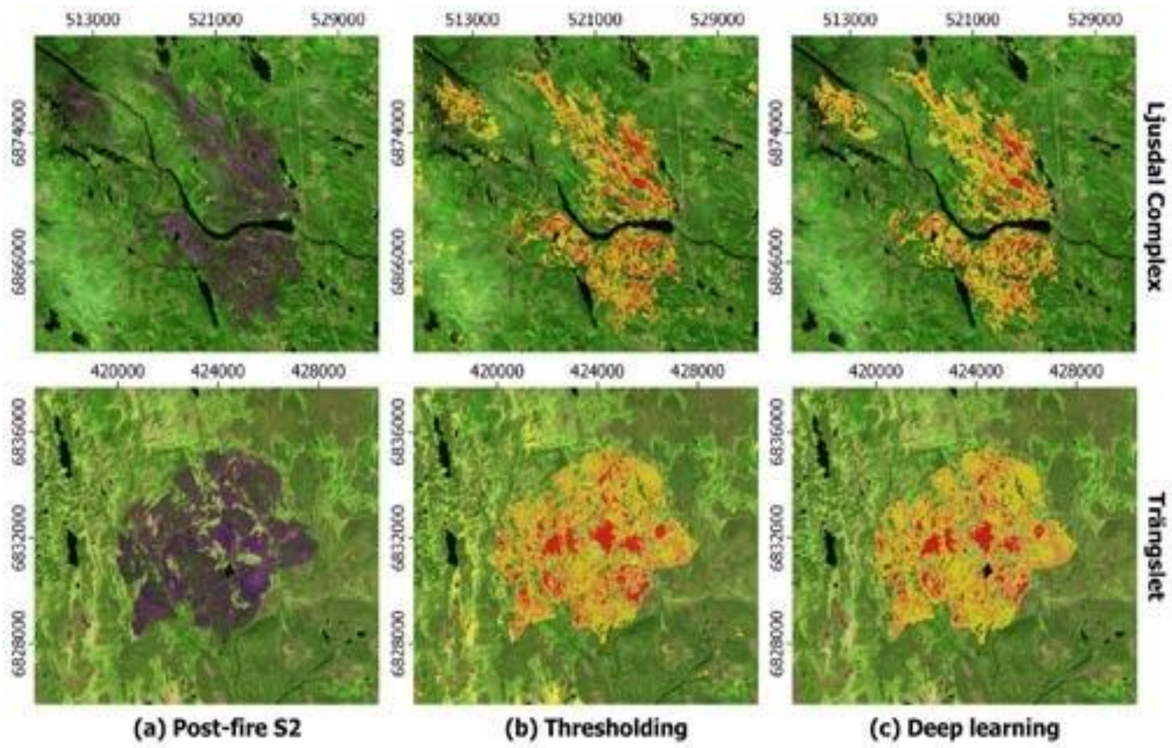
Sentinel-2 MSI for Detection of Wildfires



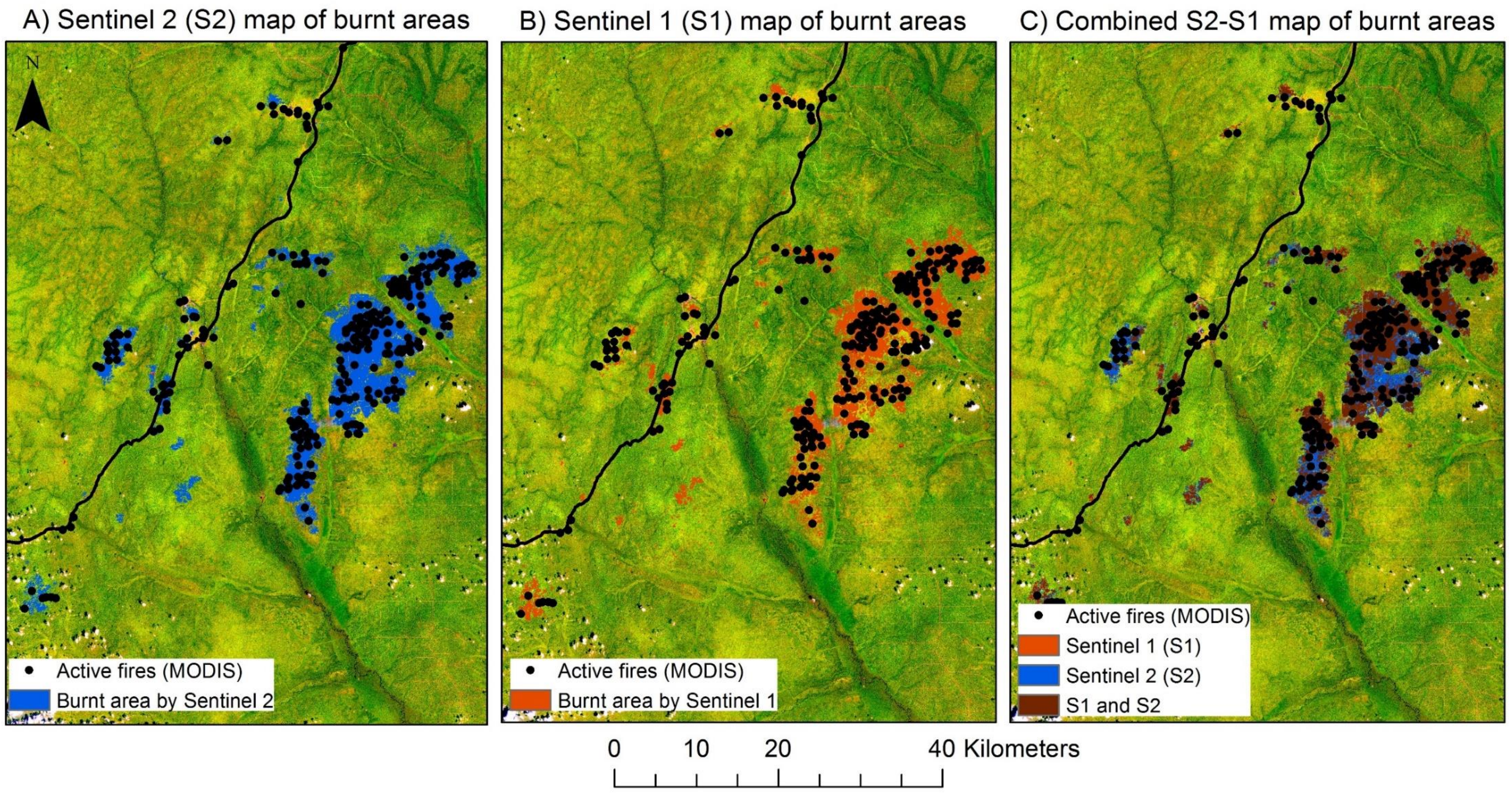
Sentinel-2 MSI for Detection of Wildfires

Sentinel-2 MSI Data for Burn Severity Mapping in Sweden with Deep Learning





Combining Sentinel-1 and Sentinel-2 to determine the source of the fires

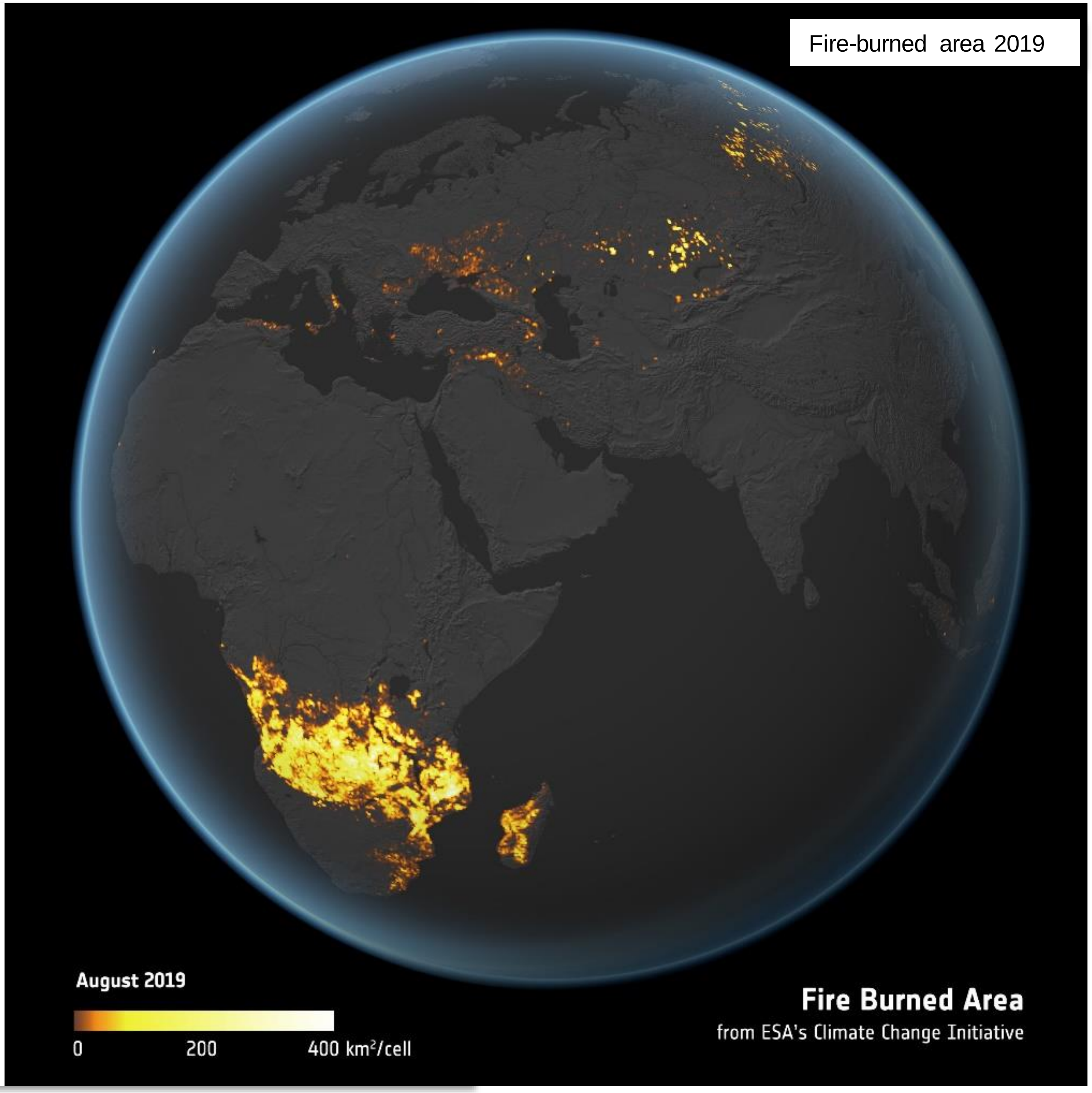


https://skywatch.com/monitoring-forest-fires-with-satellites/

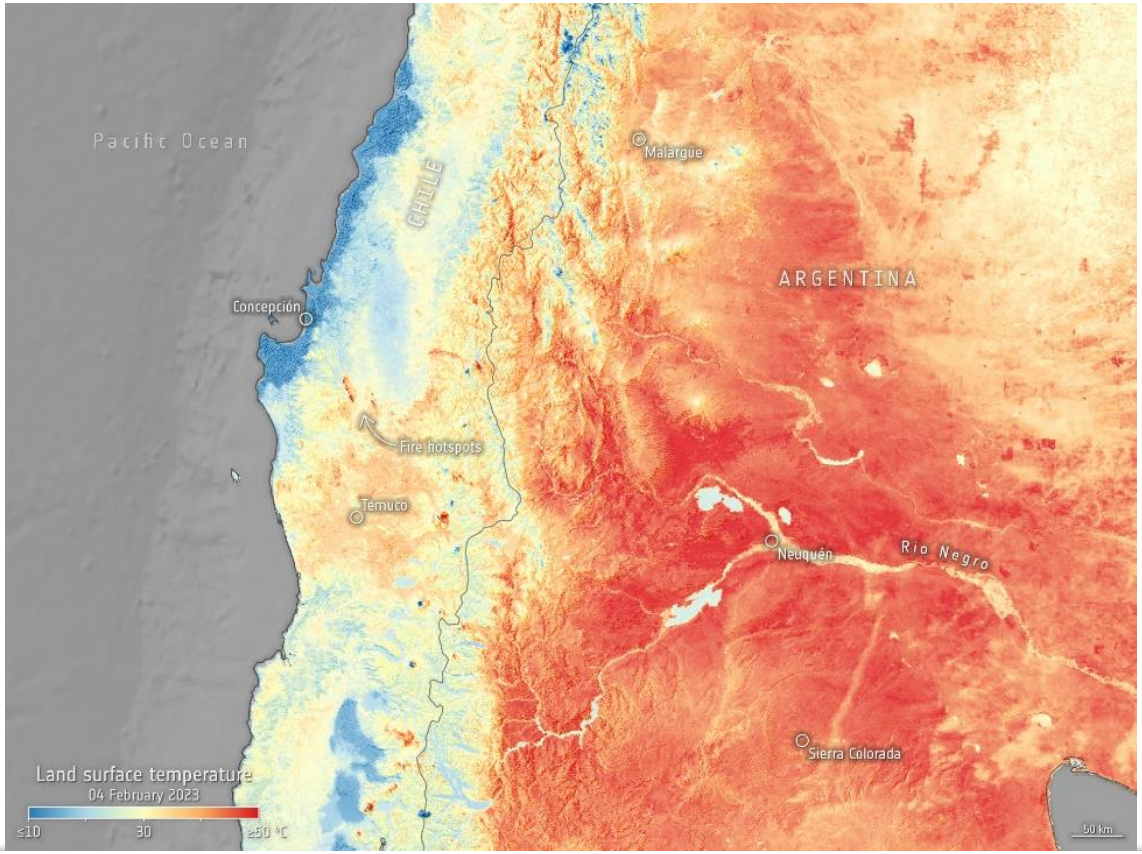
Sentinel-3 for Detection of Wildfires

- Sentinel-3 OLCI and SLSTR identifies active fire points, offering valuable information for monitoring fire spots in any area.

Fire-burned area 2019



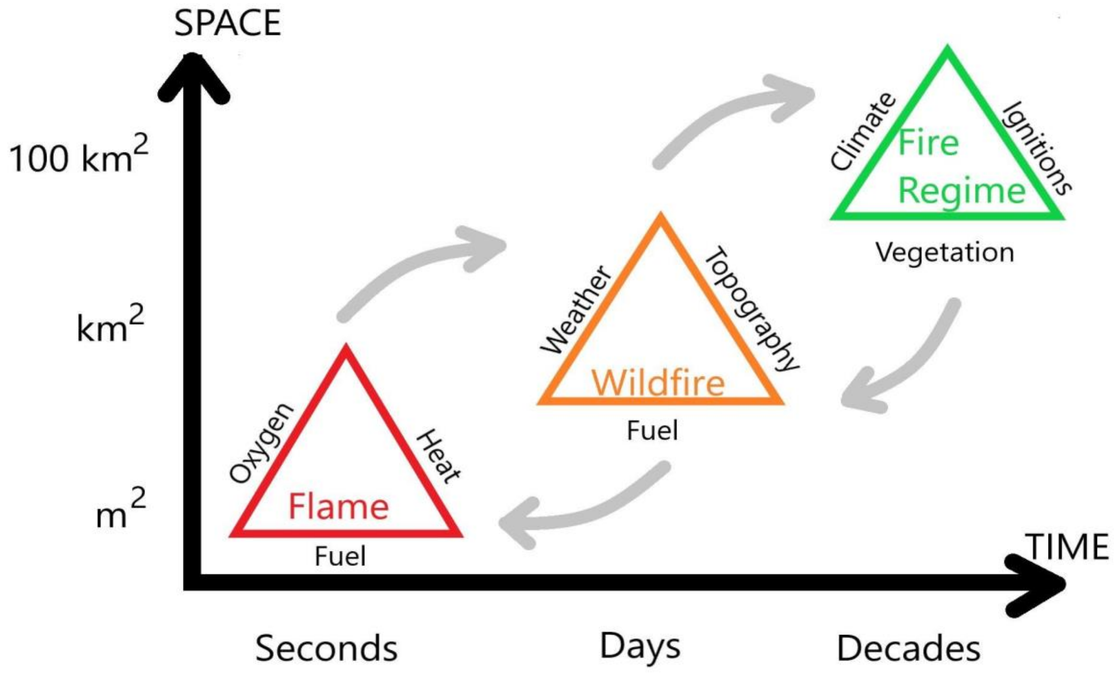
Sentinel-3 for Detection of Wildfires



Satellite images captured by the Copernicus Sentinel-3 mission on 4 February show the ongoing fires and heatwave in South America. The optical image on the left is a combination of images from the Ocean and Land Colour Instrument (OCLI) and Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3 satellite. This allows us to highlight the fire hotspots visible in shades of orange and red in the image. The map on the right, generated using data from Sentinel-3's SLSTR instrument, shows the temperature of the land surface. The data show that ground temperatures in Neuquén reached 49°C, Sierra Colorada reached 45°C and Malargüe 38°C.

Remote sensing observations and forest fires stages

Remote sensing observations and forest fires

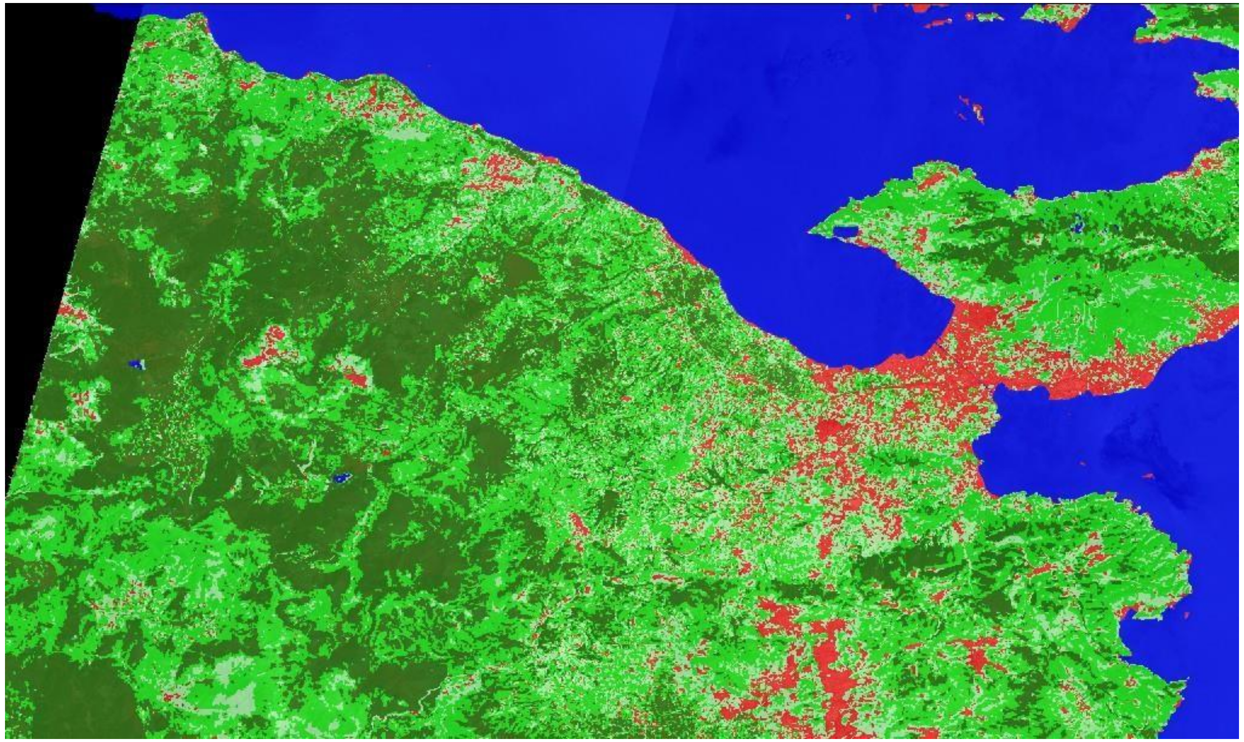


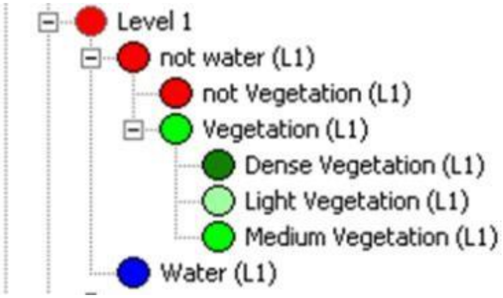
Pre-Fire Risk Assessment	Vegetation density and extent Soil moisture/drought severity Topography Fire risk mapping
Active Fire Detection	Hot Spot Detection Total area burning Fire Radiative Power and Thermal Infrared Pyro cloud formation
Post Fire Assessment	Total area burned Burn severity Post fire vegetation regrowth Landscape regeneration

The pre-fire stage

Vegetation density

- Fire risk as varies with vegetation density VD. VD also influences fire dispersion.
- Classification of a forest in terms of VD depends strongly on spatial resolution

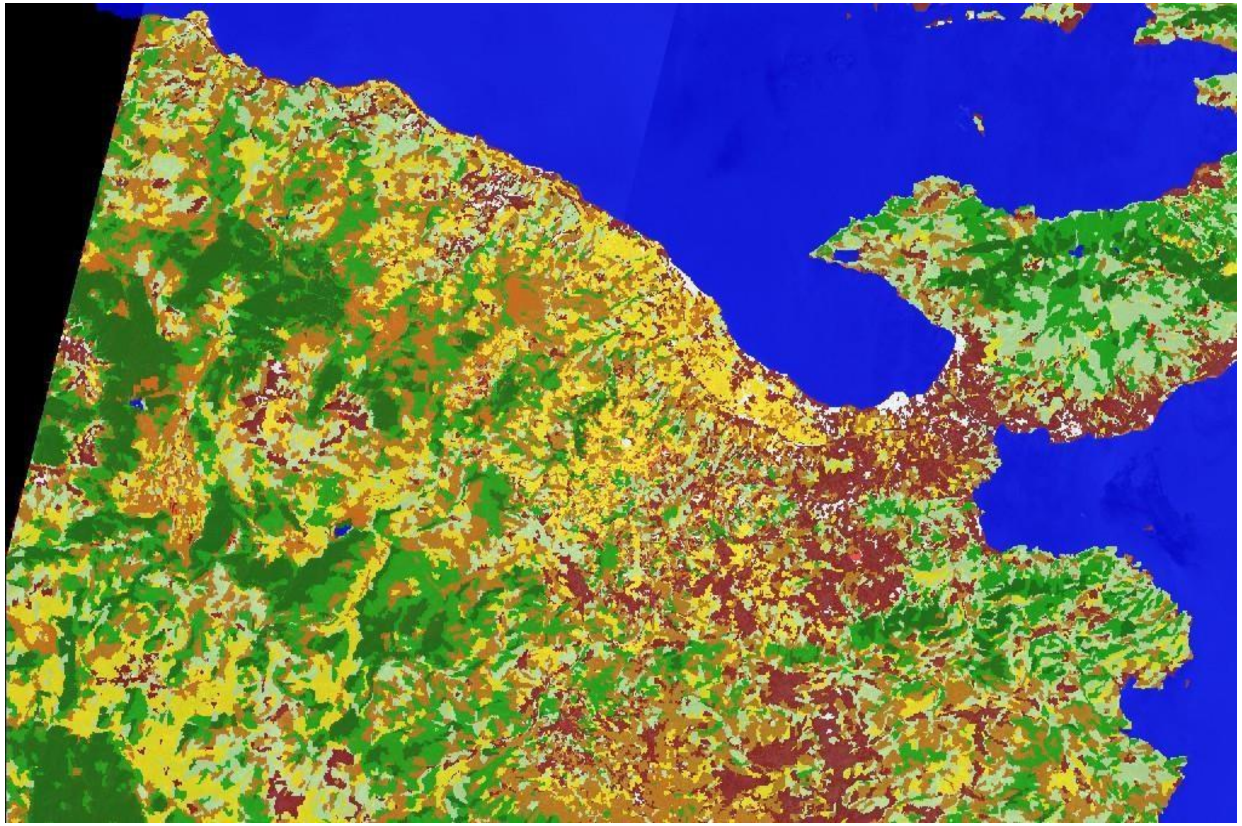




The pre-fire stage

Vegetation type

- Urban areas slow down forest fires, a fact which is important for fire modelling.
- **Fuel behavior (ignition and dispesion) varies with vegetation type (VT).**
- For instance, areas with olive trees slow down the fire. On the contrary, areas with pine trees (typical species for the Mediterranean biodiversity), ignite and disperse easier.



Brown: olive trees; Yellow: agricultural cultivations; Green: conifers; light green: Shrubs

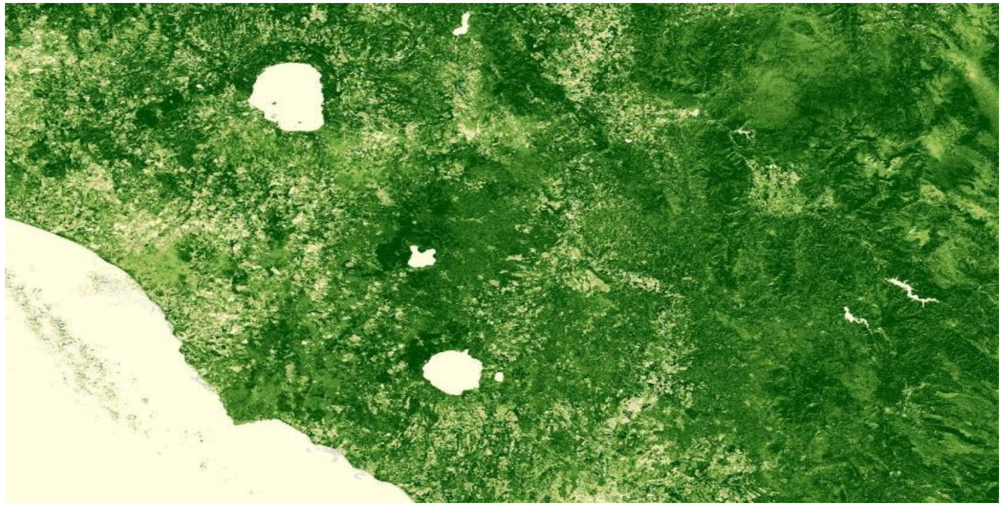
The pre-fire stage

Vegetation stage - Land Surface Phenology

Unhealthy vegetation has a higher percentage of dead leaves, providing easier to burn fuel for fires

Satellites can be used to track seasonal patterns of variation in vegetated land surfaces through indices:

- NDVI - Normalized Difference Vegetation Index
- EVI - Enhanced Vegetation Index
- SAVI - Soil-Adjusted Vegetation Index
- Vegetation index anomalies



1/ **NDVI is widely used as a metric for vegetation health**

- Values range from -1.0 to 1.0
  - Negative values to 0 mean no green leaves.
  - Values close to 1 indicate the highest possible density of green leaves.
- NDVI Formula: **(NIR – Red)/(NIR + Red)**

$$EVI = G * \left(\frac{(NIR-R)}{(NIR+C1*R-C2*B+L)}\right)$$

Constants
$G = 2.5$
$C1 = 6$
$C2 = 7.5$
$L = 1$

2/ **Enhanced Vegetation Index (EVI)**

More sensitive in areas with dense vegetation, making it better for fuels assessment in dense forests

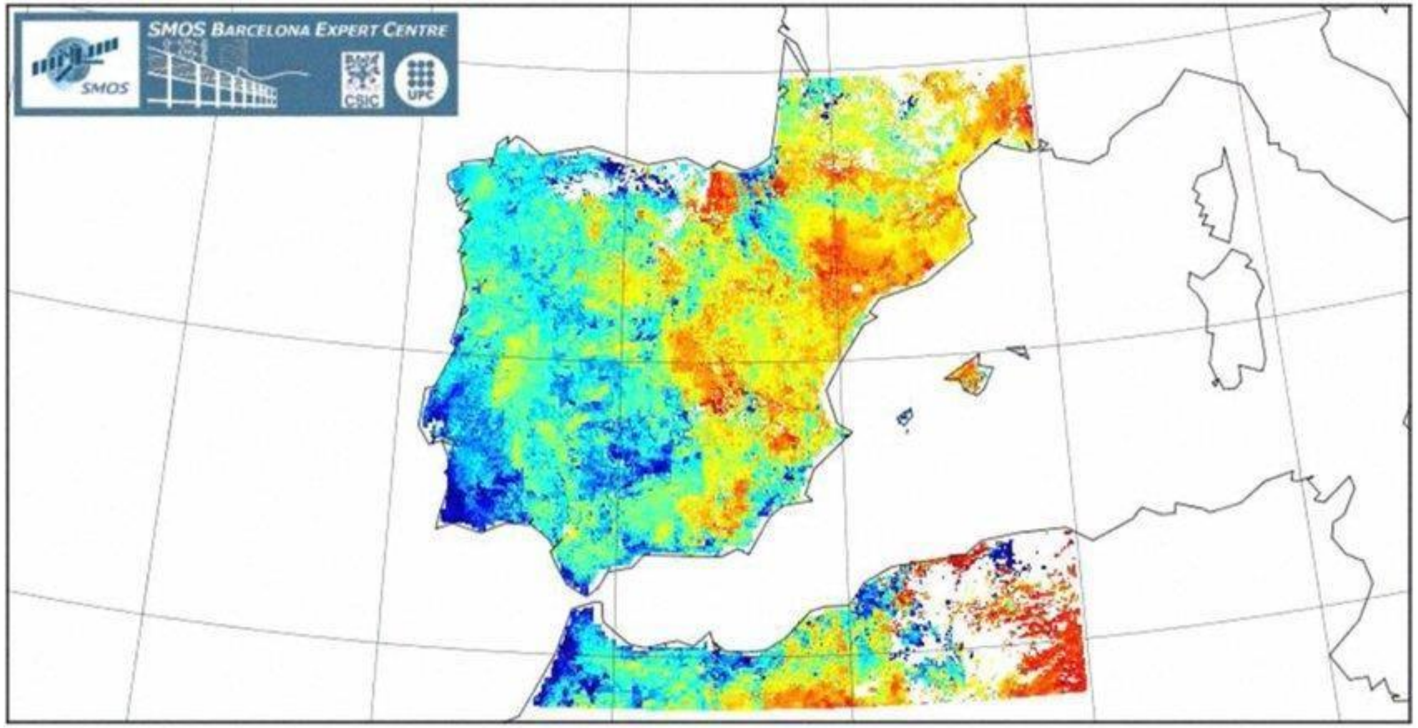
The pre-fire stage

Soil Moisture

Vegetation-Based Fire Applications:

- Vegetation Moisture: Soil moisture acts as a proxy for vegetation moisture and evaporative stress.
- Drought information can also identify areas with dry fuel.
- Soil moisture is measured by active microwave scatterometers, e.g. ERS1&2/AMI and MetOp/ASCAT as well as by passive microwave radiometers such as Sentinel 1, Aqua/AMSR-E, Coriolis/WindSat...

- SMOS measures the moisture in the top 5 cm of the soil globally every 3 day

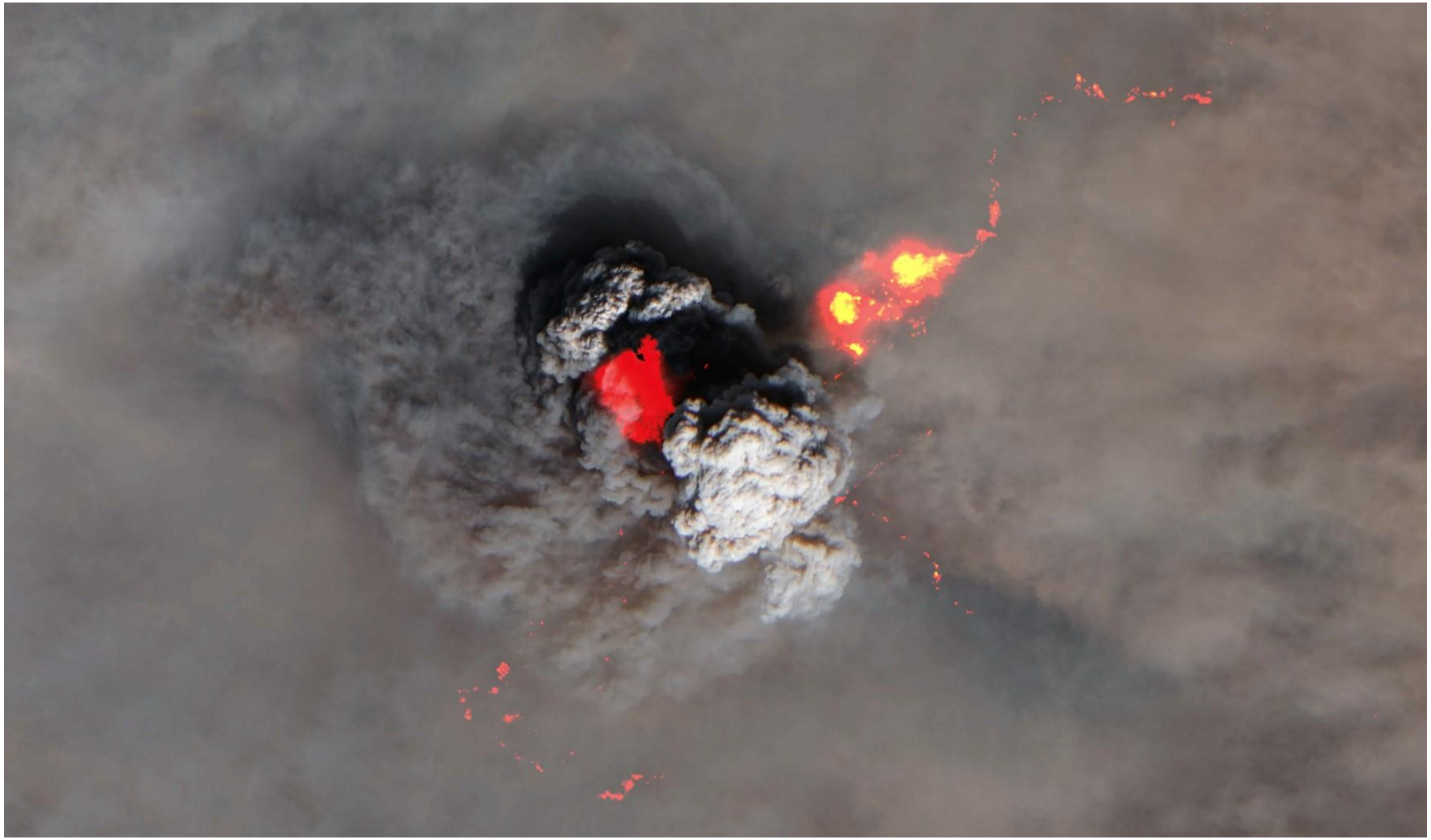


Example of high resolution (1 km) soil moisture maps of the Iberian peninsula generated from SMOS data (10 days average)

https://directory.eoportal.org/web/eoportal/satellite-missions/s/smos

The pre-fire stage

Local meteorology (pyrocumulus)



Copernicus Sentinel-2 catches impressive smoke cloud

This image acquired on 9 September 2020, by Copernicus Sentinel-2 features the impressive pyrocumulus cloud forming over the complex wildfire in California. This true-colour image is combined with short-infrared bands to highlight the location of the fire hot spots.

Contains modified Copernicus Sentinel data (2020)/processed by P. Markuse

The pre-fire stage

SAR in support of optical remote sensing for forest fires

Sentinel-1 SAR (C-band SAR data, 12-day revisit, Resolution: 5 x 20 meters)

- Vegetation-Based Fire Applications:

– Vegetation Type and Extent: Land classification, fuels mapping

– Vegetation Structure: Density and height

– Vegetation Moisture: Fuel moisture content and dryness

Sentinel-2 (-day revisit, Resolution: 10 meters)

- Vegetation-Based Fire Applications:

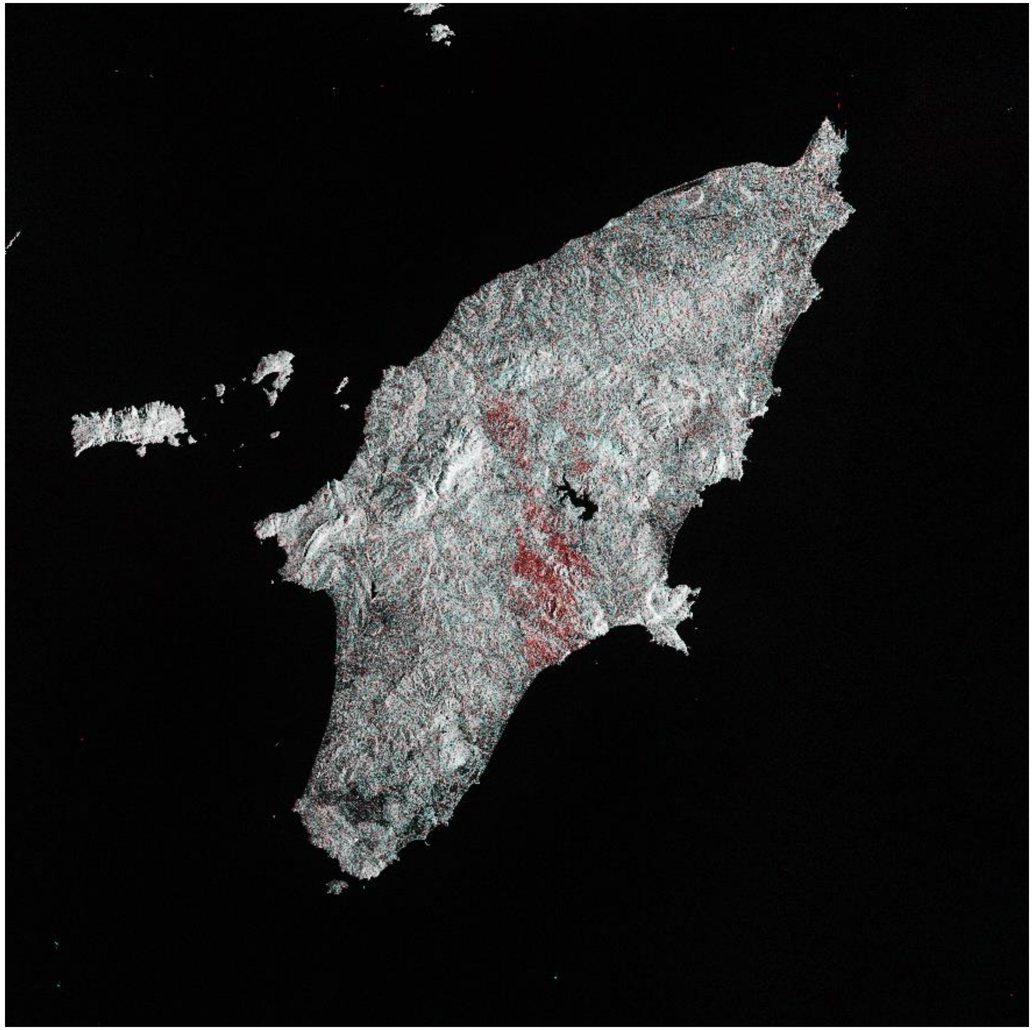
– Vegetation Extent and Type: Land cover classification

– Vegetation Stage and Health: Variety of vegetation indices, including NDVI, EVI, SAVI

– Vegetation Moisture: NDWI

The pre-fire stage

SAR in support of optical remote sensing for forest fires



Between 18 and 28 July 2023, wildfires broke out on Rhodes. Fierce blazes ravaged almost 18,000 hectares of land, destroyed buildings, trapped animals and led to a mass evacuation of thousands of tourists.

This Copernicus Sentinel-1 image shows the burn scars left by fires on the Greek island of Rhodes.

The pre-fire stage

Fire Risk Mapping	Ignition	NO	-
	Land cover	YES	VIS and SAR
	Soil moisture and drought severity	YES	Microwaves
	Vegetation type and stage	YES	VIS
	Burning fuel	YES	VIS
	Topography	YES	VIS and SAR
	Meteorological parameters	LIMITED	VIS and TIR
	Land surface temperature	YES	TIR

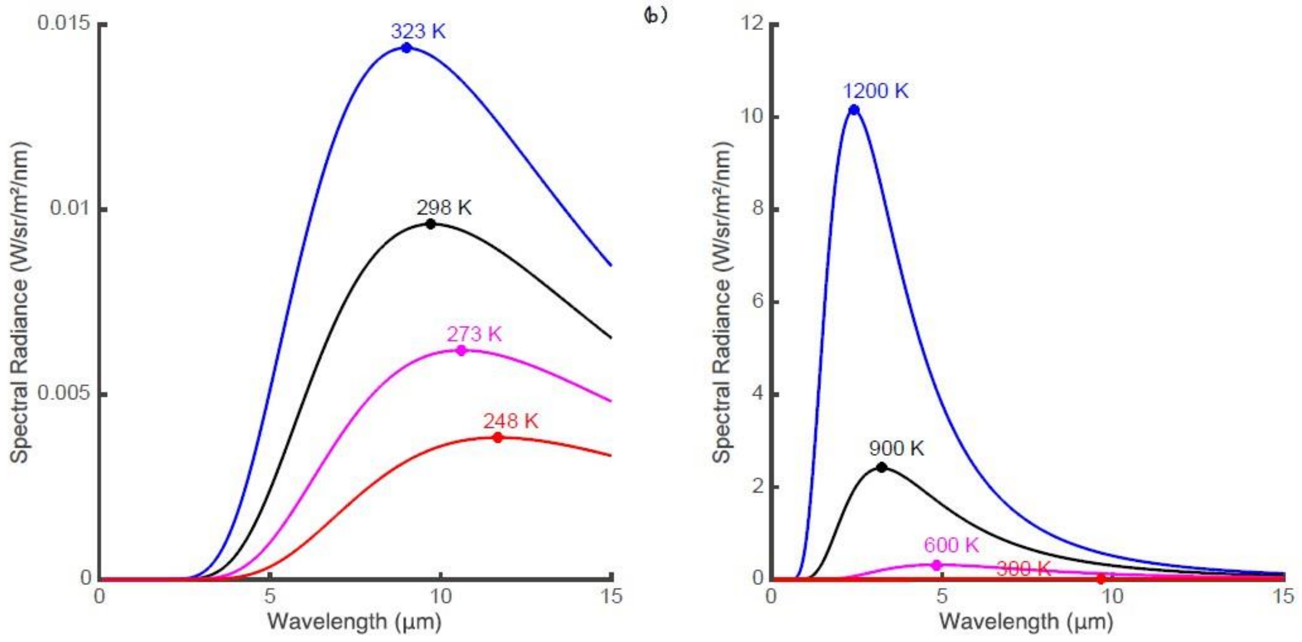
To provide reliable Fire Risk Mapping, spatial resolution needs to be high

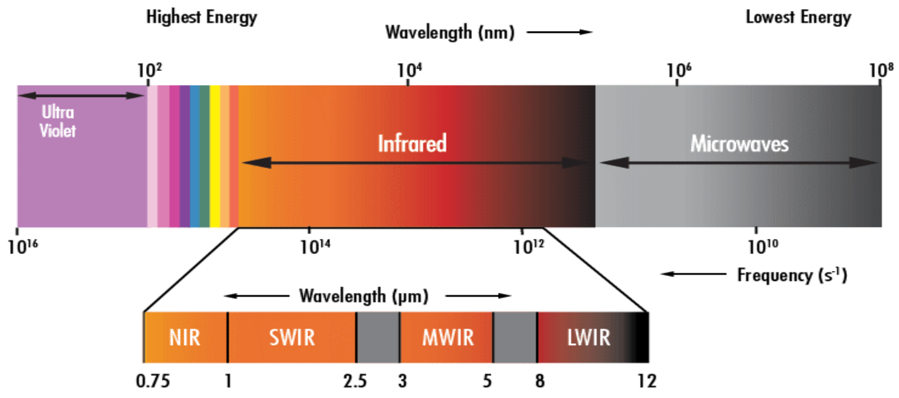
The Active fire stage

As fires burn much hotter than the typical temperature of surfaces on the Earth, heat provides a strong signal for the detection of fire.

The total energy radiated from a surface increases rapidly with its temperature (proportional to the fourth power of temperature as described by the Stefan-Boltzmann law).

However, the radiance is not uniform across wavelength and the distribution peaks at a wavelength that varies inversely with the temperature.



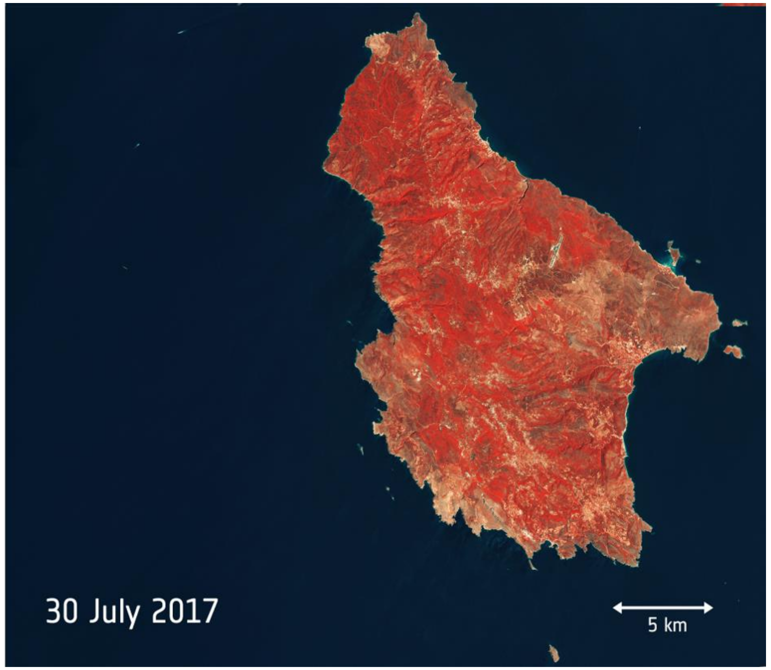


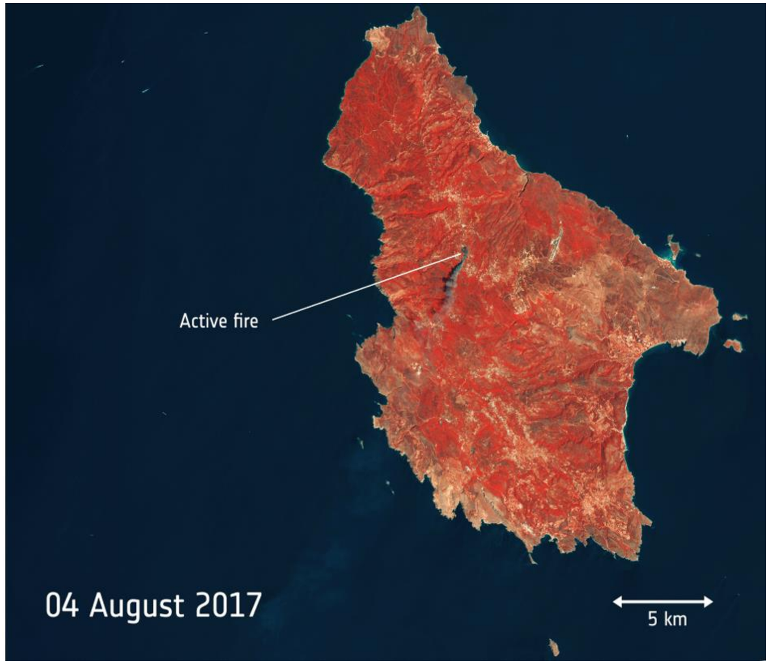
At normal ambient temperature, the peak is in the range 8–12 µm and most of the radiant energy lies at wavelengths greater than 5 µm (left image).

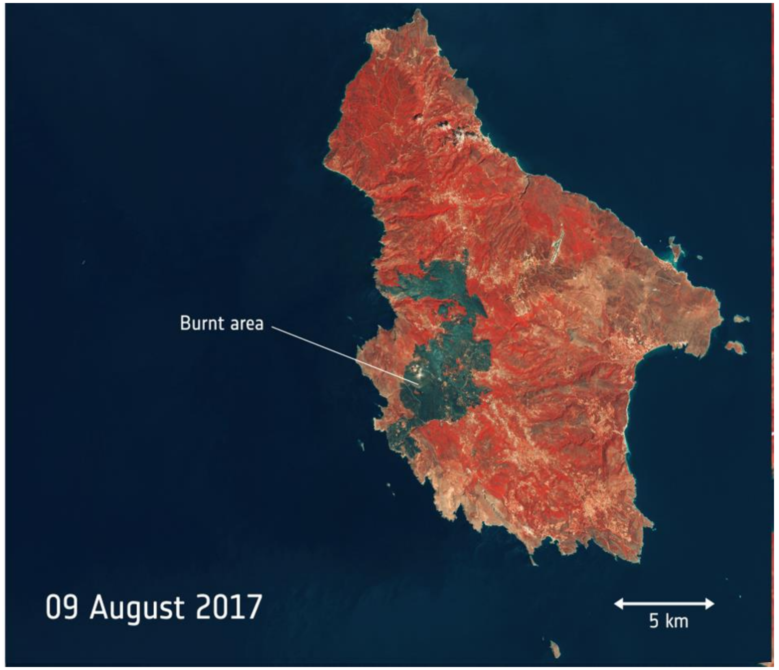
At higher temperatures typical of forest fires, the peak of the response shifts to mid-wave infrared (MWIR, 3–5 µm) or shorter wavelengths (right image).

The Active fire stage

Detecting hotspots and Total area burning







Kythira wildfires

Southern Europe experienced a relentless heatwave this summer, fuelling wildfires in a number of countries. The Copernicus Sentinel-2 satellite pair captured the start of a fire on the Greek island of Kythira on 4 August. Five days later, a huge burn scar is visible across the western part of the island.

Source: modified Copernicus Sentinel data (2017), processed by ESA

The Active fire stage

Fire Radiative Power and Thermal Infrared

Comparing window channels in near and thermal infrared

Near infrared (1.6 μm)	More adequate for smoke detection than 3.9 μm Small fires not visible No CO_2 absorption (higher fire temperature) High sub pixel sensitivity
Middle infrared (3.9 μm)	High temperature sensitivity - major sub pixel effects (hotspots are easily detected) Negligible absorption by atmospheric humidity Close to a CO_2 absorption band, 4-7 Kelvin signal reduction Brightness is temperature of the CO_2 layer above the fire
Thermal infrared (10.8 μm)	1-2 Kelvin absorption by atmospheric humidity No signal reduction by CO_2 Lower temperature sensitivity (small subpixel effects) No risk of sensor blinding by fires Low values compared with 3.9 μm due to semi transparent cloud or smoke

The Active fire stage

Temporal resolution – a critical parameter

- The majority of satellites providing earth imagery are either geostatic or in the near-polar sun-synchronous orbit and include multispectral imaging sensors.
- Sun-synchronous satellites provide data with **high spatial resolution but low temporal resolution**
- while geostationary satellites have **high temporal resolution but low spatial resolution.**

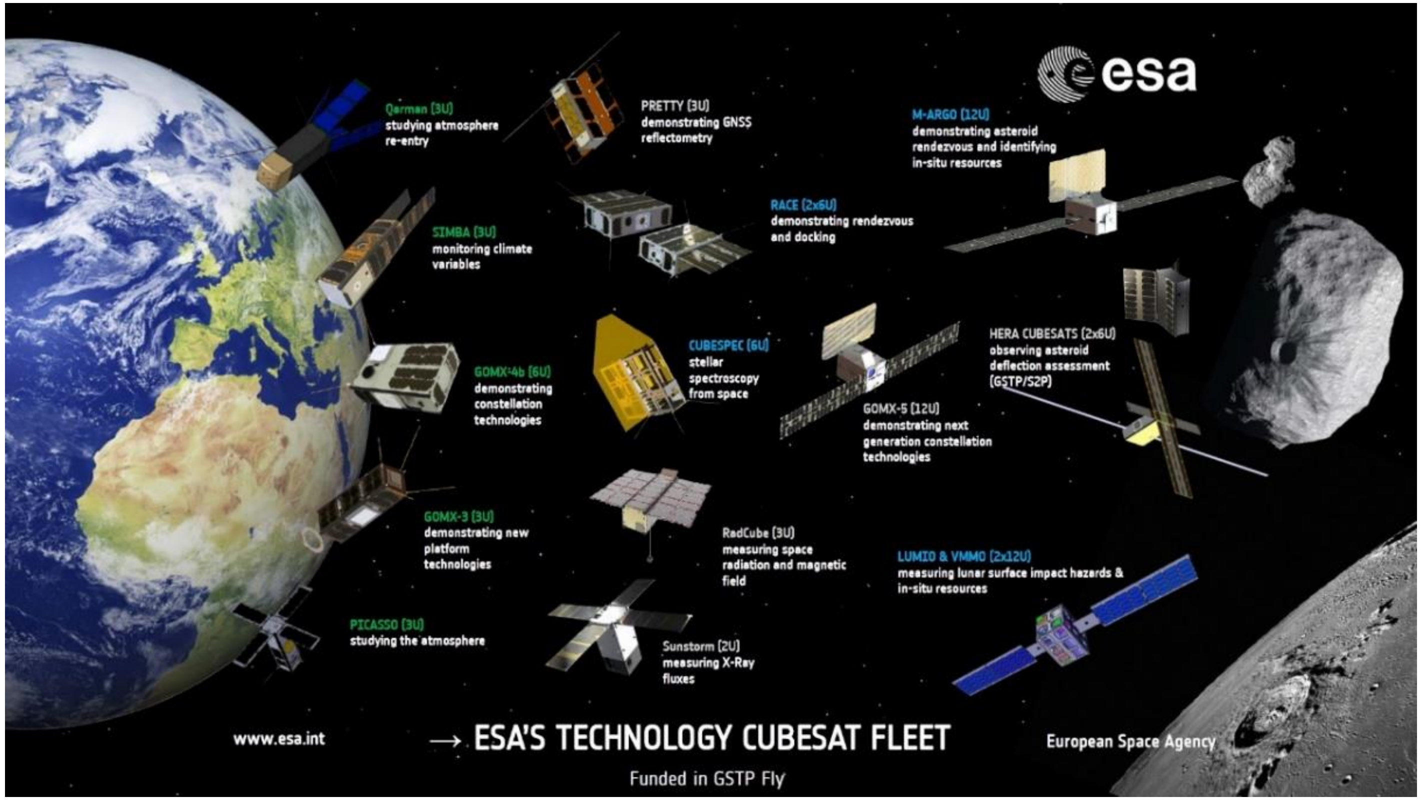
Sensor/Satellite	Channels	Product	Spatial/Temporal
SEVIRI/Meteosat	3.9µm, 10.8µm	FIR (Active Fire Monitoring)	3 km/5 min
MODIS/Aqua and Terra	4µm, 11µm	Active Fire	1km/ 1-2 days per satellite
SLSTR/SENTINEL 3	3.7µm, 10.8µm	Active Fire	1km/approx. 1 day
SENTINEL 1	Radar	Burned area	5m/2 days at mid-latitudes
SENTINEL 2	Vis	Burned area	10 m/2-3 days at mid-latitudes
AVHRR/NOAA	3.7µm	FIMMA	1km/ 5-6 times per day
VIIRS/ Suomi-NPP	4µm, 11µm	Active fire	375m/ 3-4 times per day

The Active fire stage

Temporal resolution – a critical parameter

Recently, advances in nanomaterials and micro-electronics technologies have allowed the use of tiny low-Earth-orbiting satellites, known as **CubeSats**.

CubeSats by launched in constellations succeed in improving considerably the temporal resolution while at the same time they reflect high spatial resolution (due to their low orbit).



The post-fire stage

Normalized Burn Ratio (NBR)

- Used to measure burn severity by distinguishing areas that have been significantly altered in their spectral signature after a wildfire event
- It is calculated using the energy intensity from the NIR and SWIR wavelength bands from the remotely sensed satellite imagery.

- Healthy vegetation has very high NIR reflectance and low reflectance in the SWIR portion of the spectrum
- Burned areas on the other hand have relatively low reflectance in the NIR and high reflectance in the SWIR band

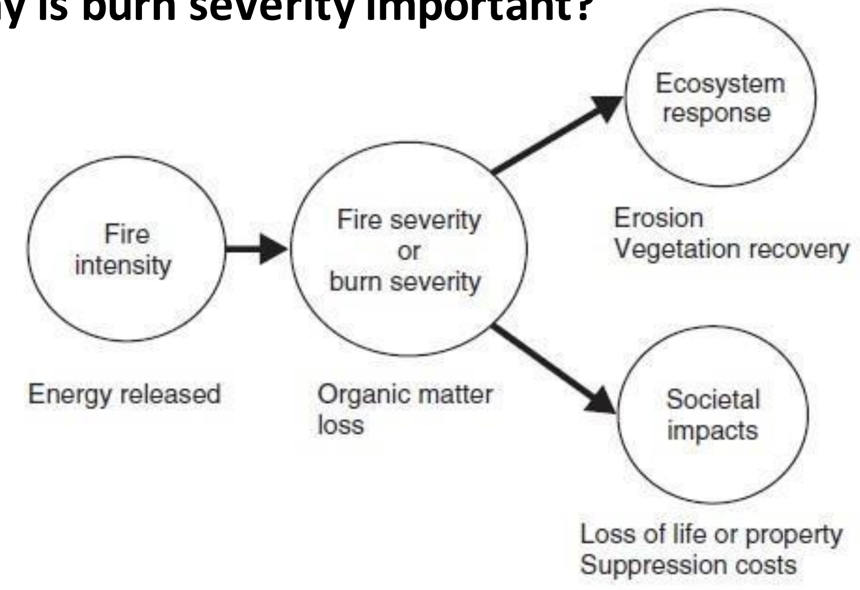
$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)} = \frac{(Band\ 8 - Band\ 12)}{(Band\ 8 + Band\ 12)}$$

The post-fire stage

Burn Severity and the delta normalized burn ratio

- **Burn severity** - degree to which an ecosystem is impacted by a wildfire event.
- **The difference between pre-fire and post-fire NBR (the delta normalized burn ratio (dNBR) index) -** frequently used to identify recently burned areas and differentiate them from other non- vegetated areas.
- Areas with high dNBR value correspond to a higher degree of damage or burn severity. In contrast, low dNBR values represent areas that are unaffected from the fire event or regions that have rebounded via regrowth of plant species following a wildfire incident.

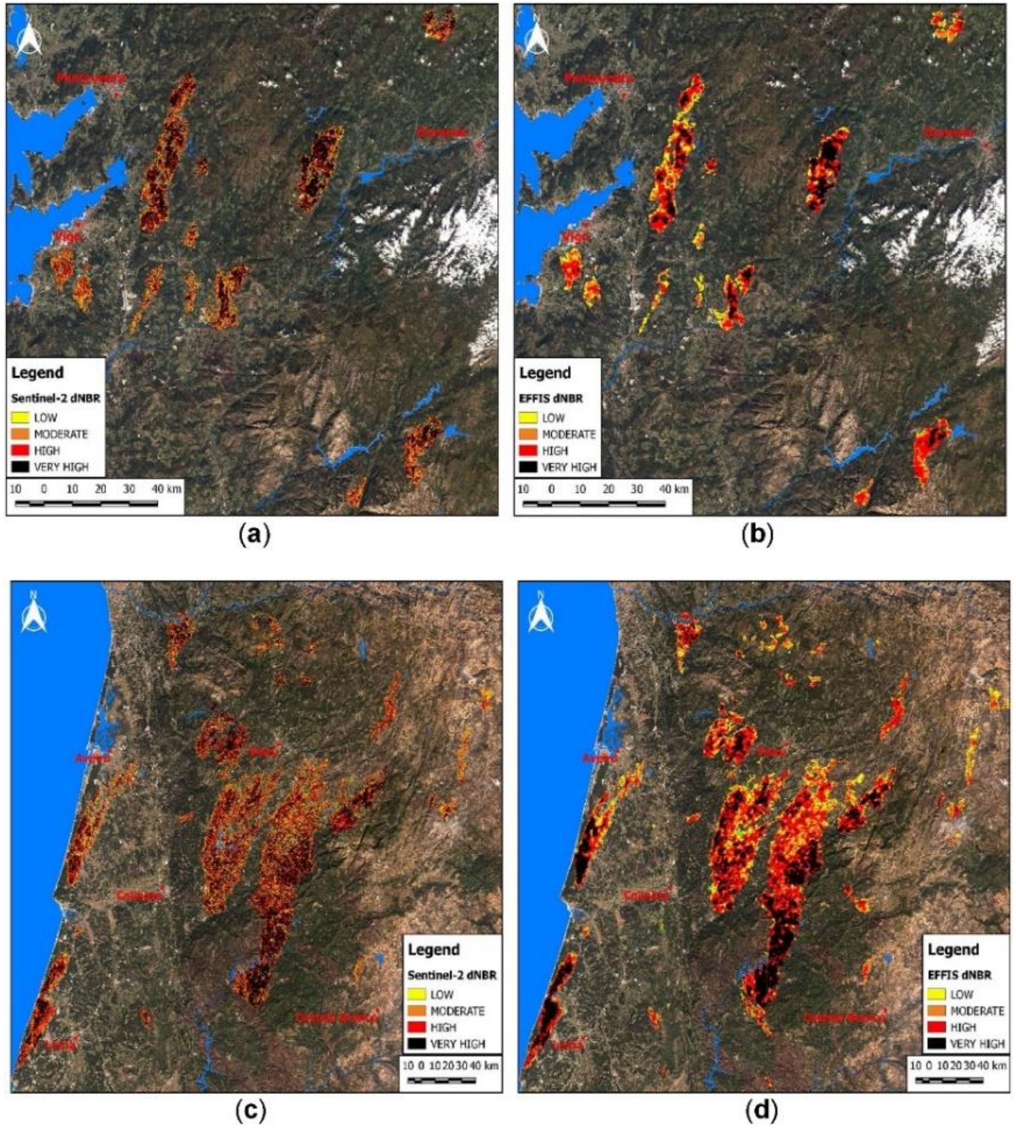
Why is burn severity important?



EFFIS thresholds	Severity Level
dNBR < 0.100	Unburned / Very Low
0.100 ≤ dNBR ≤ 0.255	Low
0.256 ≤ dNBR ≤ 0.419	Moderate
0.420 ≤ dNBR ≤ 0.660	High
dNBR > 0.660	Very High

The post-fire stage

Burned areas and burn severity – Spain and Portugal 2017



(a) Sentinel-2 dNBR image using Post-1 images in Galicia wildfires;
(b) EFFIS dNBR image in Galicia wildfires;
(c) Sentinel-2 dNBR image using Post-1 images in Portugal wildfires;
(d) EFFIS dNBR image in Portugal wildfires. Water areas are masked (blue color).

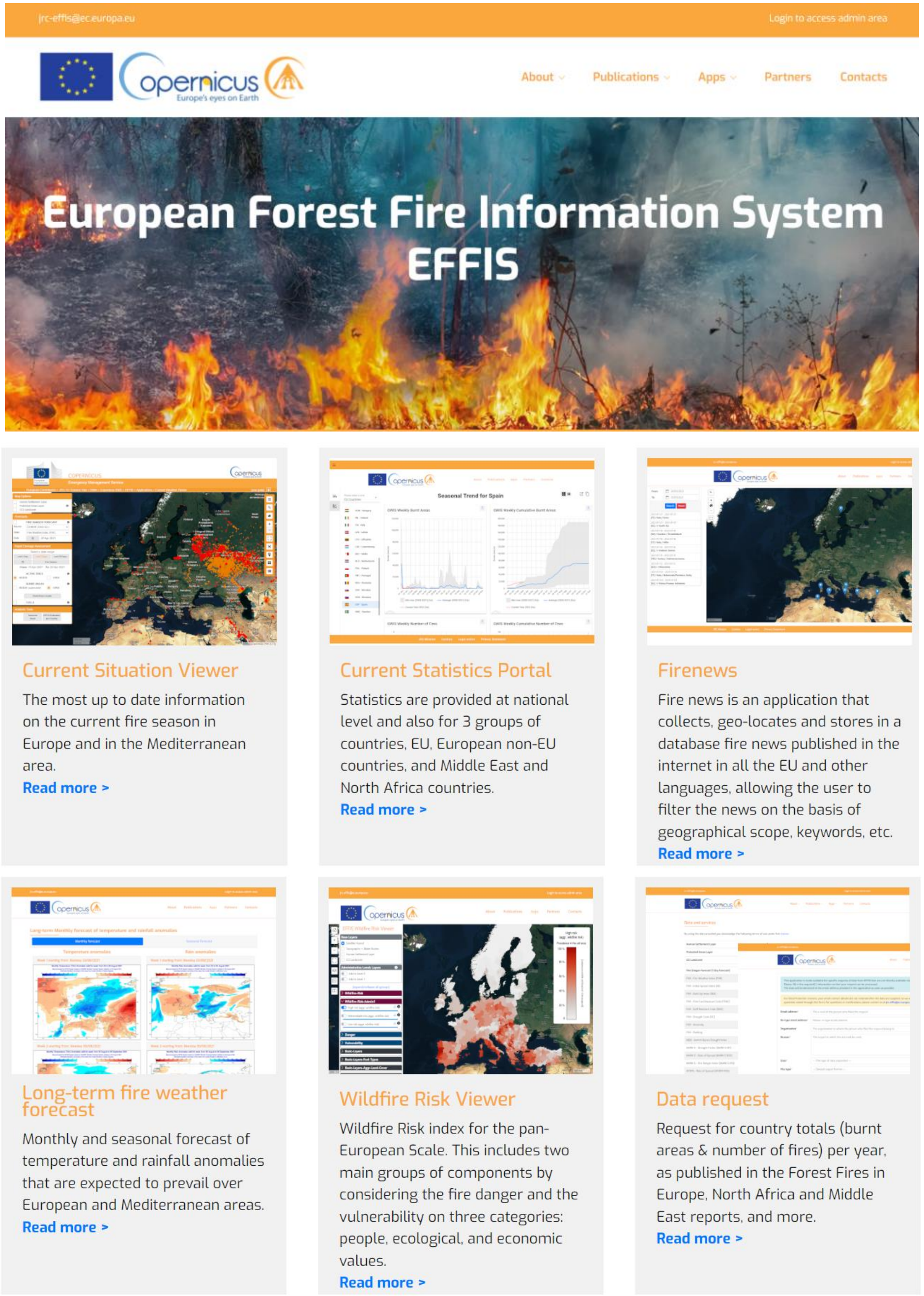
from:
Rafael Llorensa, José Antonio Sobrino, Cristina Fernández, José M.Fernández-Alonso, José Antonio Vega, A methodology to estimate forest fires burned areas and burn severity degrees using Sentinel-2 data. Application to the October 2017 fires in the Iberian Peninsula, International Journal of Applied Earth Observation and Geoinformation Volume 95, March 2021, 102243 https://doi.org/10.1016/j.jag.2020.102243

Sources of information

The European Forest Fire Information System (EFFIS)

- The European Commission has developed the European Forest Fire Information System (EFFIS) ([http://effis.jrc.ec.europa.eu/)](http://effis.jrc.ec.europa.eu/) to provide a fire risk forecast and a fire danger assessment in EU countries.

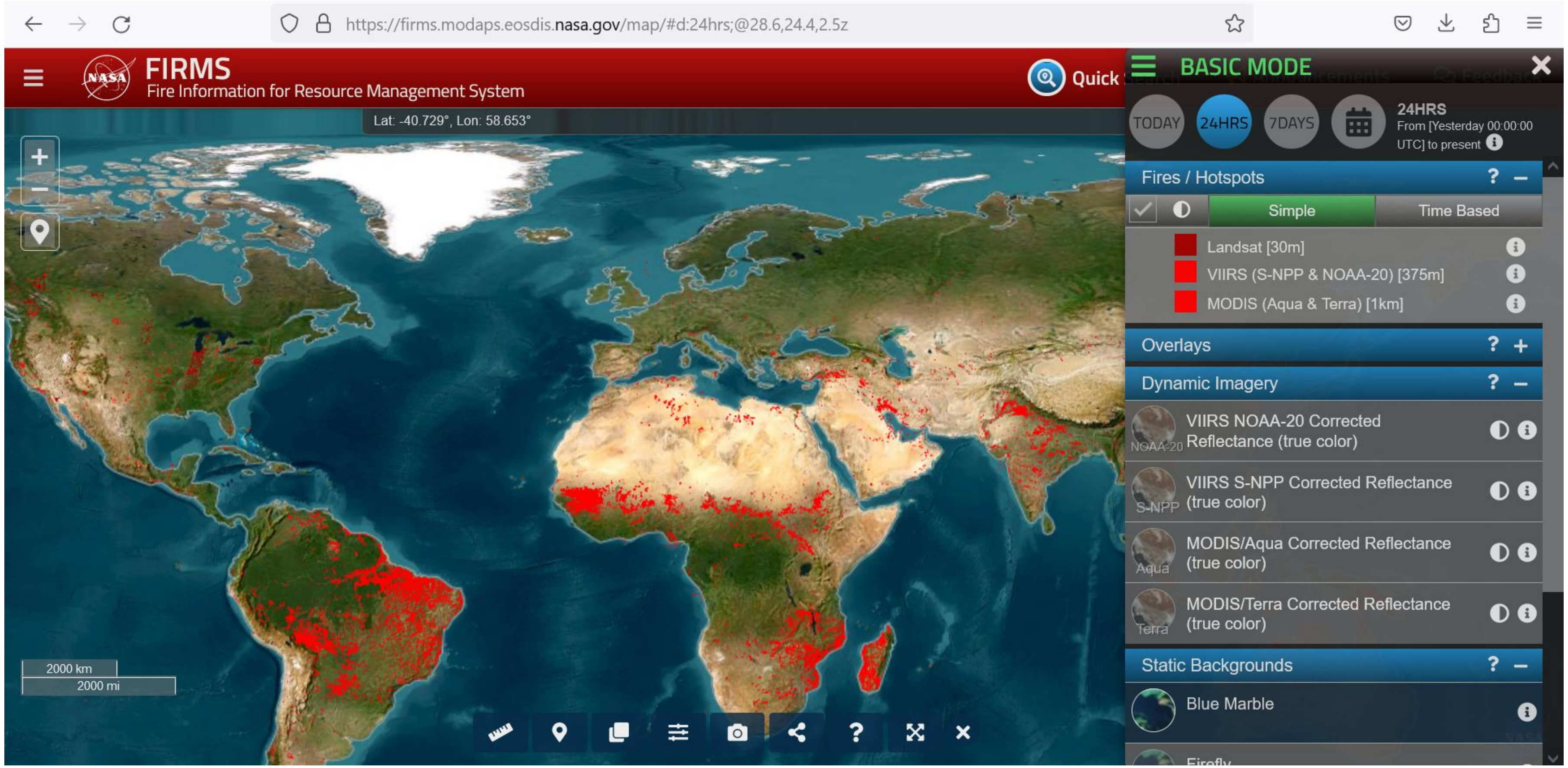
- EFFIS is one of the **Copernicus Emergency Services** and becomes an essential tool for providing most up-to date information on fire danger in EU



The Global Wildfire Information System (GWIS)

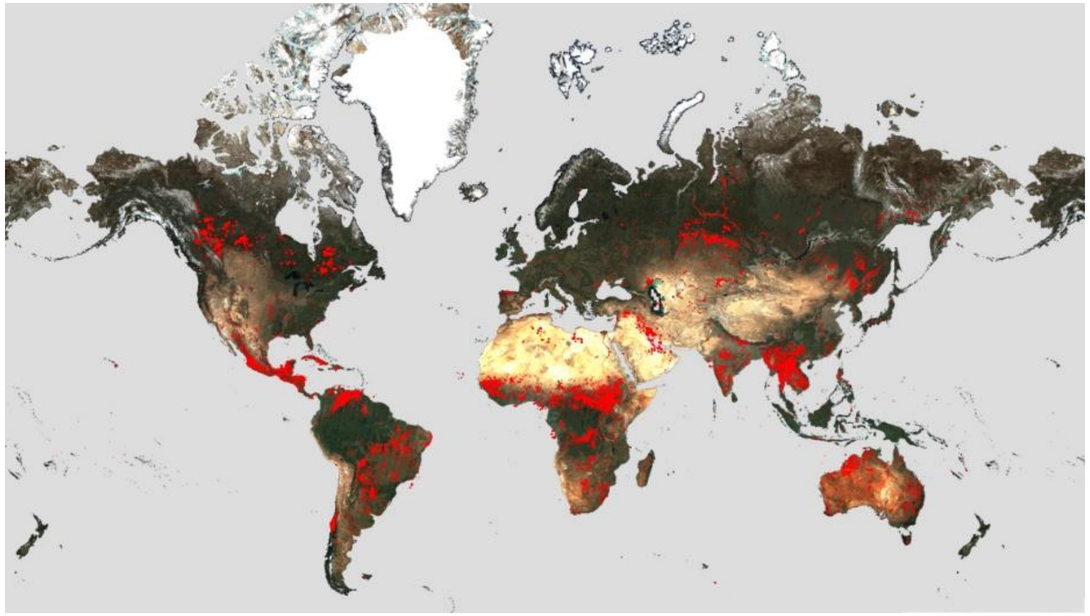
Joint initiative of the Group on Earth Observations (GEO), the NASA Applied Research and the EU Copernicus work programmes. Using advanced methods on data processing for wildfire detection and monitoring, numerical weather prediction models, and remote sensing, GWIS enables enhanced wildfire prevention, preparedness and effectiveness in wildfire management.

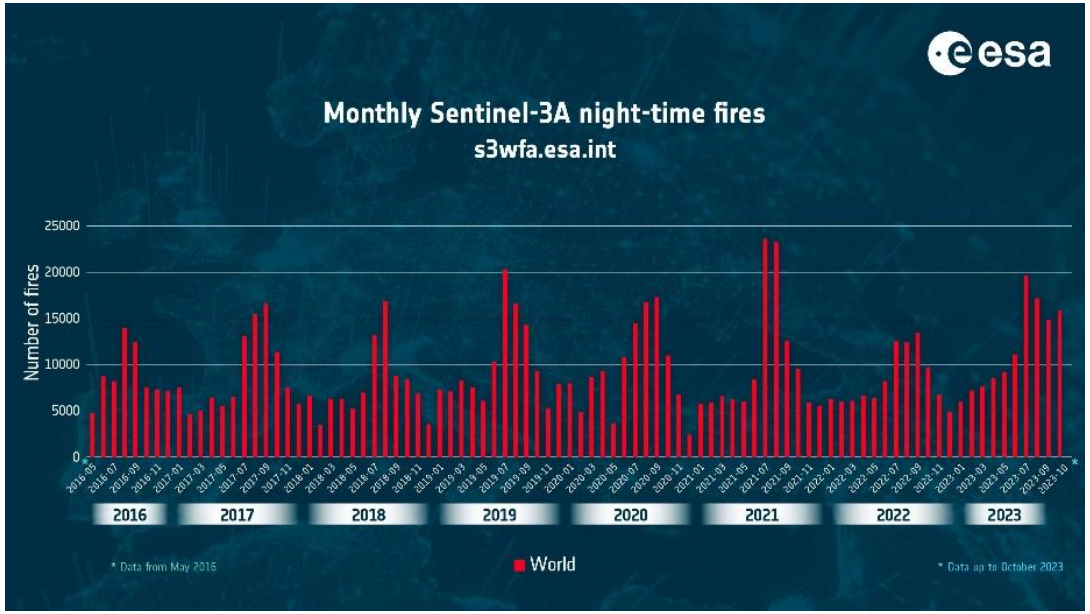
Fire Information for Resource Management System (FIRMS)



NASA's FIRMS distributes Near Real-Time (NRT) active fire data within 3 hours of satellite observation from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) and NASA's Visible Infrared Imaging Radiometer Suite (VIIRS). https://firms.modaps.eosdis.nasa.gov/

Worldwide fires from ESA's Sentinel-3 World Fire Atlas



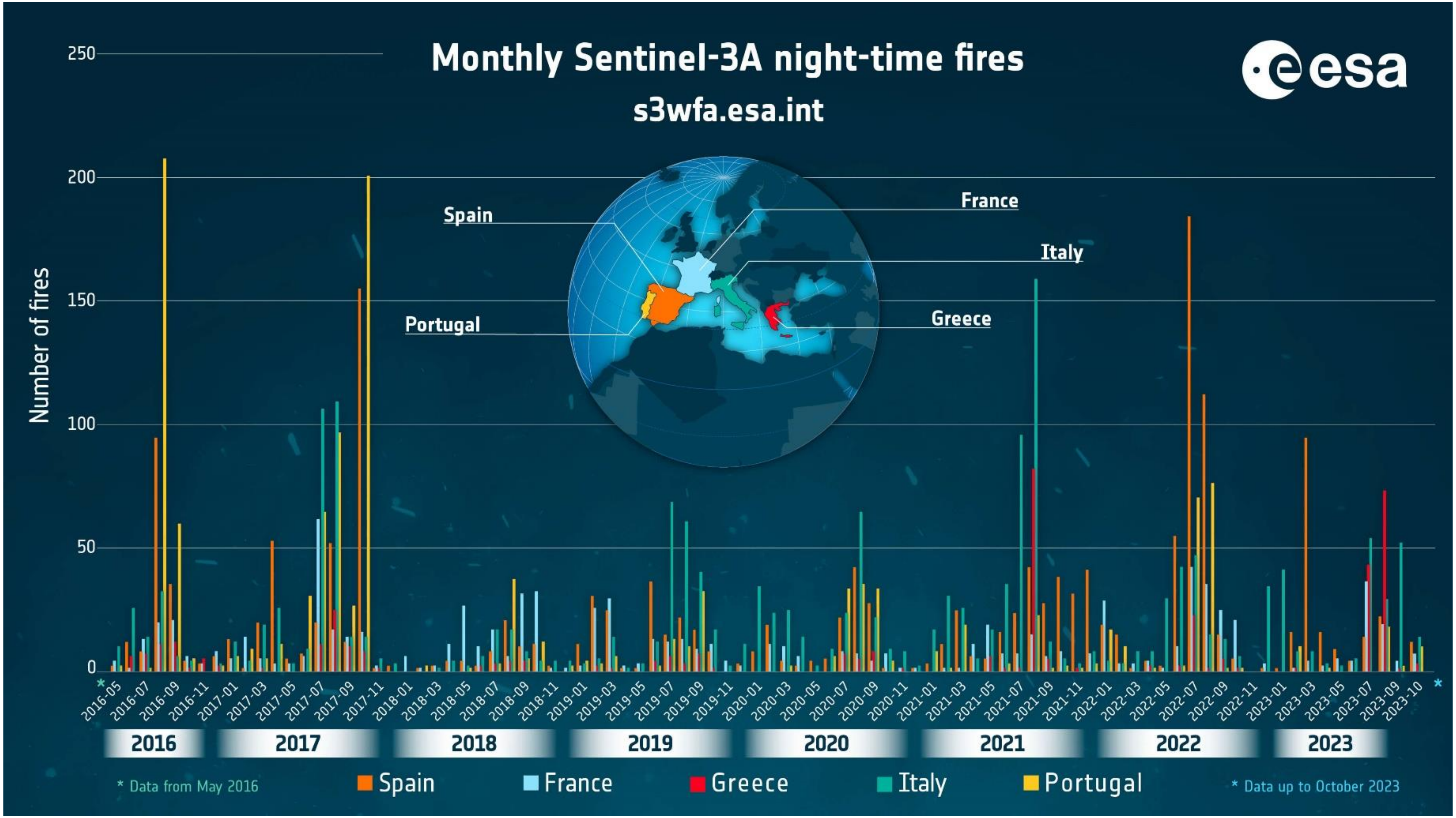


- The atlas provides a detailed analysis of wildfires across the globe and utilised nighttime data from the Sea and Land Surface Temperature Radiometer (SLSTR) onboard the Sentinel-3A satellite. The data have been overlaid onto ESA's World Cover map which uses data from the Copernicus Sentinel-2 mission from 2021.

- The map and graph shows fires taking place across the globe between May 2016 and June 2023, using data from the World Fire Atlas.

Source: https://s3wfa.esa.int/

Worldwide fires from ESA's World Fire Atlas

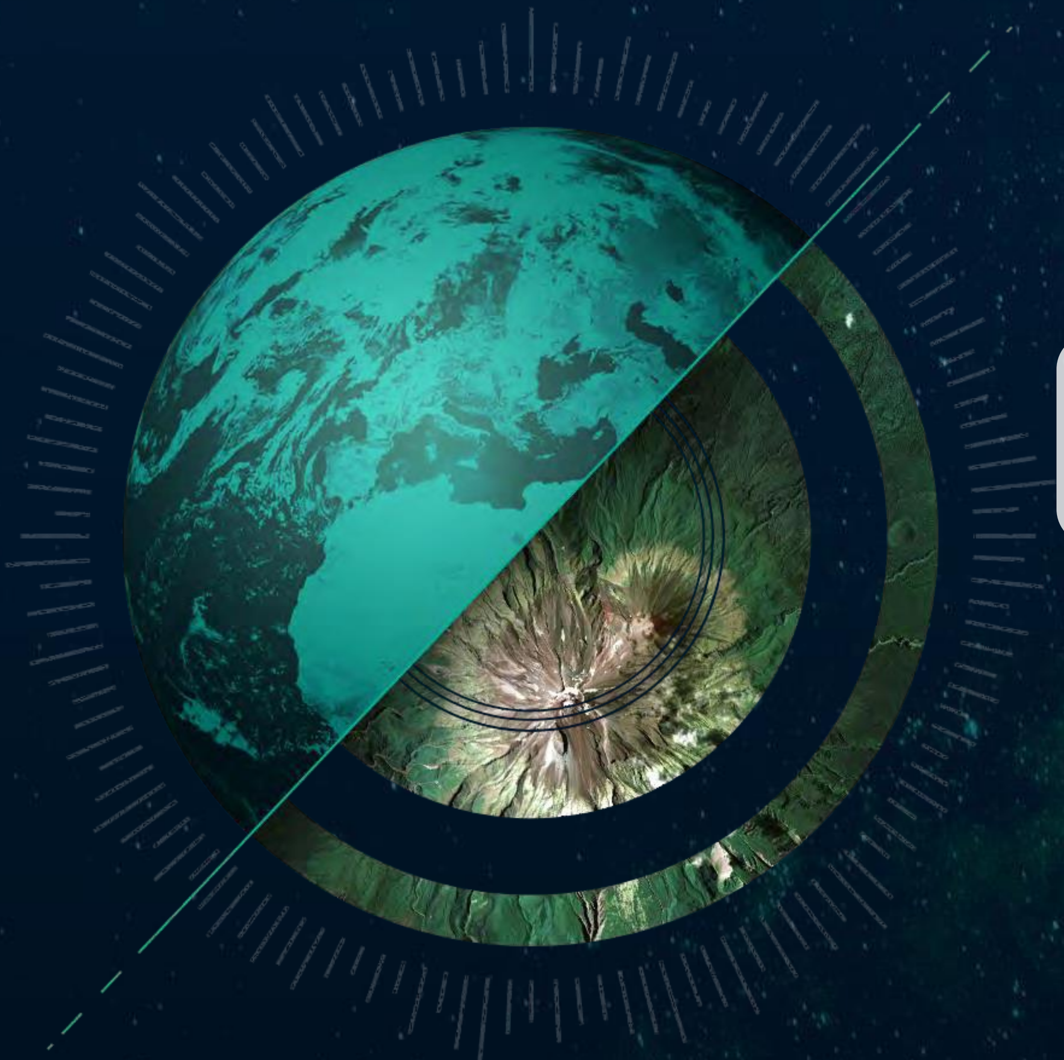


Conclusions

- Optical and thermal infrared RS observations → supportive for the pre-fire and post-fires stages
- Fire detection is technically feasible (in mid and thermal infrared; Sentinel 3, SEVIRI on Meteosat, Landsat TM), yet satellites with good temporal resolution have poor spatial one and vice versa → contribution to operational plans in the active fire stage is constrained
- Sentinel 2 and 3 facilitate research and operation applications with respect to forest fires. Results are complemented by Sentinel 1 SAR observations
- Low spatial resolution satellites/sensors (VIIRS, MODIS) - used for pre-fire risk mapping; satellites of high spatial resolution - during the post-fire stage - may be used instead (Sentinel- 2, Landsat, Worldview, etc.)
- Cubesats reflect a promising development to improve both temporal and spatial resolution
- Several forest fire related applications have been developed in the framework of the EU, ESA, as well in other parts of the world.

For more information, see the tutorial:
7. Wildfire Mapping with Sentinel-1 & Sentinel-2 using the SNAP software

esa space solutions
Copernicus Academy
ÚSTAV GEOGRAFIE
Prírodovedecká fakulta UPJŠ v Košiciach

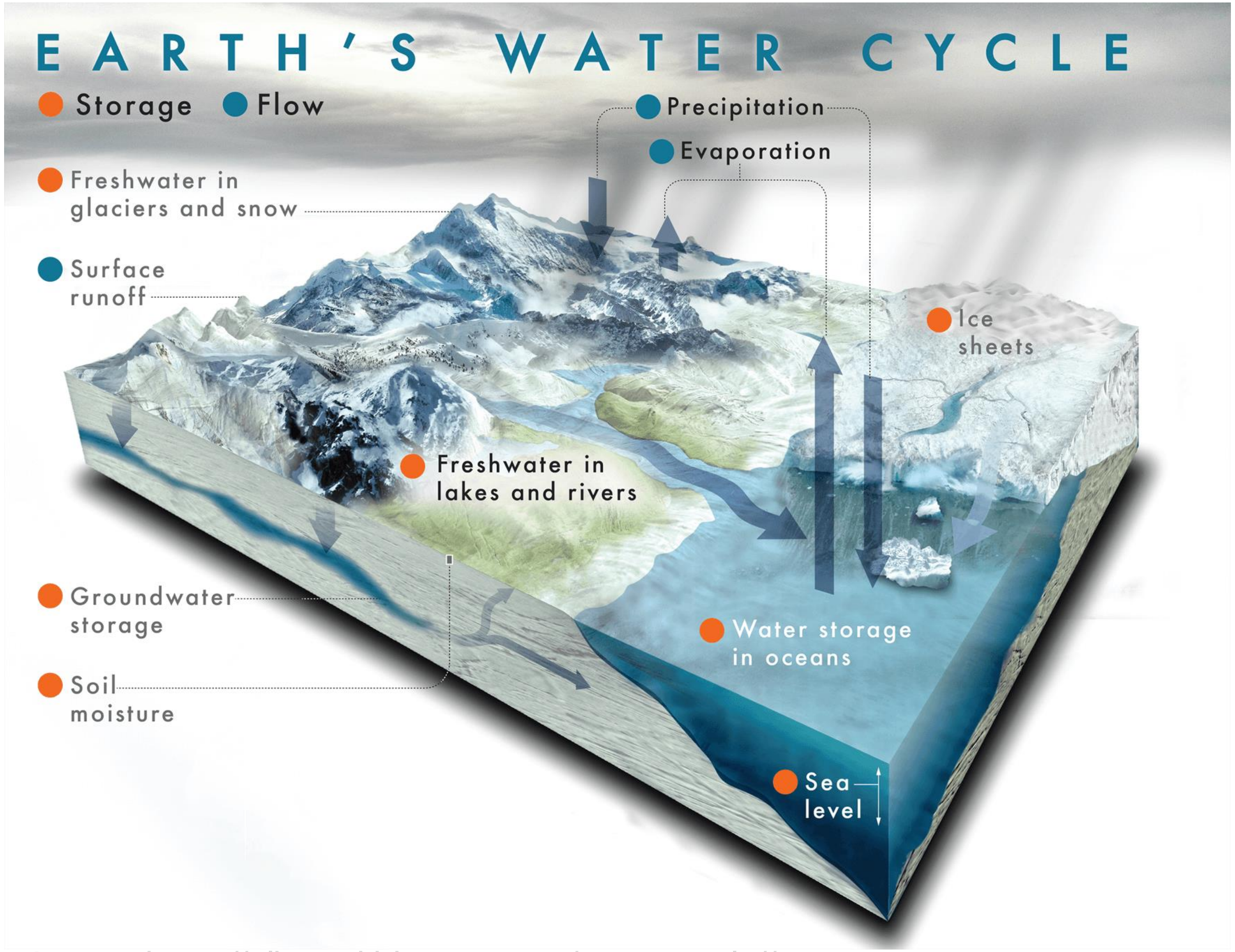


8. SAR and Optical remote sensing for mapping snow

Why do we need information about snow

Information on snow is essential for several reasons:

- Climate Monitoring
- Water Resource Management
- Natural Hazard Assessment
- Ecosystem Monitoring
- Sea Level Rise



Source:https://climatekids.nasa.gov/water-cycle//

Cryosphere

- The portion of Earth's surface where water is found in its (mostly) solid form, including snow, ice, glaciers, ice caps, ice sheets, frozen ground (permafrost), and sea ice
- It encompasses regions of both land and sea that experience freezing temperatures, and it plays a crucial role in Earth's climate system.
- The cryosphere interacts with other components of the Earth system, such as the atmosphere, oceans, and biosphere, through processes like melting, freezing, and ice-albedo feedback
- Changes in the cryosphere can have significant impacts on global climate patterns, sea level rise, freshwater availability, and ecosystems.

Source:https://discoveringthearctic.org.uk/introducing-the-arctic/snow-water-ice-permafrost/cryosphere/

Examples of snow patterns in different environments

https://www.gadventures.com/trips/antarctica-classic-in-depth/XVAESX/, https://www.mergili.at/worldimages/picture.php?/8968,, https://www.antarcticglaciers.org/glacial-geology/glacial-landsystems/glaciated-valley-landsystems/debris-covered-glacier-landsystems/

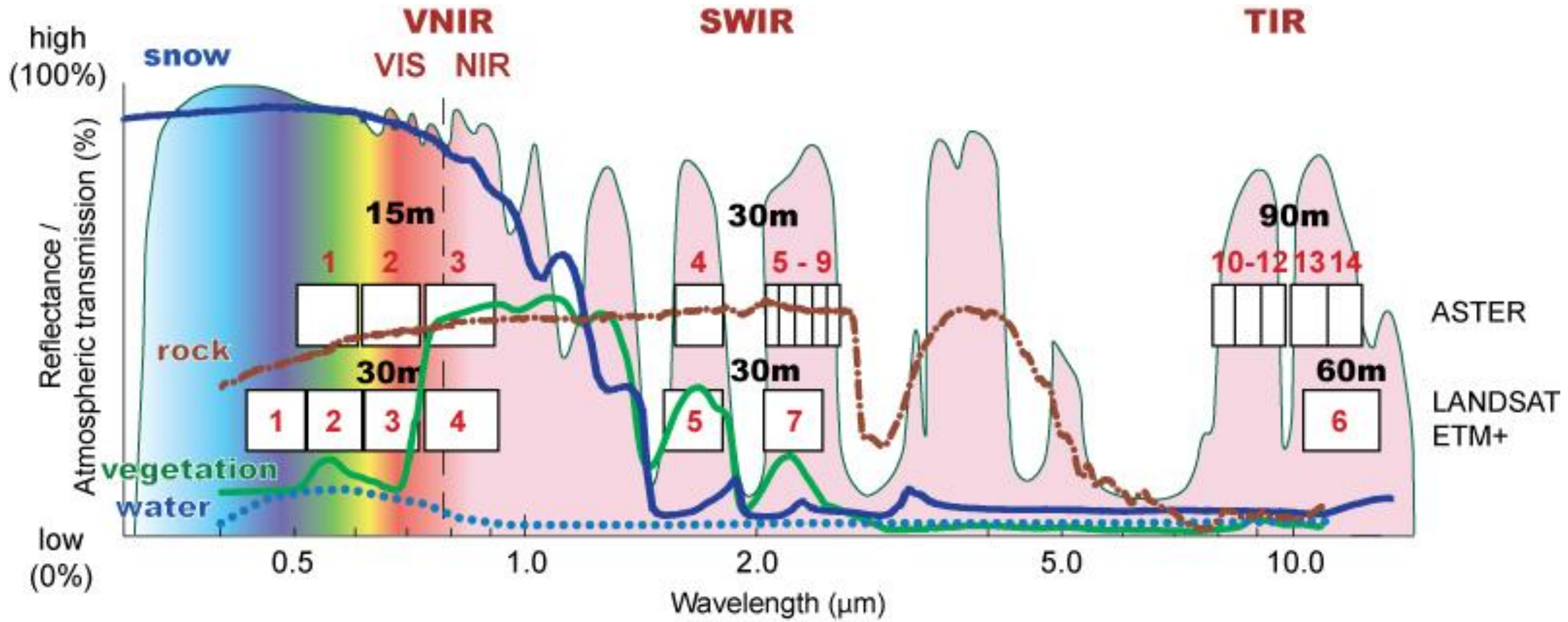
Typical densities of snow (and ice)

Typical densities of snow and ice (kg/m^3)	
New snow (immediately after falling in calm)	50-70
Damp new snow	100-200
Settled snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-917

Source: Paterson, W.S.B. 1994. *The Physics of Glaciers.*

Remote Sensing of Snow

Selected satellites used i.a. for cryospheric applications			
C-Band	Sentinel-1	Optical	Sentinel-2 MSI
	Envisat ASAR		SPOT-5 – 7 HRV/NAOMI
	ERS-1/-2		Terra ASTER
	Radarsat-1/-2		Sentinel-3 SLSTR/OLCI
X-Band	Cosmo-Skymed		Aqua/Terra MODIS
			NPP VIIRS

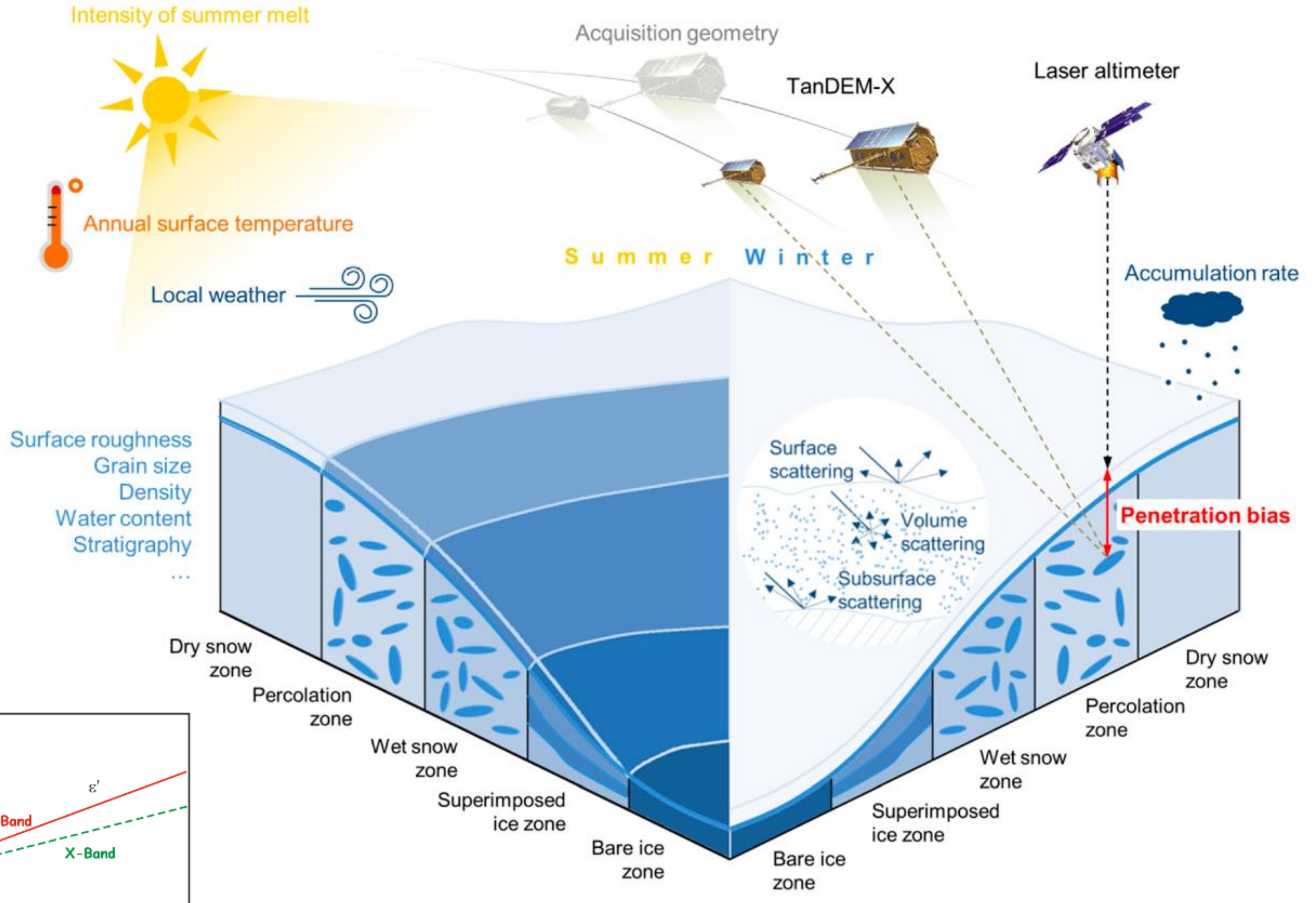


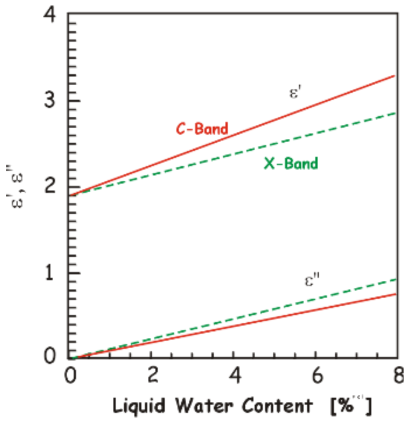
Radar for snow

Sensor	*Satellite*	*[GHz].*	*Resolution/Swath*	*Repeat*
AMI	ERS-1,-2(1991-2011)	5.3 VV	25 m - 100 km	35d/1 d
SIR-C/X-SAR	Shuttle (1994)	1.2,5.3,9.6	25 m - 40 km	2 Campaigns
SIR-C/X-SAR	SRTM (Feb.2000)	5.3 & 9.6	50/100 m - 100/200 DEM	
Present				
SAR	Radarsat1(1995-)	5.3	10,30,100 m - 100-500 km	24 d
ASAR	Envisat (2002-12)	5.3	30,100,1000 - 100-400 km	35 d
PALSAR	ADEOS (2007-11)	1.2	15/100 m - 40-350 km	46 d
TerraSAR	TerraSAR-X(2007-)	9.6	1, 3,10 m - 10,30,100 km	11 d
TerraSAR2	TanDEM-X (2010-)	9.6	in Tandem with TerraSAR-X (InSAR)	
SAR	COSMO-SkyMed	9.6	1, 3,10 m - 10-100 km	16 d, 1d, 8d
SAR	Radarsat2 (2007-)	5.3	3, 10, 30 m, □20 km 24 d	
SAR	Sentinel-1 (2013-)	5.3	10 m, 30 m 250, 400 km	12 d x 2 Sat.
Future				
SAR Constellation	Radarsat (2019 -)	5.3	3 m …100m 30 …500 km	16 d x 3 Sat.

Radar back-scatter signal

- **Physical factors:** dielectric constant of the surface materials (depends on the moisture content)
- **Geometric factors:** surface roughness, slopes, shape and orientation of the objects relative to the radar beam direction
- **The types of landcover**
- **Sensor characteristics:** Microwave frequency, polarisation and incident angle





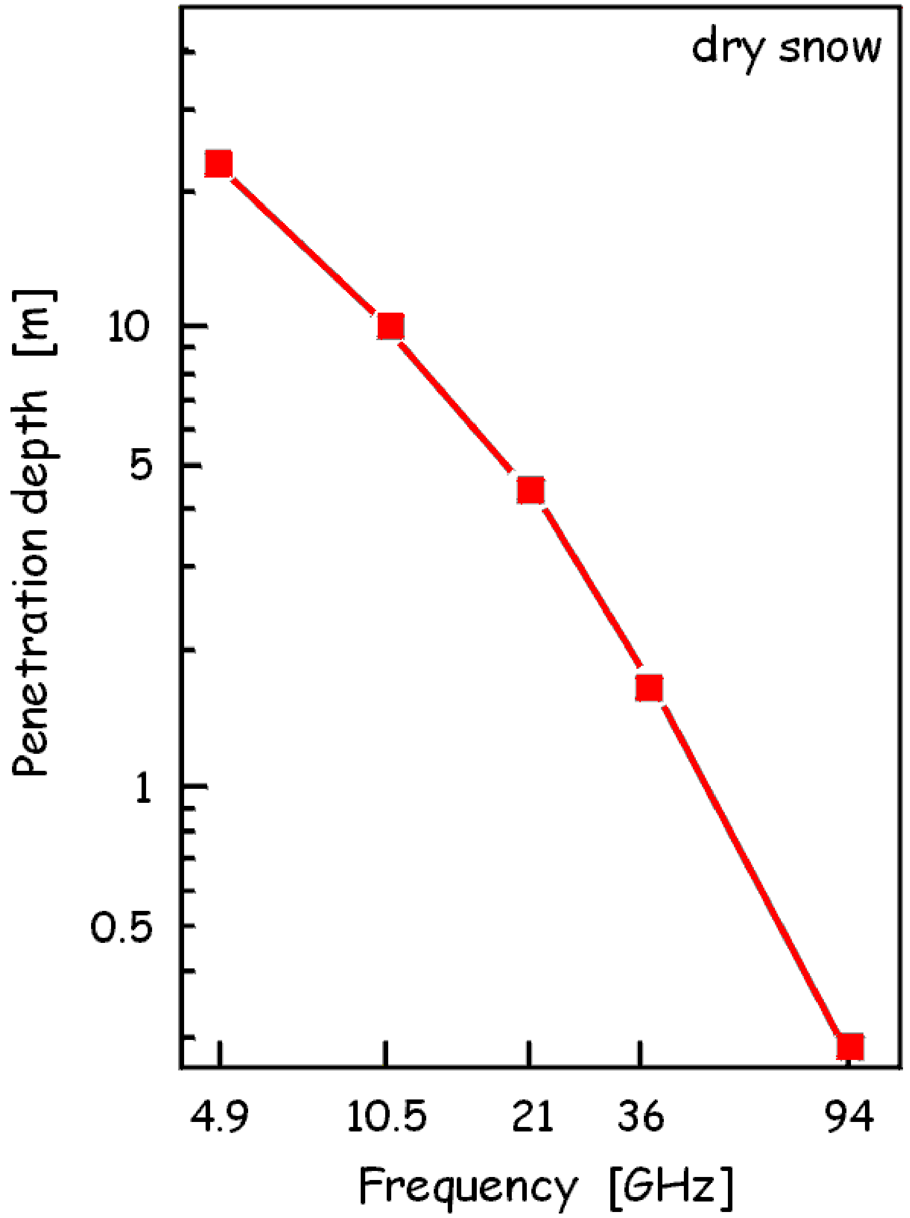
Microwave Permittivity

Source: https://www.mdpi.com/2072-4292/11/24/2903

Microwave Penetration Depth in Dry Snow

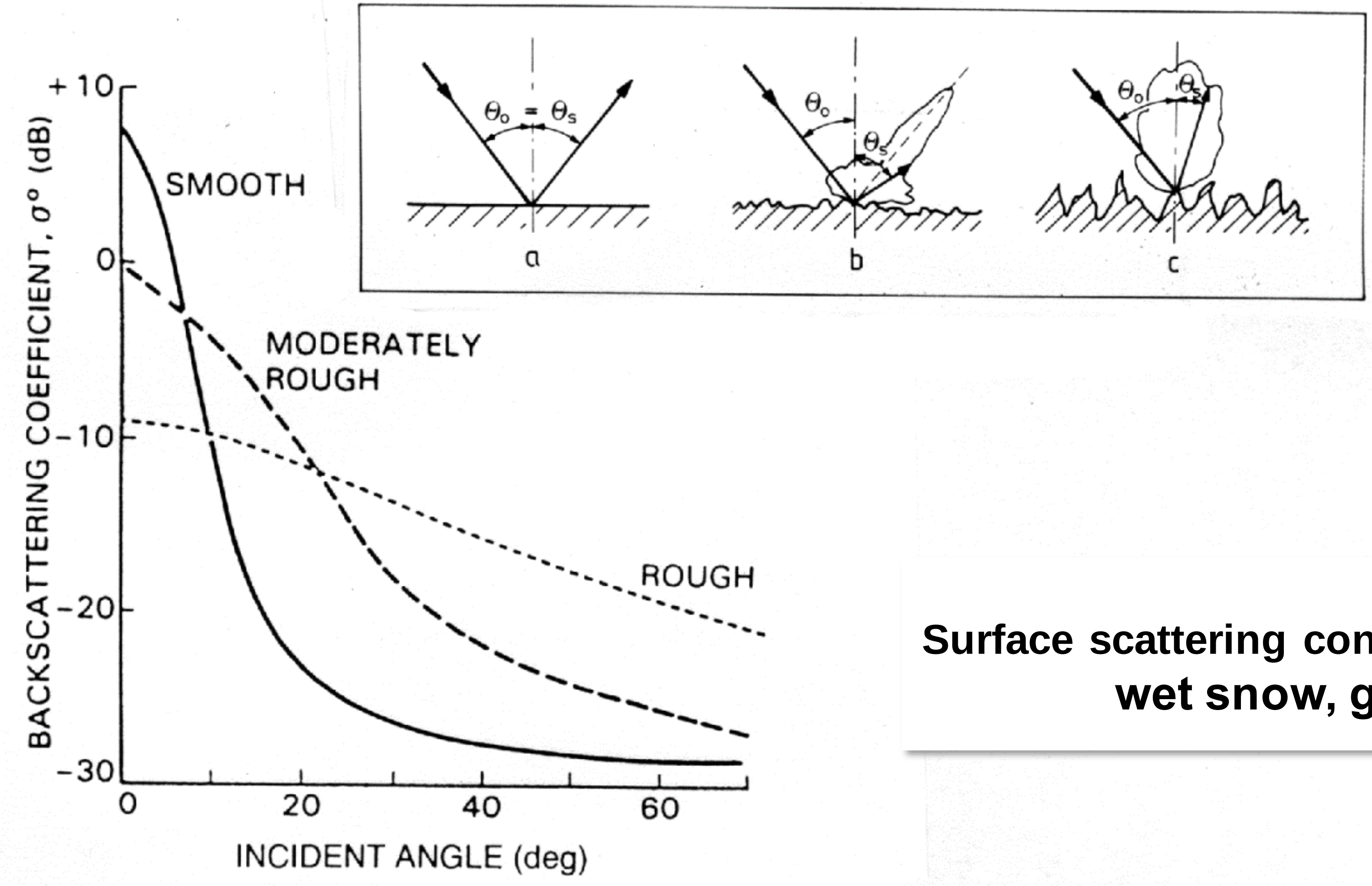
Measured by microwave radiometry:

- Alpine snowpack (Mätzler, 1987)
- Antarctic snow (Rott, 1993)
- Retrieved by inversion of satellite MW radiometry (SMMR) data, Antarctic



Dry snow: ***Attenuation dominated by scattering losses***

Backscattering from a Rough Surface



Surface scattering contribution dominates for wet snow, glacier ice, soil, …

Factors for Backscattering of Snow (Ku to L-Band)

WET SNOW *Dominant Scattering Mechanism:* **Surface Scattering**

- **Liquid water content** ***dominant factor***
- **Surface roughness** ***important***
- **Grain size** ***small effect***

DRY SEASONAL SNOW: Scattering in the Volume and/or at Lower Interface

- **σ° of medium below snow** ***dominating for seasonal snow at f<10 GHz***
- **Grain size** ***important for f> 10 GHz***
- ***Snow Mass (snow water equivalent, SWE)*** → ***Little sensitivity of at X- to L-band; Ku-band sensitive to SWE, but ambiguity with grain size***

REFROZEN SNOW (*e.g. firn area on glaciers*) Volume Scattering

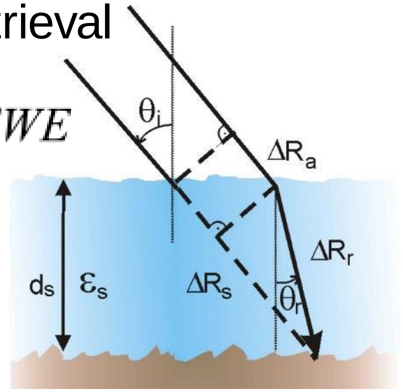
- **Volume inhomogeneities (grains, grain clusters, ice lenses, ice pipes, ..)**
- **Internal interfaces between snow layers of different density**

EO Concepts for SWE Monitoring

Approach	Strengths	Weaknesses
Passive MW 18.7 & 37 GHz 10.6 & 32 GHz	sensitive to SWE & melt; global daily coverage; independent of clouds/illumination; very long record	Coarse resolution, not suitable for mountains and forests, saturation at higher SWE
Radar (Scat or SAR): Dual: Ku & Ka Single: Ku, Ka	sensitive to SWE & melt; high resolution; independent of clouds/illumination	algorithm maturity, coverage, SWE saturation, forests
InSAR L- , C-Band	direct SWE sensitivity; high resolution avoids volume scattering issues	forests, complexity; requires advanced acquisition plan
LIDAR	direct observation of snow depth; very high resolution, minor forests and topographic issues	SWE retrieval requires snow density; No Sensor

InSAR SWE Retrieval

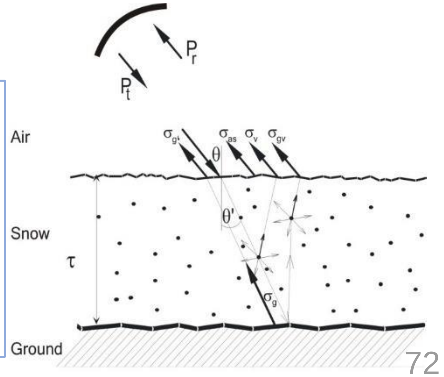
$$\Delta\phi_{snow} = \frac{1.6k}{\cos\theta_i}\Delta SWE$$



Radar (Scat or SAR)

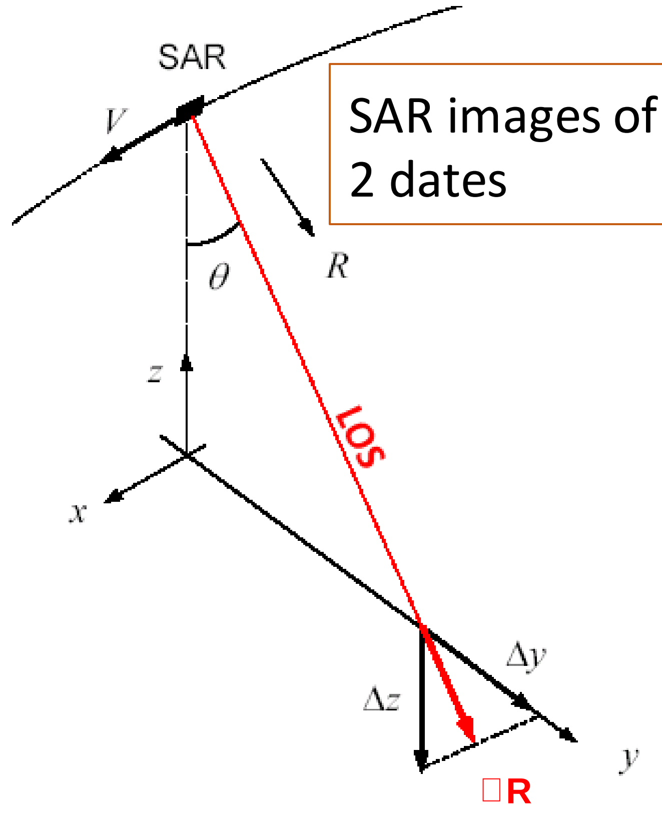
Sensitivity of backscatter to SWE depends on scattering albedo:

Dual F: Ku + Ka
Single F: Ku, Ka



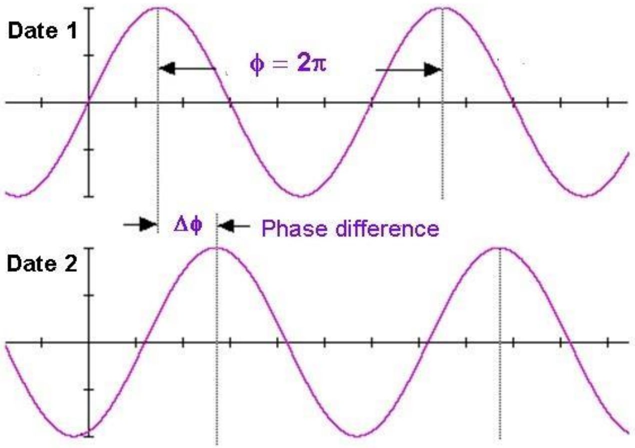
Interferometric measurement of displacement

Measurement of Displacement

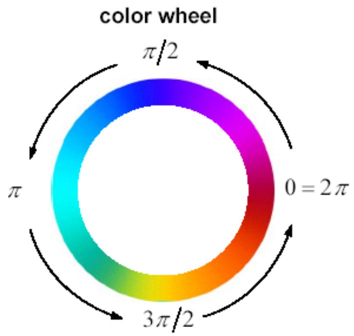


SAR images of 2 dates

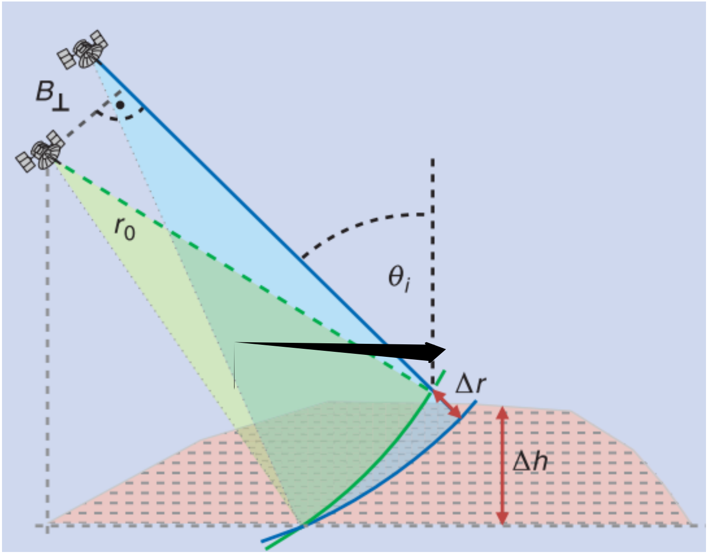
TanDEM-X



1 Fringe



InSAR for Topography

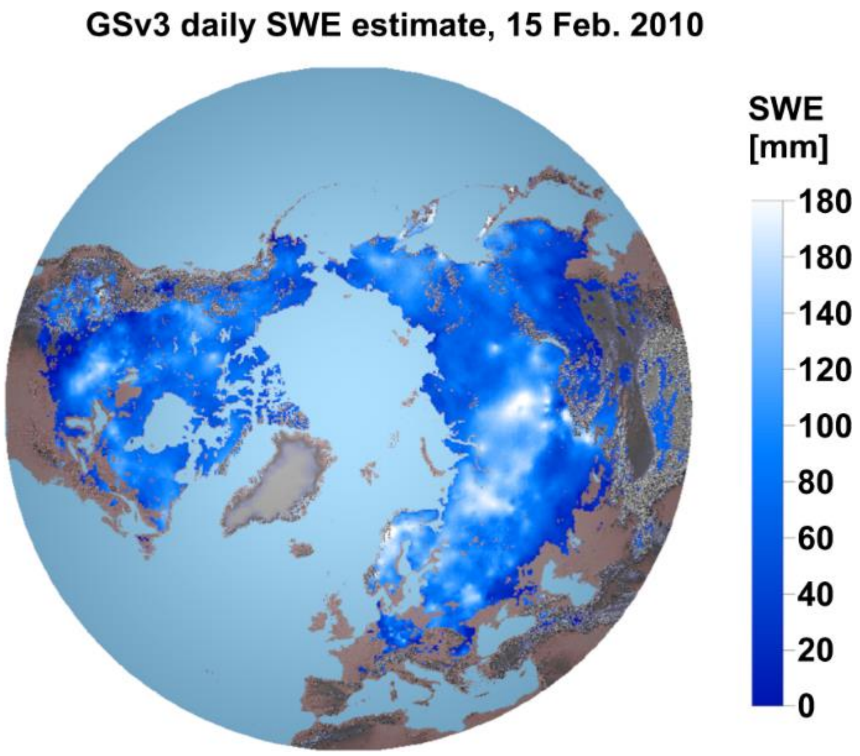


InSAR repeat track measures displacement

Requires temporal stability of radar signal phase (coherence)

Applications in Cryosphere: Radar Sensors

- Snow Water Equivalent (SWE)
- Dynamics and mass balances of ice sheets
- 3D ice surface deformation



Source: https://www.nature.com/articles/s41597-021-00939-2

Optical for snow

Incoming electromagnetic energy $_{I}(\lambda)$) is affected by:

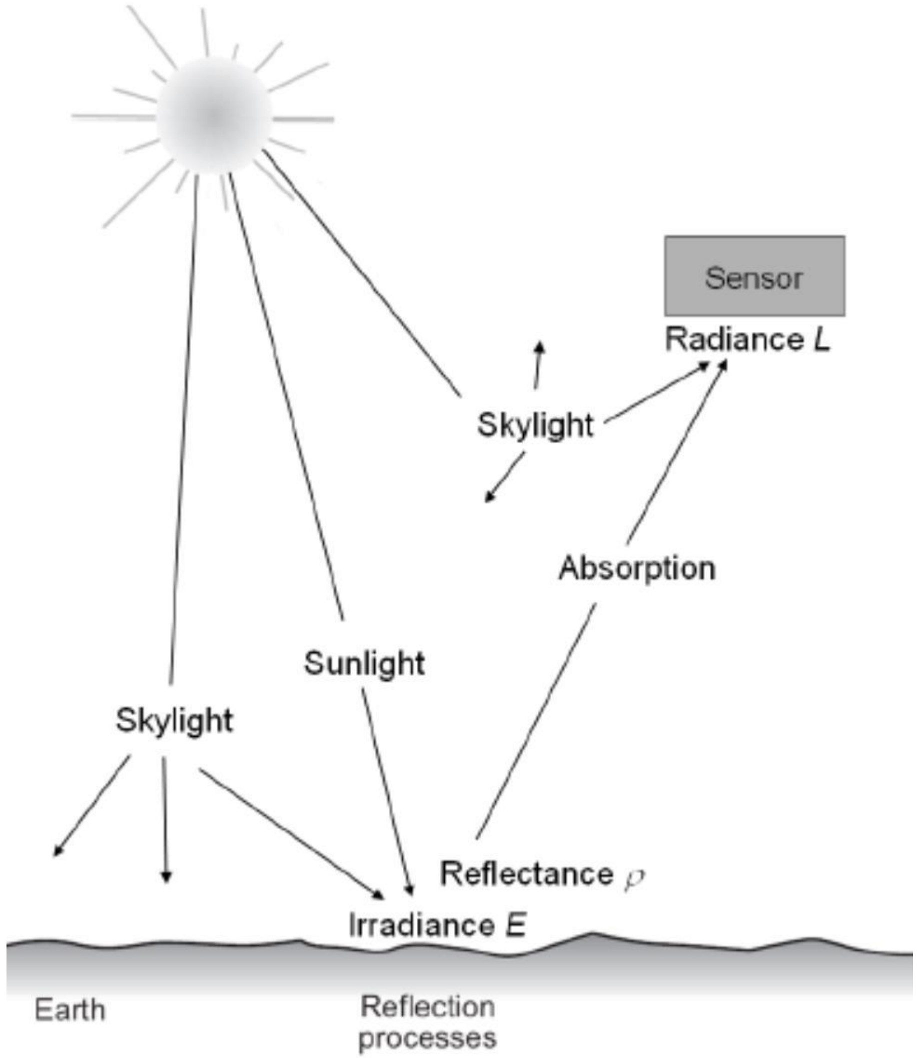
- Absorption ($E_A(\lambda)$)
- Scattering ($E_S(\lambda)$)
- Transmission ($E_T(\lambda)$)

Principle of energy conservation:

(energy can only be transferred, but neither be created nor destroyed)

$$E_I(\lambda) = E_A(\lambda) + E_S(\lambda) + E_T(\lambda)$$

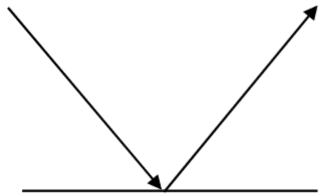
Optical sensors measure the amount of light receiving the satellite (= at-satellite radiance L), which is often converted to

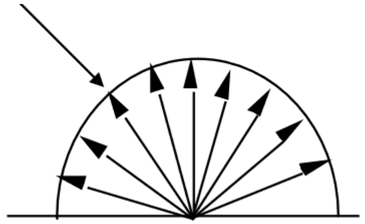


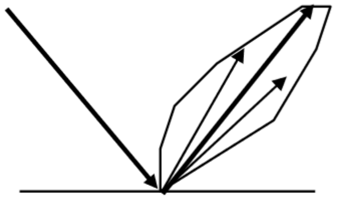
Optical for snow

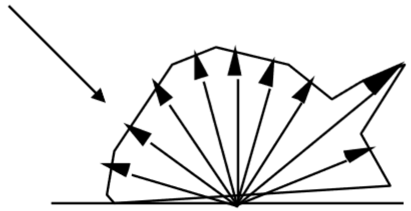
Reflectance depends on

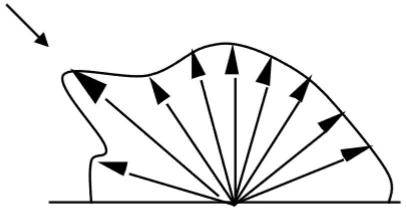
- Wavelength energy
- Atmospheric attenuation
- Geometry of the Surface
- Surface Materials


Specular reflector (mirror)


diffuse reflector (lambertian)


Nearly Specular reflector (water)


nearly diffuse reflector

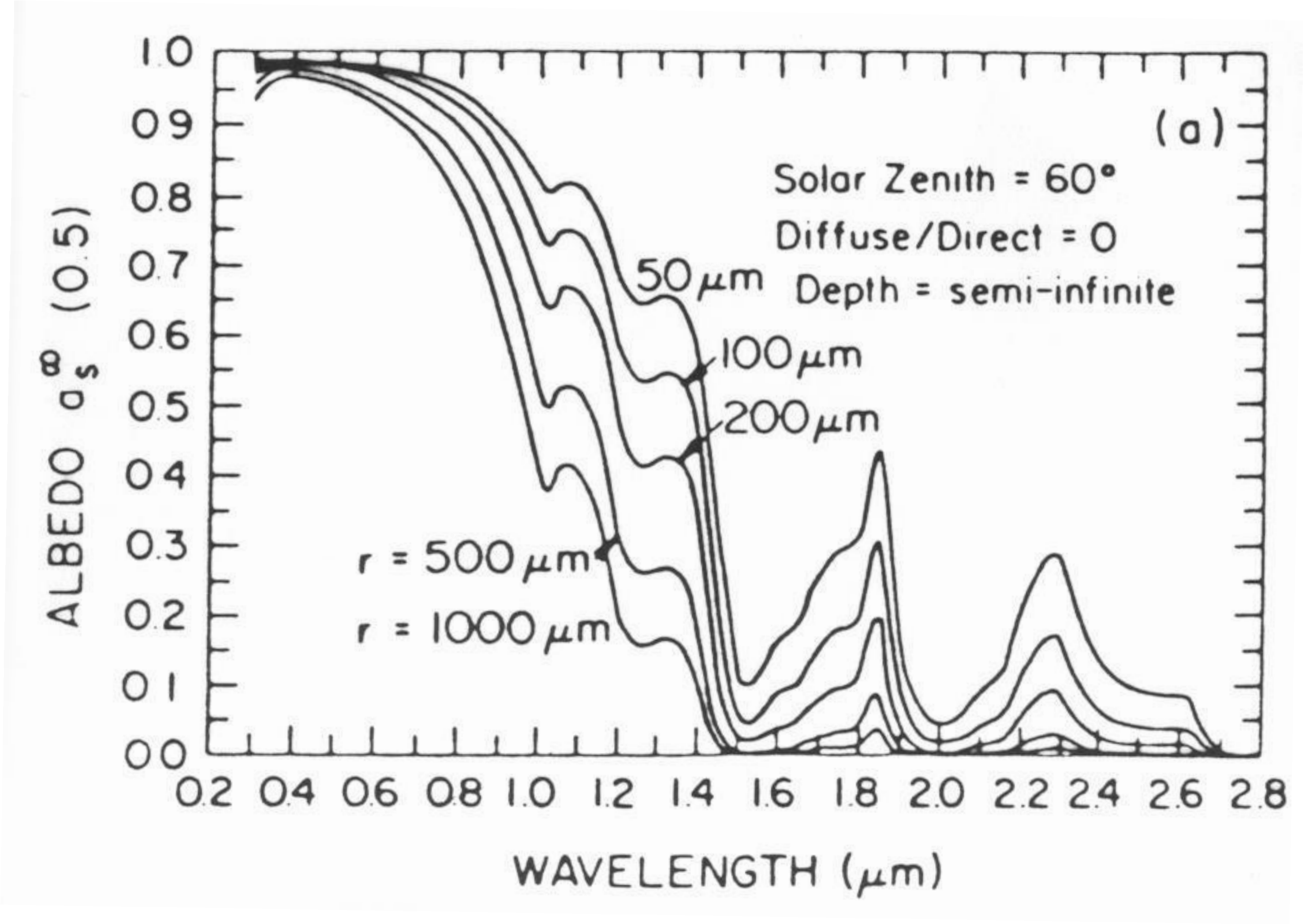

Hot spot reflection

Selected Optical Sensors for Snow Monitoring

Sensor	*Satellite*	*Bands*	*Resolution*
MSI	Sentinel-2	VIS, SWIR	10, 20, 60 m
OLCI, SLSTR	Sentinel-3	VIS, SWIR, TIR	300, 500, 1000 m
AVHRR	NOAA	VIS, SWIR, TIR	1 km
MODIS	TERRA, ACQUA	0.4 – 12 µm (36 Ch.)	250, 1000 m
ASTER	TERRA	VIS, SWIR, TIR, Stereo	15, 30, 90 m
ETM+	LANDSAT 5,7	VIS, SWIR, TIR	15, 30, 60 m
OLI - LDCM	LANDSAT 8	VIS, SWIR, TIR	15, 30, 100 m
HRV	SPOT5	VIS, SWIR	2.5, 5, 10 m
Dig-Camera	Ikonos	VIS, NIR (4 Kan.)	1, 4 m
Dig-Camera	QuickBird	VIS, NIR (4 Kan.)	0.7, 2.5 m
Dig-Camera	PLEIADES	VIS, NIR	0.5, 2.0 m

IR Bands: *NIR 0.7 – 1.2 µm; SWIR 0.7 - 2.3 µm; TIR 8 – 12 µm*

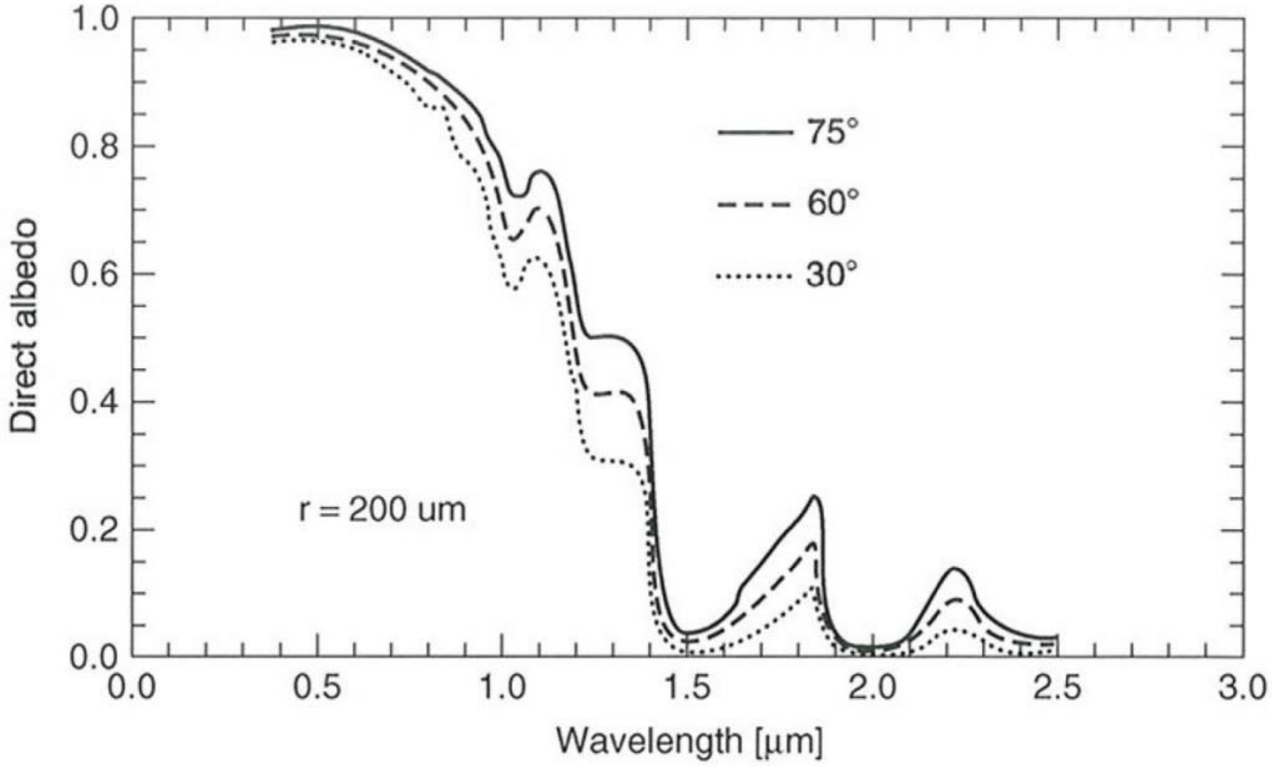
Spectral Reflectivity of Snow: Grain Size



Strong effect of grain size in near IR

Model Calculation by Wiscomb and Warren (1980)

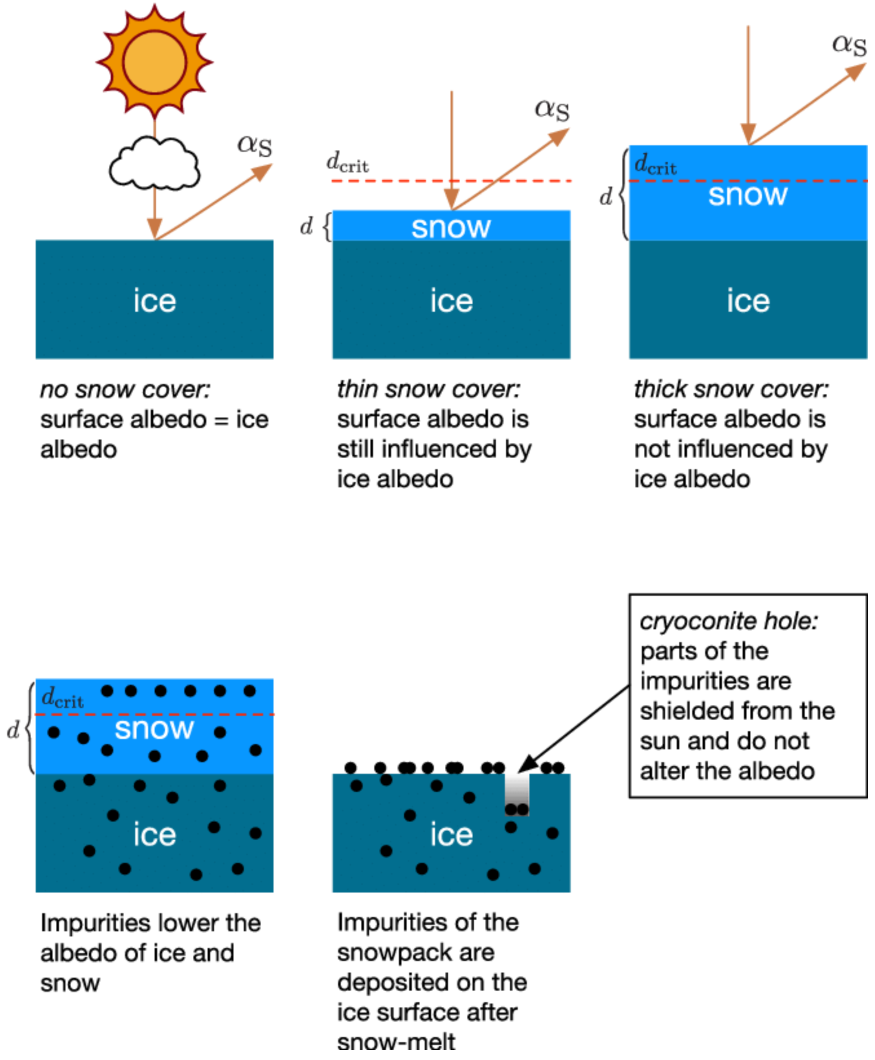
Angular Dependence of Snow Reflectivity



Snow albedo dependence on solar zenith angle

Main Factors for Spectral Reflectance of Snow

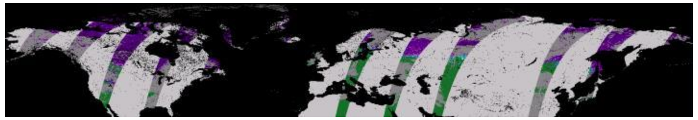
- Impurities (Soot, Dust, ...) - main factor at visible wavelengths
- Grain size; important at λ > ~ 1 μm
- Liquid water content (relevant in shortwave IR; primarily an indirect effect through grain size)
- Illumination and observation geometry (bi-directional reflectance)
- Surface roughness



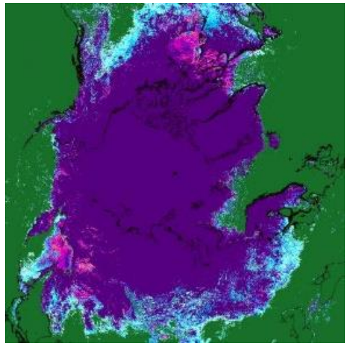
https://www.cambridge.org/core/journals/journal-of-glaciology/article/albedo-reduction-of-ice-caused-by-dust-and-black-carbon-accumulation-a-model-applied-to-the-ktransect-west-greenland/3FE93E004C1793A5DC4D78FD4CD1ECB4

Selected Snow Products from Optical Satellite data

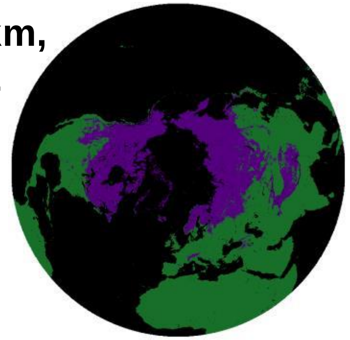
GlobSnow, 1 km, Fractional SE



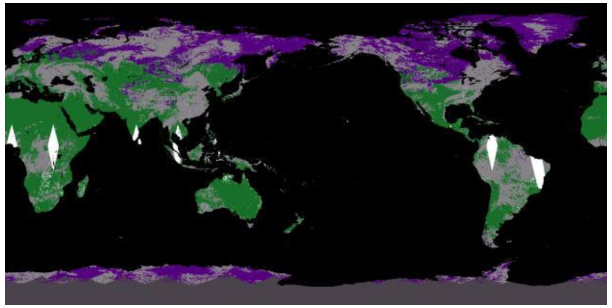
Pathfinder, 5 km, Fractional SE



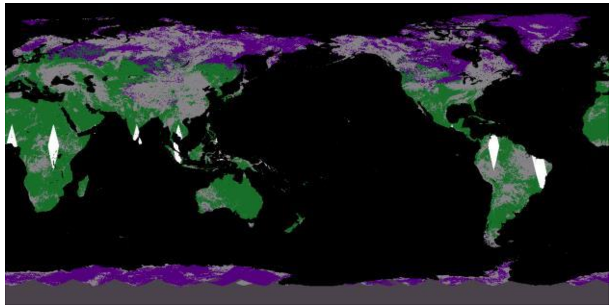
CryoClim, 5 km, Fractional SE



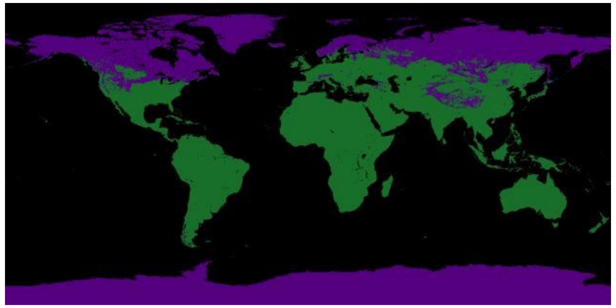
JAXA MDS10C, 5 km, Binary SE



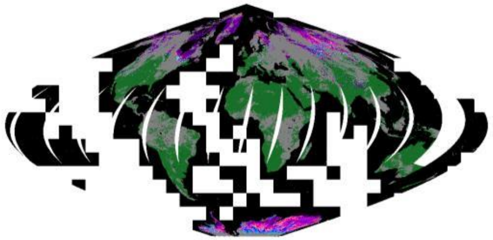
JAXA GHRM5C, 5 km, Binary SE



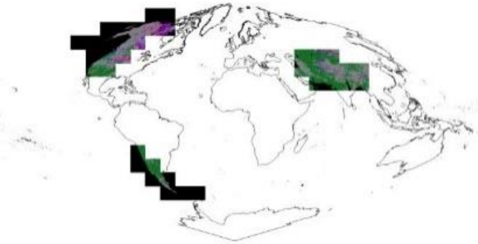
AutoSnow, 4 km, Binary SE



MOD10_C5, 0.5 km, Fractional SE



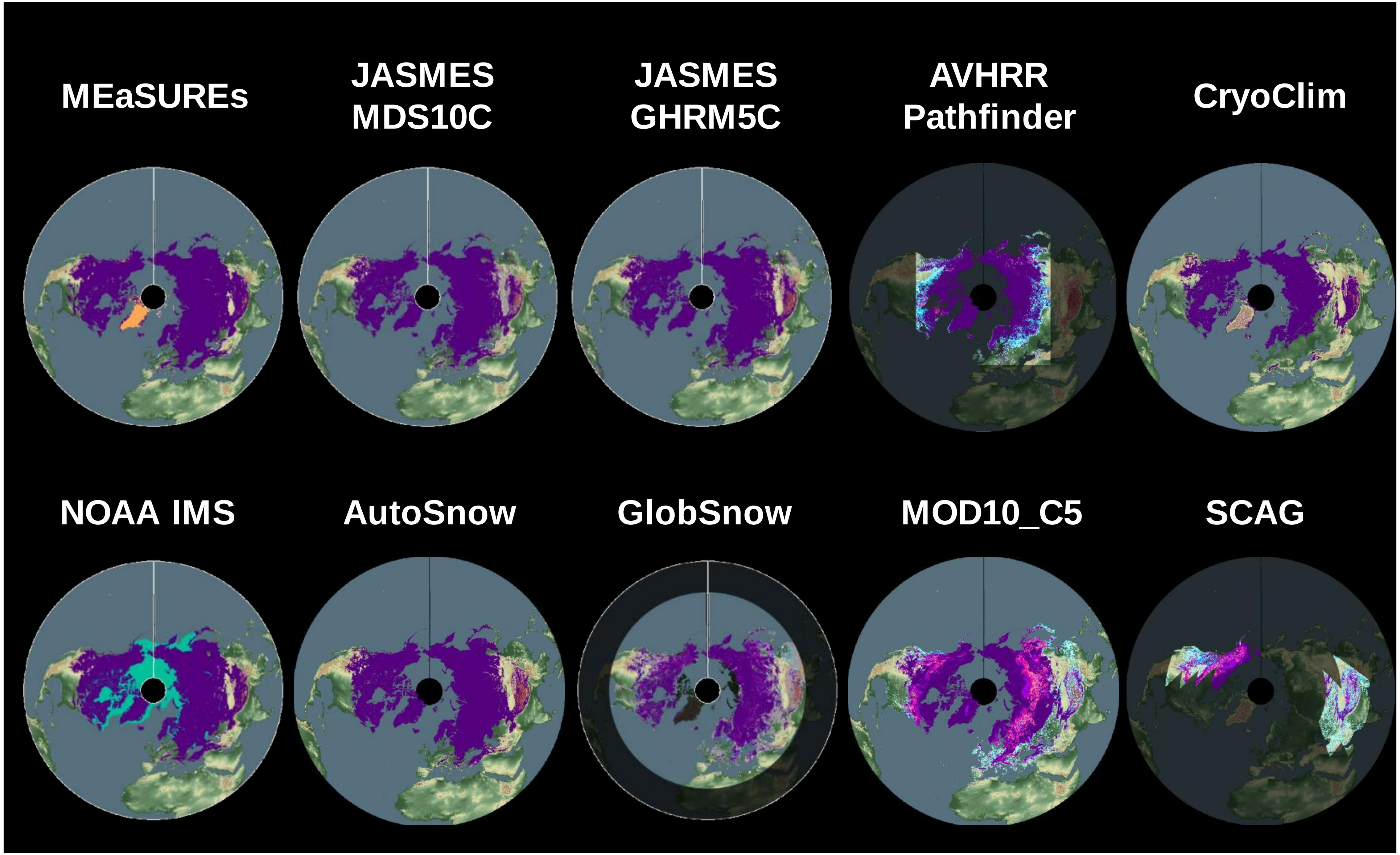
MODSCAG, 0.5 km, Fractional SE



MEaSUREs, 25 km, Binary SE

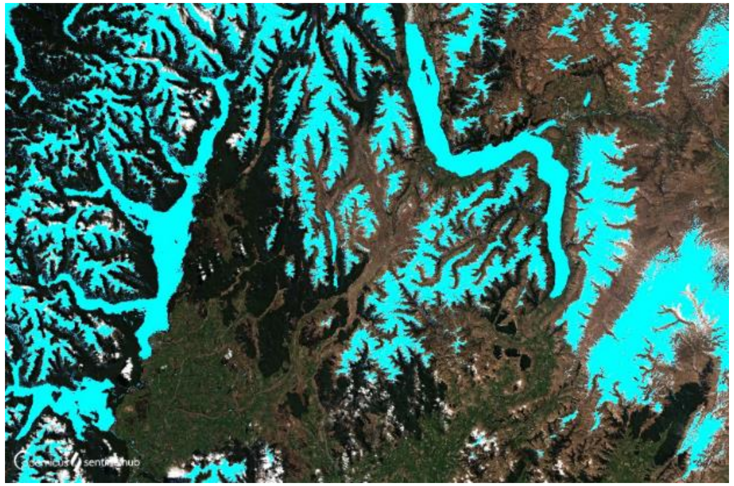
IMS, 4 km, Binary SE

Hemispheric snow products reprojected in EASE-GRID 2.0

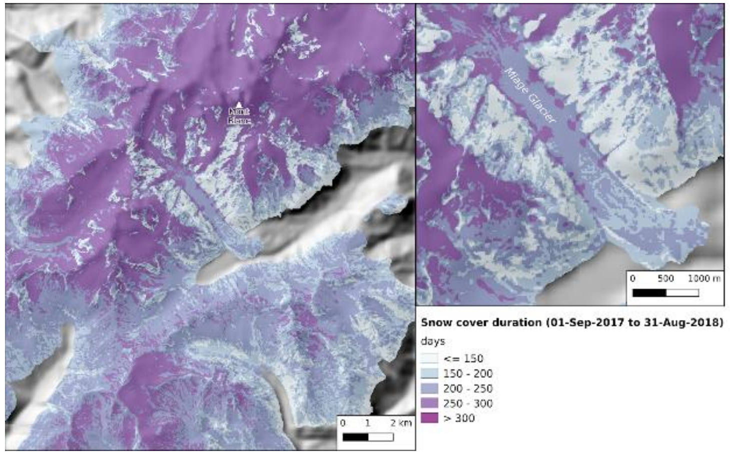


Applications in Cryosphere: Optical Sensors

- Snow and ice areas mapping
- Lake ice monitoring
- Glacier mapping
- Albedo
- Glacier facies (snow, firn, ice, debris, supraglacial lakes, etc.)
- Snow and ice properties
- Ice motion (offset tracking)
- Ice sheet boundaries
- Surface topography



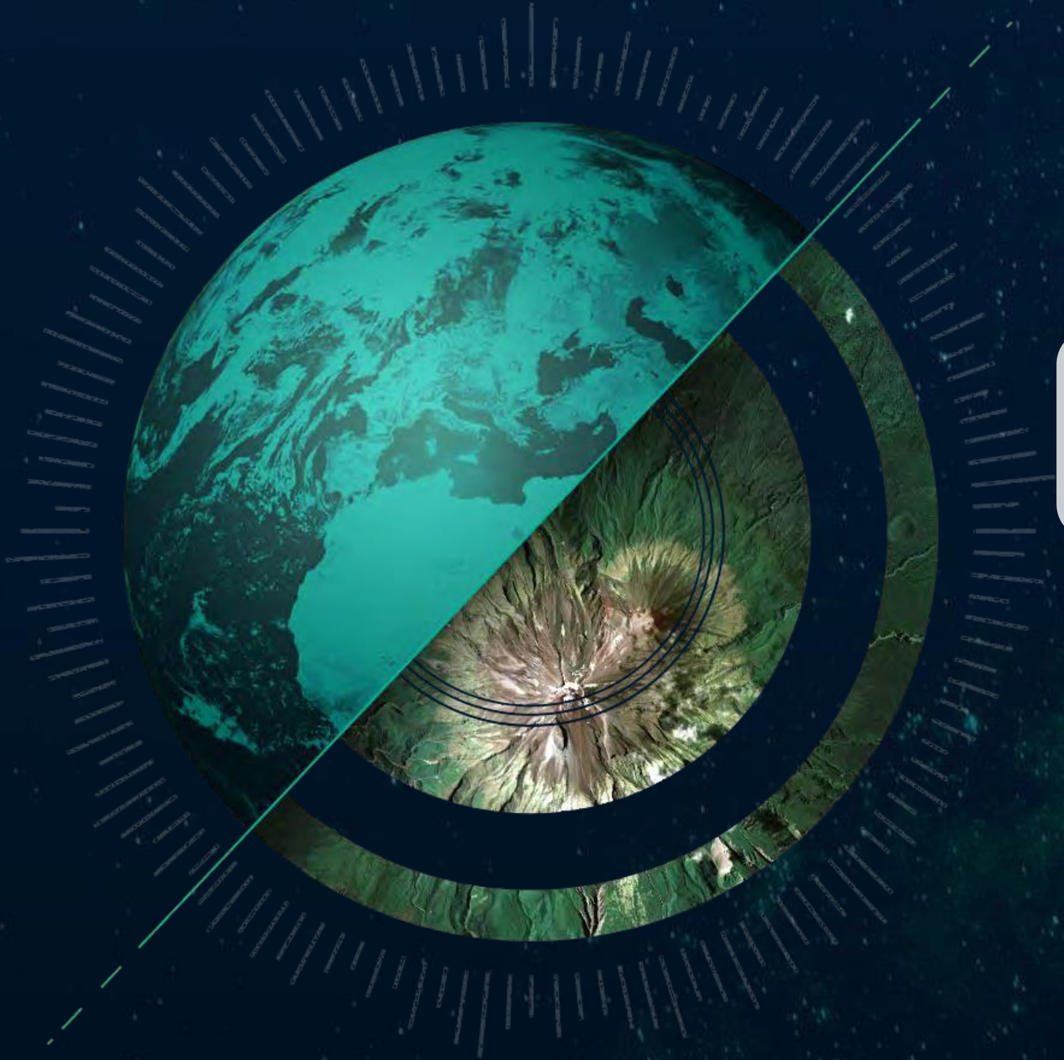
Visualized NDSI over New Zealand, acquired on 2019-09-19.



Snow Cover Duration for Mont-Blanc area during an hydrological year (1 September 2016 to 31 August 2017) produced by synthesis of Theia snow-covered surface products.

For more information, see the tutorial:
[8. Sentinel-1 & Sentinel-2 for Snow and Ice using the SNAP software and EO Browser]

Source: https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndsi/, https://www.theia-land.fr/en/product/snow/

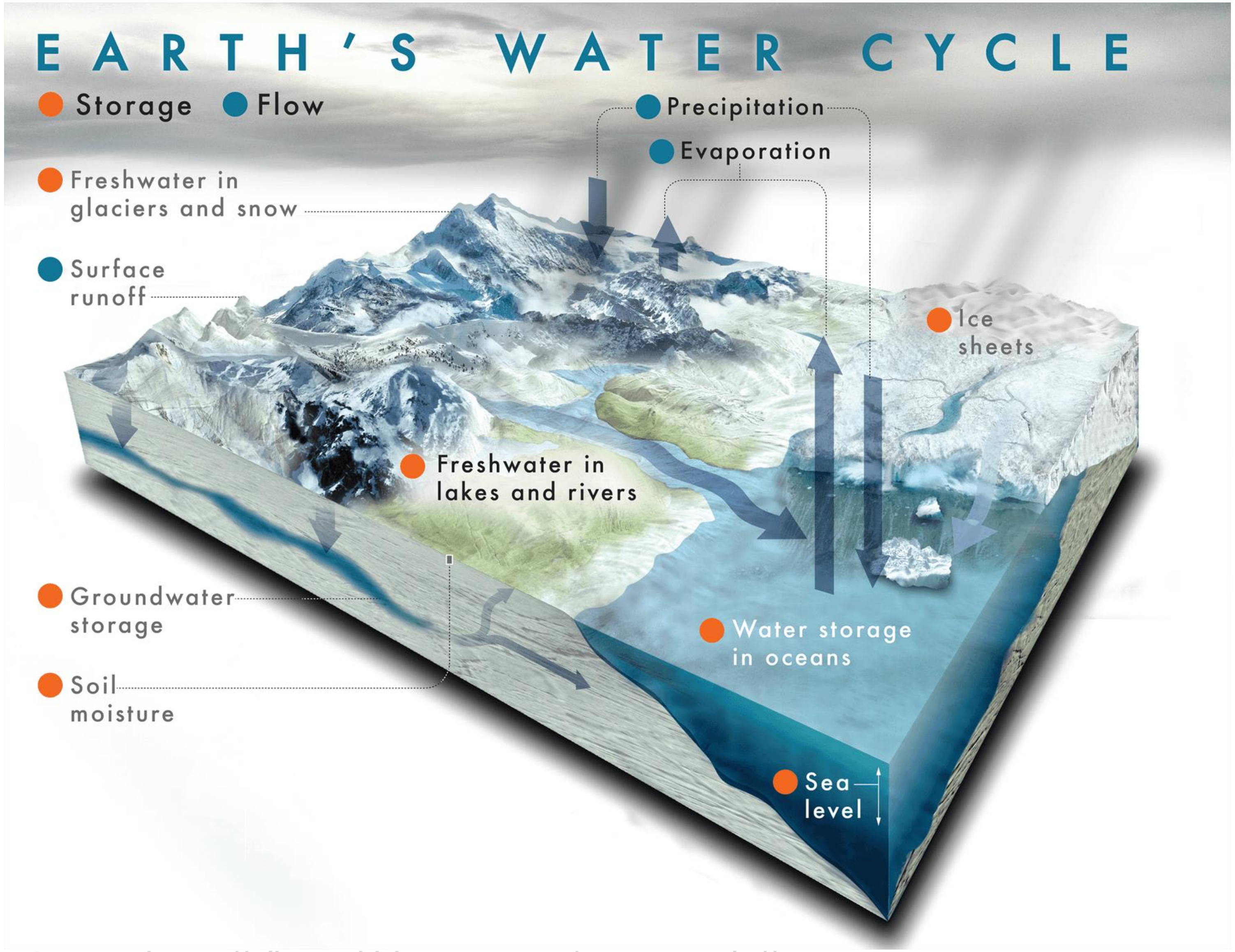


9. SAR and optical remote sensing for mapping ice

Why do we need information about ice

Information on snow and ice is essential for several reasons:

- Climate Monitoring
- Water Resource Management
- Natural Hazard Assessment
- Ecosystem Monitoring
- Sea Level Rise



Source:https://climatekids.nasa.gov/water-cycle//

Cryosphere

- The portion of Earth's surface where water is found in its (mostly) solid form, including snow, ice, glaciers, ice caps, ice sheets, frozen ground (permafrost), and sea ice
- It encompasses regions of both land and sea that experience freezing temperatures, and it plays a crucial role in Earth's climate system.
- The cryosphere interacts with other components of the Earth system, such as the atmosphere, oceans, and biosphere, through processes like melting, freezing, and ice-albedo feedback
- Changes in the cryosphere can have significant impacts on global climate patterns, sea level rise, freshwater availability, and ecosystems.

Source:https://discoveringthearctic.org.uk/introducing-the-arctic/snow-water-ice-permafrost/cryosphere/

Examples of ice patterns in different environments

https://blogs.egu.eu/divisions/cr/2022/04/21/more-pancakes-in-the-future/, https://www.mergili.at/worldimages/picture.php?/8968,, https://www.antarcticglaciers.org/glacial-geology/glacial-landsystems/glaciated-valley-landsystems/debris-covered-glacier-landsystems/

Typical densities of ice (and snow)

Typical densities of snow and ice (kg/m^3)	
New snow (immediately after falling in calm)	50-70
Damp new snow	100-200
Settled snow	200-300
Depth hoar	100-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-917

Source: Paterson, W.S.B. 1994. *The Physics of Glaciers.*

Basic Classes and Mechanisms of Ice Formation

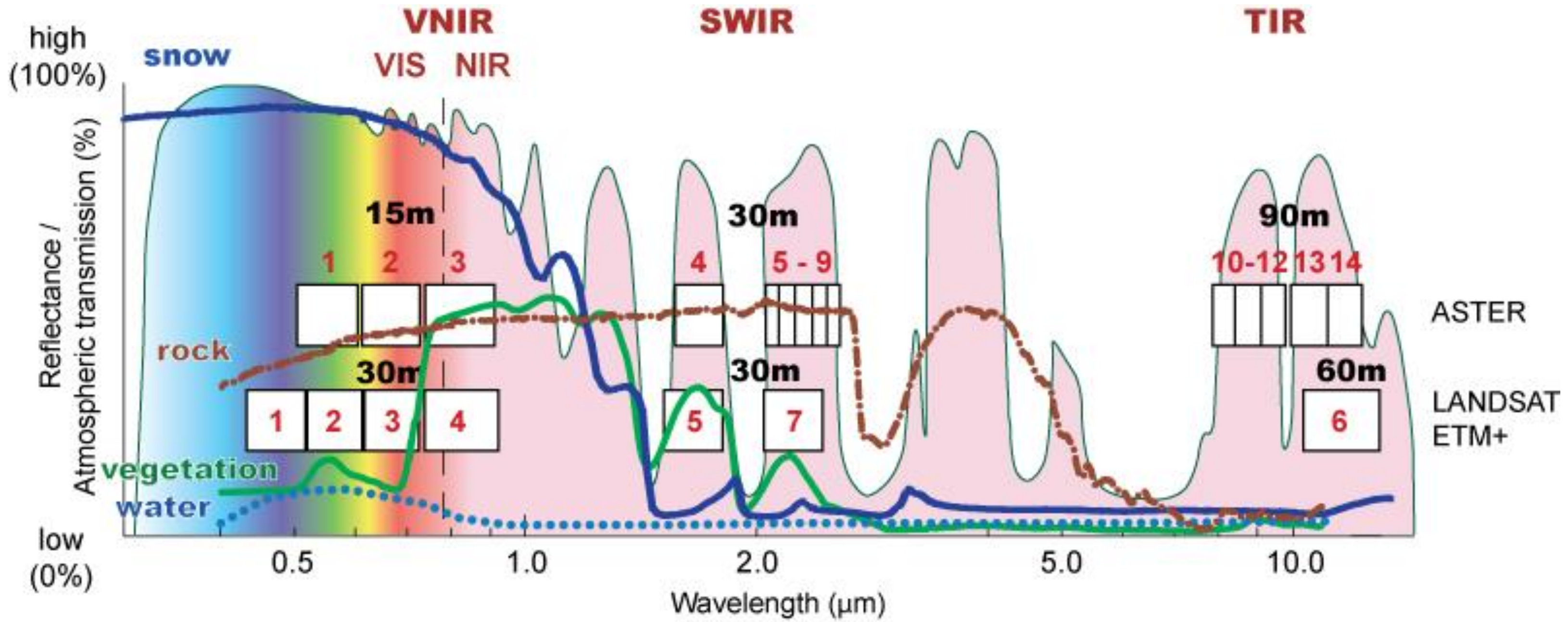
Class	Description	Thickness
New Ice	Ice which began to grow a few hours or days ago	0 – 10 cm
Young Ice	Transition between new and first-year ice	10 - 30 cm
First-Year Ice	Ice of no more than one winter's growth	30 – 200 cm
Old Ice	Ice that has survived at least one summer's melt; most topographic features are smoother than on first-year ice	> 200 cm

High ↓ Low

Source: https://appliedsciences.nasa.gov/sites/default/files/2023-10/SAR_2023_Part1_Final.pdf

Remote Sensing of Ice

Selected satellites used i.a. for cryospheric applications			
C-Band	Sentinel-1	Optical	Sentinel-2 MSI
	Envisat ASAR		SPOT-5 – 7 HRV/NAOMI
	ERS-1/-2		Terra ASTER
	Radarsat-1/-2		Sentinel-3 SLSTR/OLCI
X-Band	Cosmo-Skymed		Aqua/Terra MODIS
			NPP VIIRS

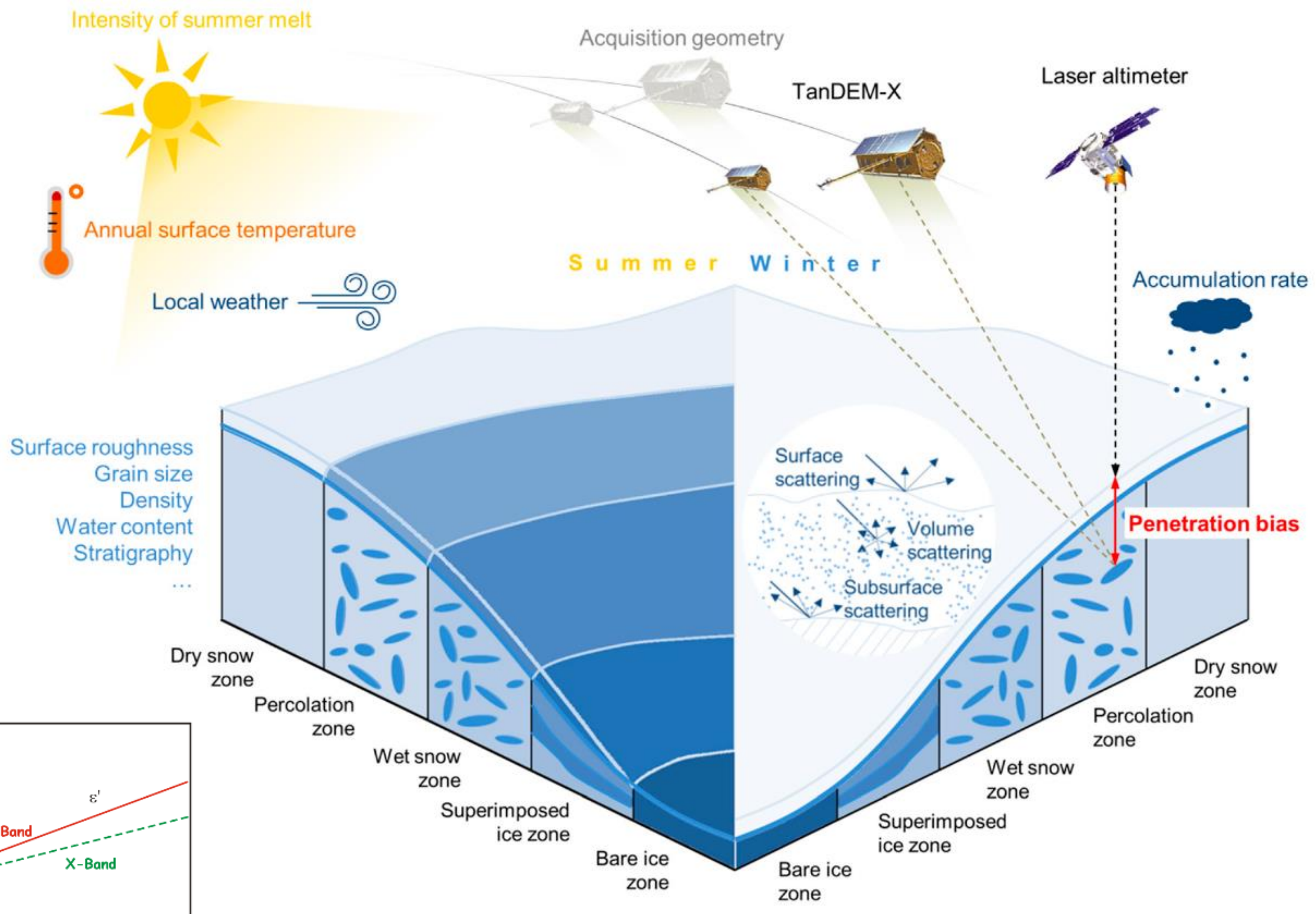


Radar for ice

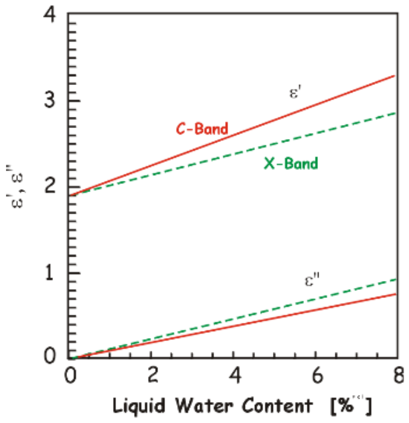
Sensor	*Satellite*	*[GHz].*	*Resolution/Swath*	*Repeat*
AMI	ERS-1,-2(1991-2011)	5.3 VV	25 m - 100 km	35d/1 d
SIR-C/X-SAR	Shuttle (1994)	1.2,5.3,9.6	25 m - 40 km	2 Campaigns
SIR-C/X-SAR	SRTM (Feb.2000)	5.3 & 9.6	50/100 m - 100/200 DEM	
Present				
SAR	Radarsat1(1995-)	5.3	10,30,100 m - 100-500 km	24 d
ASAR	Envisat (2002-12)	5.3	30,100,1000 - 100-400 km	35 d
PALSAR	ADEOS (2007-11)	1.2	15/100 m - 40-350 km	46 d
TerraSAR	TerraSAR-X(2007-)	9.6	1, 3,10 m - 10,30,100 km	11 d
TerraSAR2	TanDEM-X (2010-)	9.6	in Tandem with TerraSAR-X (InSAR)	
SAR	COSMO-SkyMed	9.6	1, 3,10 m - 10-100 km	16 d, 1d, 8d
SAR	Radarsat2 (2007-)	5.3	3, 10, 30 m, □20 km 24 d	
SAR	Sentinel-1 (2013-)	5.3	10 m, 30 m 250, 400 km	12 d x 2 Sat.
Future				
SAR Constellation	Radarsat (2019 -)	5.3	3 m …100m 30 …500 km	16 d x 3 Sat.

Radar back-scatter signal

- **Physical factors:** dielectric constant of the surface materials (depends on the moisture content)
- **Geometric factors:** surface roughness, slopes, shape and orientation of the objects relative to the radar beam direction
- **The types of landcover**
- **Sensor characteristics:** Microwave frequency, polarisation and incident angle

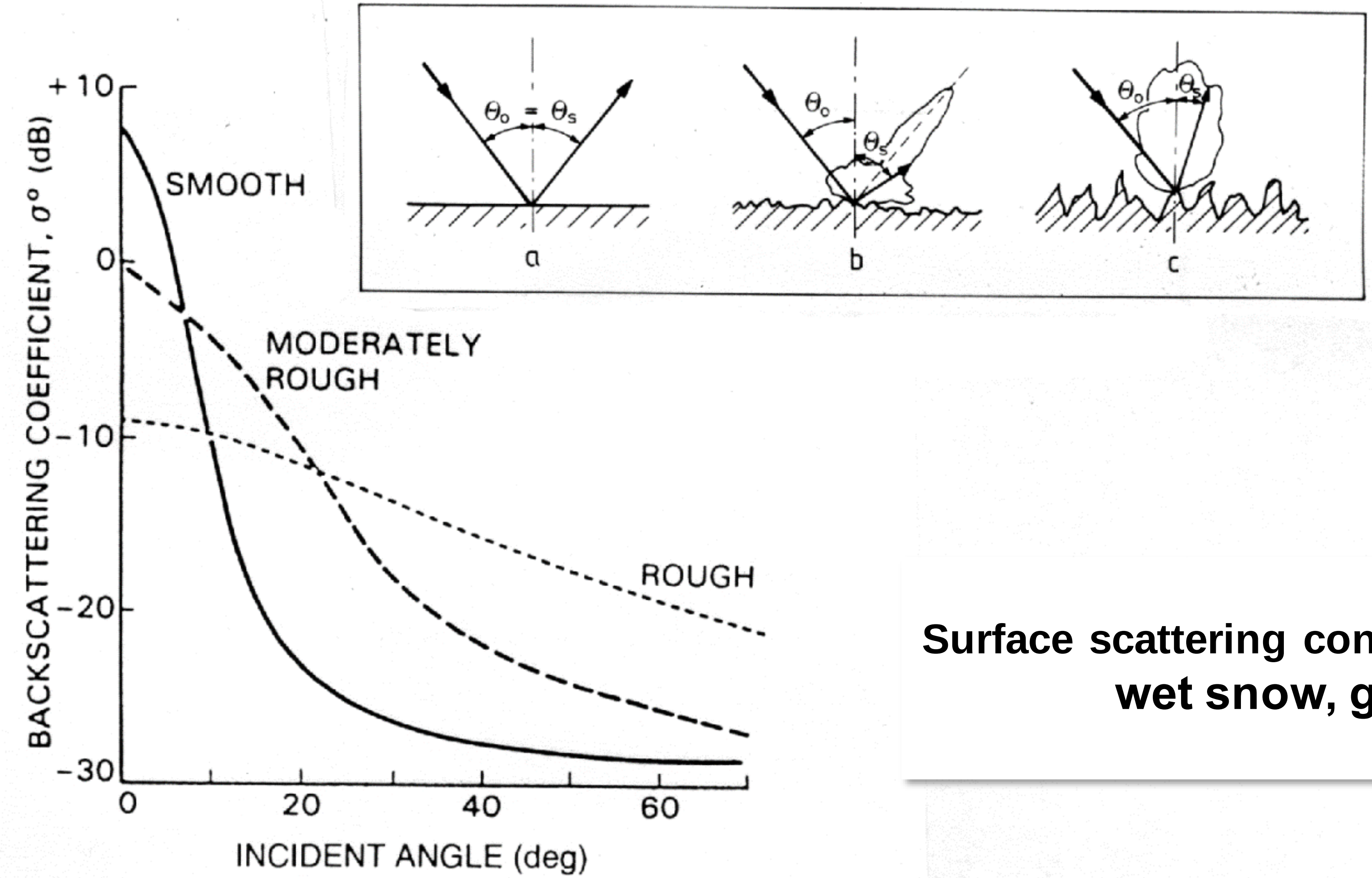


Source: https://www.mdpi.com/2072-4292/11/24/2903



Microwave Permittivity

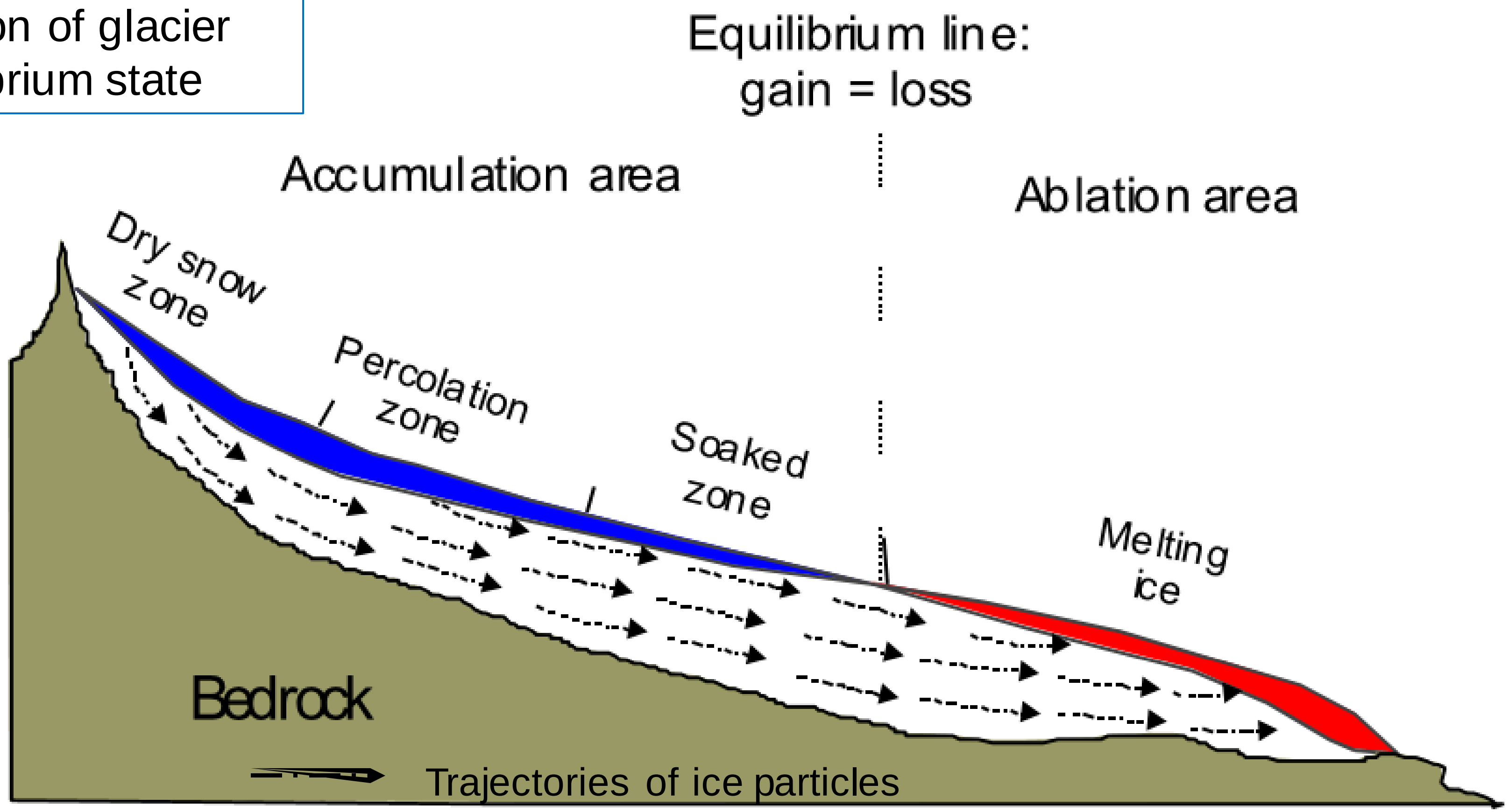
Backscattering from a Rough Surface



Surface scattering contribution dominates for wet snow, glacier ice, soil, …

Glacier Motion by InSAR and Offset Tracking

Ice motion of glacier
in equilibrium state

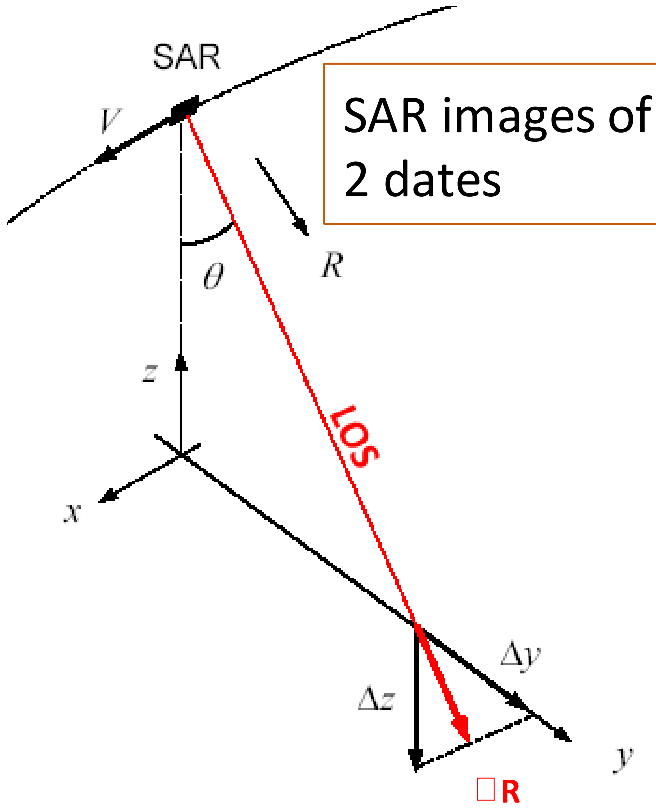


Objectives for mapping Ice Motion:

- Retrieving ice export by calving (Input/Output method for mass balance)

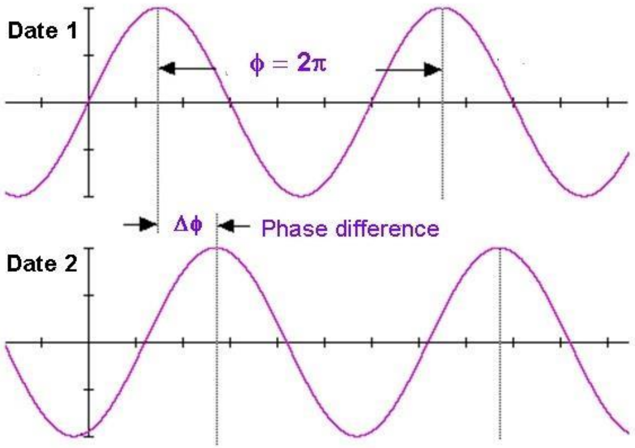
Interferometric measurement of displacement

Measurement of Displacement

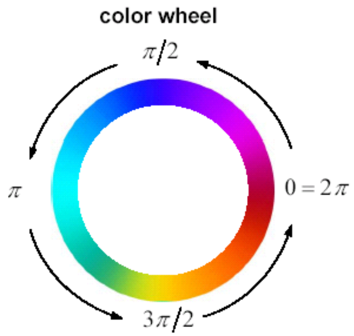


SAR images of 2 dates

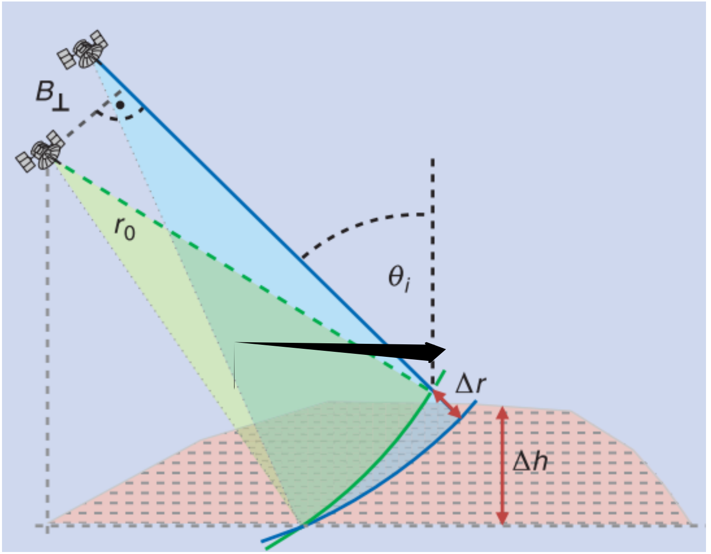
TanDEM-X



1 Fringe



InSAR for Topography



InSAR repeat track measures displacement

Requires temporal stability of radar signal phase (coherence)

Glacier Velocity Map

Basic principle: Matching of image templates by cross correlation (along track and in range) in co-registered SAR images.

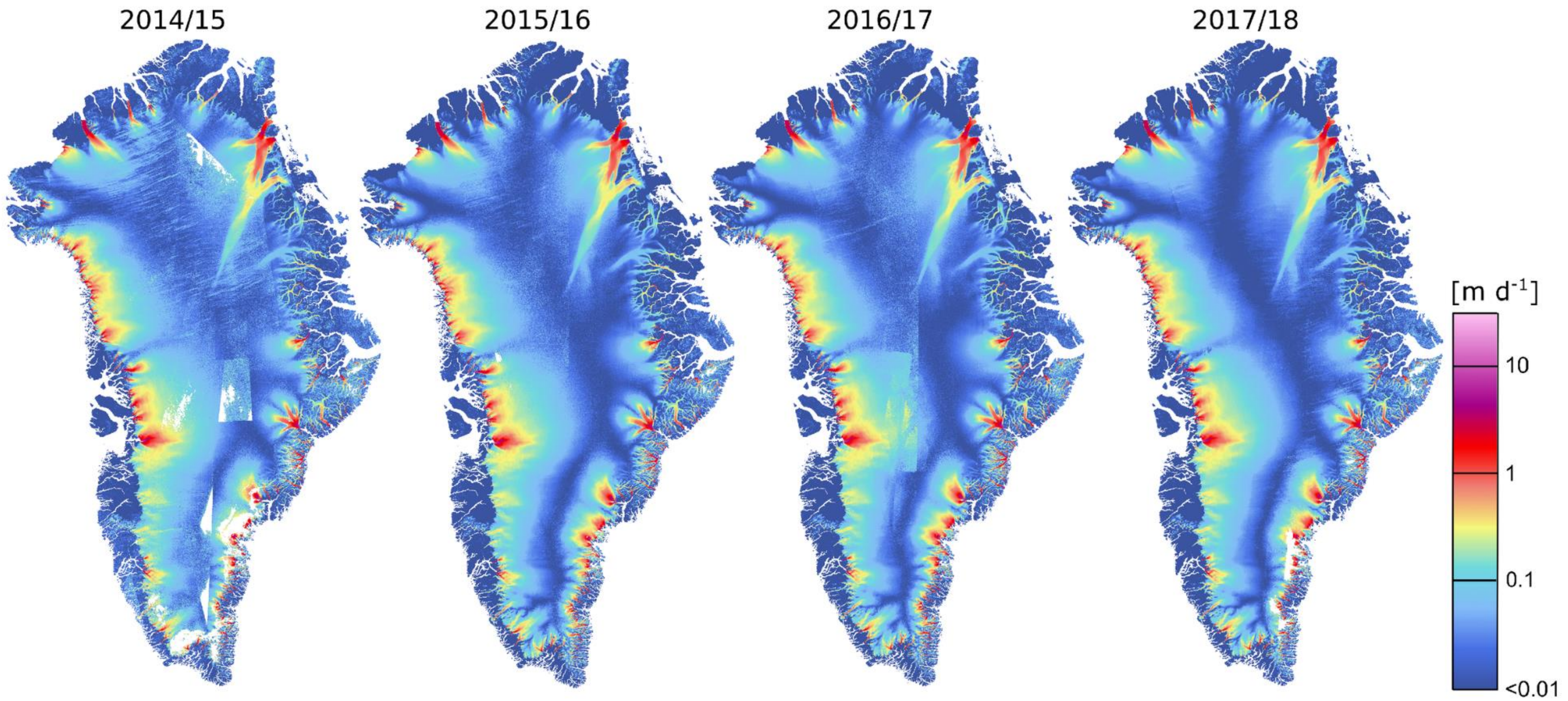
Possibilities for features to be tracked:

1. **Amplitude correlation**: Uses persistent features in backscattering amplitude images (e.g. crevasses, drainage features). Advantage: Coherence not required. Disadvantage: Lack of features in accumulation areas of glaciers (snow areas) prohibits application.
2. **Speckle tracking:** Uses coherent amplitude data (complex or magnitude). *Advantage*: Works also where no obvious amplitude features exist. No need coherence can be bridged.
3. **Coherence tracking**: Uses templates in coherence images and looks for maximum value. Method and possibilities similar to method (2).

Typical achievable accuracy in displacement: 0.2 pixels in x and y.

Errors depend on co-registration, type of features, quality of matching.

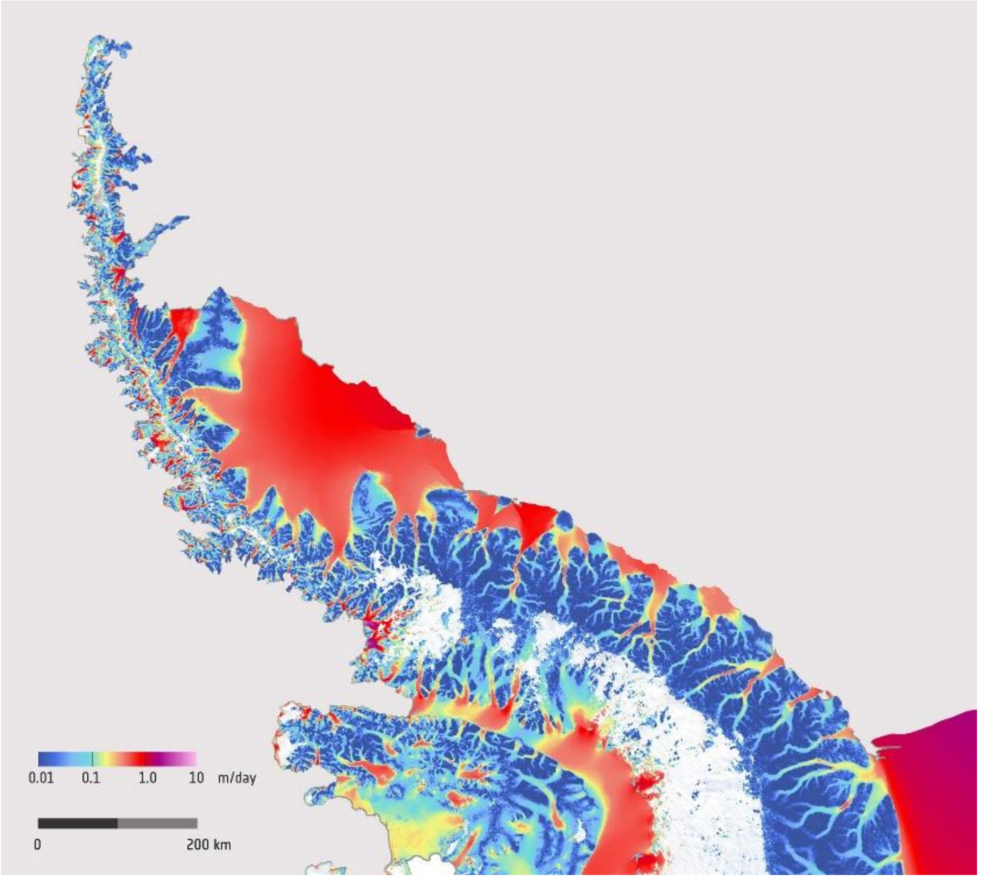
Glacier Velocity Map



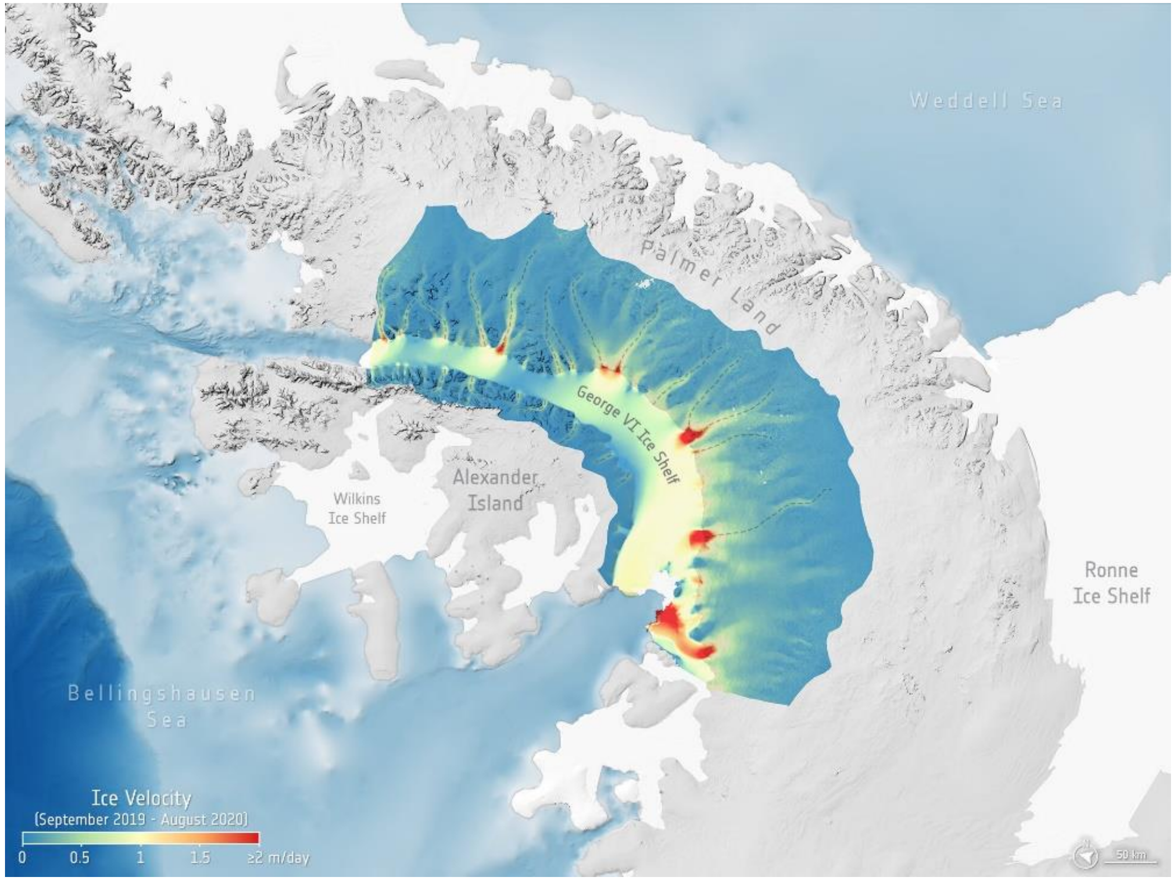
Annual ice velocity maps of Greenland from Copernicus Sentinel-1 2014-17 and winter campaign 2017/18.

Source: https://www.esa.int/ESA_Multimedia/Images/2019/07/Ice_velocity_maps_of_Greenland

Ice Flow Map



Antarctic Peninsula ice flow

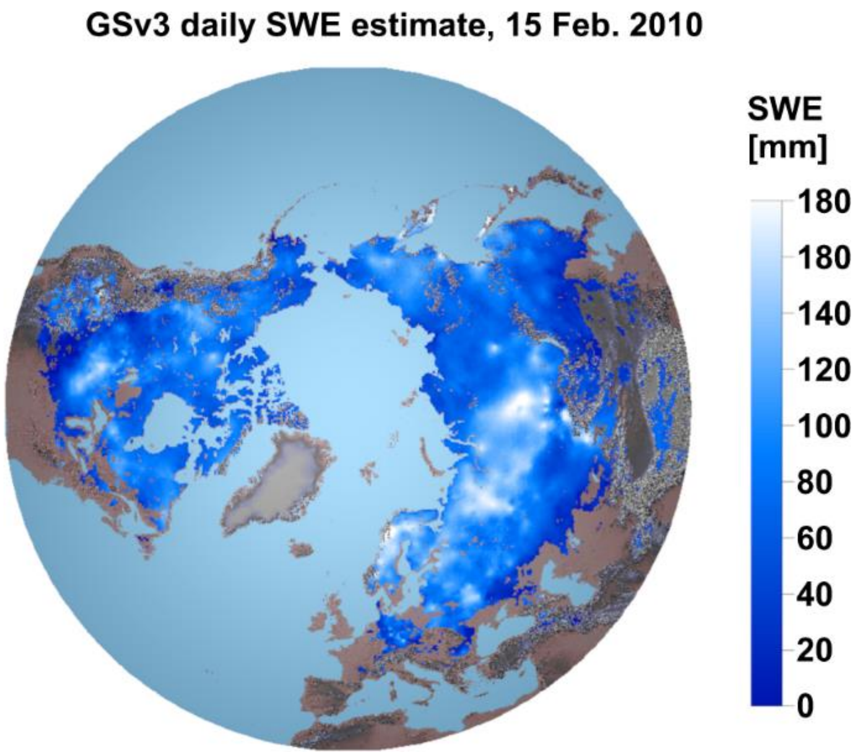


Ice-flow velocity of the George VI Ice Shelf

Source: https://www.esa.int/ESA_Multimedia/Images/2016/05/Antarctic_Peninsula_ice_flow, https://www.esa.int/ESA_Multimedia/Images/2022/10/Ice-flow_velocity_of_the_George_VI_Ice_Shelf

Applications in Cryosphere: Radar Sensors

- Snow Water Equivalent (SWE)
- Glacier topography and volume change
- Dynamics and mass balances of ice sheets
- Glacier motion
- 3D ice surface deformation
- River ice
- Sea ice



Source: https://www.nature.com/articles/s41597-021-00939-2

Optical for ice

Incoming electromagnetic energy ($E_I(\lambda)$) is affected by:

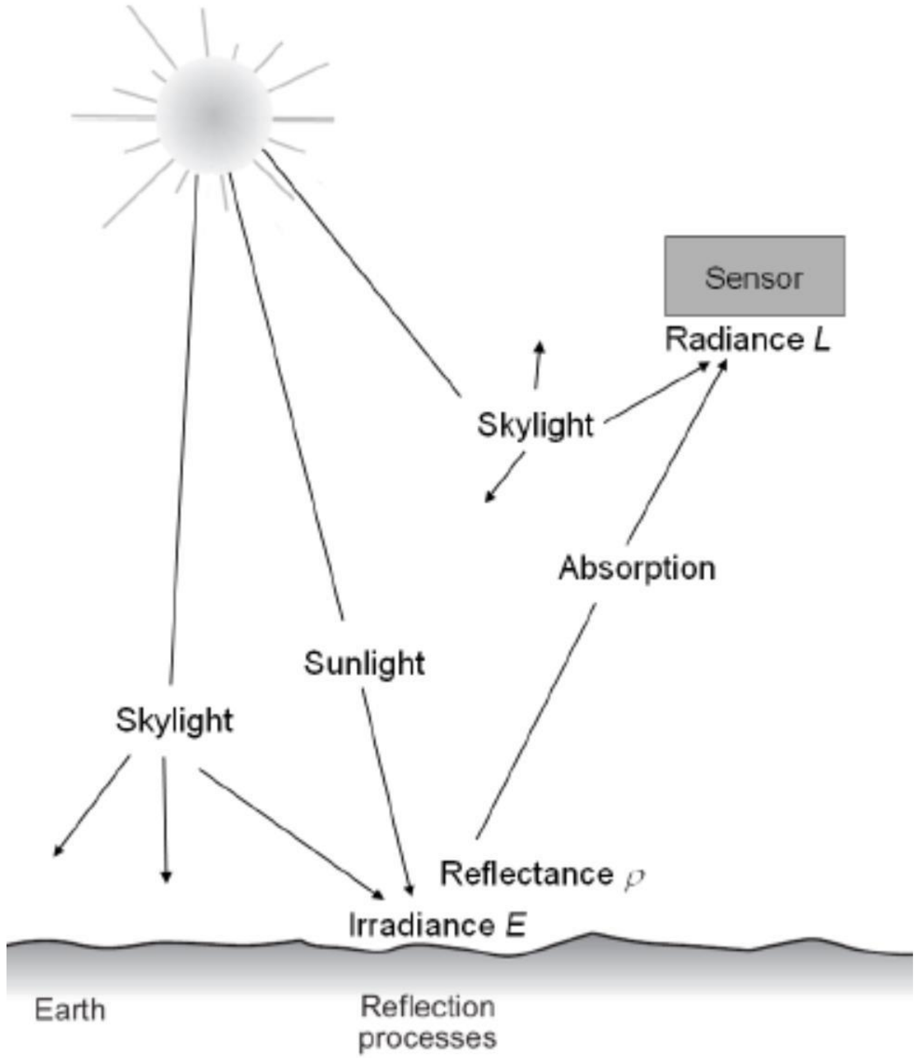
- Absorption ($E_A(\lambda)$)
- Scattering ($E_S(\lambda)$)
- Transmission ($E_T(\lambda)$)

Principle of energy conservation:

(energy can only be transferred, but neither be created nor destroyed)

$$E_I(\lambda) = E_A(\lambda) + E_S(\lambda) + E_T(\lambda)$$

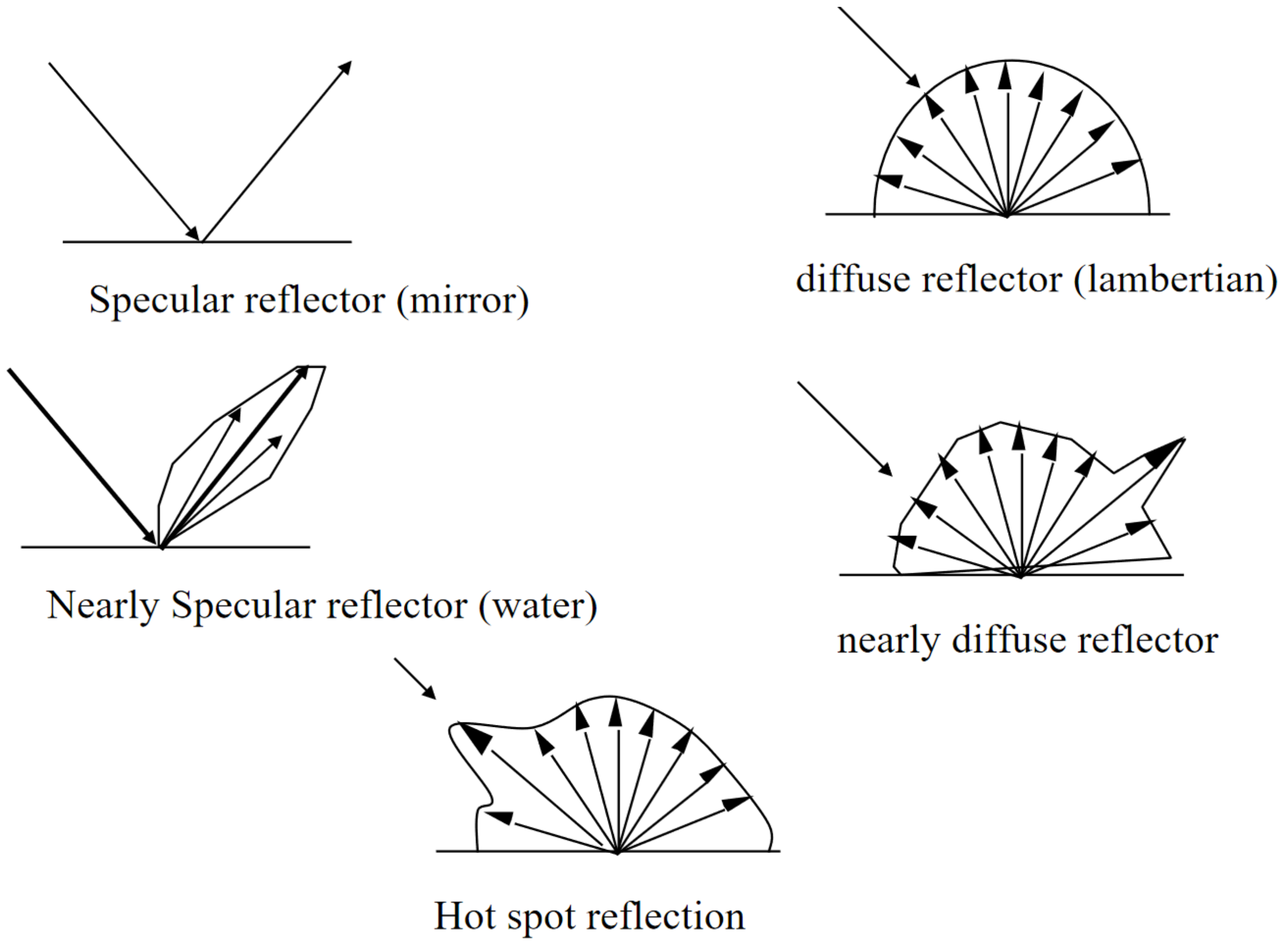
Optical sensors measure the amount of light receiving the satellite (= at-satellite radiance L), which is often converted to



Optical for ice

Reflectance depends on

- Wavelength energy
- Atmospheric attenuation
- Geometry of the Surface
- Surface Materials



Selected Optical Sensors for Glacier Monitoring

Sensor	*Satellite*	*Bands*	*Resolution*
MSI	Sentinel-2	VIS, SWIR	10, 20, 60 m
OLCI, SLSTR	Sentinel-3	VIS, SWIR, TIR	300, 500, 1000 m
AVHRR	NOAA	VIS, SWIR, TIR	1 km
MODIS	TERRA, ACQUA	0.4 – 12 µm (36 Ch.)	250, 1000 m
ASTER	TERRA	VIS, SWIR, TIR, Stereo	15, 30, 90 m
ETM+	LANDSAT 5,7	VIS, SWIR, TIR	15, 30, 60 m
OLI - LDCM	LANDSAT 8	VIS, SWIR, TIR	15, 30, 100 m
HRV	SPOT5	VIS, SWIR	2.5, 5, 10 m
Dig-Camera	Ikonos	VIS, NIR (4 Kan.)	1, 4 m
Dig-Camera	QuickBird	VIS, NIR (4 Kan.)	0.7, 2.5 m
Dig-Camera	PLEIADES	VIS, NIR	0.5, 2.0 m

IR Bands: *NIR 0.7 – 1.2 µm; SWIR 0.7 - 2.3 µm; TIR 8 – 12 µm*

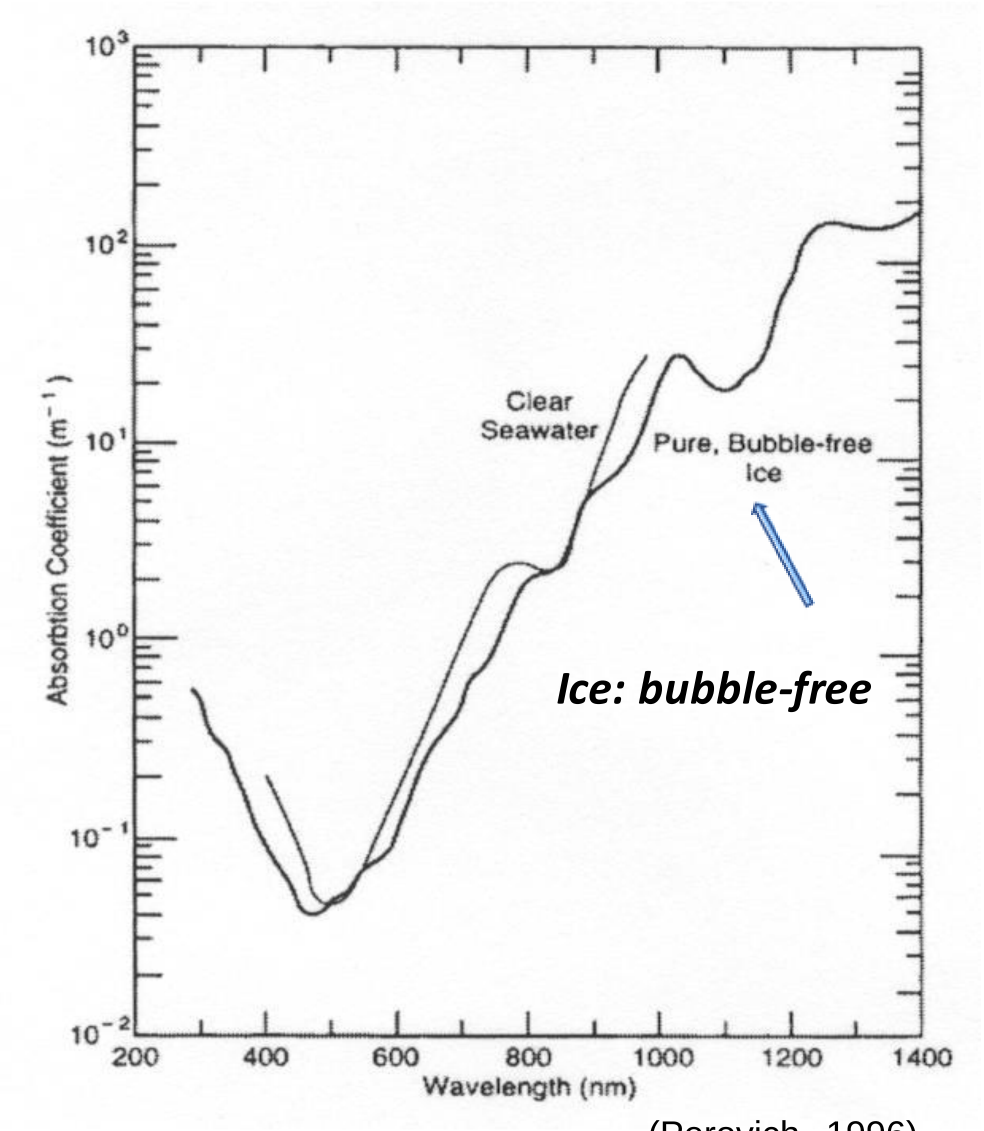
Extinction Coefficient of pure ice and sea water

Penetration depth (for intensity)

$d_p = 1/K_e$

K_e[m^{-1}] extinction coefficient

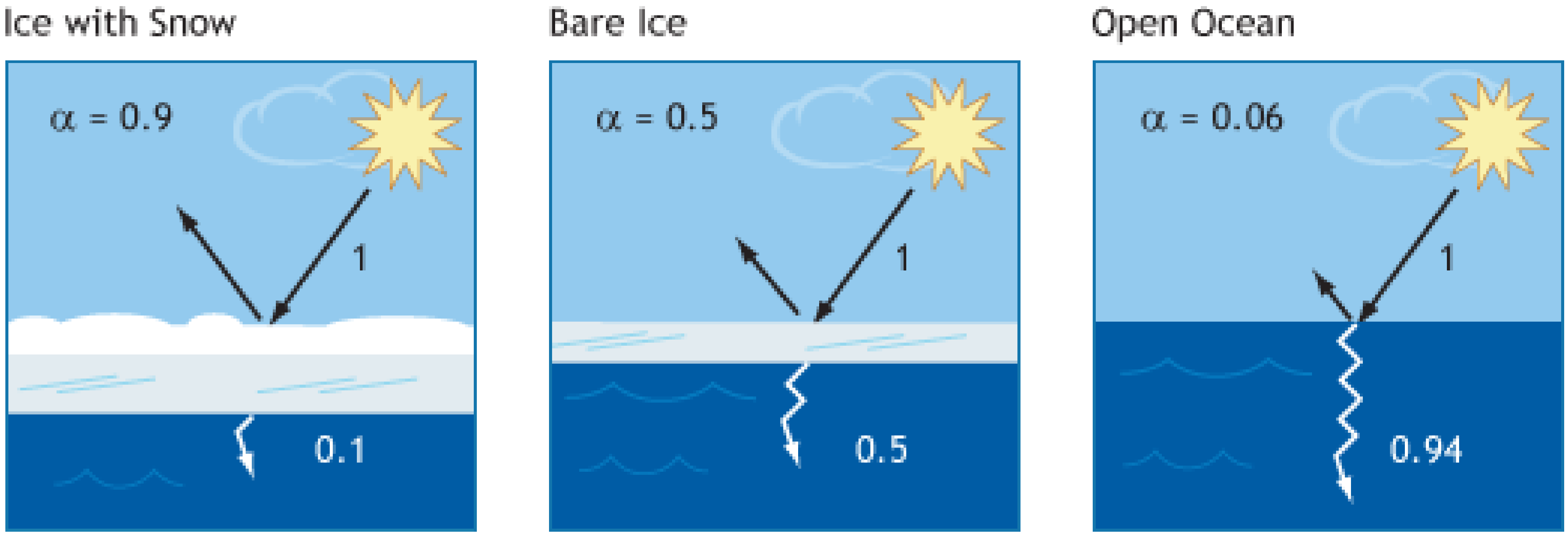
Visible light penetration in snow is a few centimetres; scattering losses dominate!



(Perovich, 1996)

Ice albedo

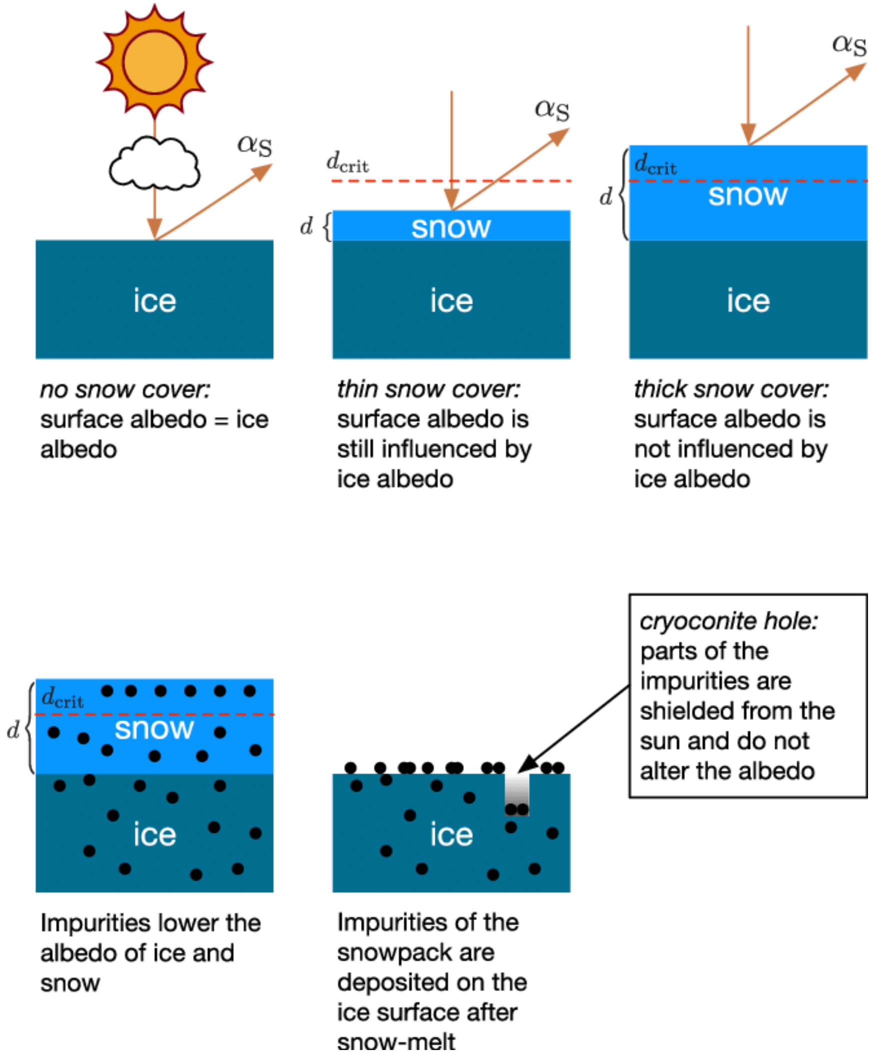
Albedo, in the context of sea ice, refers to how much solar radiation is reflected back into space. When there's no sea ice, the ocean absorbs heat. If there's sea ice, it has a higher albedo, meaning it reflects more solar radiation, resulting in less heat being absorbed by the ocean. When there's both sea ice and snow, the albedo is even higher.



https://www.us-satellite.net/sprintt/phase2/ipy07_int_albedo/ipy07_int_albedo.html

Main Factors for Spectral Reflectance of Ice (and snow)

- Impurities (Soot, Dust, ...) - main factor at visible wavelengths
- Grain size; important at λ > ~ 1 μm
- Liquid water content (relevant in shortwave IR; primarily an indirect effect through grain size)
- Illumination and observation geometry (bi-directional reflectance)
- Surface roughness

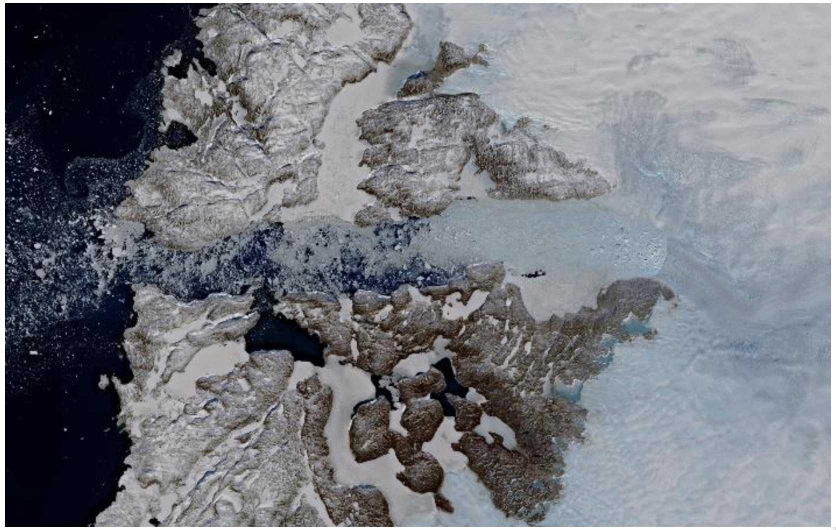


https://www.cambridge.org/core/journals/journal-of-glaciology/article/albedo-reduction-of-ice-caused-by-dust-and-black-carbon-accumulation-a-model-applied-to-the-ktransect-west-greenland/3FE93E004C1793A5DC4D78FD4CD1ECB4

Applications in Cryosphere: Optical Sensors

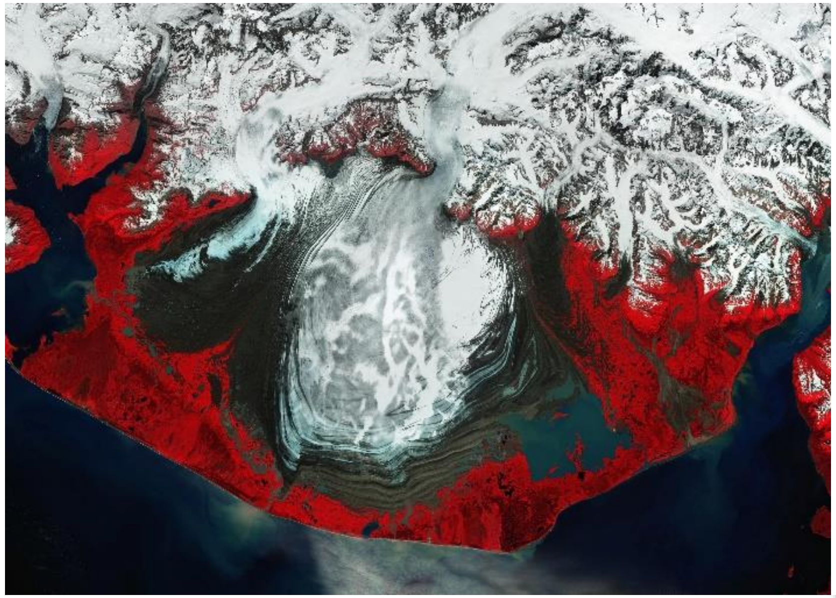
- Snow and ice areas mapping
- Lake ice monitoring
- Glacier mapping
- Albedo
- Glacier facies (snow, firn, ice, debris, supraglacial lakes, etc.)
- Snow and ice properties
- Ice motion (offset tracking)
- Ice sheet boundaries
- Surface topography

For more information, see the tutorial:
9. Sentinel-1, Sentinel-2 for Snow and Ice using the SNAP software



Jakobshavn Glacier

Jakobshavn Glacier in west Greenland viewed by the Copernicus Sentinel-2 mission on 29 April 2019.
CREDIT: containsmodified Copernicus Sentinel data (2019), processed by ESA



The moraines of Malaspina

The remarkable moraine patterns of Malaspina Glacier – the largest piedmont glacier in the world – are featured in this false-colour image acquired by Copernicus Sentinel-2.
CREDIT: contains modified Copernicus Sentinel data (2022), processed by ESA

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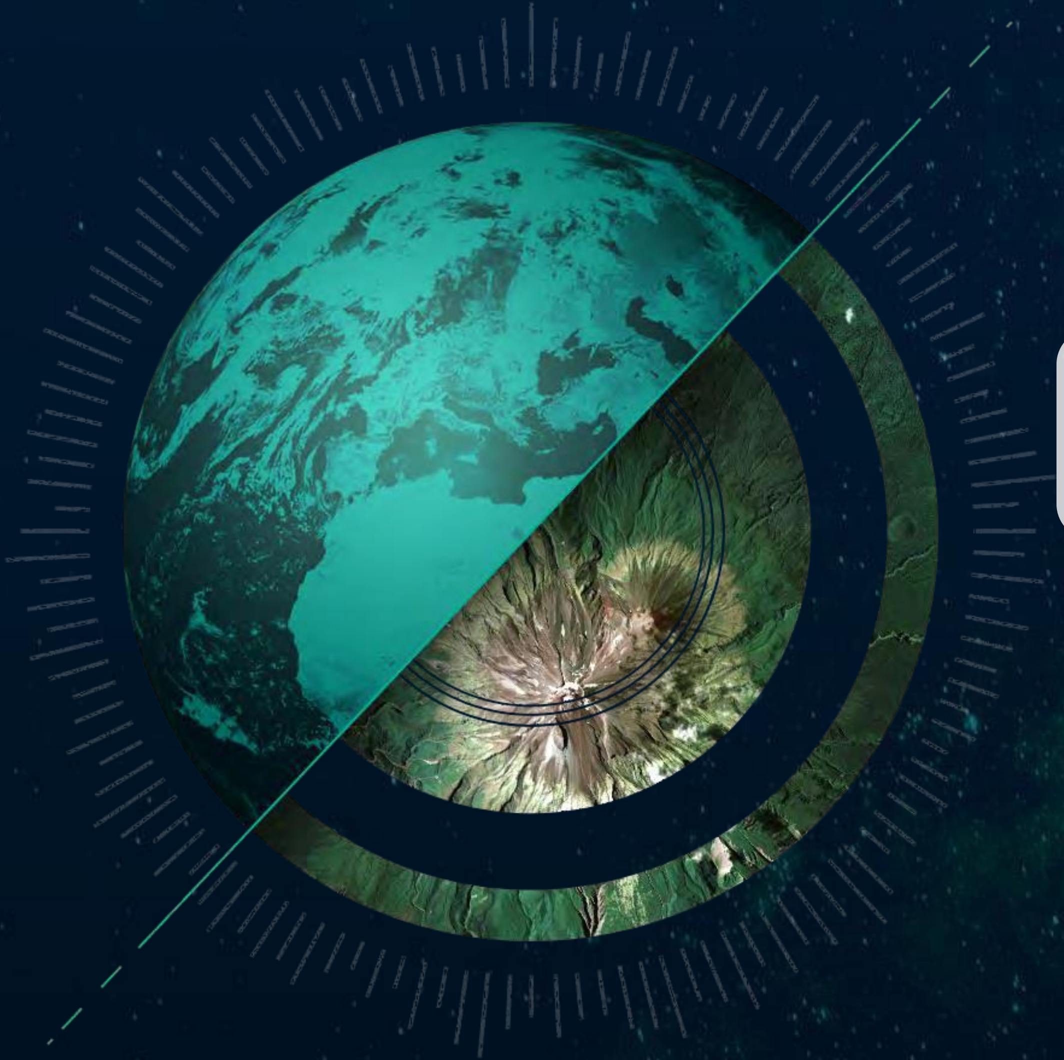
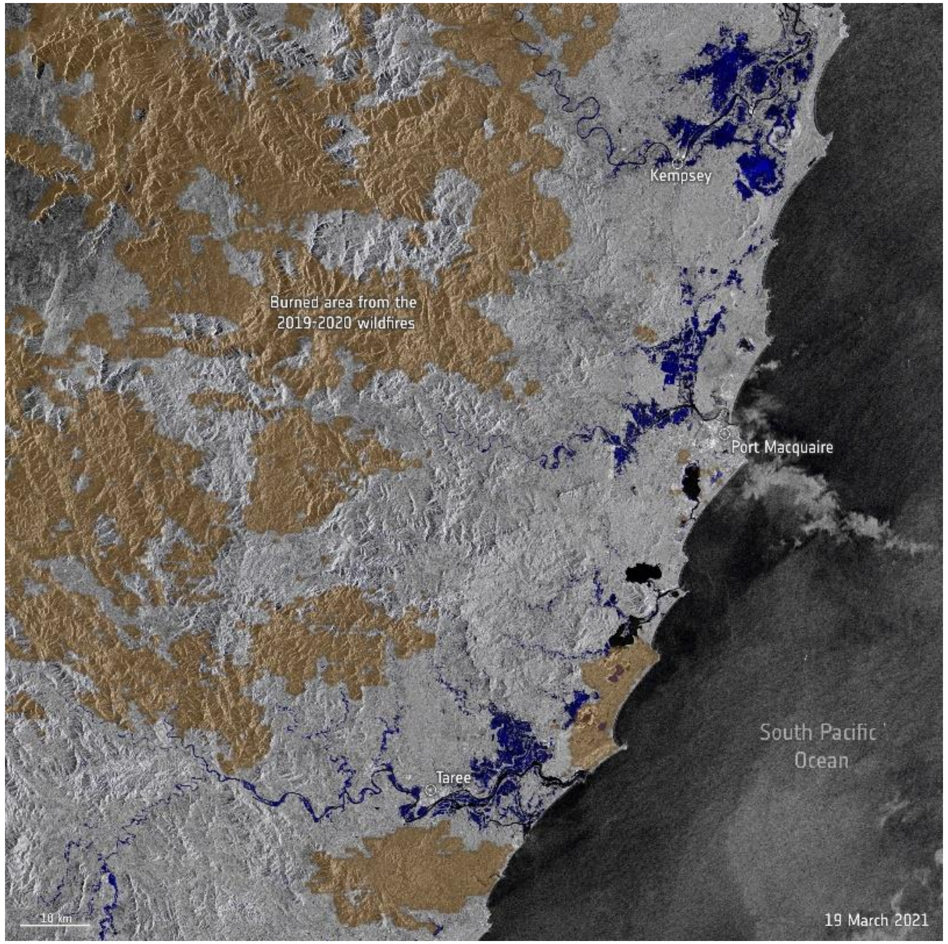


10. SAR and optical remote sensing for mapping floods

Why do we need to monitor flood events?

- Near 200 millions of affected people each year (more than half of affected people by a natural hazards)

- Timely detection and warnings allow communities to prepare and minimize damage, thus saving lives
- Flood monitoring aids in assessing flood risks, identifying vulnerable areas, and developing strategies to mitigate impacts on nature, human settlements, etc.
- Environmental monitoring helps evaluate the impacts and implement measures for conservation and restoration
- Flood monitoring data informs the design and management of infrastructure like dams, enhancing their resilience against flooding

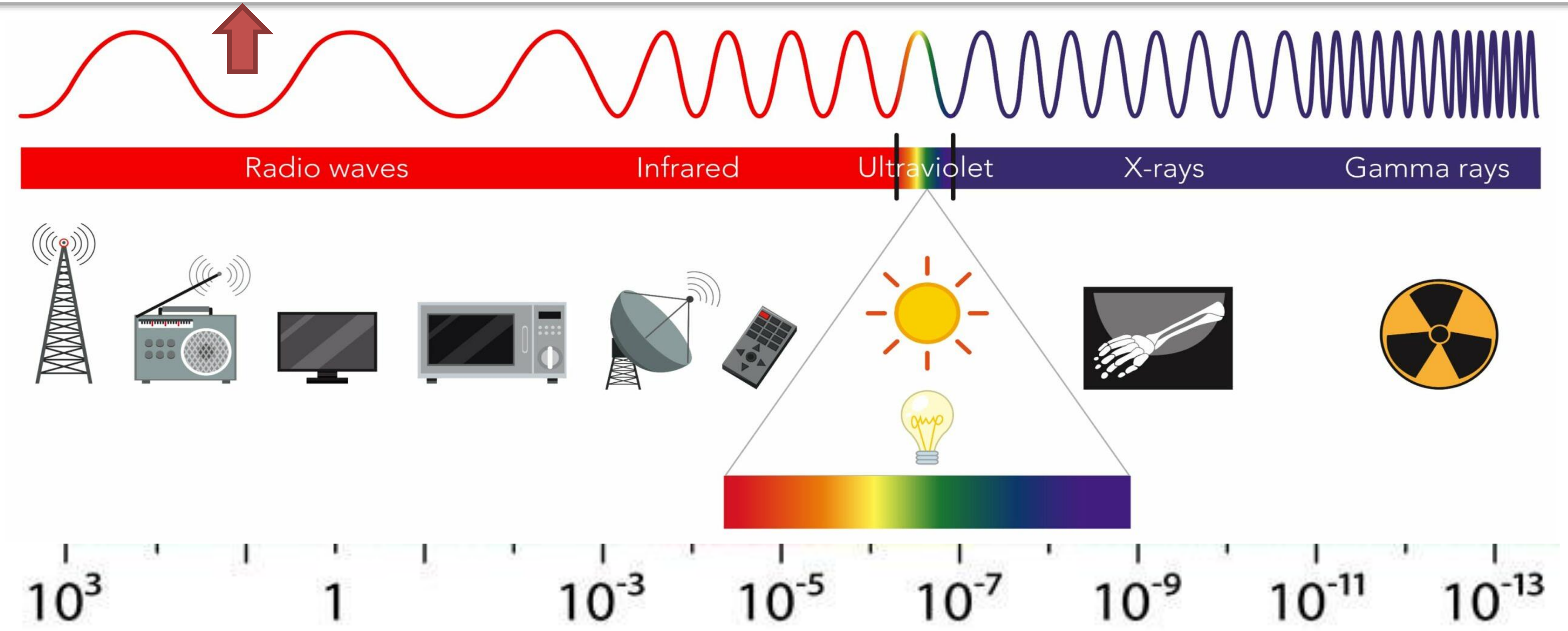


Credit: Contains modified Copernicus Sentinel data (2021), processed by ESA/NASA MODIS

SAR and optical for surface water mapping

RADAR SATELLITES
Weather & illumination independence
Penetration through cloud cover

Use: Detection of water surfaces
Changes in water levels



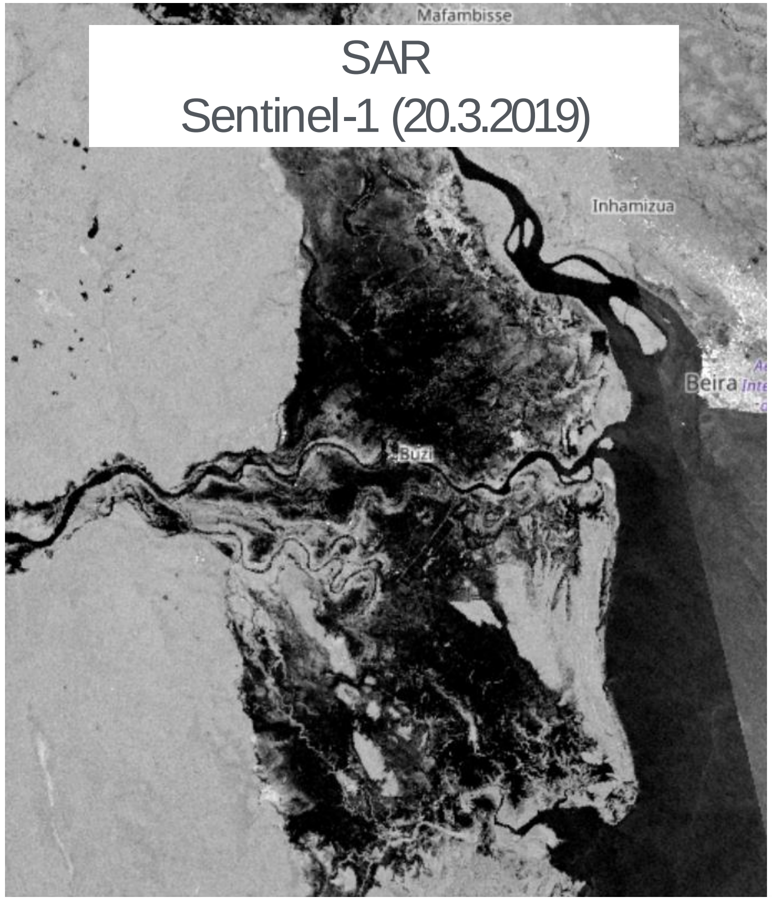
OPTICAL SATELLITES
Weather & illumination dependence
No penetration through cloud cover

Use: Flood extent, flood patterns, flood impacts
Analyzing changes before and after flooding events

Source:https://cthrumetals.com/emi-shielding/

SAR and optical for surface water mapping

Radar satellites, unlike optical ones, utilize microwave radar technology to capture data, enabling them to penetrate through clouds and atmospheric barriers. This distinct capability allows radar satellites to acquire flood mapping data even in adverse weather conditions.



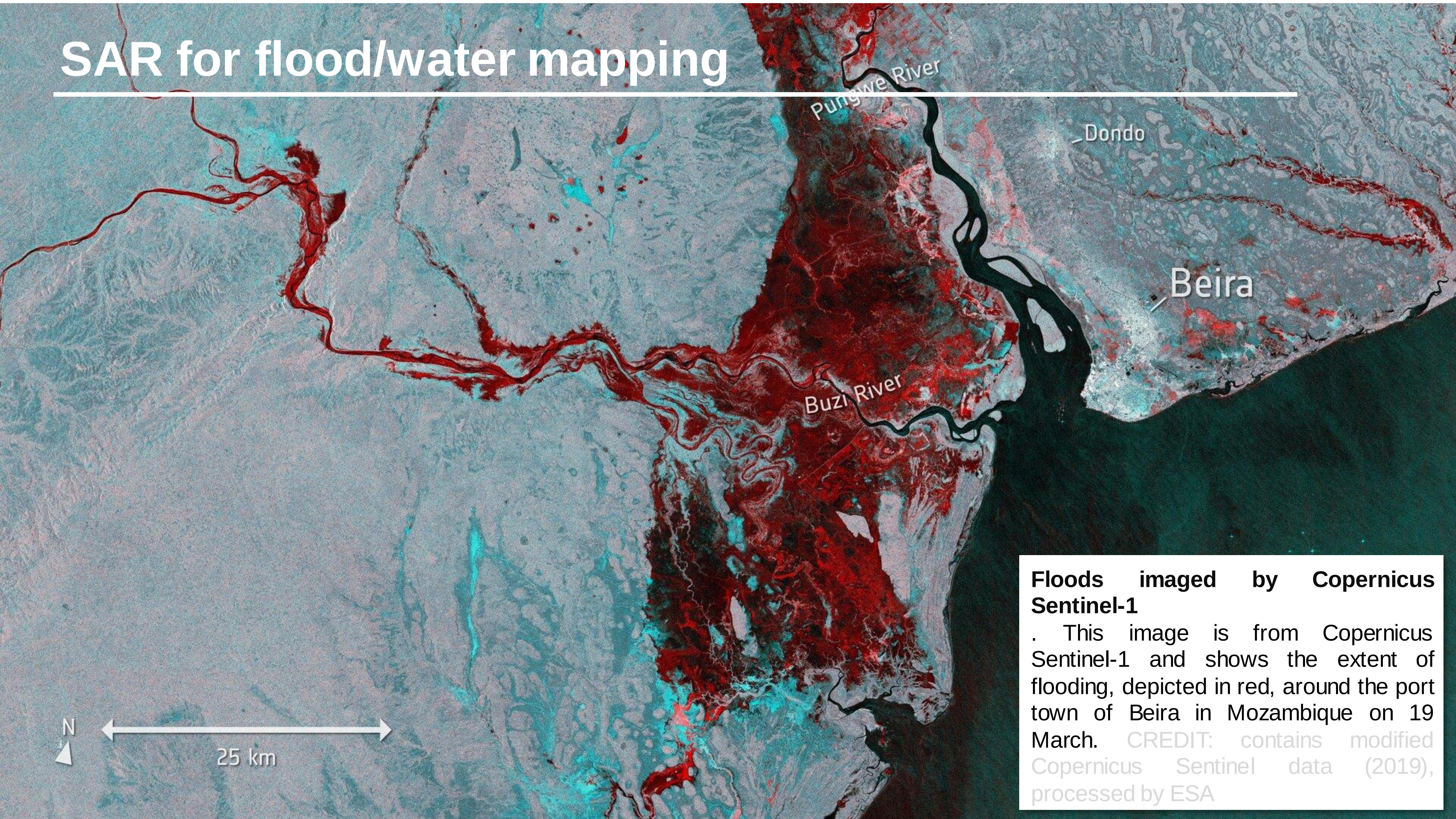
Floods in Beira, Mozambique

For more information, see the tutorials:

10. Flood Monitoring with Sentinel-1 & Sentinel-2 using the SNAP software

11. Flood Monitoring with Sentine l-1, Sentinel-2 data using the SNAP software

SAR for flood/water mapping



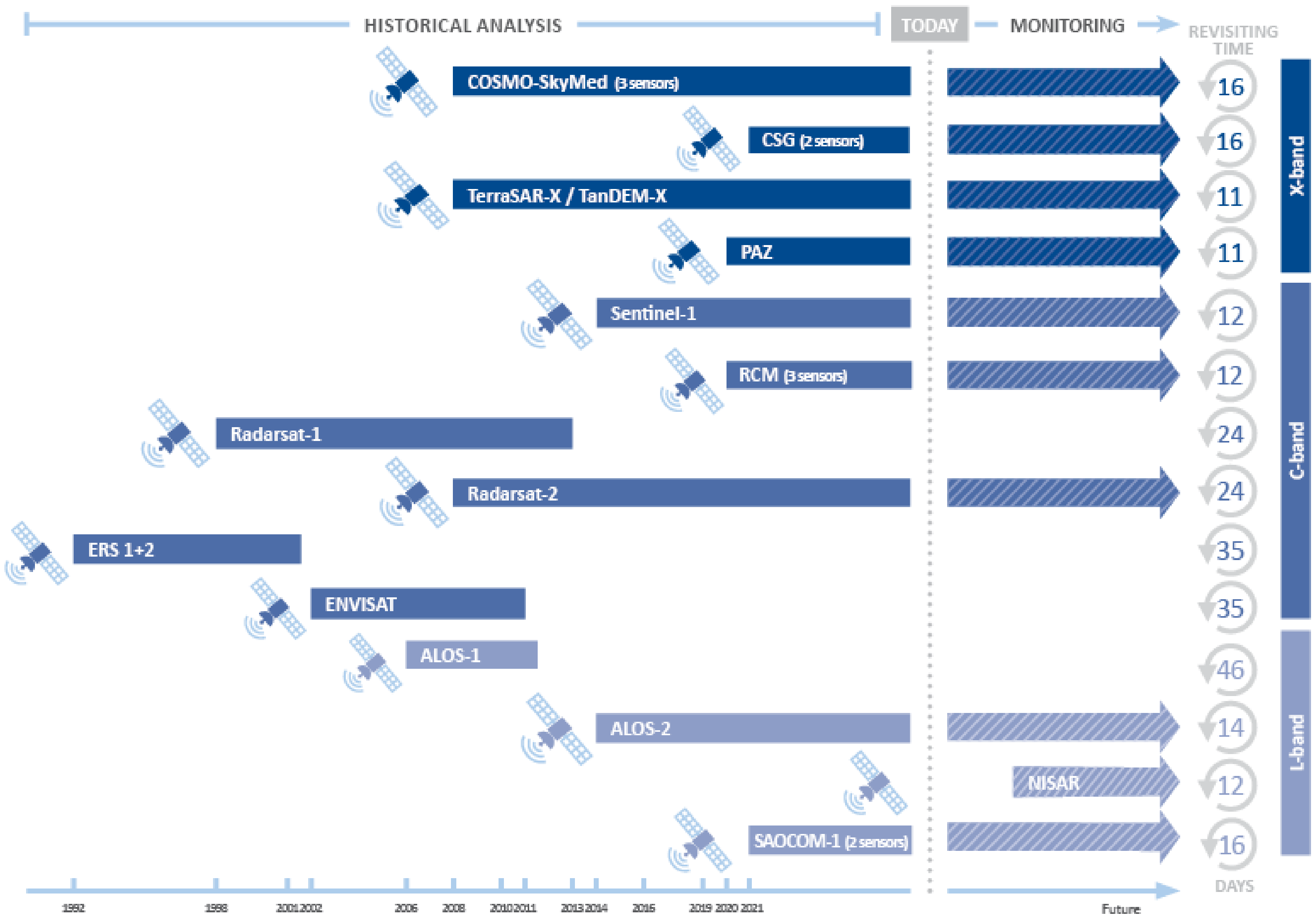
Floods imaged by Copernicus Sentinel-1

. This image is from Copernicus Sentinel-1 and shows the extent of flooding, depicted in red, around the port town of Beira in Mozambique on 19 March. CREDIT: contains modified Copernicus Sentinel data (2019), processed by ESA

The Microwave Spectrum

Band	Frequency f_0	Wavelength $\lambda = c/f_0$	Typical Application
Ka	27 – 40 GHz	1.1 – 0.8 cm	
K	18 – 27 GHz	1.7 – 1.1 cm	Rarely used for SAR
Ku	12 – 18 GHz	2.4 – 1.7 cm	
X	8 – 12 GHz	3.8 – 2.4 cm	**High-Resolution SAR** (urban monitoring; little penetration into vegetation cover □ can't see water under vegetation)
C	4 – 8 GHz	7.5 – 3.8 cm	**SAR Workhorse** (Sentinel-1; global mapping; improved vegetation penetration)
S	2 – 4 GHz	15 – 7.5 cm	**Increasing Use for SAR-Based Earth Observation**; NISAR will carry S-band
L	1 – 2 GHz	30 – 15 cm	**Medium-Resolution SAR** (NISAR; Geophysical monitoring; biomass and vegetation mapping; high penetration □ can see water under vegetation)
P	0.3 – 1 GHz	100 – 30 cm	**Biomass Estimation.** ESA Biomass will be first P-band spaceborne SAR

Former missions



https://site.tre-altamira.com/insar/

Ongoing missions

2007 : June: launches constellation Cosmo Skymed constellation , Terra SAR X
December: Radarsat 2

2012 : launch of RISAT (ISRO) , operational mode in 2015

2014 : Launch ALOS 2, band L

2014-2016: Launches of Sentinel 1A and 1B (Constellation Copernicus)

2016 : Gaofeng 3, C band (Quad Pol)

Recent advancements in InSAR

Sentinel-1, NISAR, TanDEM-L

Sentinel-1

- Launch Date: 2015, 2016
- Provides free and open data
- Globally available, acquired regularly irrespective of weather conditions
- Constellation of two C-band SAR sensors
- Wavelength: 5.6cm
- Polarization dual (VV/VH over land; HH/HV over ice)
- Image size: 250km swath with a resolution of 5mx20m
- Temporal coverage: every 6 days over Europe and every 12 days elsewhere

https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Ride_into_orbit_secured_for_Sentinel-1C

Recent advancements in InSAR

Sentinel-1, NISAR, TanDEM-L

NISAR

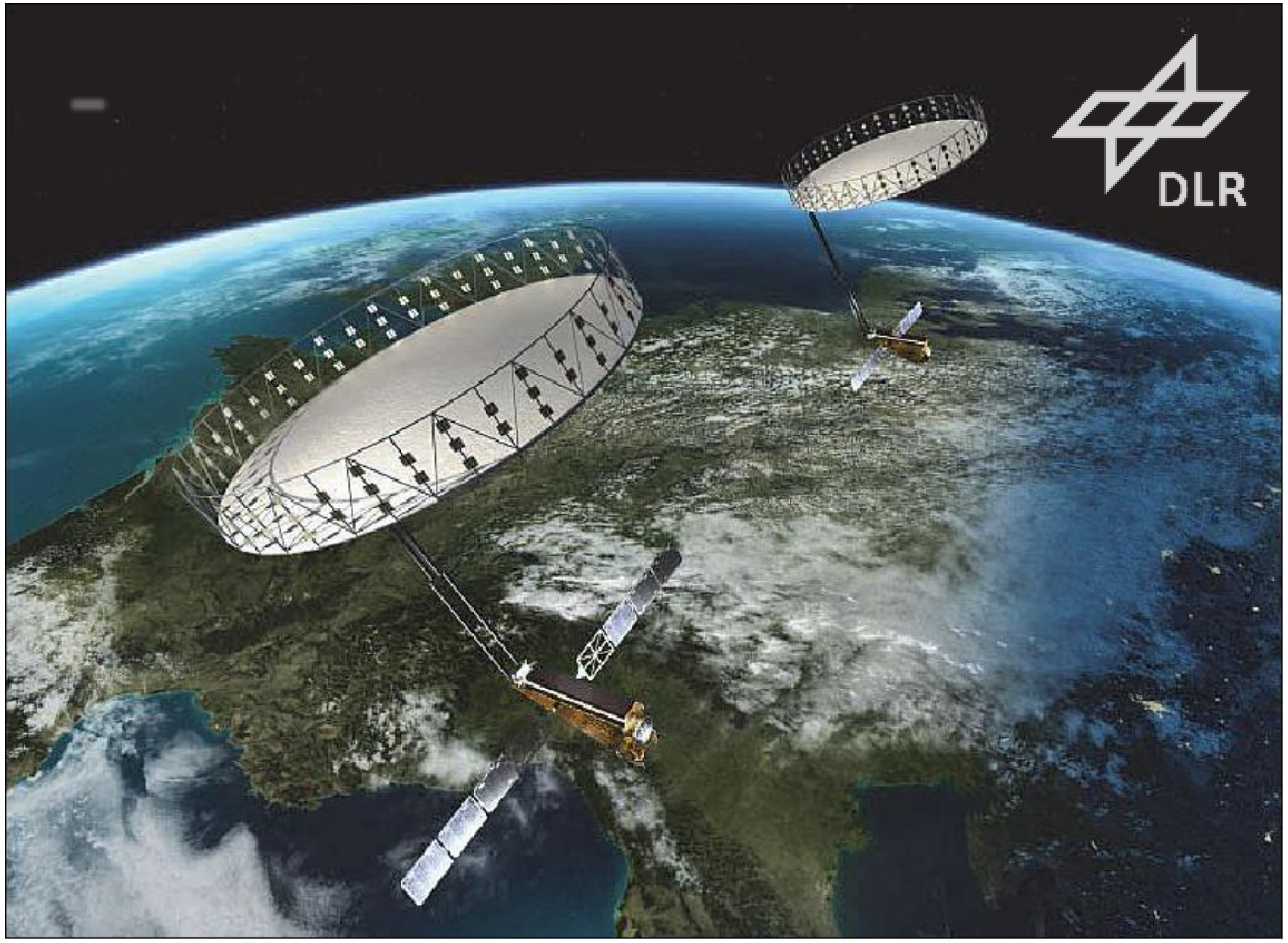
- Launch Date: 2023
- Provides free and open data
- First spaceborne L- and S- band SAR
- Temporal coverage: full global coverage in 12 days

https://www.jpl.nasa.gov/missions/nasa-isr

Recent advancements in InSAR

Sentinel-1, NISAR, TanDEM-L

TanDEM-L



- Launch Date: 2023
- Provides free and open data
- First spaceborne L- and S-band SAR
- Temporal coverage: full global coverage in 12 days

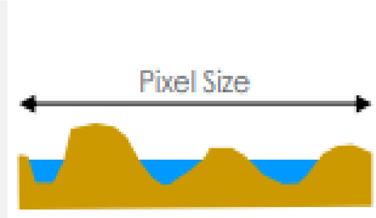
https://www.jpl.nasa.gov/missions/nasa-isr

Limitations of SAR for flood mapping

Wind Roughness on Water

Problem: Increases radar brightness and may prevent water detection

Mitigation: Use VH in addition to VV for water detection



Partially Inundated Pixels

Problem: Pixels are not dark enough for detection

Mitigation: Higher-resolution radar or combine with change detection approach

Water Under Dense Vegetation

Problem: Radar may not be able to penetrate vegetation

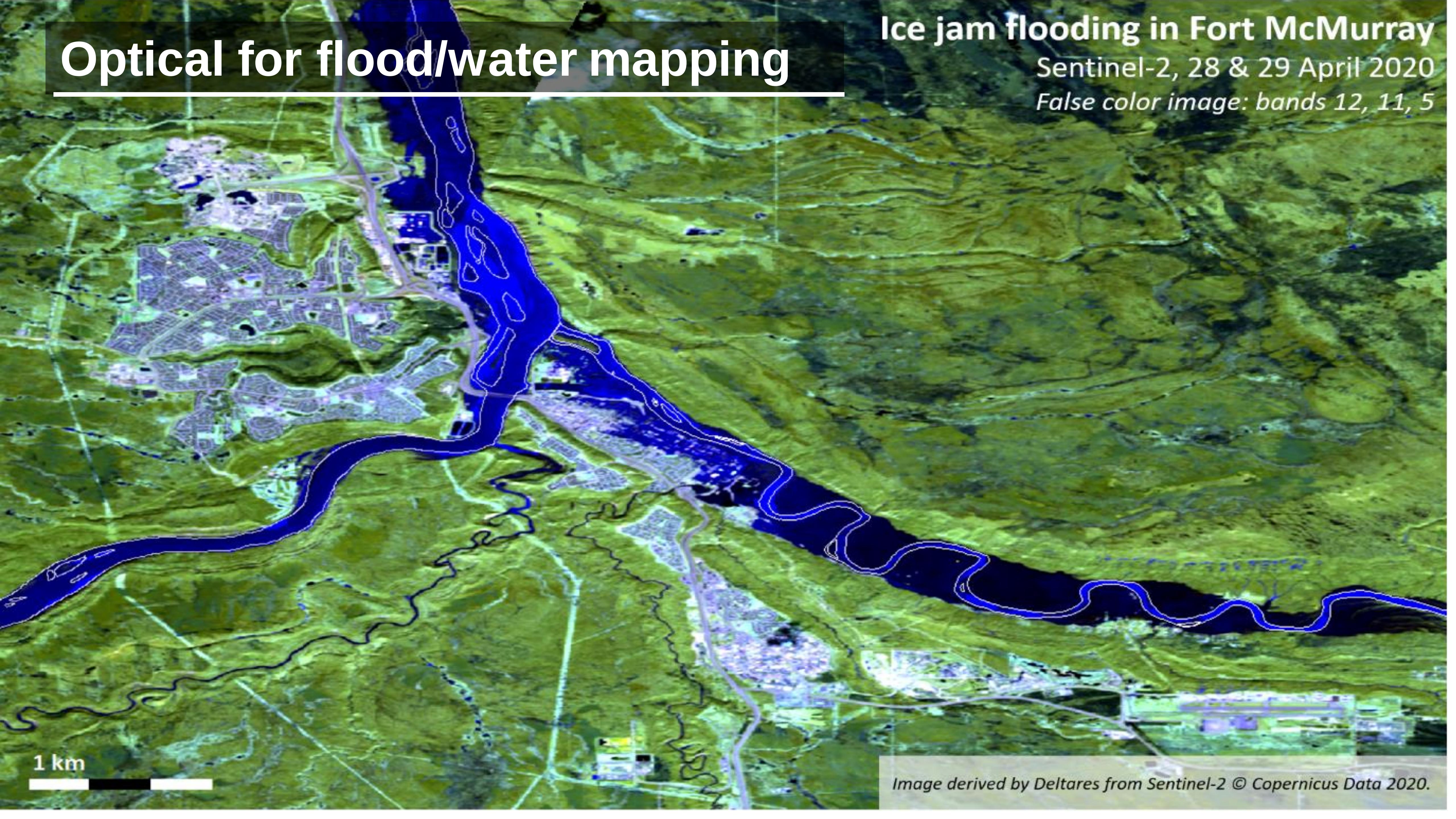
Mitigation: Use longer wavelenght (e.g. NISAR)

Water in Urban Environment

Problem: Due to side-looking geometry, buildings obstruct surface water from view

Mitigation: Use multiple viewing geometries – use optical data

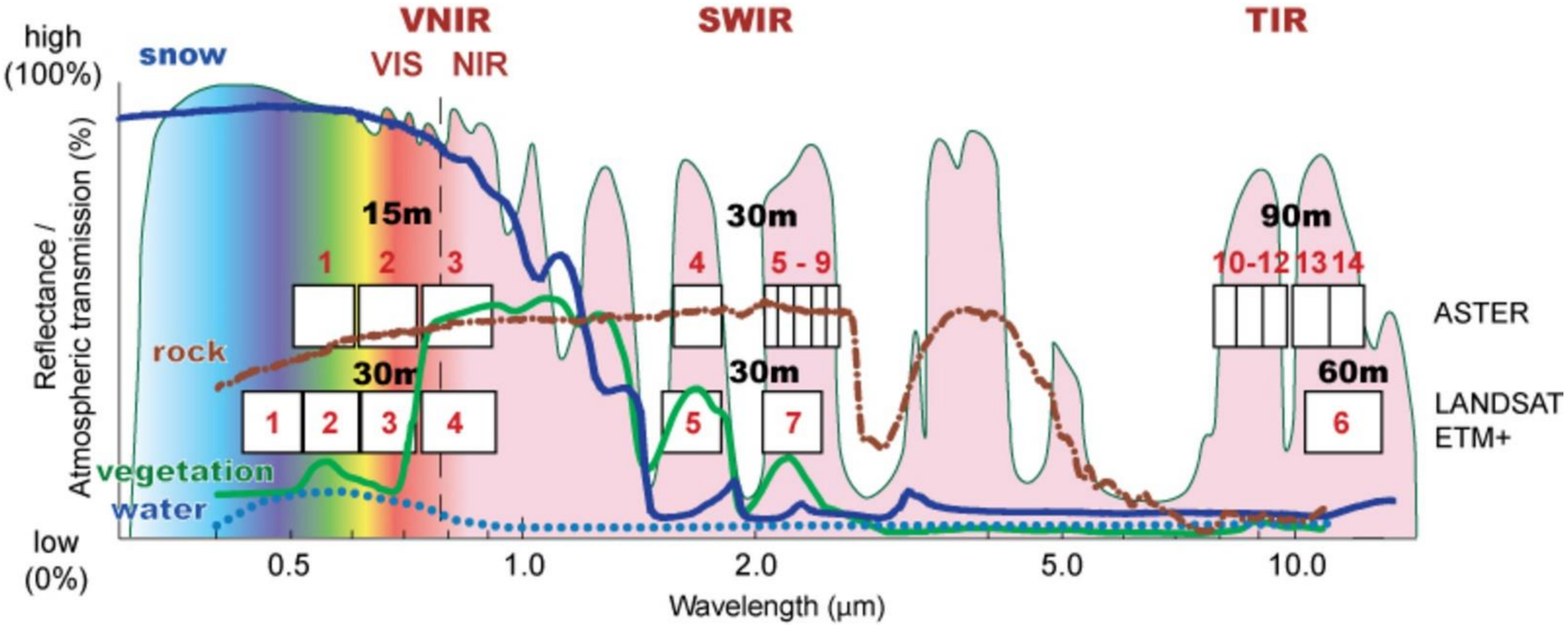
Optical for flood/water mapping



Optical Parameters to Consider for a Flood Mapping

Physical basis for Water bodies mapping

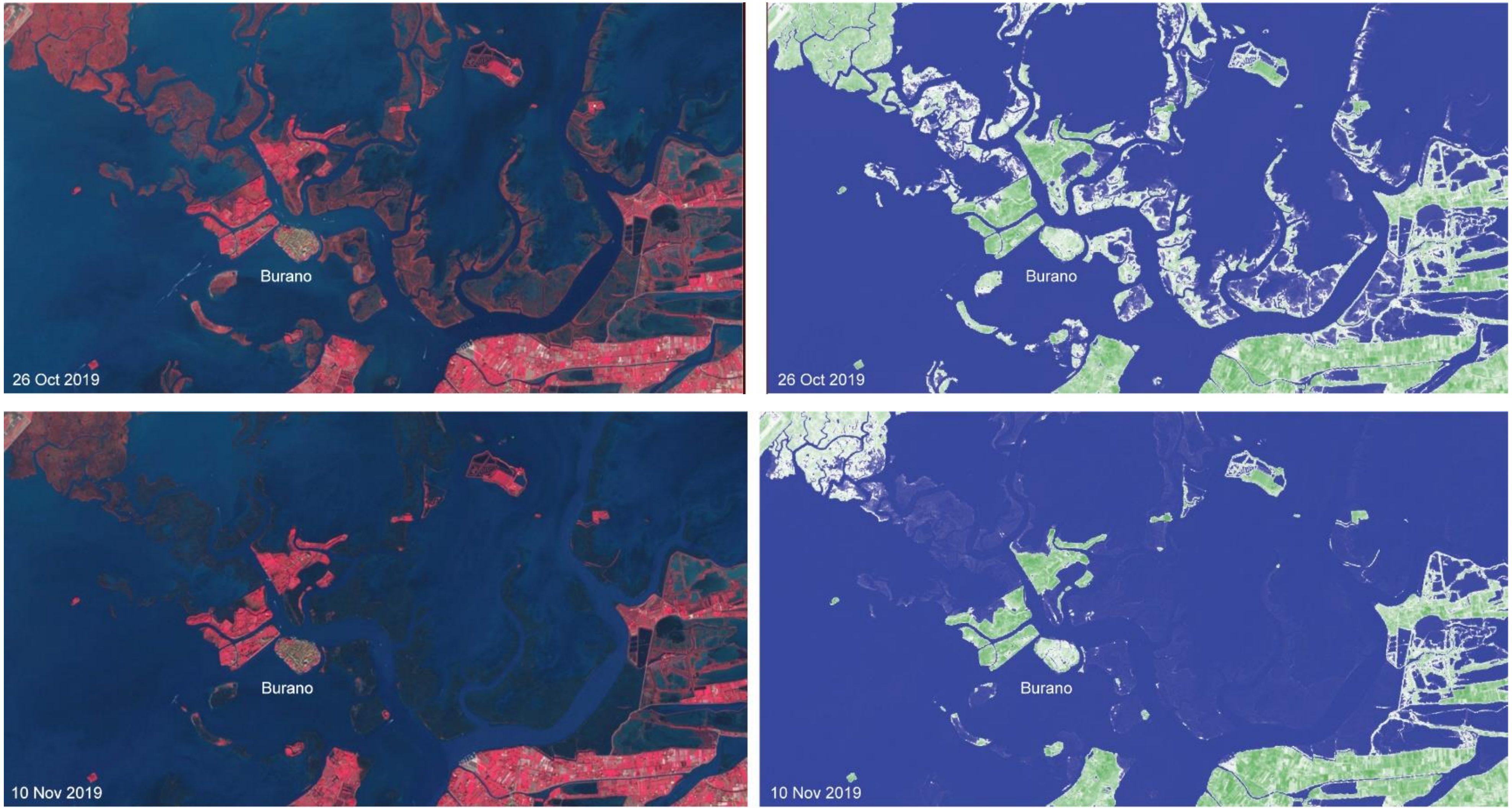
- Water absorbs the longer wavelengths of visible and NIR and SWIR domains
- Reflects the shorter wavelengths of the visible domain (blue, green)
- Water color depends on: depth, materials in suspension, vegetation



https:/www.esa.int/ESA_Multimedia/Images/2011/11/Reflectance_curves_of_snow_vegetation_water_and_rock

Optical Parameters to Consider for a Flood Mapping

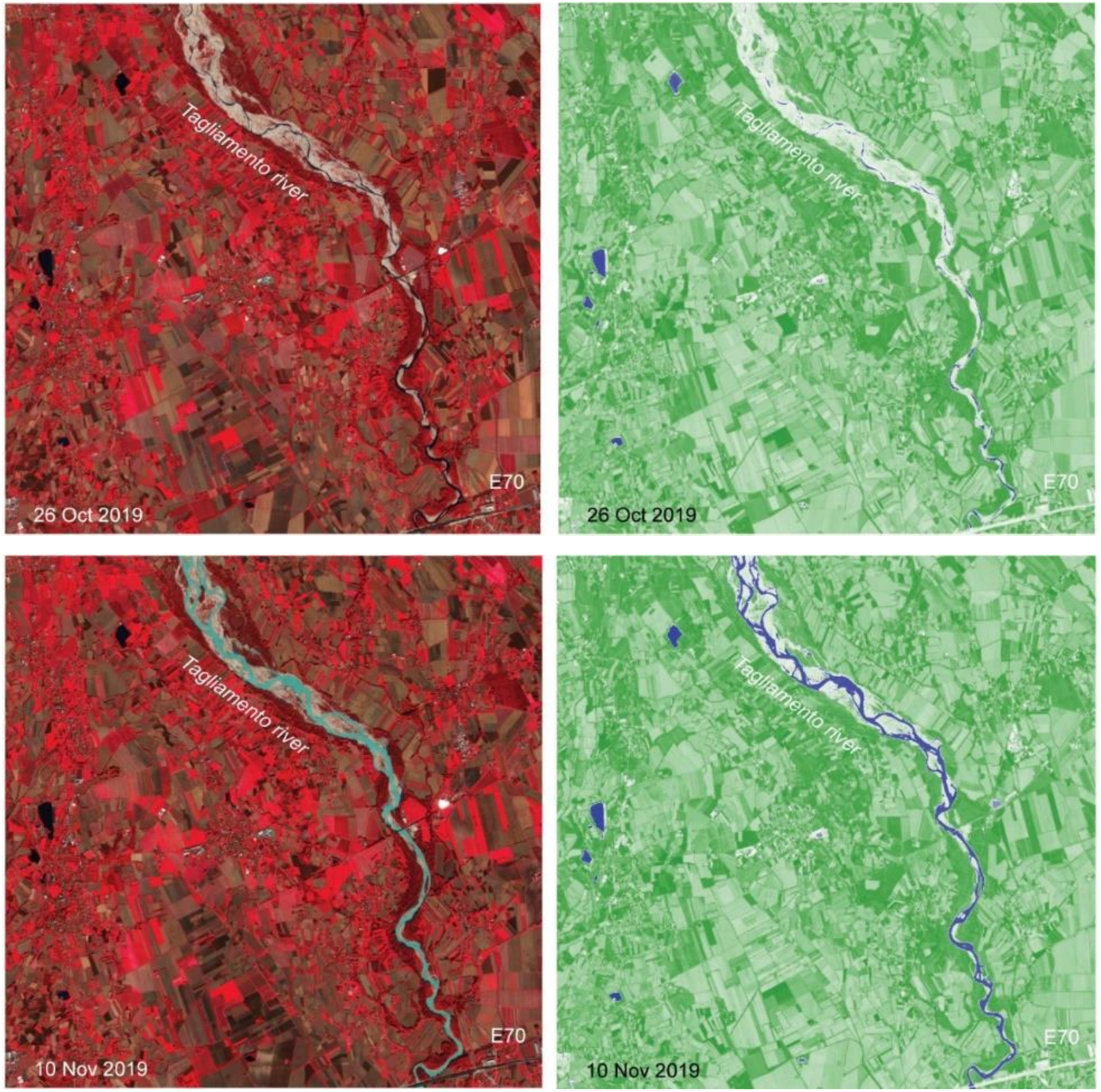
High variability of spectral answer and contrast



https://sentinel.esa.int/web/success-stories/-/copernicus-sentinel-2-captures-flooding-of-wetlands-in-the-laguna-of-venice

Optical Parameters to Consider for a Flood Mapping

High variability of spectral answer and contrast

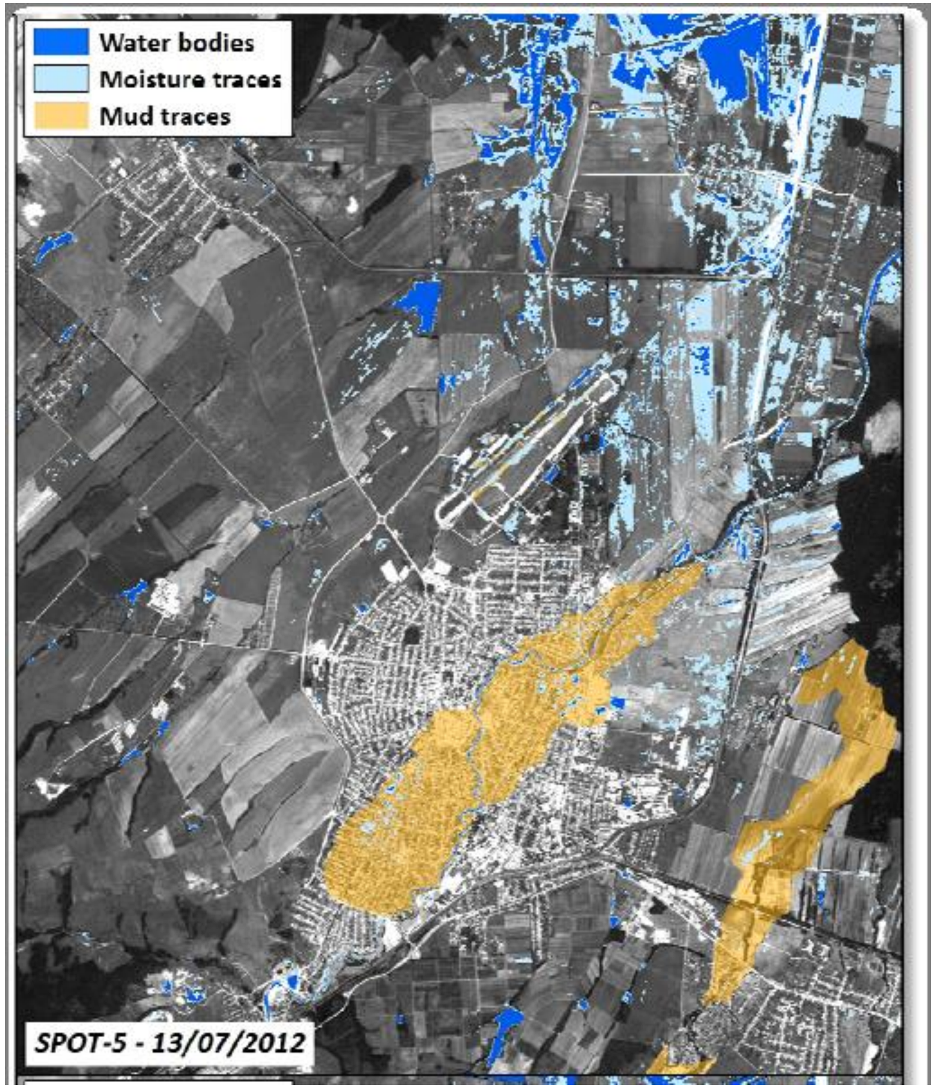


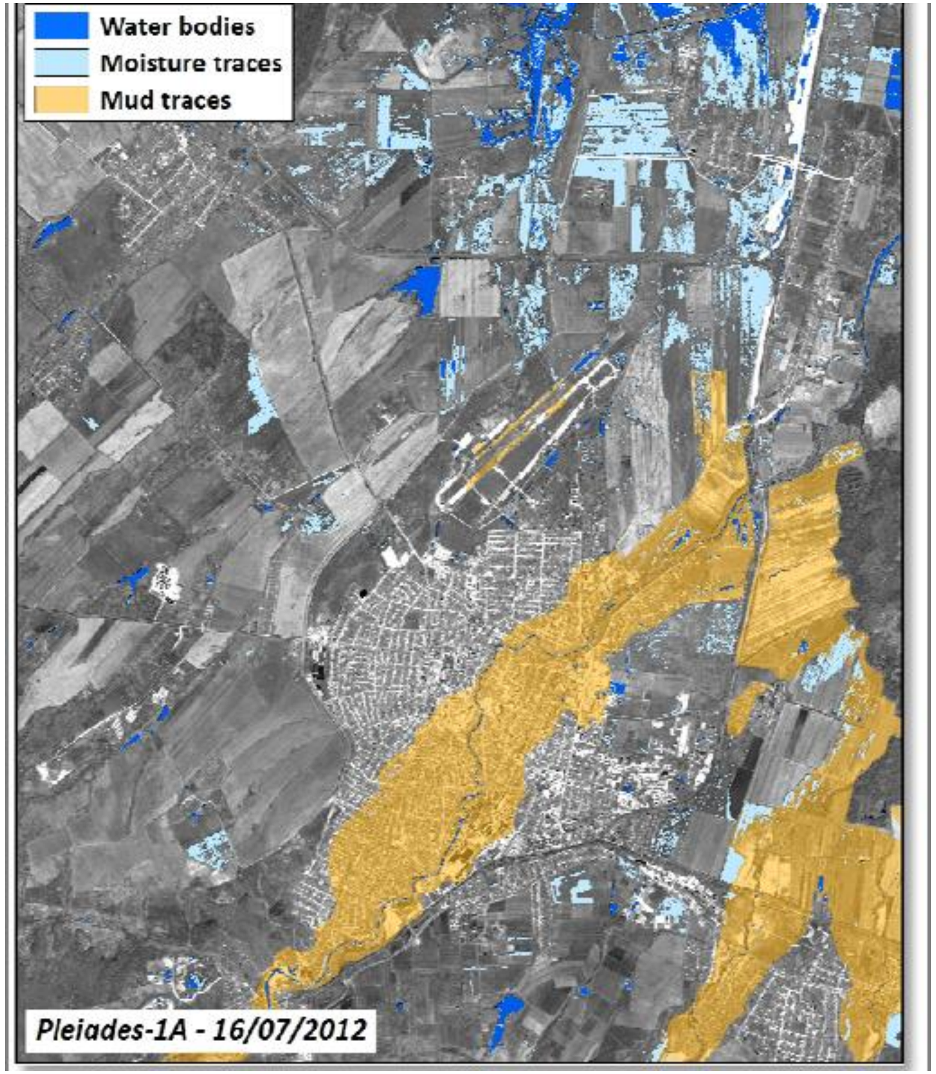
Copernicus Sentinel-2 captures rising river flow in the Tagliamento River
https://sentinel.esa.int/web/success-stories/-/copernicus-sentinel-2-captures-rising-river-flow-in-the-tagliamento-river

Common color compositions use visible, near infrared and shortwave infrared bands

Optical Parameters to Consider for a Flood Mapping

High variability of spectral answer and contrast





Flood traces classifications derived from SPOT 5 SWIR and VHR Pleiades data over Krymsk
https://ieeexplore.ieee.org/document/6723845/

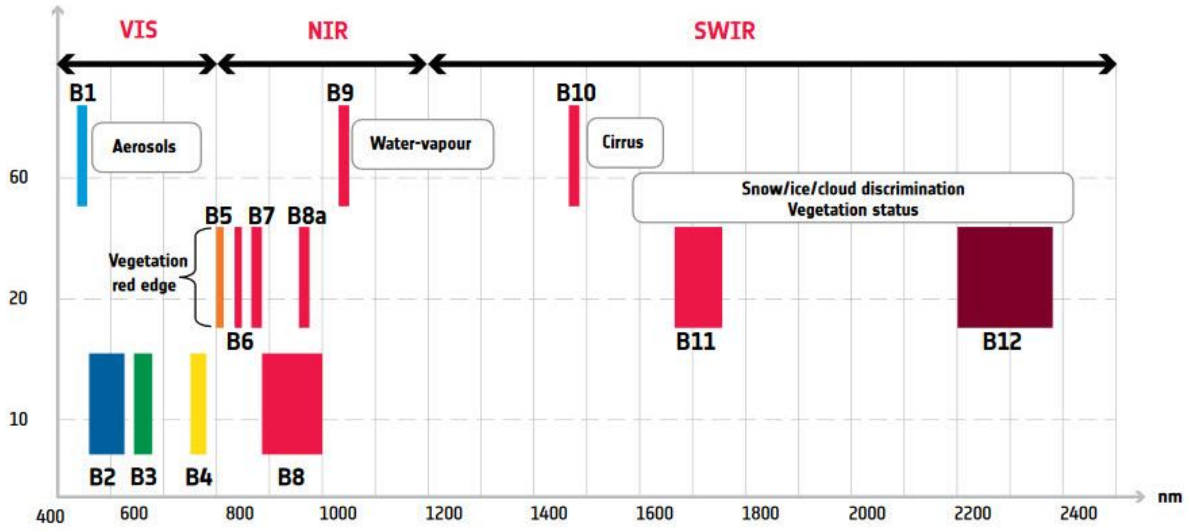
Optical Sensors for a Flood/Water Mapping

Sentinel-2

- Multi-Spectral imaging mission
- Sun-synchronous orbit 786 km,
- 290 km swath with 13 spectral bands (VIS, NIR & SWIR), at 10, 20 and 60 m spatial resolution
- 5 day revisit at Equator with 2 satellites

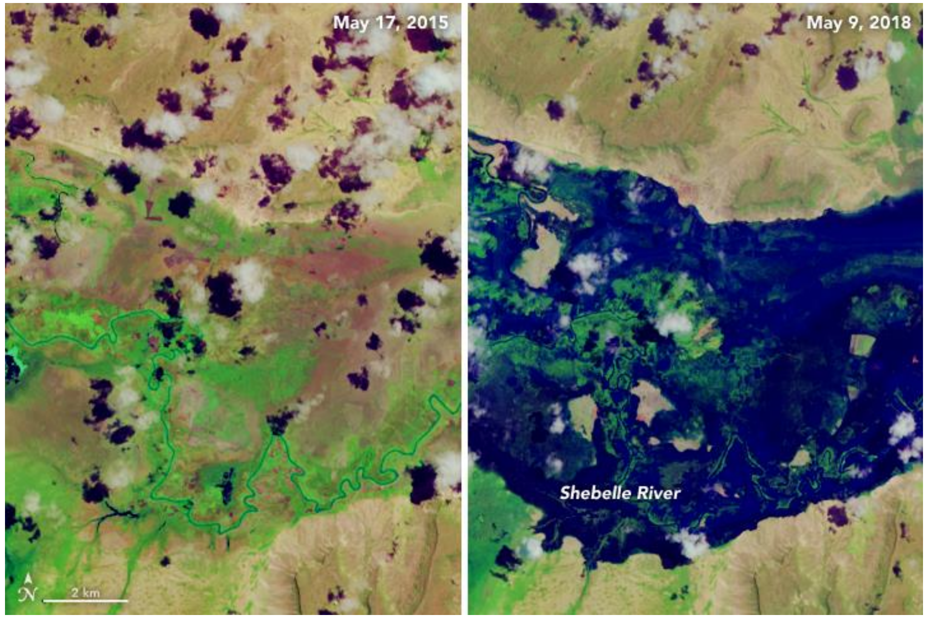
Landsat family

- Multi-Spectral imaging mission
- Systematic acquisition
- 8 days revisit (Landsat-8 and Landsat-9)
- Huge archive
- Since Landsat 4-5 . SWIR band
- 30 m



13 MSI bands are optimized for accurate atmospheric correction and vegetation monitoring

Source: http://esamultimedia.esa.int/docs/EarthObservation/Sentinel-2_ESA_Bulletin161.pdf



Source: https://landsat.visibleearth.nasa.gov/view.php?id=92130

Optical Sensors for a Flood/Water Mapping

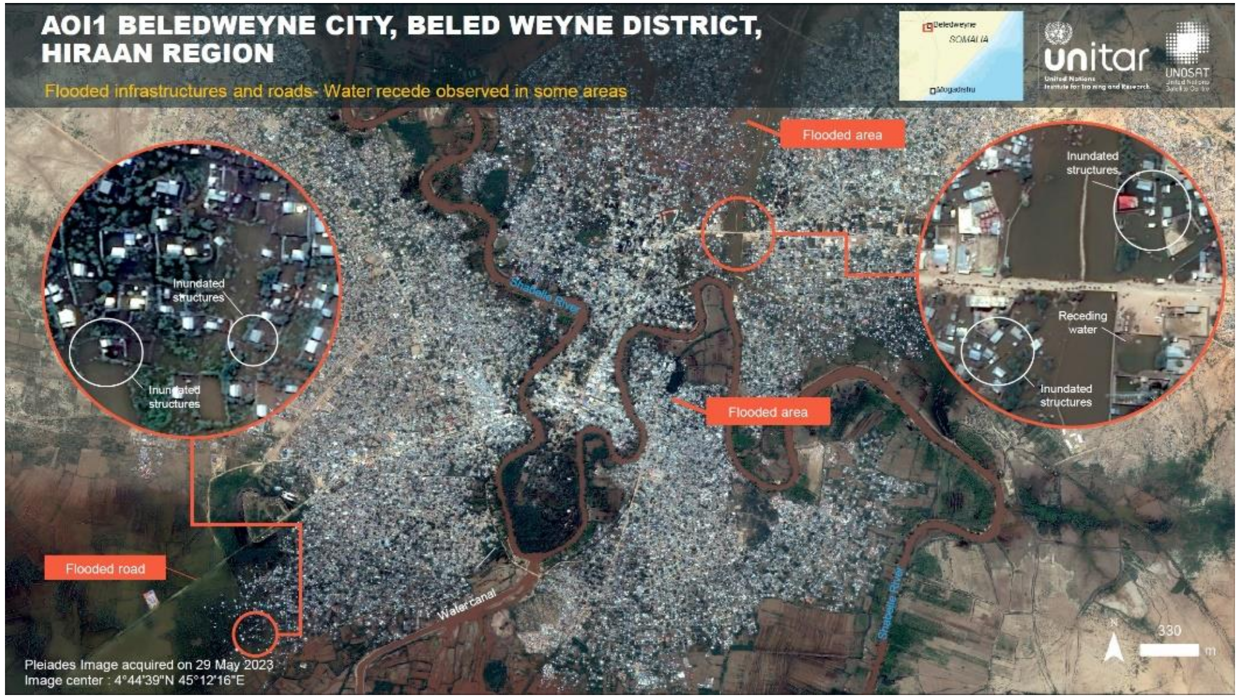
Spot family

- Very rich archive
- Visible, NIR, PAN bands
- Daily coverage capacity
- Spatial resolution 1,5-6m at nadir
- 2 satellites in constellation with Pleaides

Pleiades family

- 2 satellites in constellation
- Launch December 2011 and 2012
- 0,70 cm in PAN
- Visible, NIR, PAN bands

WorldView, etc.



Flash floods in Somalia are now affecting over 460,000 people according to the United Nations Office for the Coordination of Humanitarian Affairs (OCHA). Source:https://disasterscharter.org/es/web/guest/activations/-/article/flood-large-in-somalia-activation-821-

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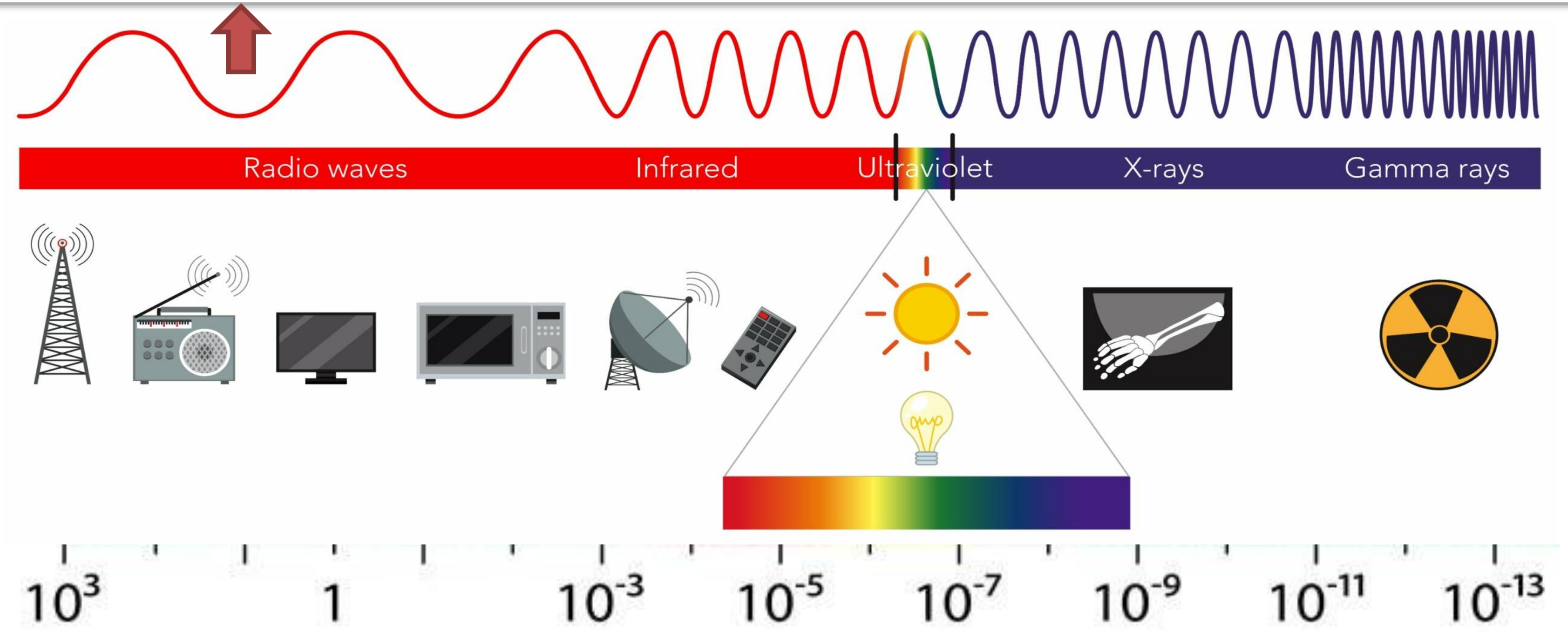
11. SAR and optical remote sensing for post-flood assessment and recovery

SAR and optical for flood/postflood mapping

RADAR SATELLITES
Weather & illumination independence
Penetration through cloud cover

Use: Detection of water surfaces
Changes in water levels



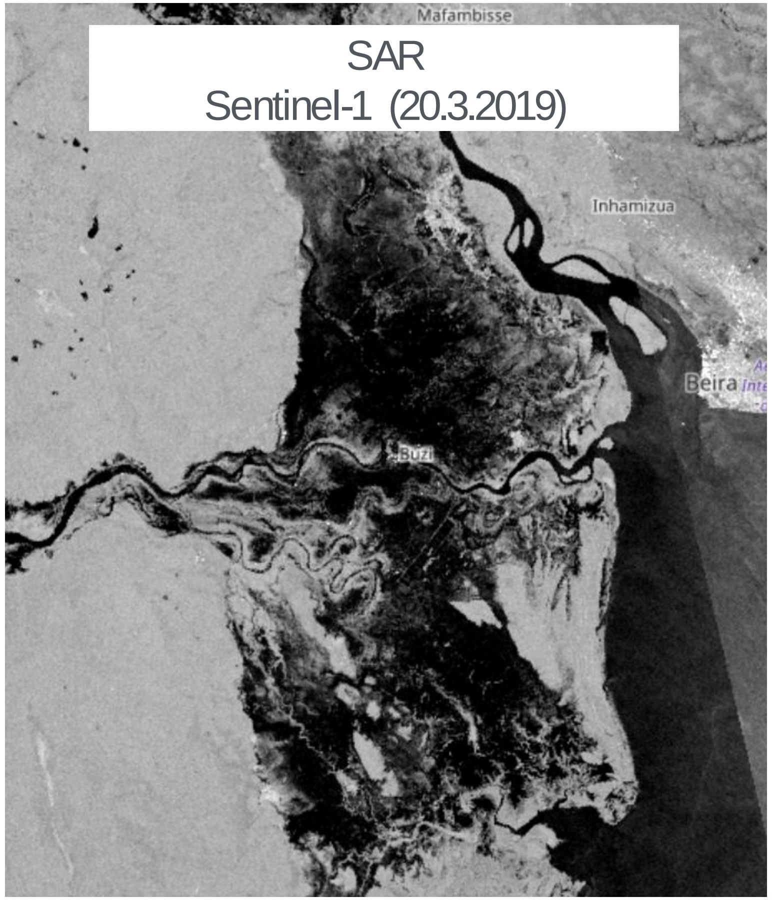
OPTICAL SATELLITES
Weather & illumination dependence
No penetration through cloud cover

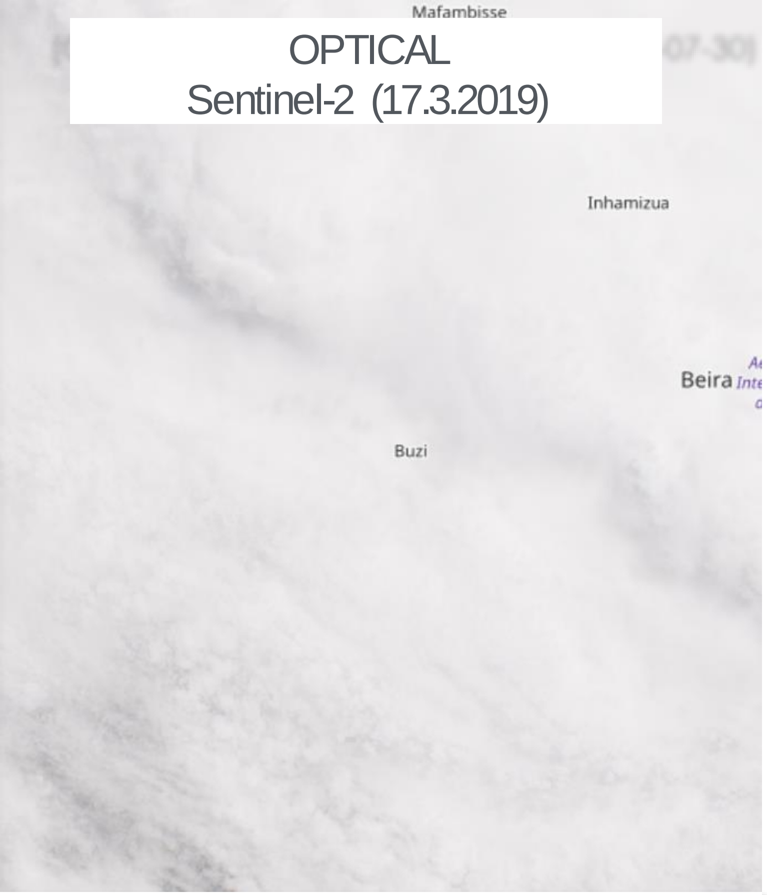
Use: Flood extent, flood patterns, flood impacts
Analyzing changes before and after flooding events

Source:https://cthrumetals.com/emi-shielding/

SAR and optical for flood/postflood mapping

Radar satellites, unlike optical ones, utilize microwave radar technology to capture data, enabling them to penetrate through clouds and atmospheric barriers. This distinct capability allows radar satellites to acquire flood mapping data even in adverse weather conditions.



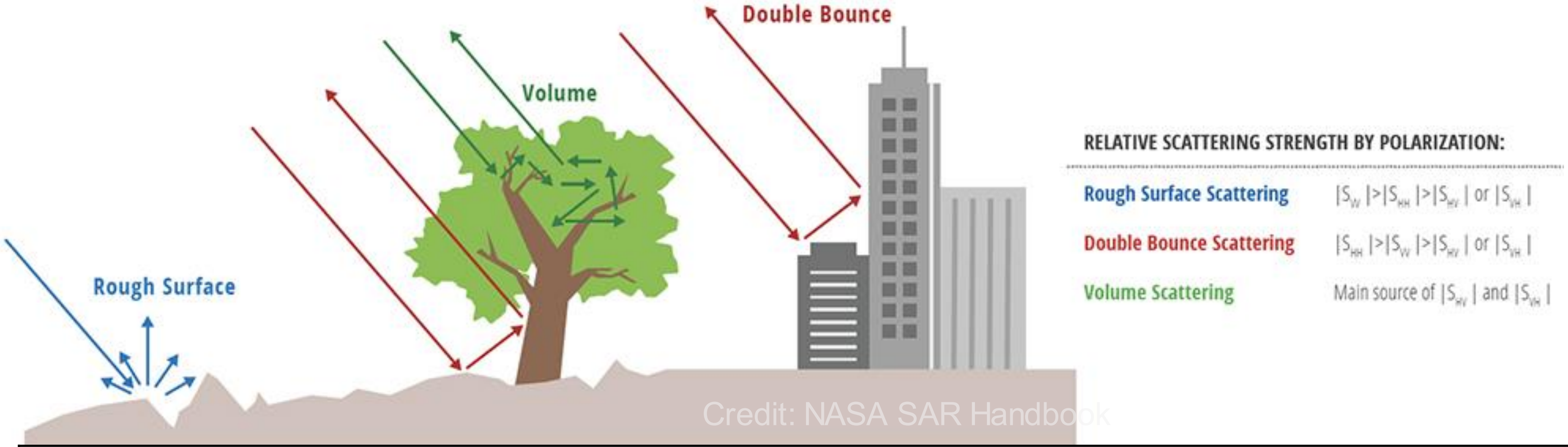


Floods in Beira, Mozambique

Radar Parameters to Consider for a Flood Mapping

Signal interacton

Analyzing the signal intensity from these various polarizations provides insights into the composition of the observed surface, as it relates to the following types of scattering:



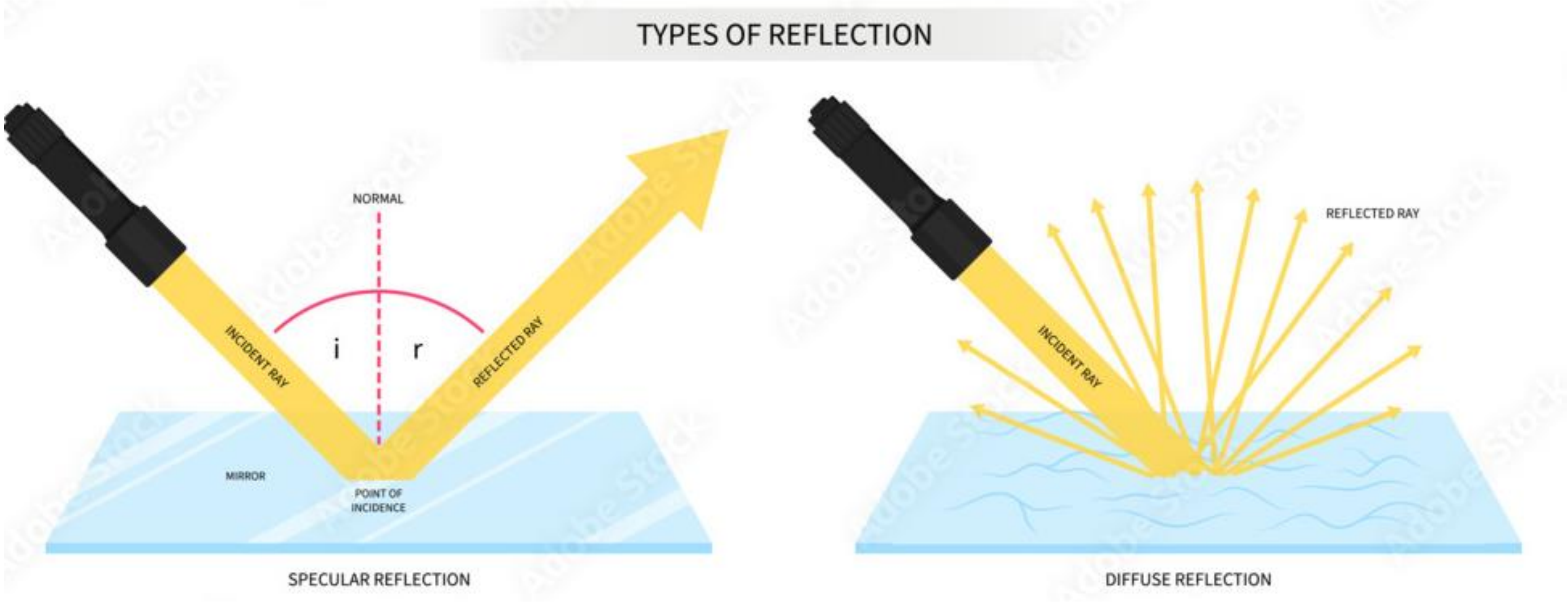
Credit: NASA SAR Handbook

Rough surface scattering	• most sensitive to VV scattering • caused f.e. by bare soil or water
Volume scattering	• most sensitive to cross-polarized data like VH or HV • scattering by the leaves and branches
Double bounce	• most sensitive to an HH polarized signal • caused by buildings, tree trunks, or inundated vegetation

Radar Parameters to Consider for a Flood Mapping

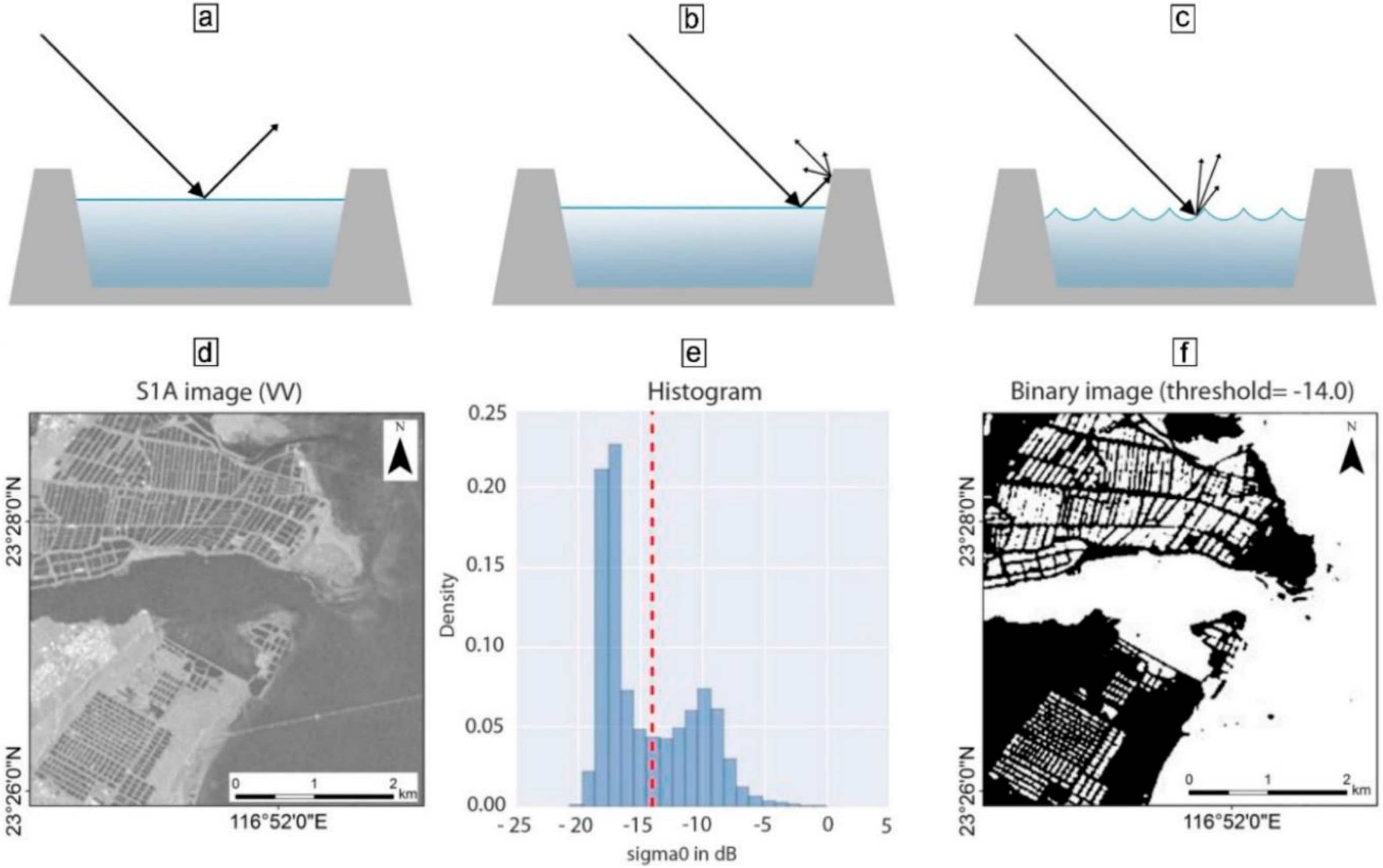
Signal interacton

- Calm water surfaces appear smooth, resulting in specular reflection and low backscatter in radar images
- In contrast, the surrounding land surface appears rougher, causing higher backscatter due to the scattering of radar waves by surface irregularities
- This difference in radar signatures allows for the mapping of water and other land surfaces



Radar Parameters to Consider for a Flood Mapping

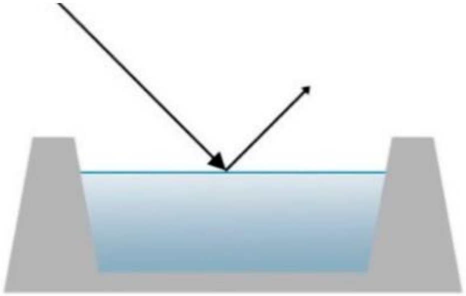
Signal interacton



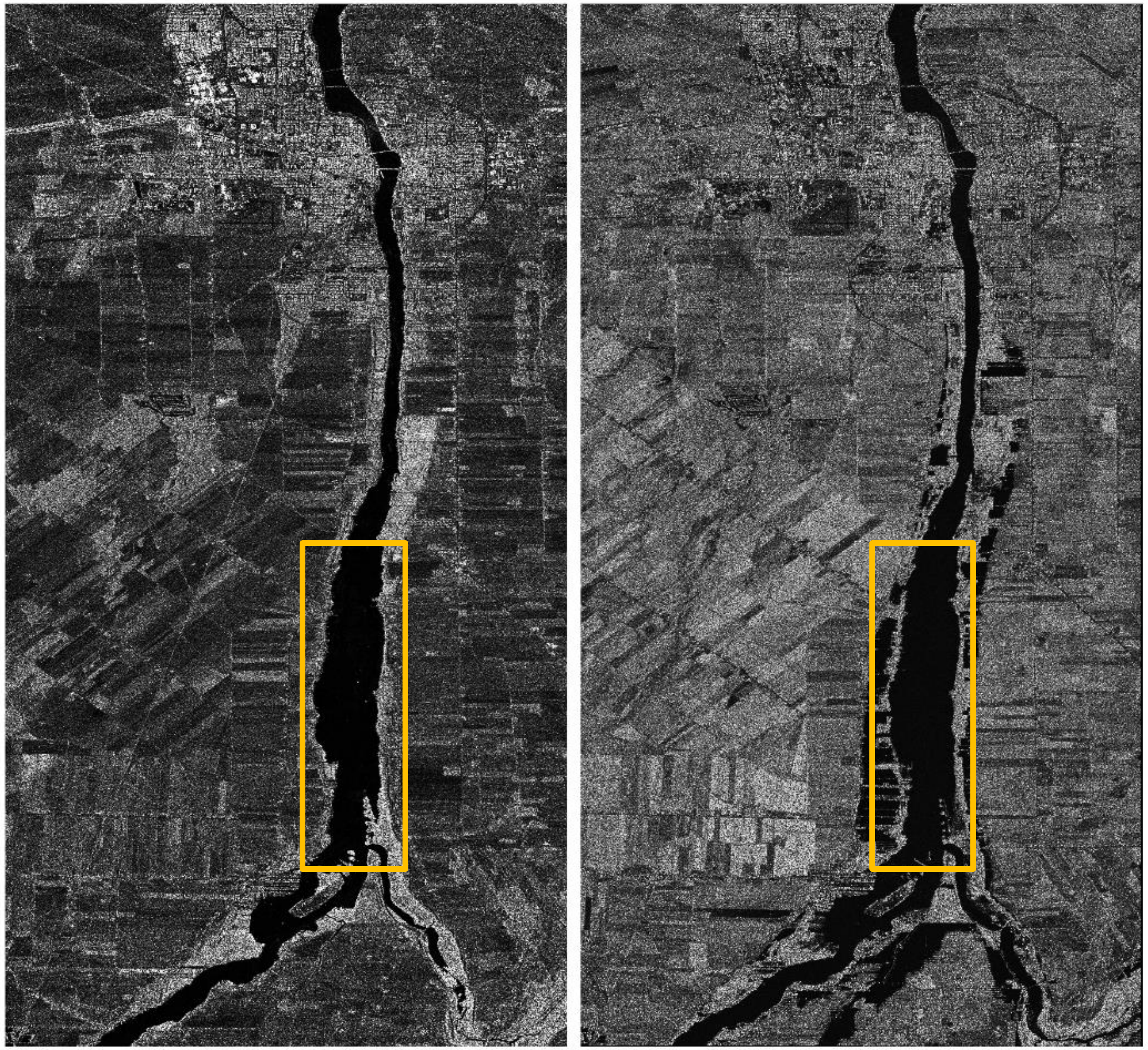
Examples of radar interaction with aquaculture ponds: (a) specular reflection (smooth water surface); (b) corner/embankment; and (c) diffuse reflection (rough water surface). (Bottom) S1A image (d); related histogram and classification threshold (e); and binary image of water and non-water after application of threshold (f). (Modified from Ottinger et al.

Source:https://www.mdpi.com/2072-4292/11/17/1985

Radar Parameters to Consider for a Flood Mapping



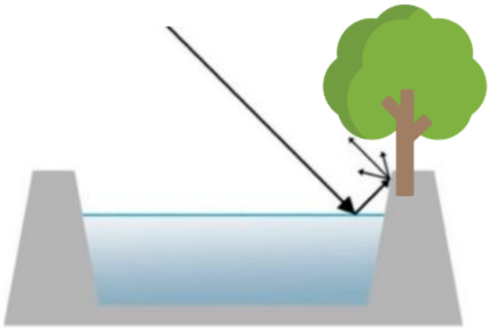
Smooth, Level Surface
(Open Water, Road)



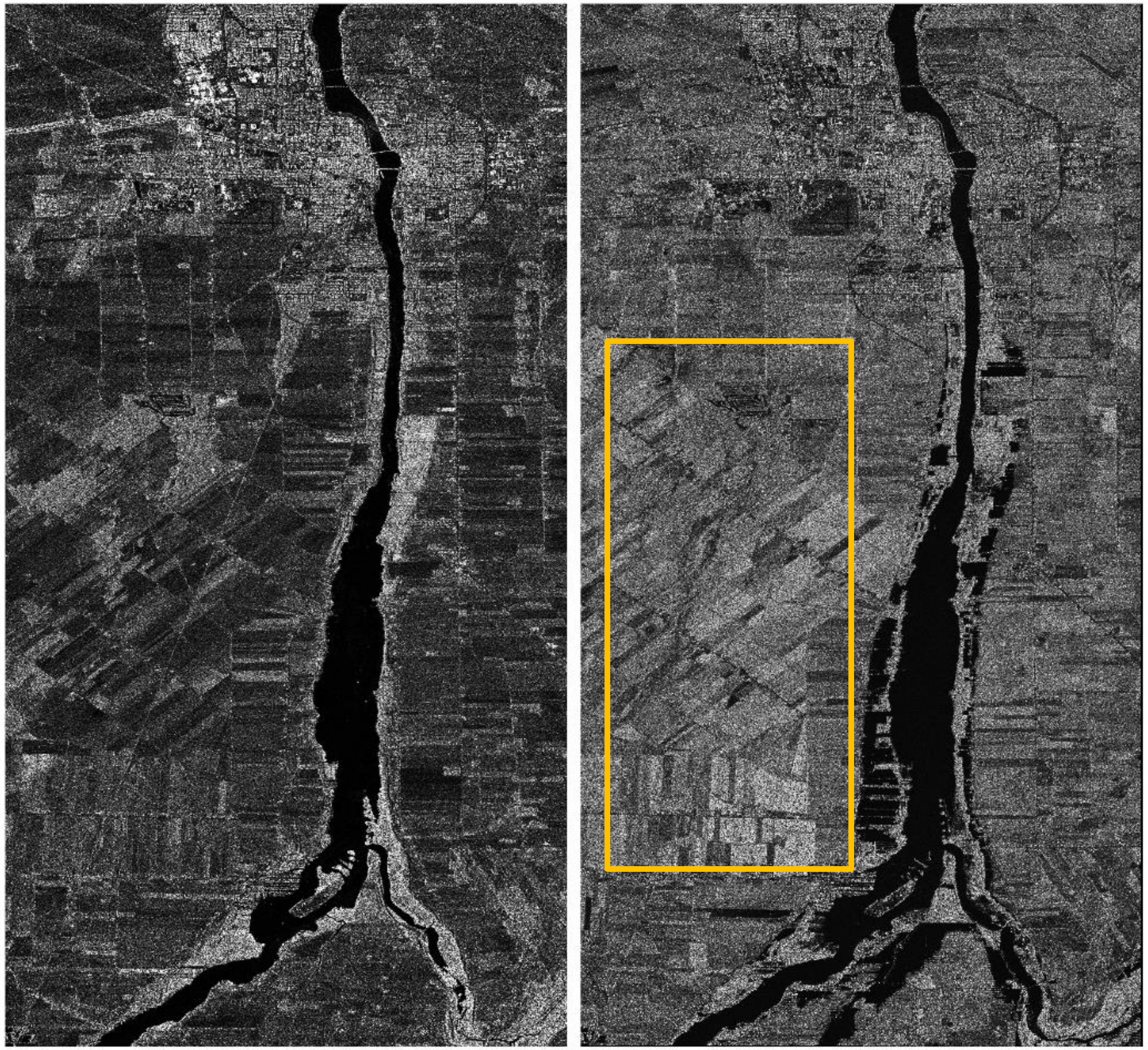
(a) (b)

https://www.mdpi.com/2072-4292/10/2/237

Radar Parameters to Consider for a Flood Mapping



Inundated Vegetation



(a) (b)

https://www.mdpi.com/2072-4292/10/2/237

Radar Parameters to Consider for a Flood Mapping

Penetration through land covers as a Function of Wavelength and dielectric characteristics

- The penetration depth is depending on **wavelength** and **dielectric characteristics** of objects
- Penetration - predominant consideration when selecting a wavelength
- Typically, longer wavelengths result in greater penetration into the target

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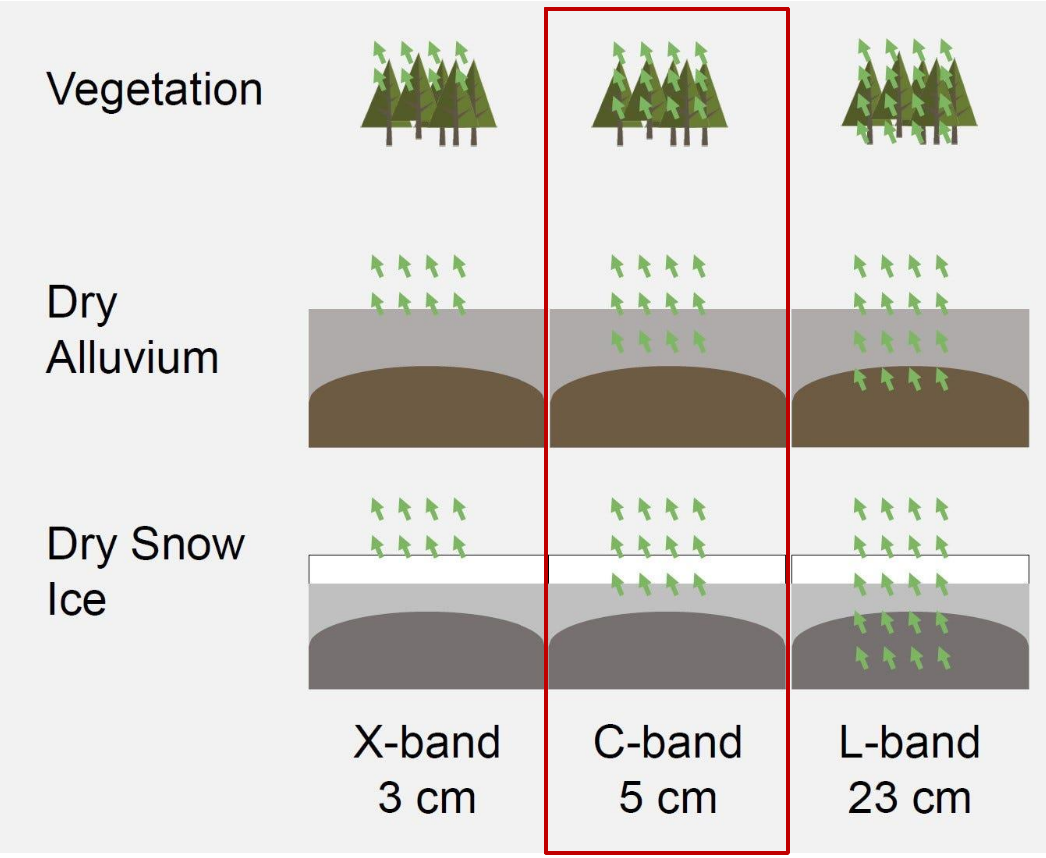
Flood Monitoring:

- X-band mostly scatters at the tops of trees
- C- and L-band signals penetrate increasingly

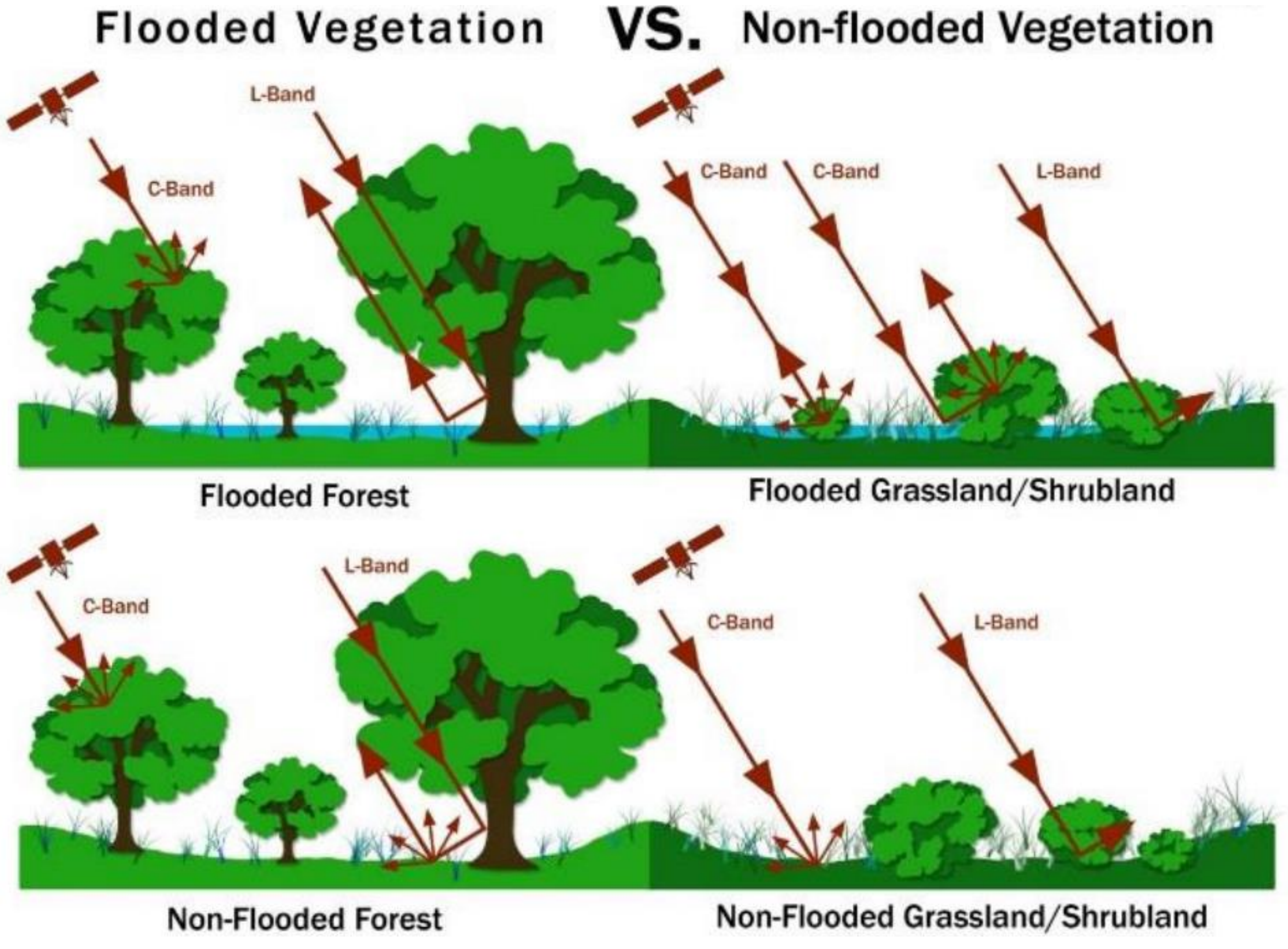
- Longer wavelength - better mapping of inundation under forest canopies



Source:https://medium.com/@preet.balaji20/decoding-synthetic-aperture-radar-sar-remote-sensing-sar-series-part-1-getting-started-d3409eb3b2e3

Radar Parameters to Consider for a Flood Mapping

Flooding under Vegetation Canopies



C-band:

~6cm, 4-8GHz

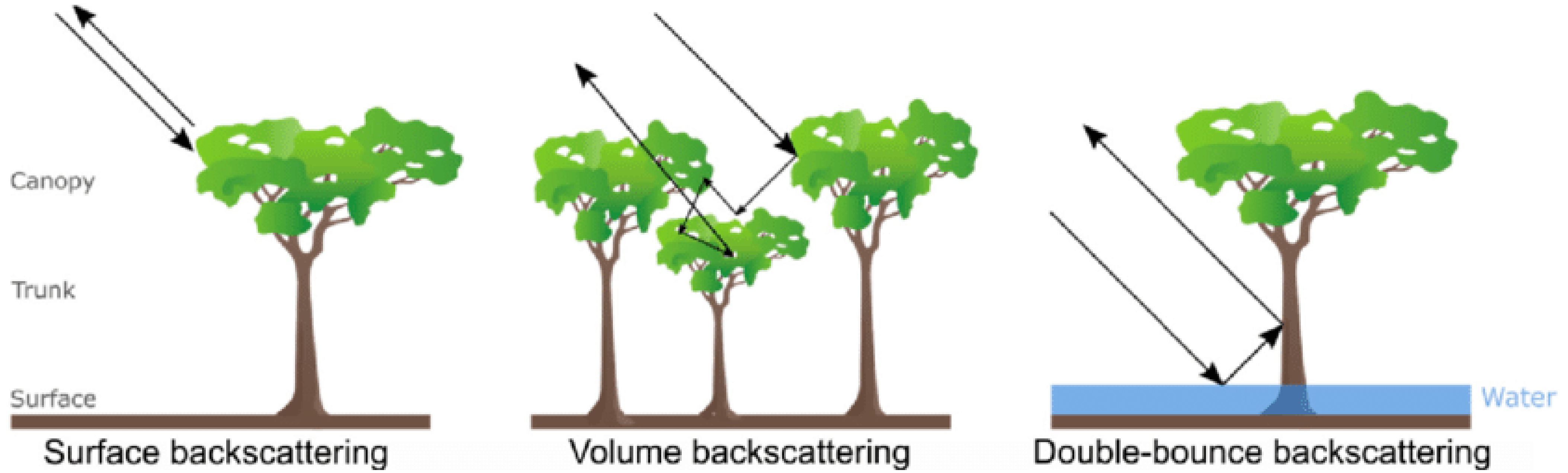
L-band:

~23cm, 1-2GHz

Enhanced return if tree cover underlain by water (double bounce effect – smooth water surface – vertical vegetation structures

Radar Parameters to Consider for a Flood Mapping

Flooding under Vegetation Canopies



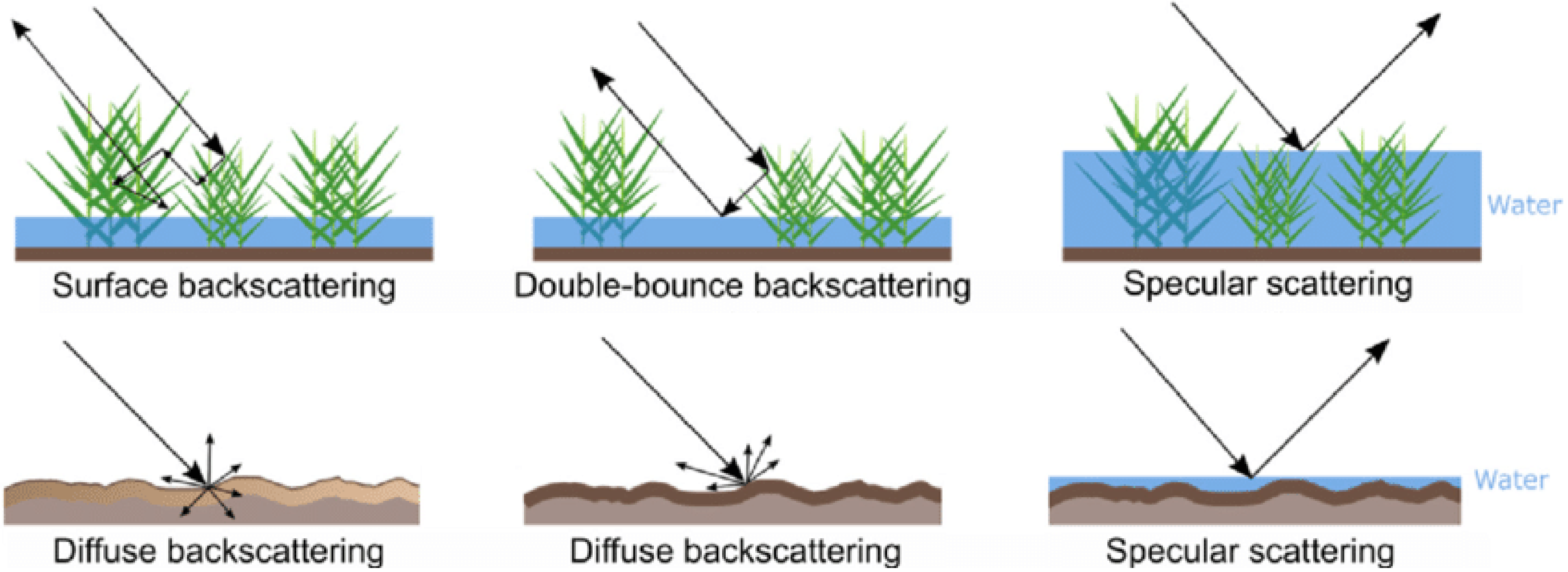
Nonflooded condition
- Signal scattering in the crown and on the ground

Flooded condition
- Submerged wetland/open water
- Strong double-bounce reflection between the tree trunks and the water surface

https://www.mdpi.com/2072-4292/12/14/2228

Radar Parameters to Consider for a Flood Mapping

Innundation in Crops and Meadows



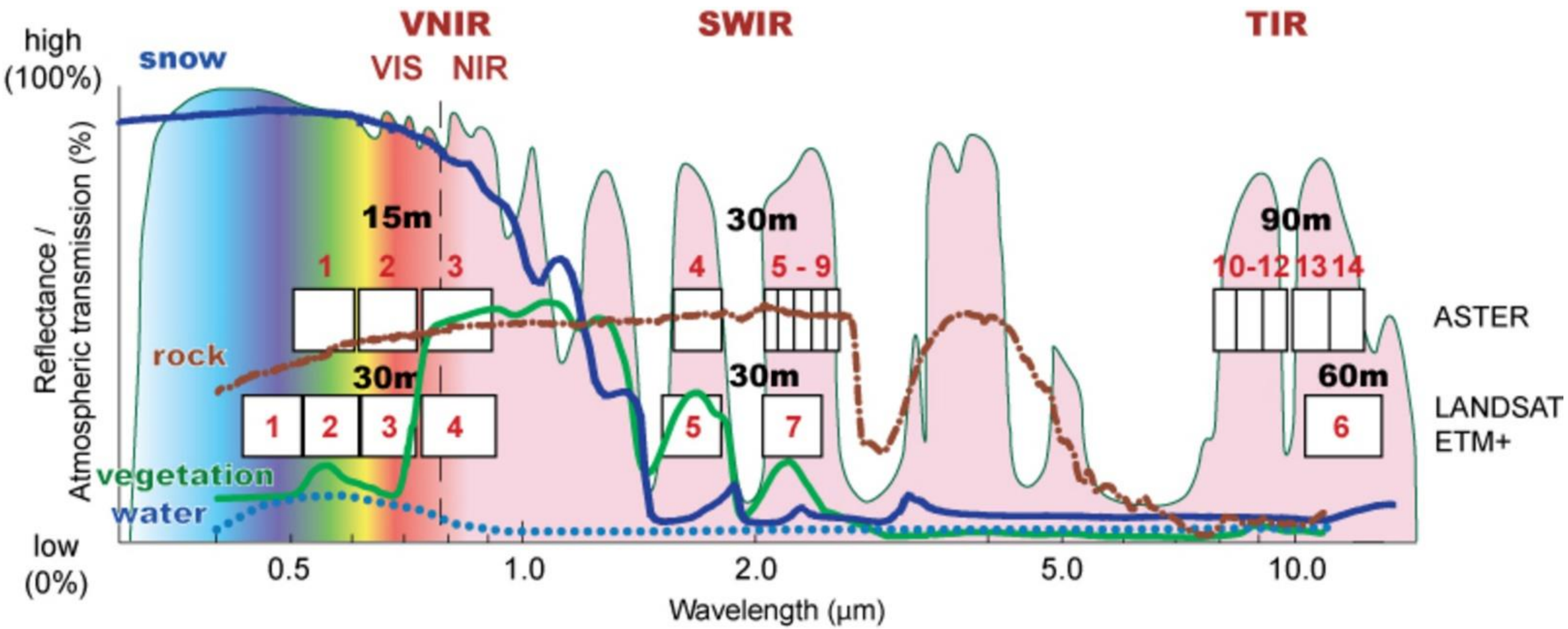
- Backscatter increases with soil moisture
- With increasing water level, backscatter becomes weaker with more specular reflection (scattering away from the sensor)

https://www.mdpi.com/2072-4292/12/14/2228

Optical Parameters to Consider for a Postfloods/Flood Mapping

Physical basis for Water bodies mapping

- Water absorbs the longer wavelengths of visible and NIR and SWIR domains
- Reflects the shorter wavelengths of the visible domain (blue, green)
- Water color depends on: depth, materials in suspension, vegetation



https://www.esa.int/ESA_Multimedia/Images/2011/11/Reflectance_curves_of_snow_vegetation_water_and_rock

Optical Parameters to Consider for a Postfloods/Flood Mapping

Inidices for floods/postfloods mapping

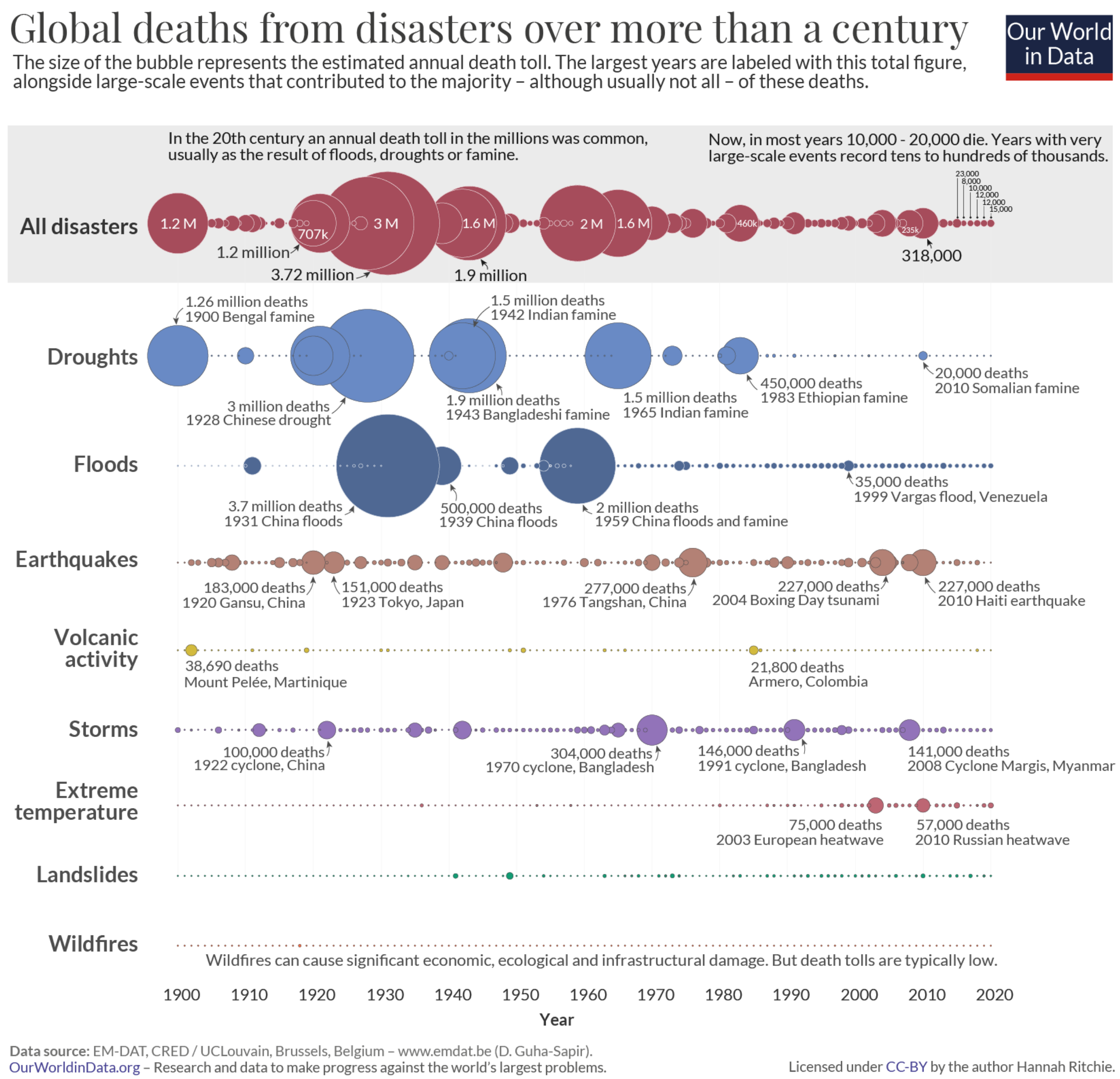
Index	Equation	Remark
Normalized Difference Water Index	NDWI = (Green − NIR)/(Green + NIR)	Water has positive value
Normalized Difference Moisture Index	NDMI = (NIR − MIR)/(NIR + MIR)	Water has positive value
Modified Normalized Difference Water Index	MNDWI = (Green − MIR)/(Green + MIR)	Water has positive value
Water Ratio Index	WRI = (Green + Red)/(NIR + MIR)	Value of water body is greater than 1
Normalized Difference Vegetation Index	NDVI = (NIR − Red)/(NIR + Red)	Water has negative value
Automated Water Extraction Index	AWEI = 4 × (Green-MIR) − (0.25 × NIR + 2.75 × SWIR)	Water has positive value

Earth Observation Applications for Post-Flood Recovery

- Satellite imagery and data products have played a crucial role in addressing the floods along, facilitating effective response efforts
- The varied spatial, temporal, and spectral resolution of Earth observation (EO) data enables numerous applications for flood recovery
- Key areas where EO can aid in flood recovery efforts:

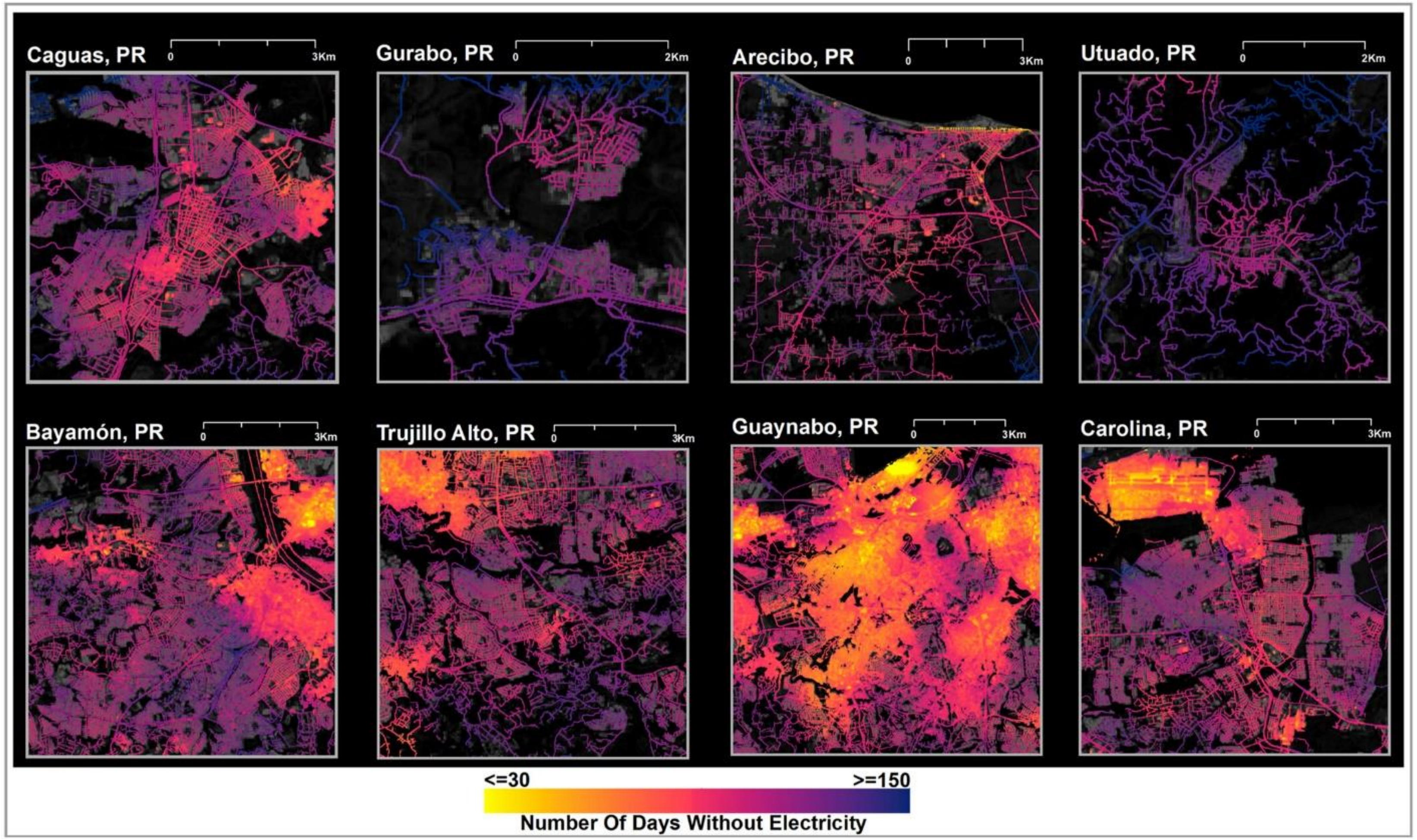
  - mapping flood extent
  - monitoring impacts
  - reducing flood risk
  - evaluating flood-related adaptation programs

Source:https://ourworldindata.org/natural-disasters#extreme-precipitation-and-flooding



Earth Observation Applications for Post-Flood Recovery

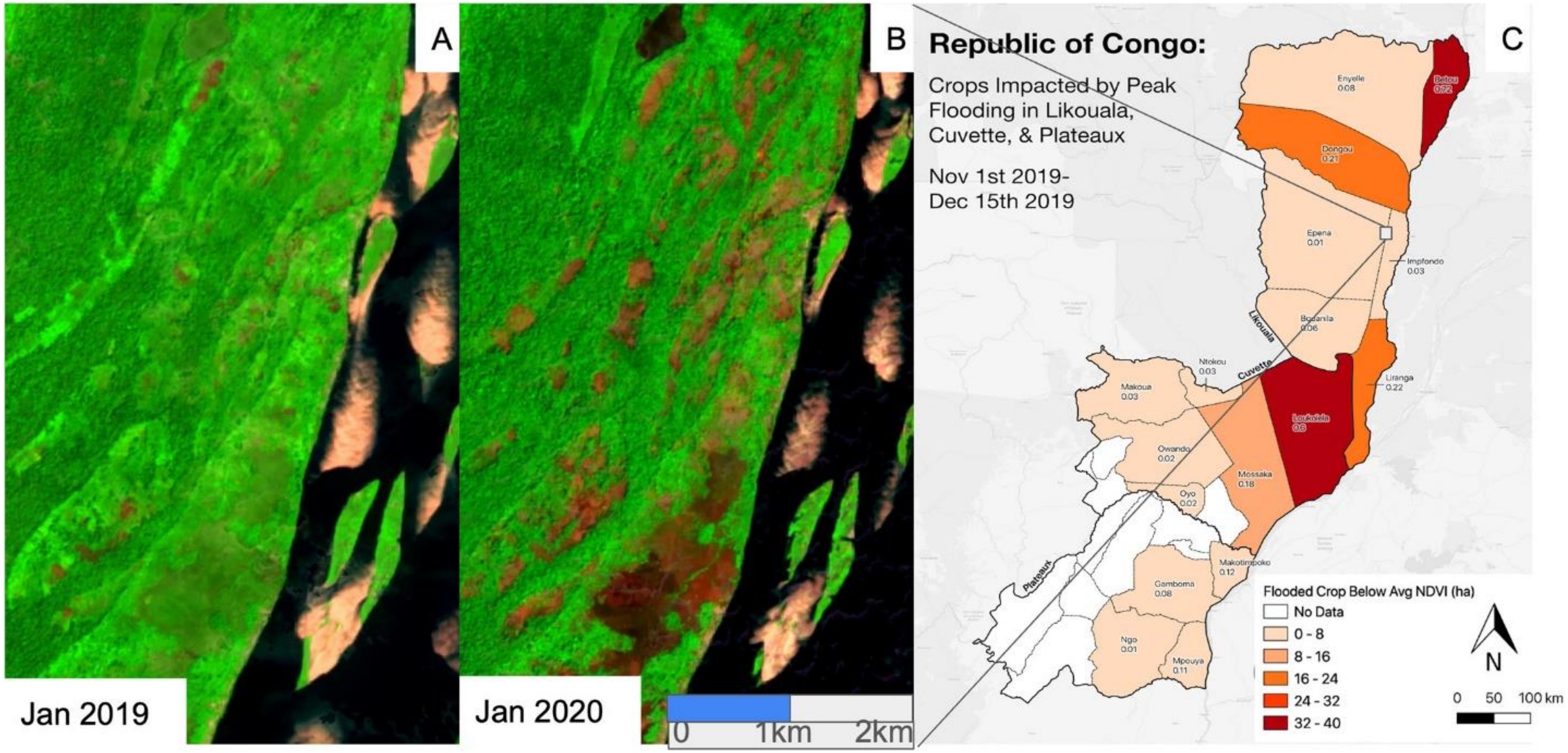
Monitoring impacts



- Variation in electricity outages for different locations in Puerto Rico following Hurricane Maria based on time series of NASA Black Marble nighttime light imagery. Image from Román et al. (2019).
- https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023EF003606

Earth Observation Applications for Post-Flood Recovery

Flood Risk Reduction



- An example of Earth Observation to provide flood recovery decision support. Series of Sentinel-2 imagery in a flood-affected area before the December 2019 flood in January 2019 (a) and after in January 2020 (b) in the Republic of Congo

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023EF003606

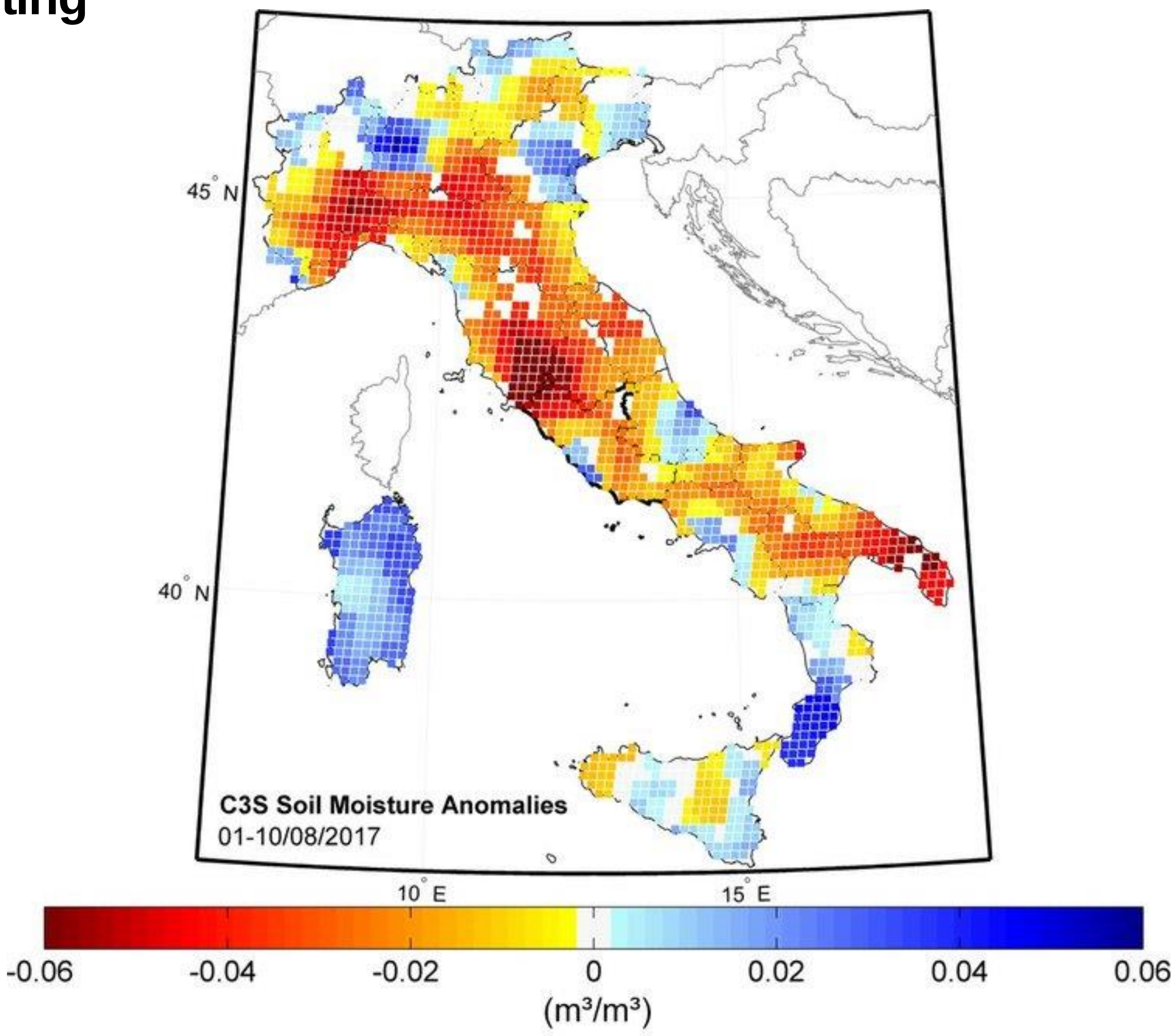
Improving flood forecasting with Earth observation data

Hydrological models to improve flood forecasting

- River discharge is a variable that is not typically easy to measure from satellites. However, new models using a combination of optical data from MODIS, to estimate river velocity, and radar altimetry measurements, to assess river levels rising – the same way scientists monitor sea levels rising

- Developing new models and leveraging cutting-edge sensor technology is crucial, especially with the deployment of new satellite constellations

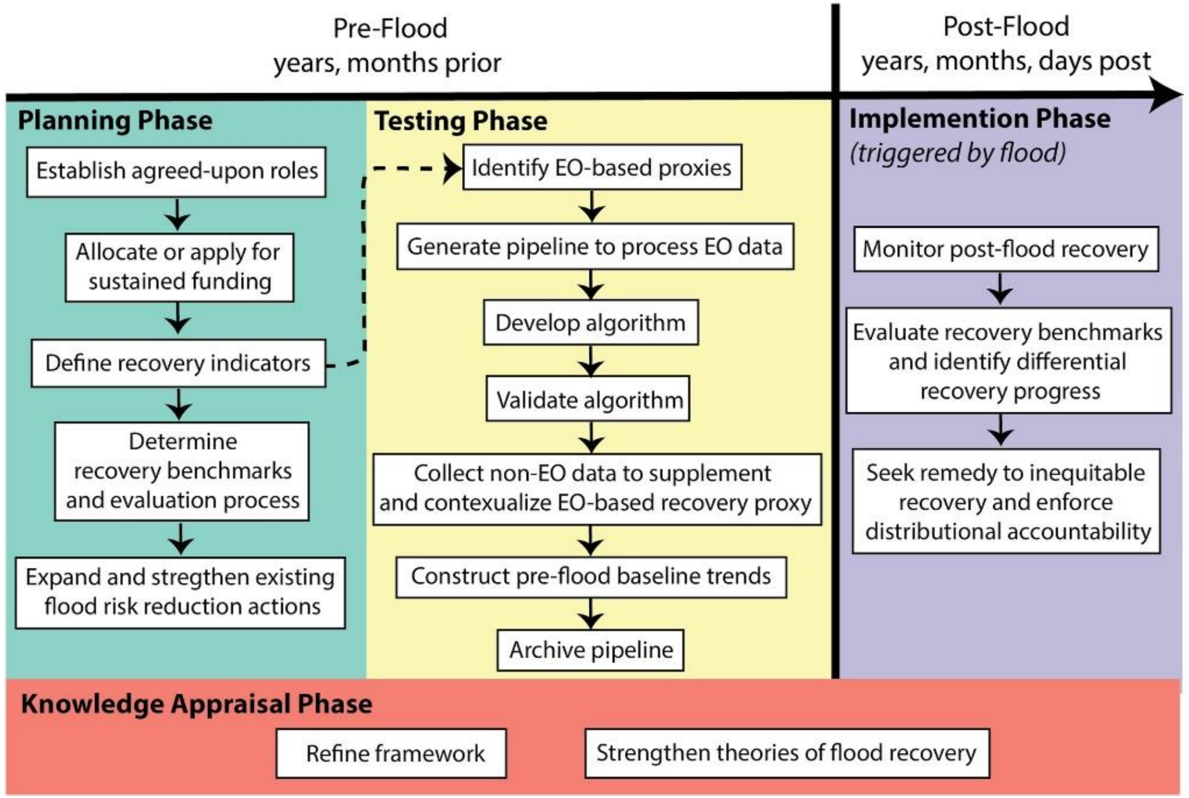
https://skywatch.com/improving-flood-forecasting-with-earth-observation-data/



Improving flood forecasting with Earth observation data

A Framework to Guide EO Monitoring of Flood Recovery

- Framework to guide Earth Observation monitoring flood recovery and redress inequitable post-flood recovery outcomes

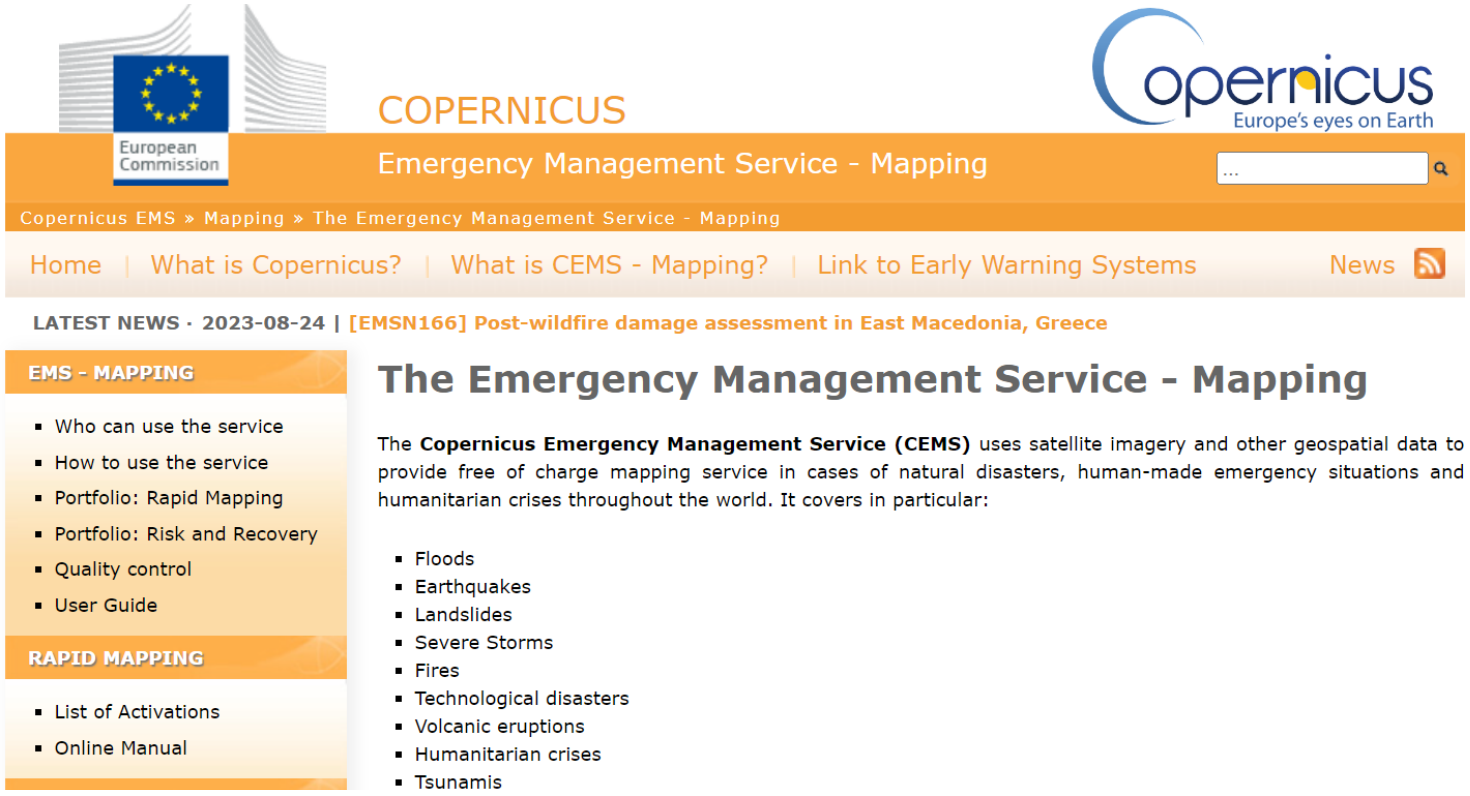


https://skywatch.com/improving-flood-forecasting-with-earth-observation-data/

Improving flood forecasting with Earth observation data

Operational Entities Monitoring Post-Flood Recovery

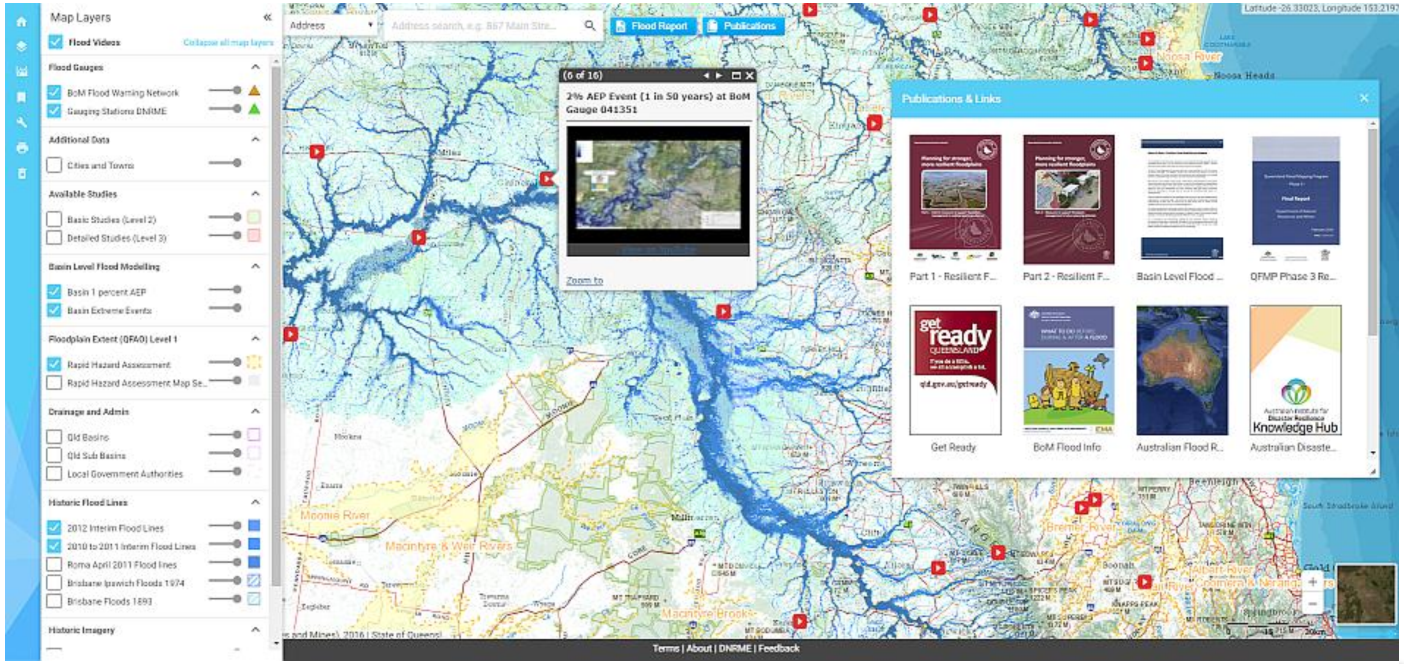
- EO can bolster effective disaster risk management, as demonstrated by established protocols that integrate EO into disaster response and recovery
- Notably, initiatives like the Committee on Earth Observations Satellites (CEOS) Recovery Observatory and Copernicus Emergency Management Service (CEMS) Risk and Recovery Mapping offer recovery mapping services.



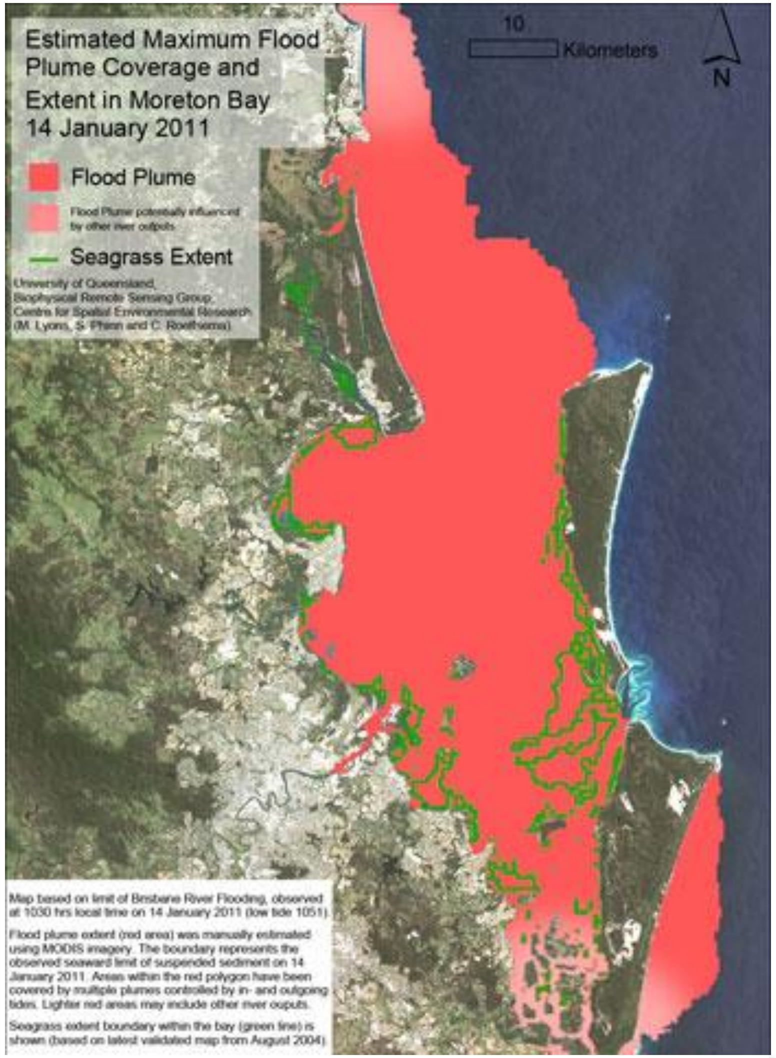
https://emergency.copernicus.eu/

Improving flood forecasting with Earth observation data

Improve understanding of disaster risks and costs to society



FloodCheck is an online tool developed by Geoscience Australia, providing access to flood mapping and related information for Australia. It offers interactive maps and datasets to help users understand flood risks, monitor flood events, and support decision-making related to flood preparedness and response. FloodCheck integrates various data sources, including satellite imagery, rainfall data, and topographic information, to provide comprehensive flood information to the public, emergency responders, and policymakers.



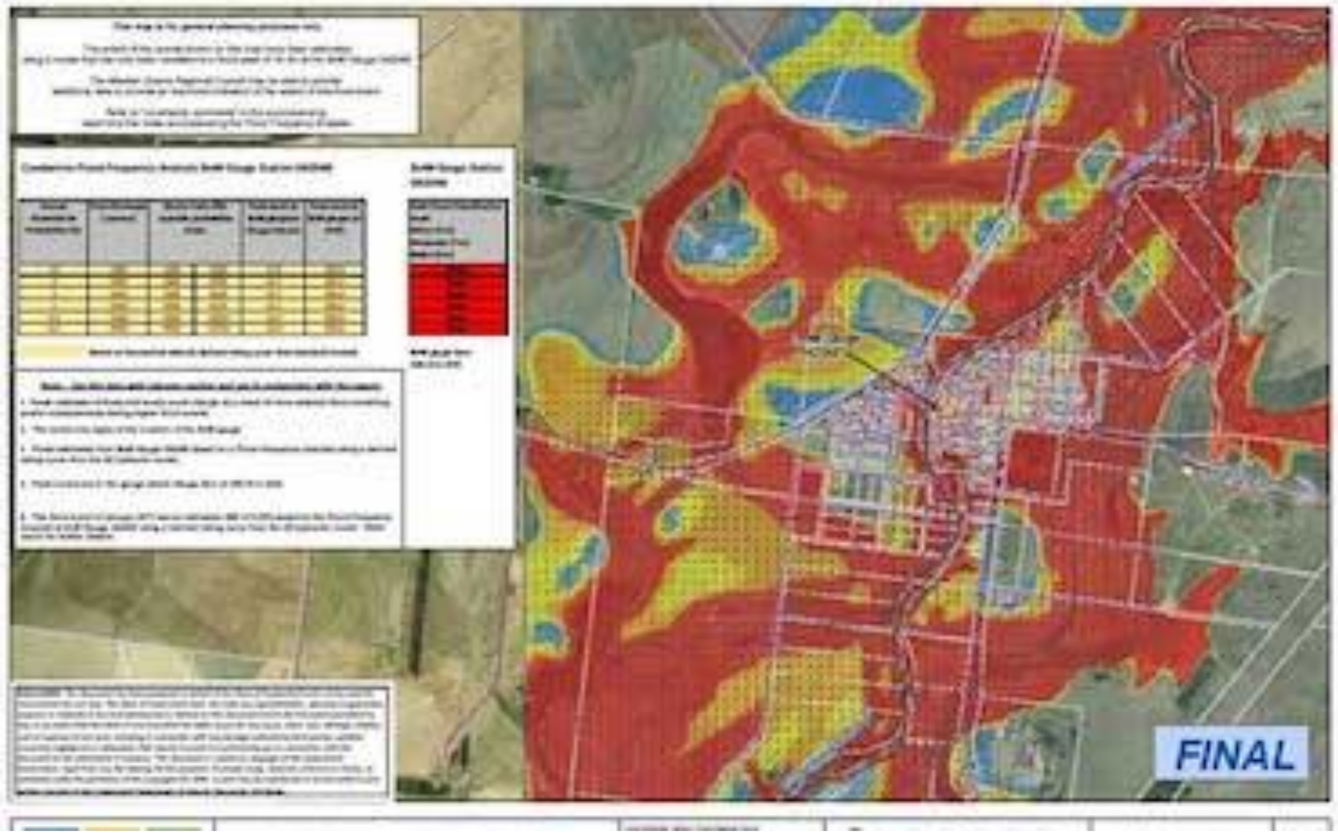
A visualisation of the flood plume in Moreton Bay. Courtesy Mitchell Lyons

https://floodcheck.information.qld.gov.au/, https://www.uq.edu.au/news/article/2011/01/uq-experts-map-moreton-bay

Improving flood forecasting with Earth observation data

Improve understanding of disaster risks and costs to society

- Access to reliable and openly accessible data regarding disaster risks, expenses, impacts, and public investments in recovery and resilience is crucial for enhancing awareness and planning
- While there have been notable advancements in data quality for certain hazards, such as state-wide flood mapping, limitations persist in terms of data availability, consistency, and usability across various natural disaster risks



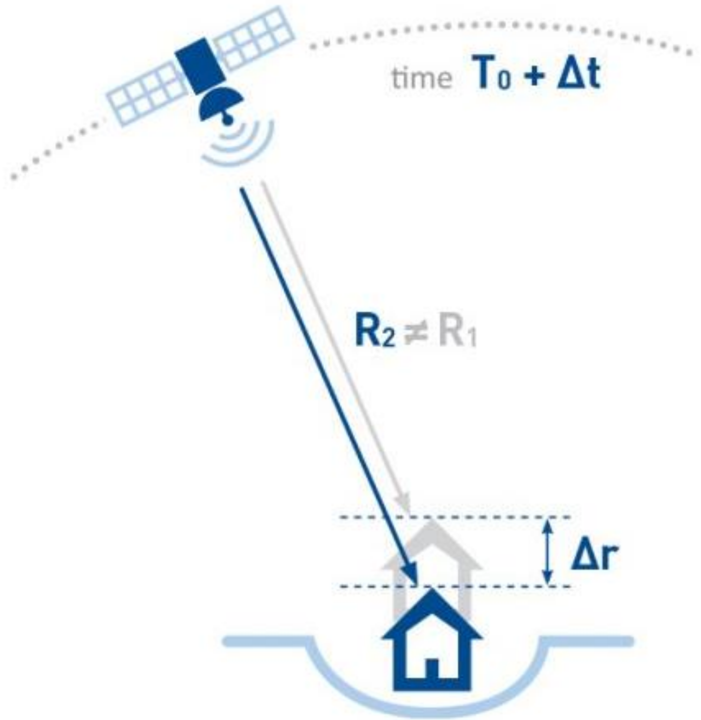
https://www.watertech.com.au/projects/flood-risk-mapping-queensland/

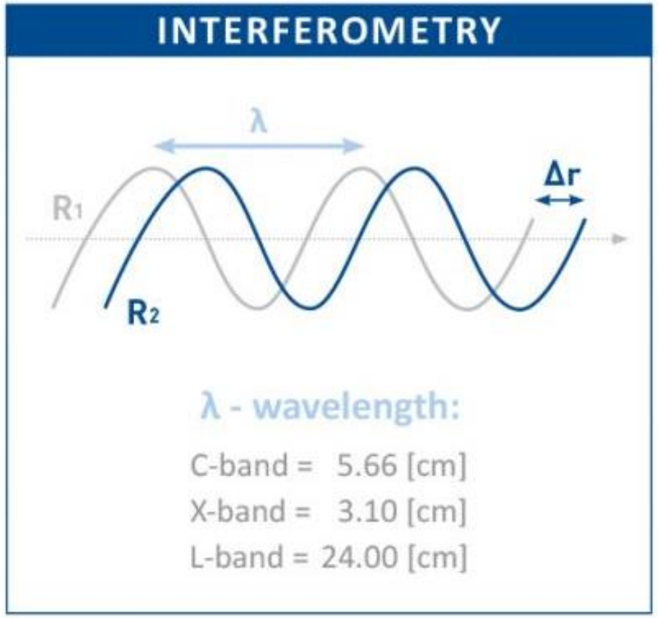
For more information, see the tutorials:
[10. Flood Monitoring with Sentinel-1 & Sentinel-2 using the SNAP software]
[11. Flood Monitoring with Sentine l-1, Sentinel-2 data using the SNAP software]

12. SAR for land subsidence

SAR Interferometry (InSAR) – use of phase for change detection

Interferometric Synthetic Aperture Radar (InSAR) also known as SAR Interferometry, is the measurement of signal phase change between two images acquired over the same area at different time. When a point on the ground moves, it alters the distance between the sensor and the point, resulting in a change in the signal phase.





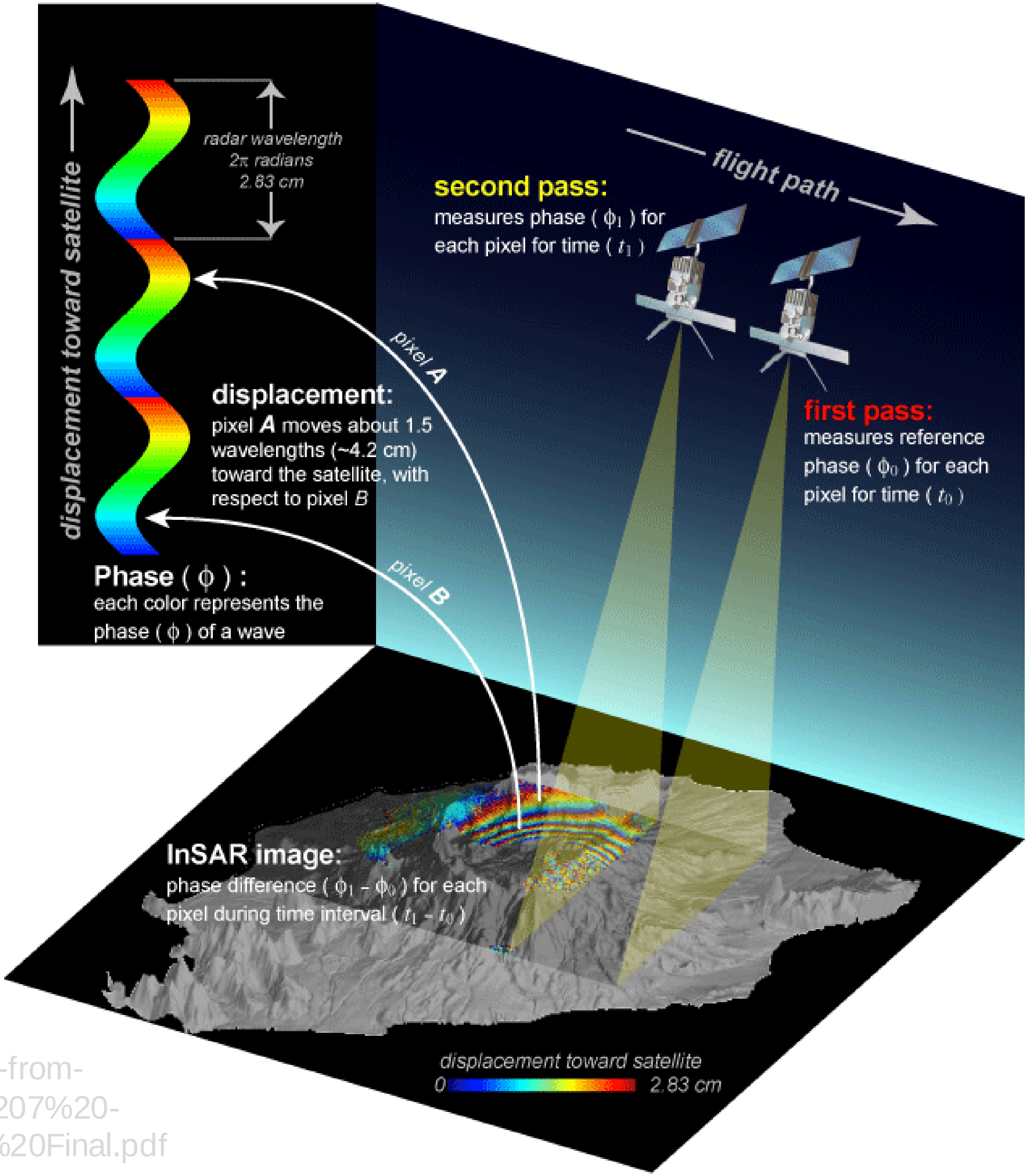
The radar signal's phase represents the number of oscillation cycles the wave completes during its journey from the radar to the surface and back.

Interferometry is the only solution for resolving this issue!

https://site.tre-altamira.com/company/our-technology/

Differential Interferometry

- Differential Interferometry or DInSAR is a intererometric technique in which topographic effects are compensated by using a Digital Elevation Model (DEM)
- Small surface deformations in the Earth's surface, such as subsidence, uplift, or deformation, can be detected with high precision, sometimes down to the millimeter level
- Particularly useful for monitoring ground movements caused by natural phenomena like earthquakes, landslides, or human activities such as mining or groundwater extraction.



https://britgeopeople.blogspot.com/2017/01/assessing-ground-motion-from-spaceby.html, https://dges.carleton.ca/courses/IntroSAR/SECTION%207%20-%20Carleton%20SAR%20Training%20-%20InSAR%20Theory%20-%20Final.pdf

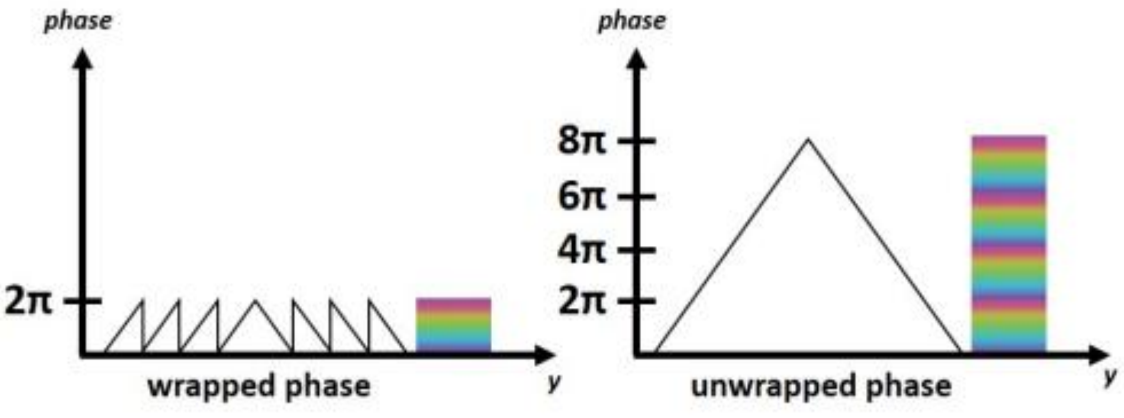
Phase unwrapping

- In order to correlate the interferometric phase with topographic height, the phase must undergo an unwrapping process
- Then, the proper 2p phase “ambiguity” must be determined
- The altitude of ambiguity refers to the altitude difference that causes a change in the interferometric phase
- Phase unwrapping resolves this ambiguity by integrating the phase difference between adjacent pixels

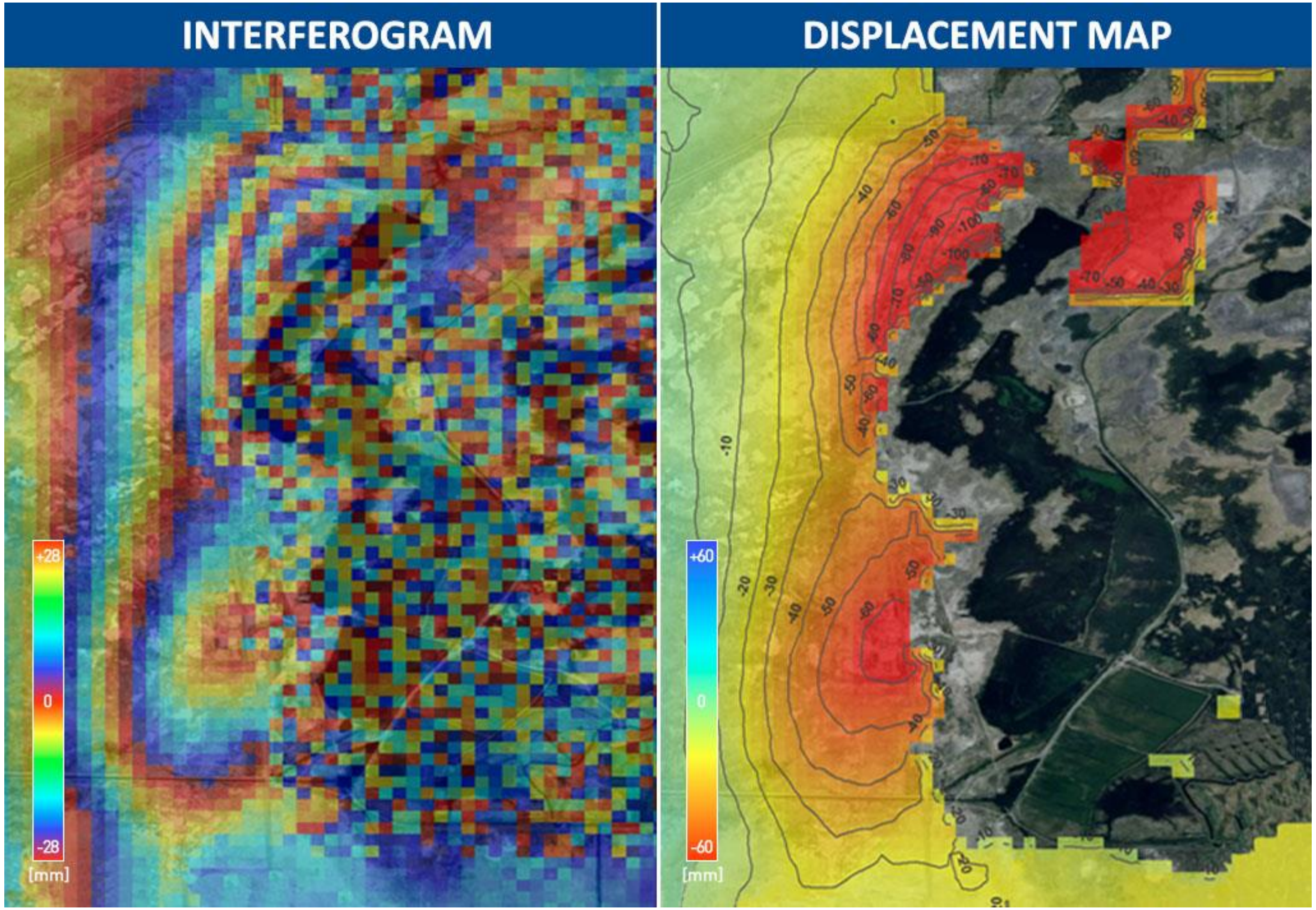
$$\Delta\phi_{topo} = \frac{2\pi p}{\lambda}(\rho_1 - \rho_2) = \frac{2\pi p}{\lambda}\vec{b} \bullet \vec{l}$$

$$\Delta\phi_{meas} = \mathrm{mod}\left(\Delta\phi_{topo}, 2\pi\right)$$

$$\Delta\phi_{unwrap}(s,\rho) = \Delta\phi_{topo}(s,\rho) + \Delta\phi_{const}$$



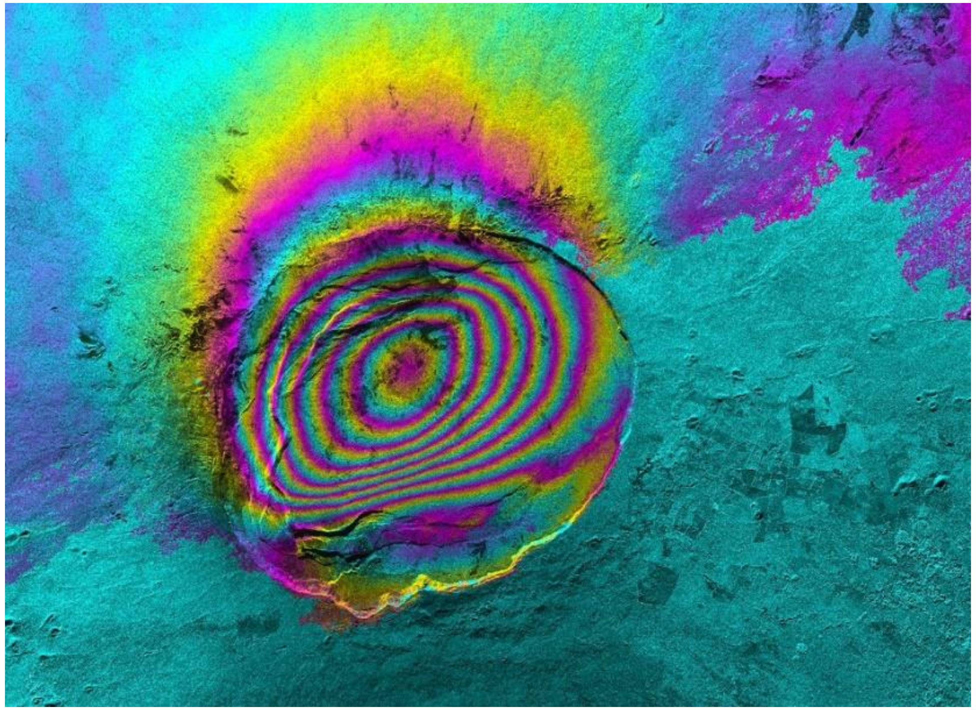
Phase unwrapping



https://site.tre-altamira.com/insar/

- Consequently, unwrapped results should be interpreted as relative height or displacement between pixels in two images.

Interferogram



One cycle of color represents one cycle of relative phase.

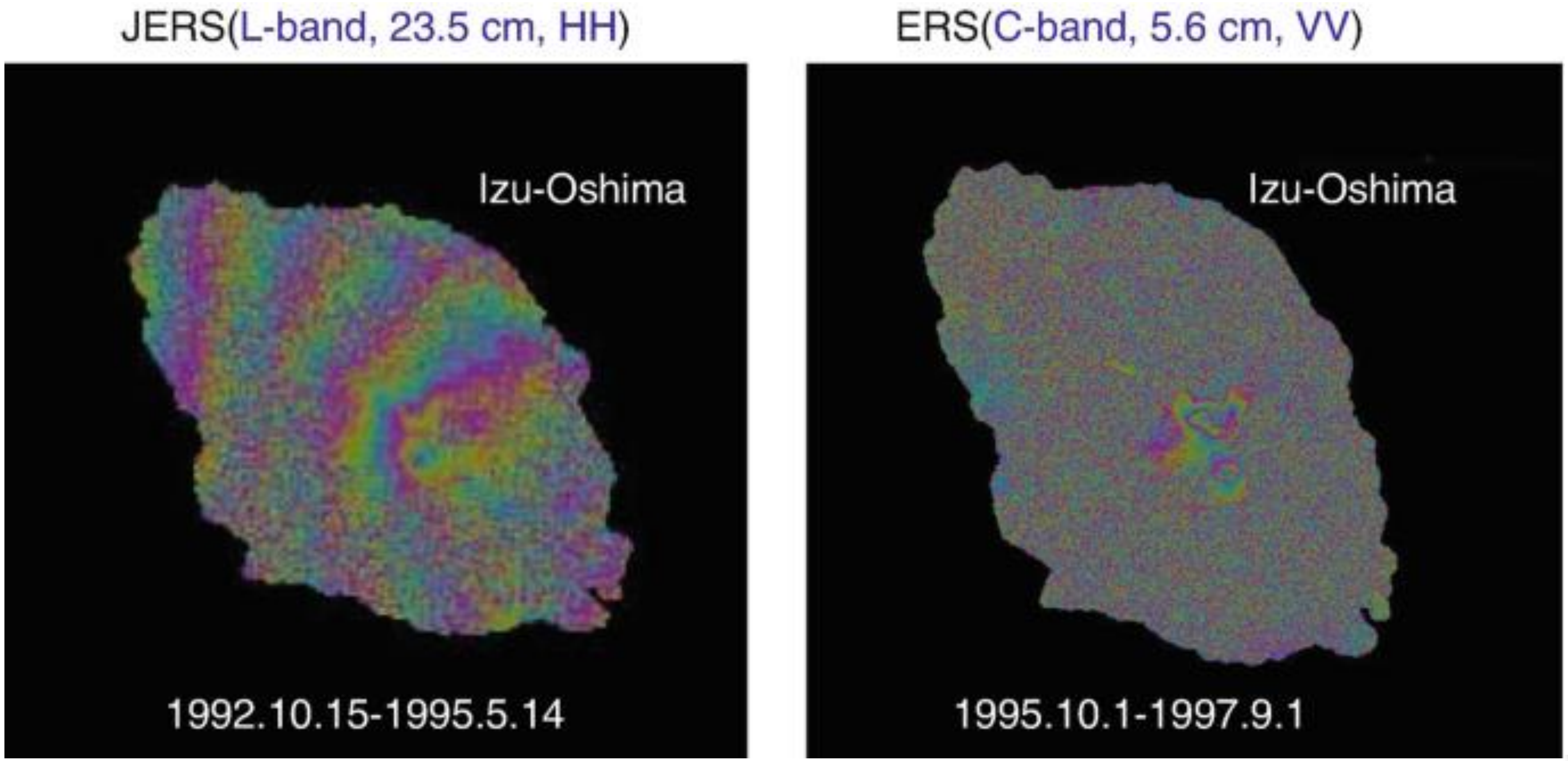
https://nisar.jpl.nasa.gov/mission/get-to-know-sar/interferometry/

- The SAR interferogram is created by multiplying each pixel of the first SAR image with the complex conjugate of the corresponding pixel in the second image
- Consequently, the amplitude of the interferogram is determined by the product of the amplitudes of the two images, while its phase, represents the difference in phase between the two images. This phase difference is caused by variations in path length due to differences in elevation, motion, or deformation.
- The resulting interference pattern, referred to as FRINGE, is represented within the range of [-π , π].

Coherent Change Detection

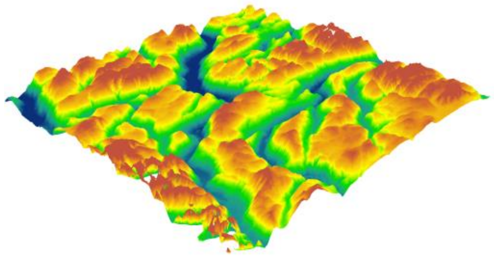
SIR-C L and C-band Interferometry

- Simultaneous C and L band
- InSAR experiments have shown good correlation at L-band

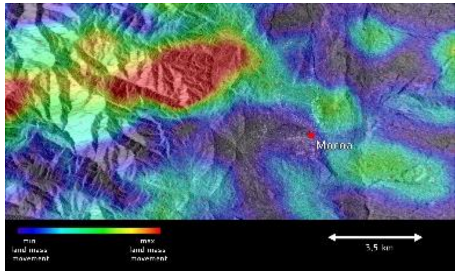


https://media.springernature.com/lw685/springer-static/image/prt%3A978-3-030-58631-7%2F17/MediaObjects/978-3-030-58631-7_17_Part_Fig7-97_HTML.png

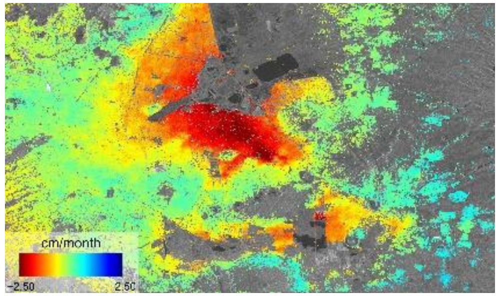
Applications of InSAR



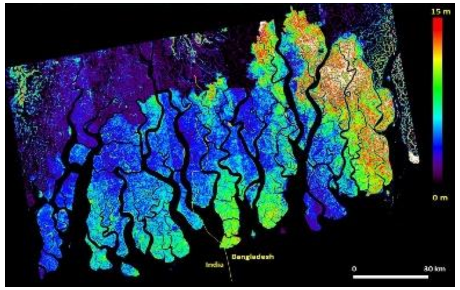
DEM generation



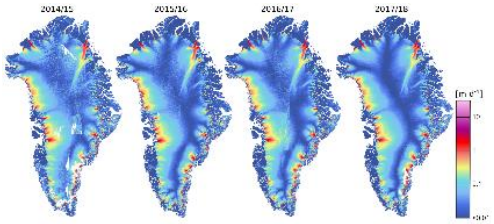
Land surface



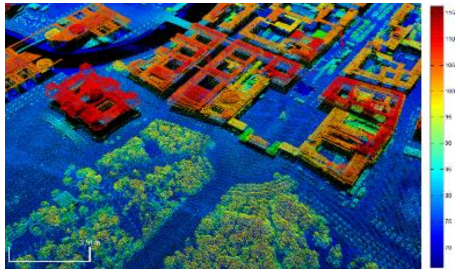
Crustal deformation



Forest monitoring



Cryosphere

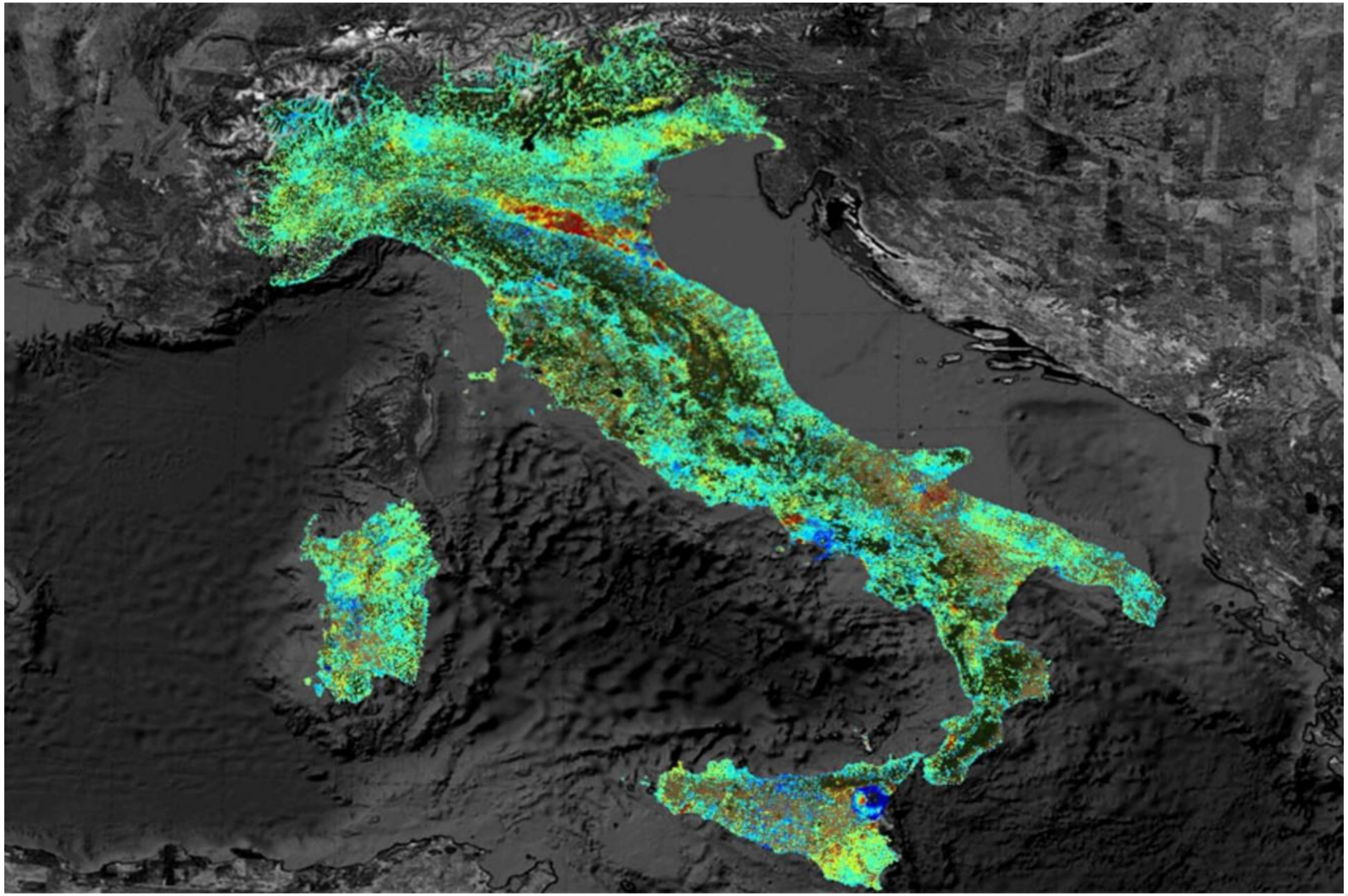


SAR Tomography

https://gisgeography.com/free-global-dem-data-sources/, https://www.esa.int/ESA_Multimedia/Images/2014/12/Mexico_City_subsidence, https://www.esa.int/ESA_Multimedia/Images/2019/07 /Ice_velocity_maps _of_Greenland, https://www.esa.int/ESA_Multimedia/Images/2017/04/Sentinel-1_sees_Mocoa_landslide, https://www.esa.int/Applications/Observing_the_Earth/Mapping_forest_structure_from_space

Applications of InSAR

Subsidence of Italy

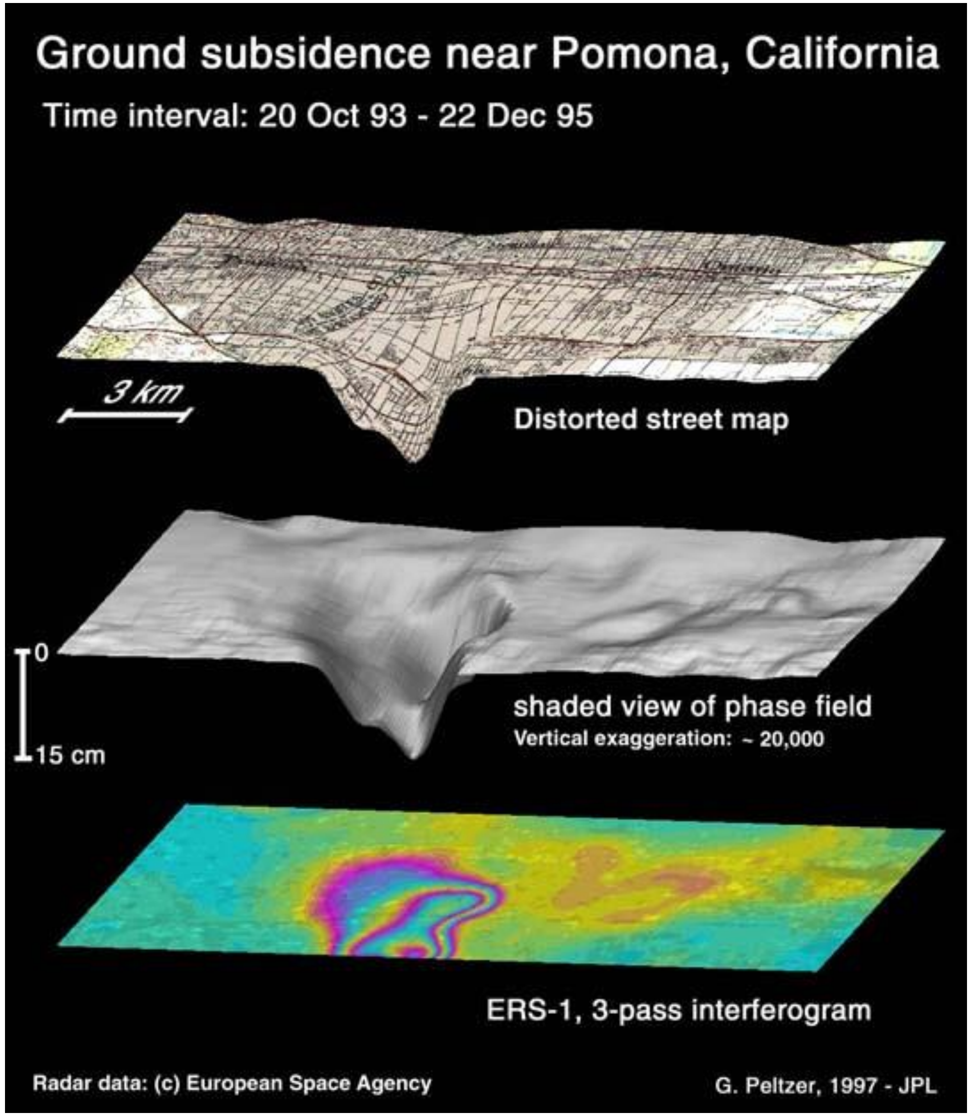


With advances in the methods of interferometry, subsidence of entire countries can now be mapped. This image shows the average displacement rates over millions of permanent scatterers identified over Italy using data from ESA's ERS missions (1992–2001). The project was financed by the Italian Ministry of the Environment and carried out by e-GEOS, TRE and Compulab.

CREDIT: Tele-Rilevamento Europa (TRE)

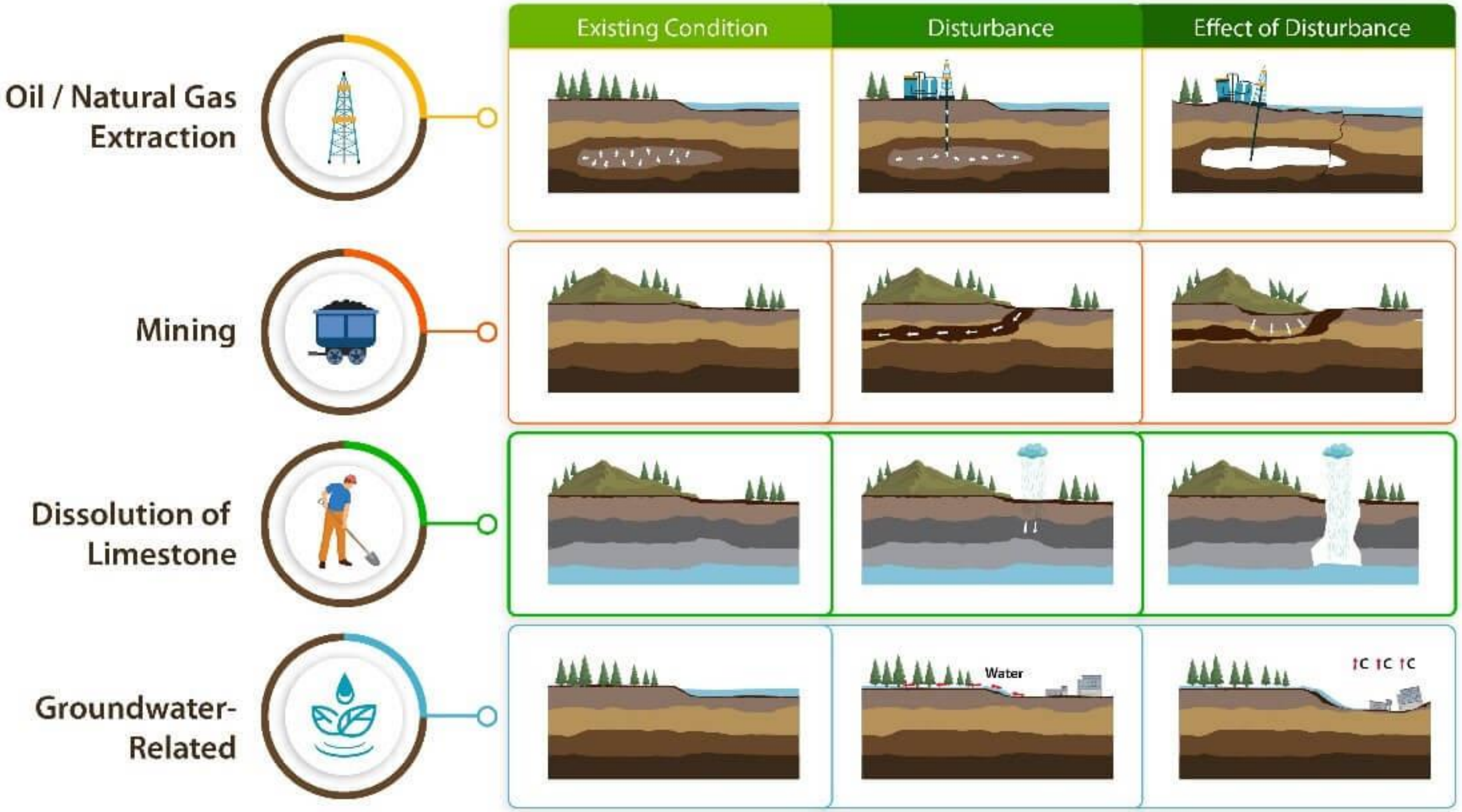
Crustal deformation

- Gradual changes in the Earth's crust over time, typically caused by:
  - natural processes - tectonic plate movements, earthquakes, volcanic activity
  - human-induced activities: mining or groundwater extraction
- Displacements of the Earth's surface: including uplift, subsidence, faulting, folding, or other
- Key indicator to understand the dynamic processes occurring beneath the Earth's surface and to assess the potential for seismic hazards



Crustal deformation

Landslip and land subsidence

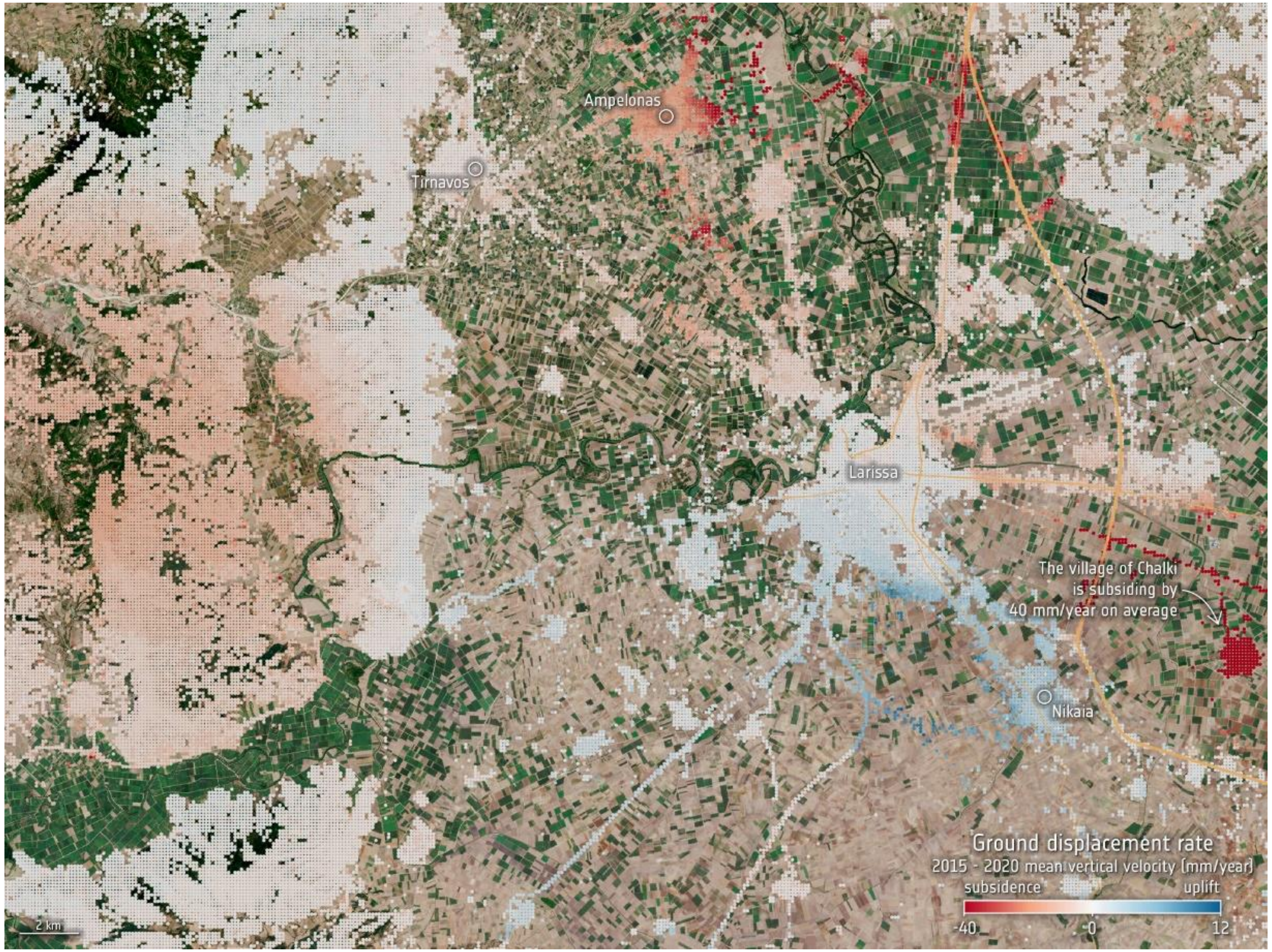


Downward movement of soil or sinking of the land from its previous level

https://spacegen.guru/landslip-and-land-subsidence/

SAR for Land Subsidence - Applications

Monitoring of groundwater extraction



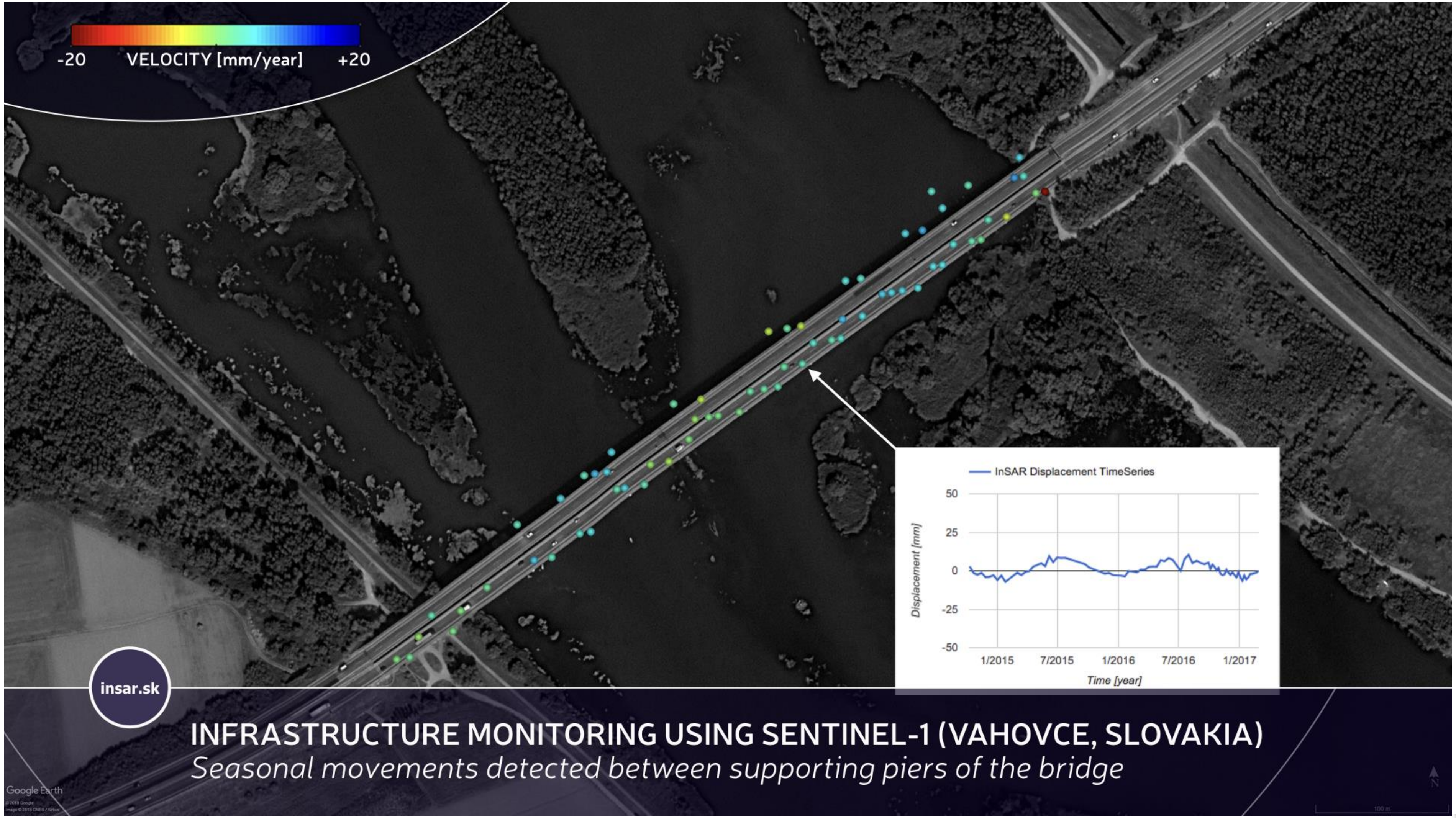
Larissa's ups and downs

For example, this image shows the rate of ground displacement between 2015 and 2020 in and around Larissa, the capital of the Thessaly region in Greece. While the southern outskirts of Larissa experience some uplift, the village of Chalki to the southeast subsided by an average of 40 mm a year, largely as a result of groundwater extraction. Ampelonas to the northwest also experienced subsidence.

CREDIT: contains modified Copernicus Sentinel data (2015–2020), processed by EGMS/ESA

SAR for Land Subsidence - Applications

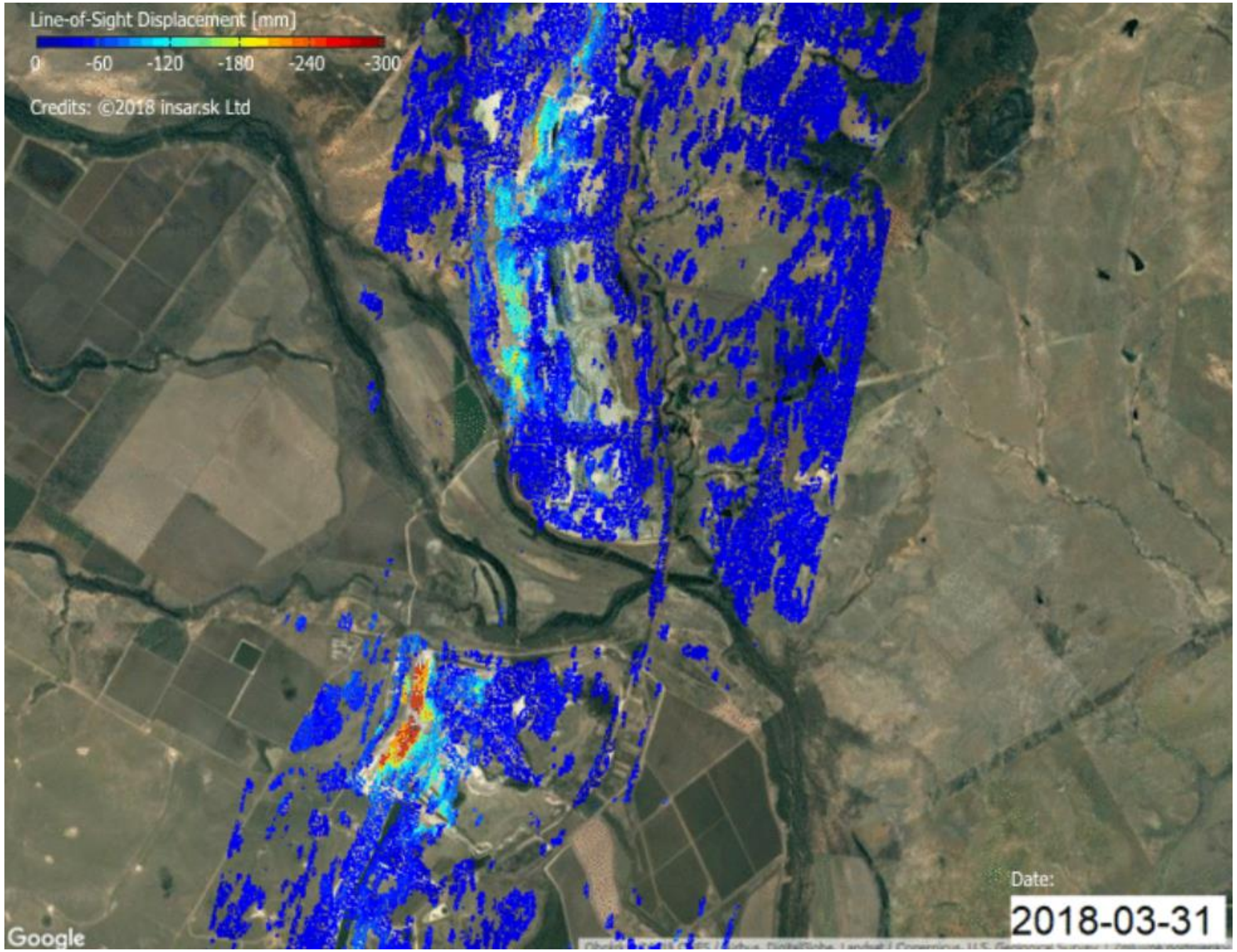
Infrastructure monitoring



https://insar.space/projects/

SAR for Land Subsidence - Applications

Monitoring of coal mining activity



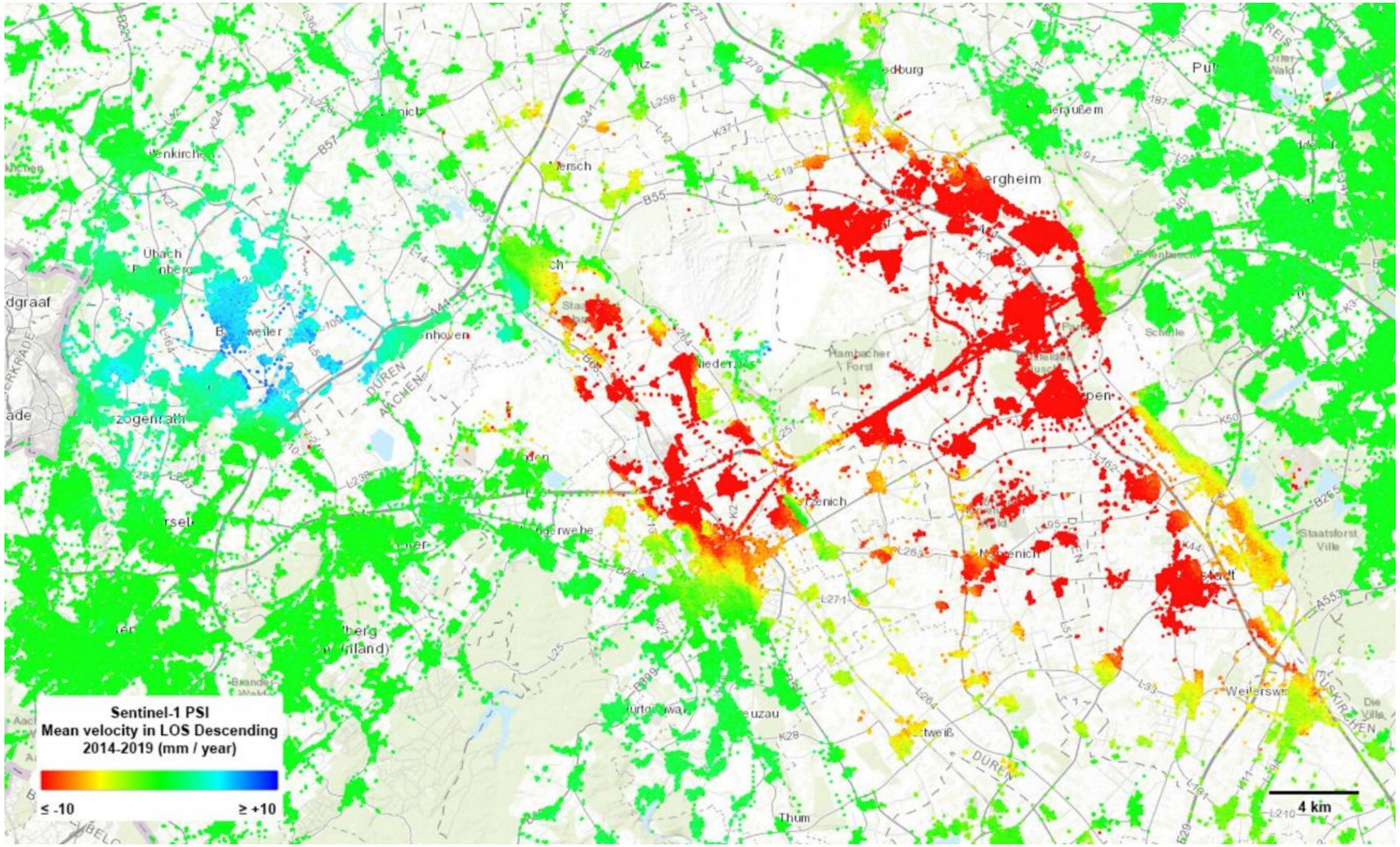
Downward movement of soil or sinking of the land from its previous level

https://spacegen.guru/landslip-and-land-subsidence/

https://insar.space/projects/

SAR for Land Subsidence - Applications

Monitoring of coal mining activity

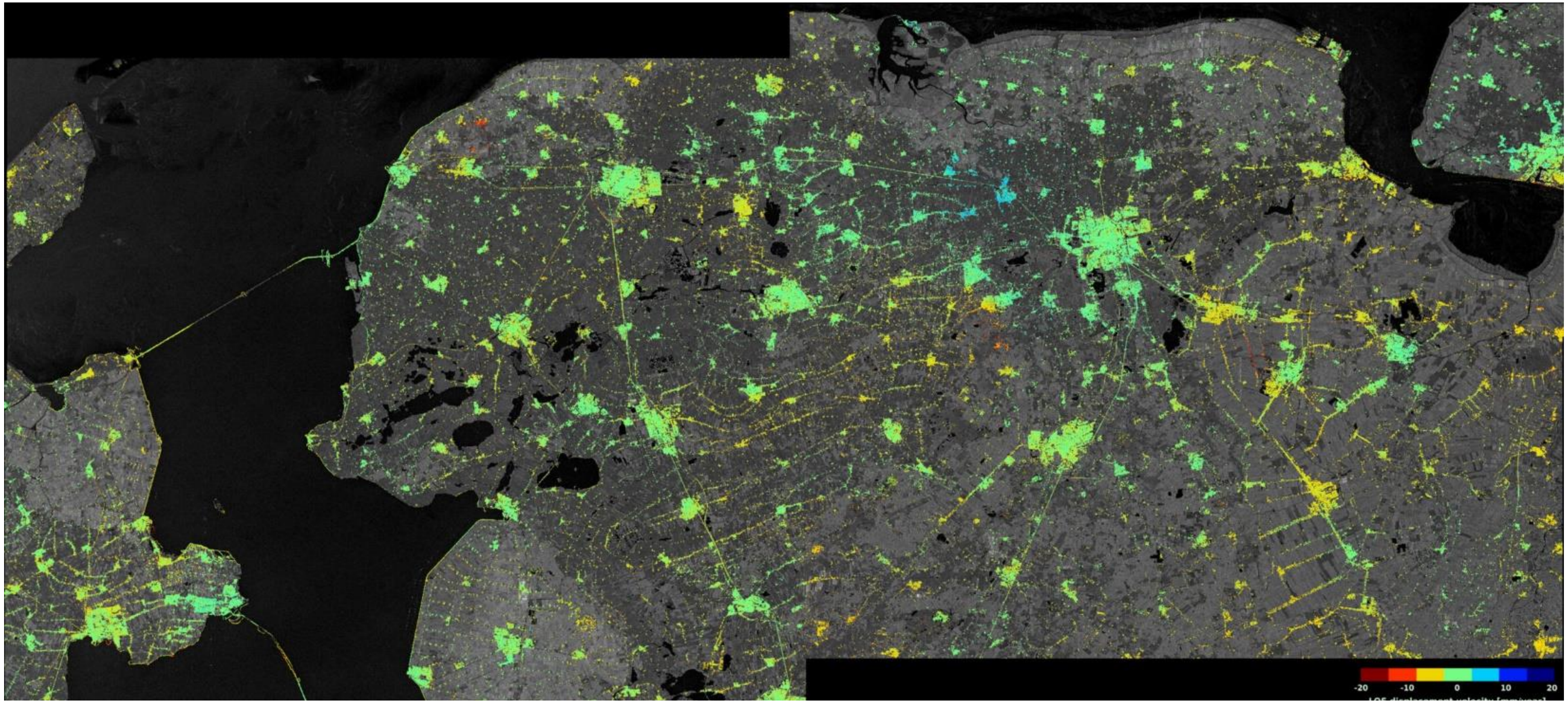


Based on ‘Persistent Scatterer Interferometry’ radar data from the Copernicus Sentinel-1 mission, the map shows how the land surface shifted in millimetres a year between 2014 and 2019 in the Ruhr in Germany. The subsidence shown in red is because of open pit lignite mining accompanied by groundwater lowering. Blue patches in the adjacent area are likely to be related to the rise of groundwater after mining activities ceased.

CREDIT: contains modified Copernicus Sentinel data (2014–19), processed by BGR (2020)

SAR for Land Subsidence - Applications

Monitoring the sinking

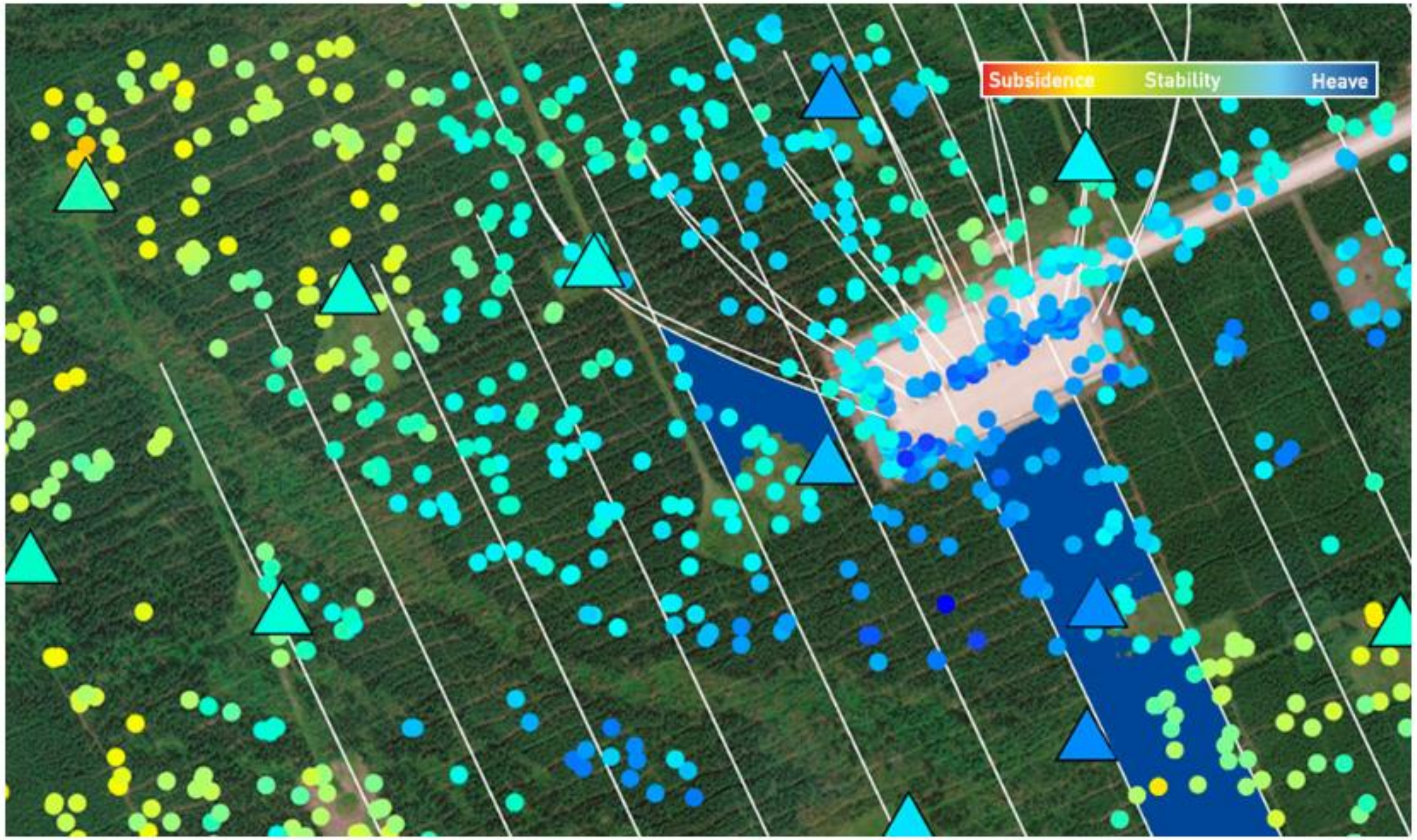


Using images that Sentinel-1A acquired between November 2014 and April 2016, this map shows subsidence (red) and uplift (blue) in the northeast of the Netherlands.

https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Mapping_that_sinking_feeling

SAR for Land Subsidence - Applications

Monitoring of ground displacements over the drainage pots

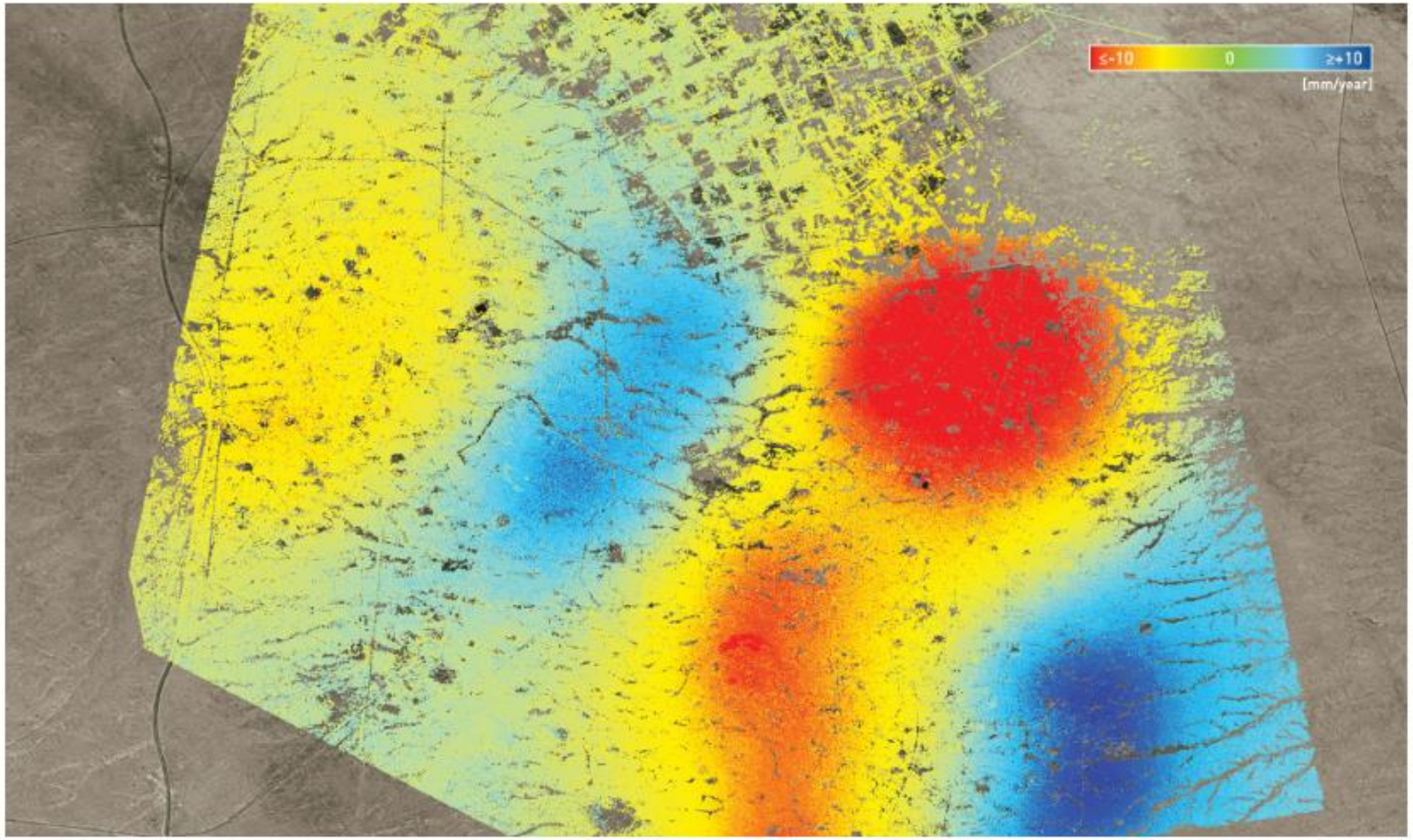


SAGD field in Alberta. SqueeSAR® analysis provided measurements of ground displacement over the drainage pads.

https://site.tre-altamira.com/oil-gas-operations/

SAR for Land Subsidence - Applications

Monitoring displacements over active oil operations

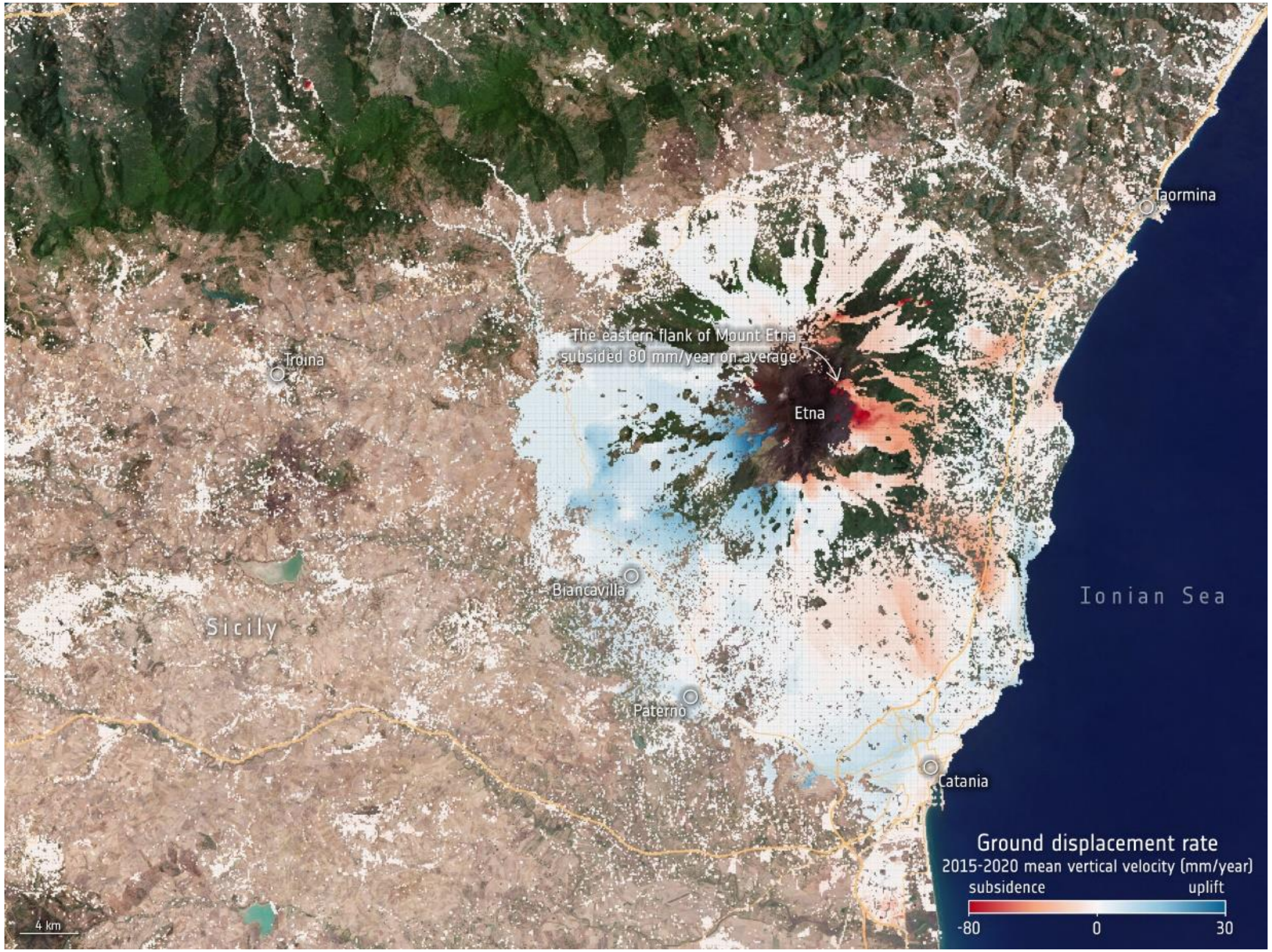


Displacement over active oil operations. Red and blue indicate areas of rapid subsidence and heave detected by SAR satellites. © DLR e.V. 2009-2013 and © Airbus Defense and Space GmbH

https://site.tre-altamira.com/oil-gas-operations/

SAR for Land Subsidence - Applications

Volcano uplift and subsidence



Etna's uplift and subsidence

This image shows the rate of ground displacement between 2015 and 2020 around Mount Etna and surroundings on the Italian island of Sicily. While the volcano's western flank experienced some uplift, its eastern flank subsided, on average, 80 mm a year.

CREDIT: contains modified Copernicus Sentinel data (2015–2020), processed by EGMS/ESA

For more information, see the tutorials:

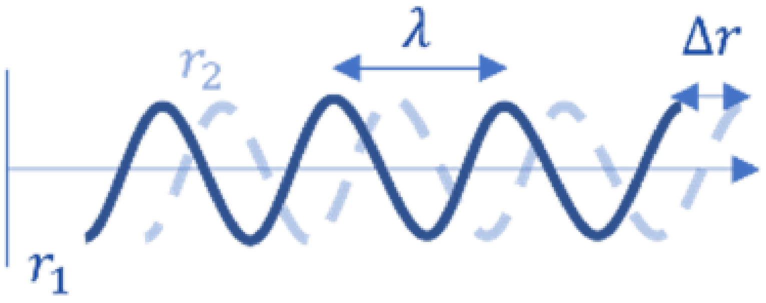
12. Land subsidence mapping using SAR interferometry (InSAR) using the SNAP software

13. SAR for earthquake monitoring

SAR Interferometry (InSAR) – use of phase difference

It is all about the phase of the SAR signal...

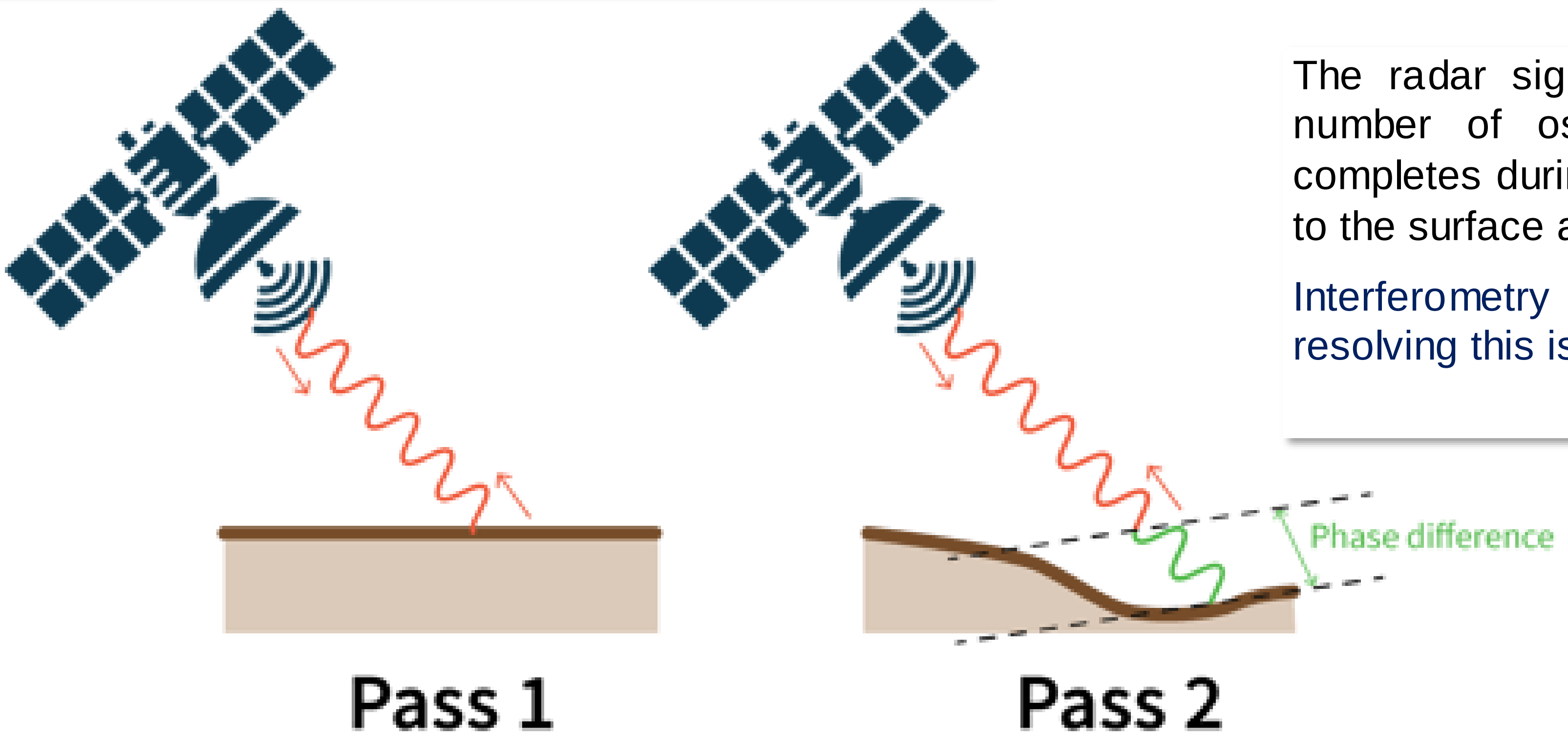
SAR Interferometry (InSAR) makes use of the phase difference between two complex valued images from different view angle, i.e. forming baseline, so that topography of the area can be imaged.



Change in phase allows detection of ground movement

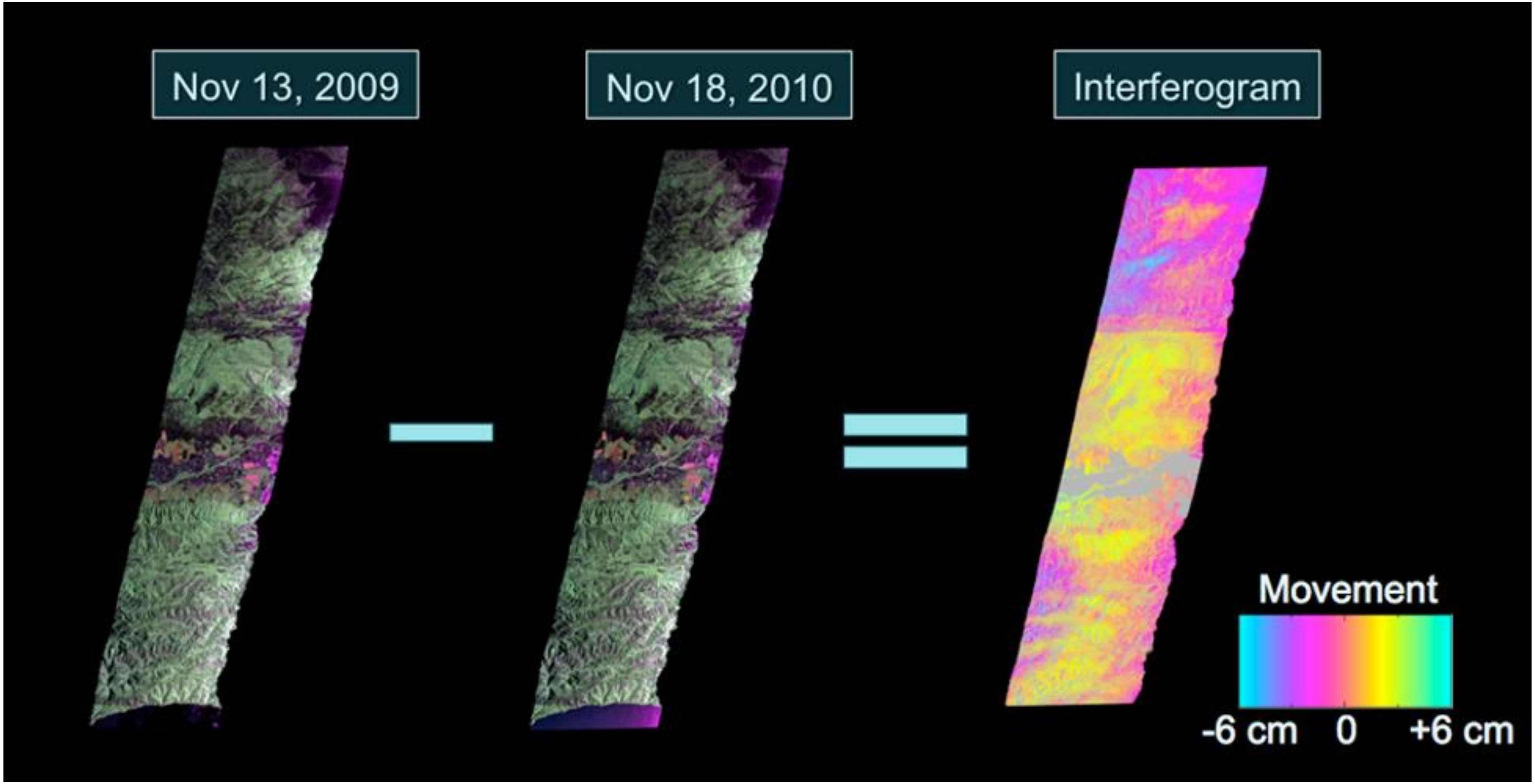
The radar signal's phase represents the number of oscillation cycles the wave completes during its journey from the radar to the surface and back.

Interferometry is the only solution for resolving this issue!



https://blog.descarteslabs.com/hs-fs/hubfs/GDS%20Blog%20series/InSAR-phase.png?width=500&name=InSAR-phase.png

SAR Interferometry (InSAR) – use of phase difference



https://nisar.jpl.nasa.gov/mission/get-to-know-sar/interferometry/

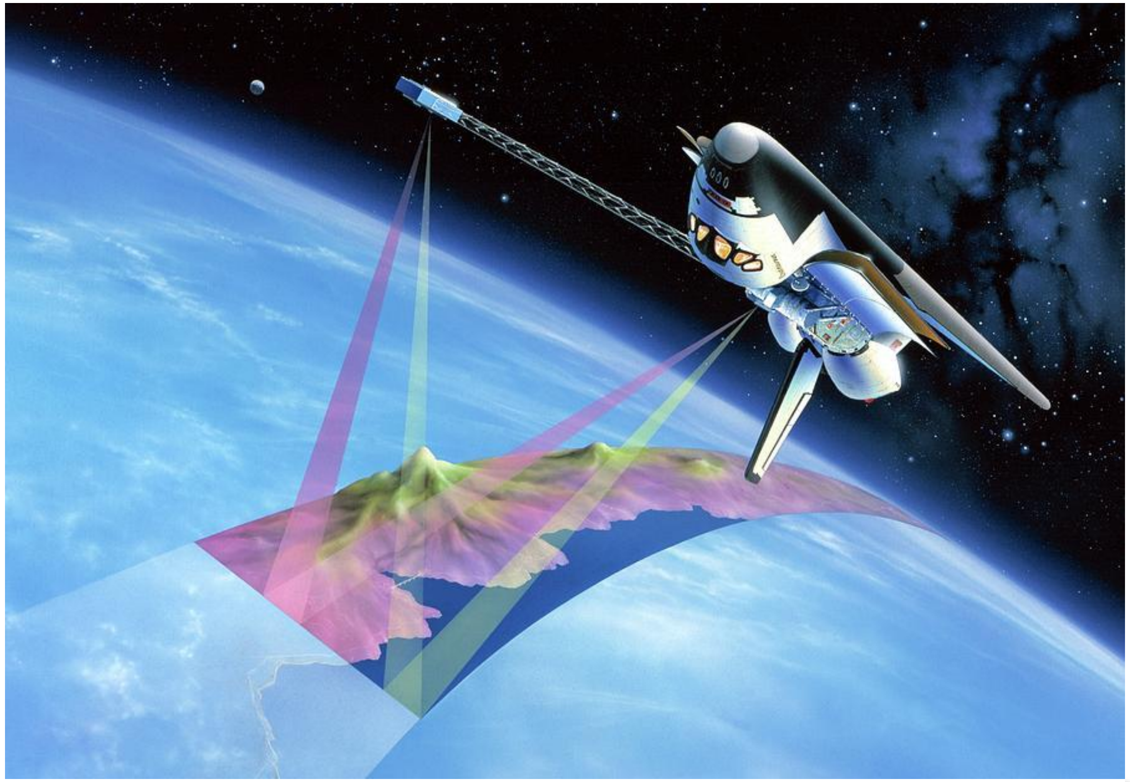
SAR Interferometry (InSAR) – applications

Topographic mapping/Cartography

- SAR interferometry played a crucial role in the 2000 Shuttle Radar Topography Mission (SRTM)

  → Updated in the 2018 release known as NASADEM

- Radar interferometry from airborne platforms is commonly employed to generate topographic maps in the form of digital elevation models (DEMs)



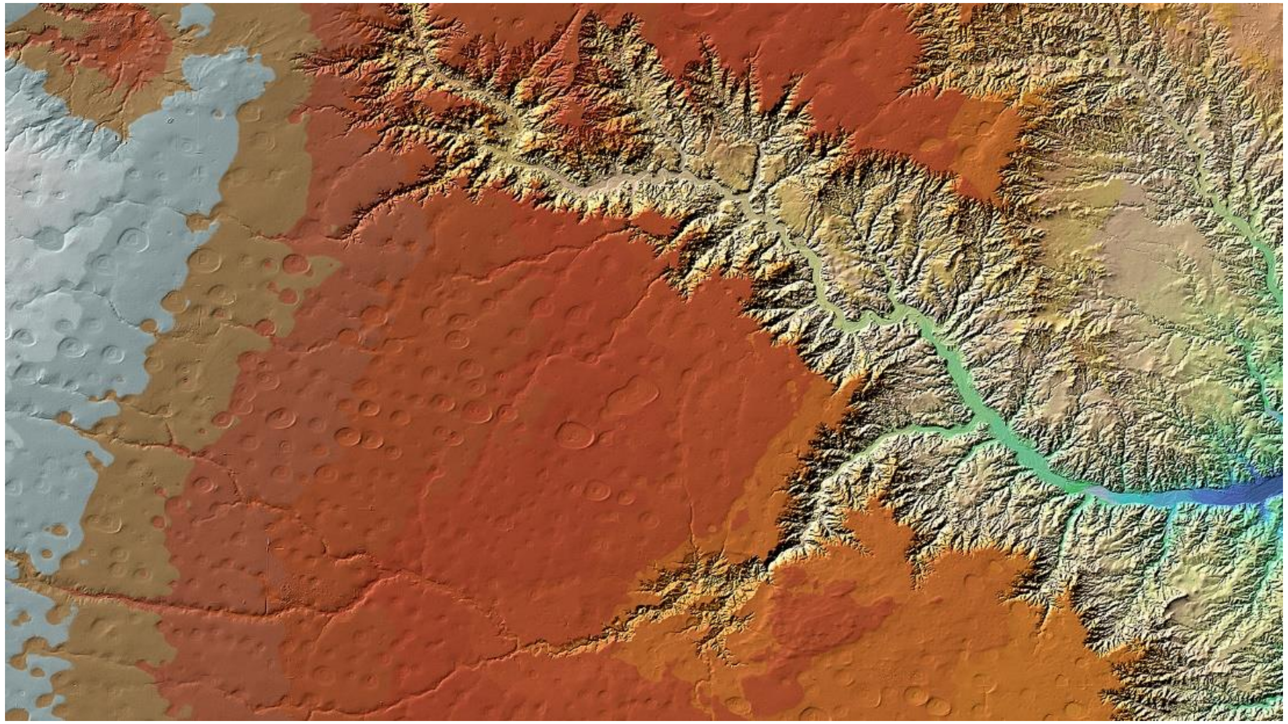
https://sciencephotogallery.com/featured/shuttle-radar-topography-mission-detlev-van-ravenswaay.html

SAR Interferometry (InSAR) – applications

Topographic mapping/Cartography

- Technology facilitates various applications enabled by topography, particularly in rapid mapping scenarios, such as:

  - land use management
  - classification
  - hazard assessment
  - urban planning
  - geology
  - hydrology



Source: https://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-11930/20984_read-23316/

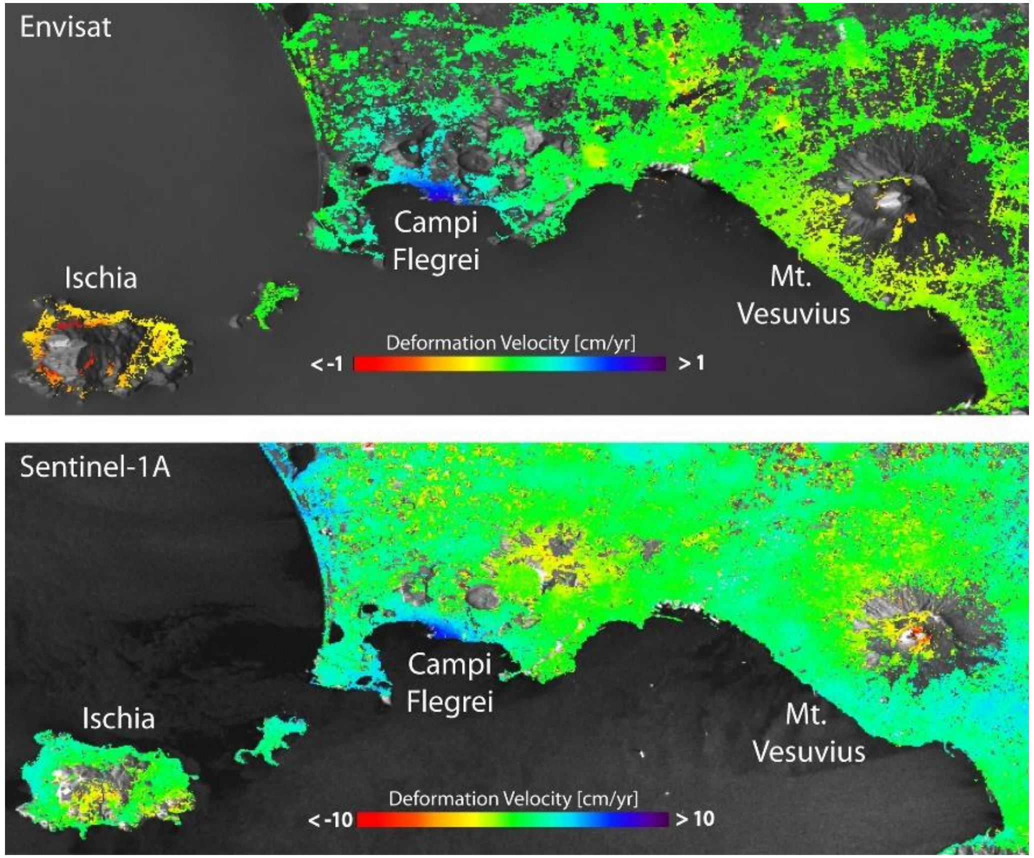
SAR Interferometry (InSAR) – applications

Deformation Mapping and Change Detection

- Repeat Pass Radar Interferometry is commonly employed to generate topographic change maps - digital displacement models (DDMs).
- Relative displacement accuracy: 0.1-1 cm
- Post spacing and resolution ranging: 10-100 m
- DDMs widths: 10-350 km

Common applications:

- Monitoring and modeling of earthquakes, volcanoes, landslides, land subsidence
- Detecting deforestation, change detection, disaster monitoring, glacier dynamics

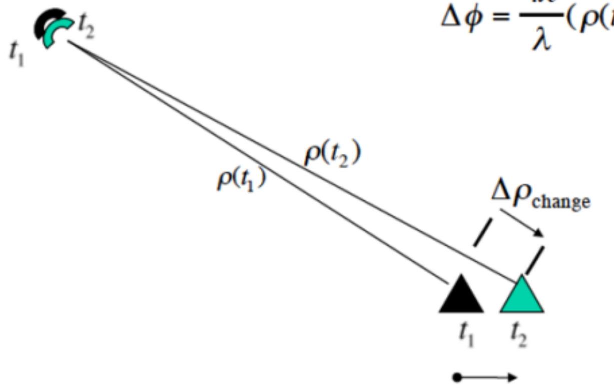


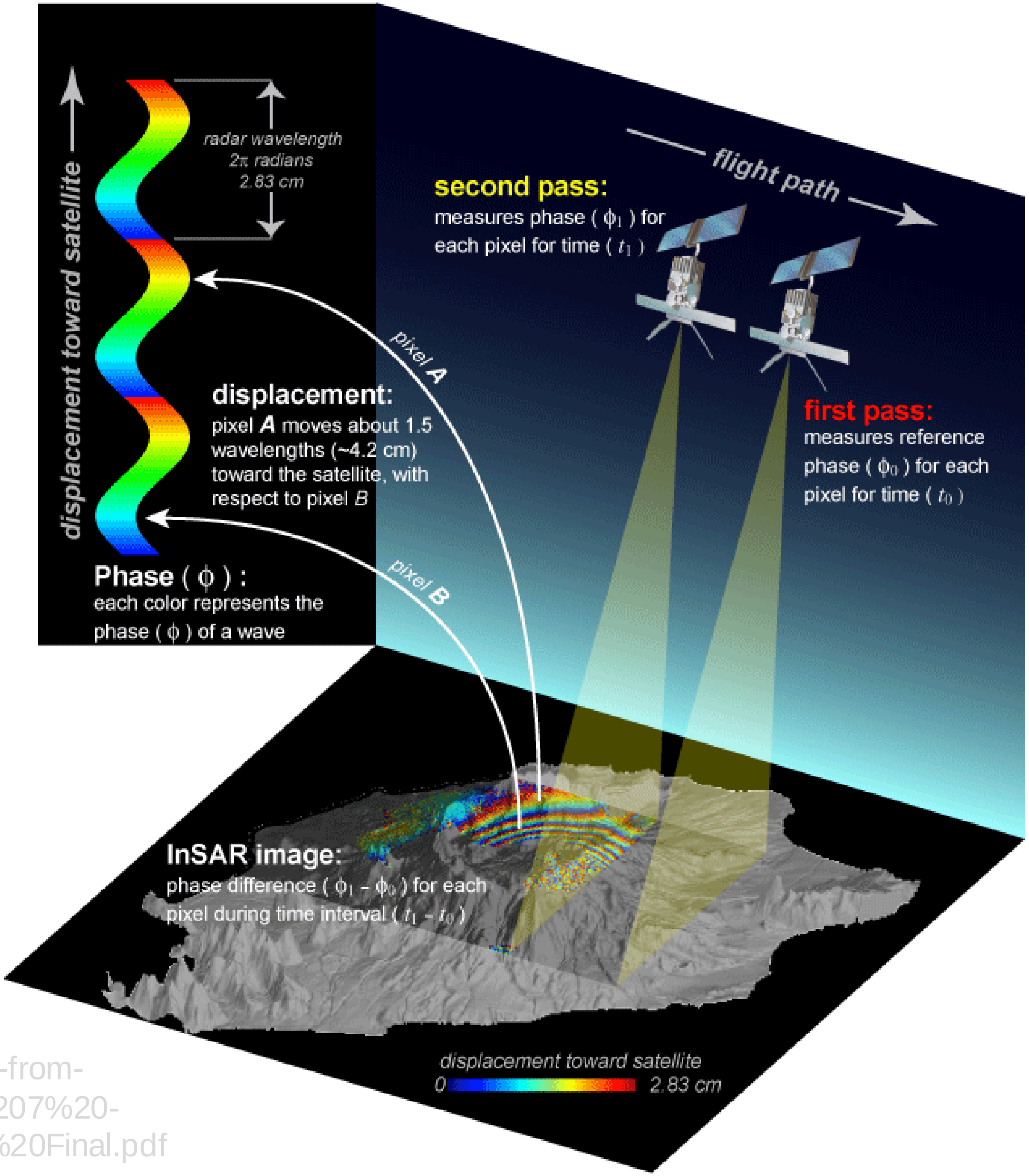
https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Sentinel-1_brings_radar_remote_sensing_to_new_level

Differential Interferometry

When two observations are conducted from identical positions in space but at separate times, any alteration in the range of a surface feature is directly proportional to the interferometric phase.

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{change}$$





https://britgeopeople.blogspot.com/2017/01/assessing-ground-motion-from-spaceby.html, https://dges.carleton.ca/courses/IntroSAR/SECTION%207%20-%20Carleton%20SAR%20Training%20-%20InSAR%20Theory%20-%20Final.pdf

Differential Interferometry - Sensitivities

- Differential interferometry detects millimeter-level surface deformation by comparing the phase difference between two radar images acquired at different times
- Changes in the surface elevation cause a shift in the interference pattern, which is reflected in the phase of the radar signal
- By analyzing these phase differences, even subtle surface deformations on the order of millimeters can be detected and measured.

$$\frac{\partial \phi}{\partial h} = \frac{2\pi p b \cos(\theta - \alpha)}{\lambda \rho \sin\theta} = \frac{2\pi p b_{\perp}}{\lambda \rho \sin\theta}$$ Topographic Sensitivity

$(\phi \Leftrightarrow \Delta\phi)$ $$\frac{\partial \phi}{\partial \Delta\rho} = \frac{4\pi}{\lambda}$$ Displacement Sensitivity

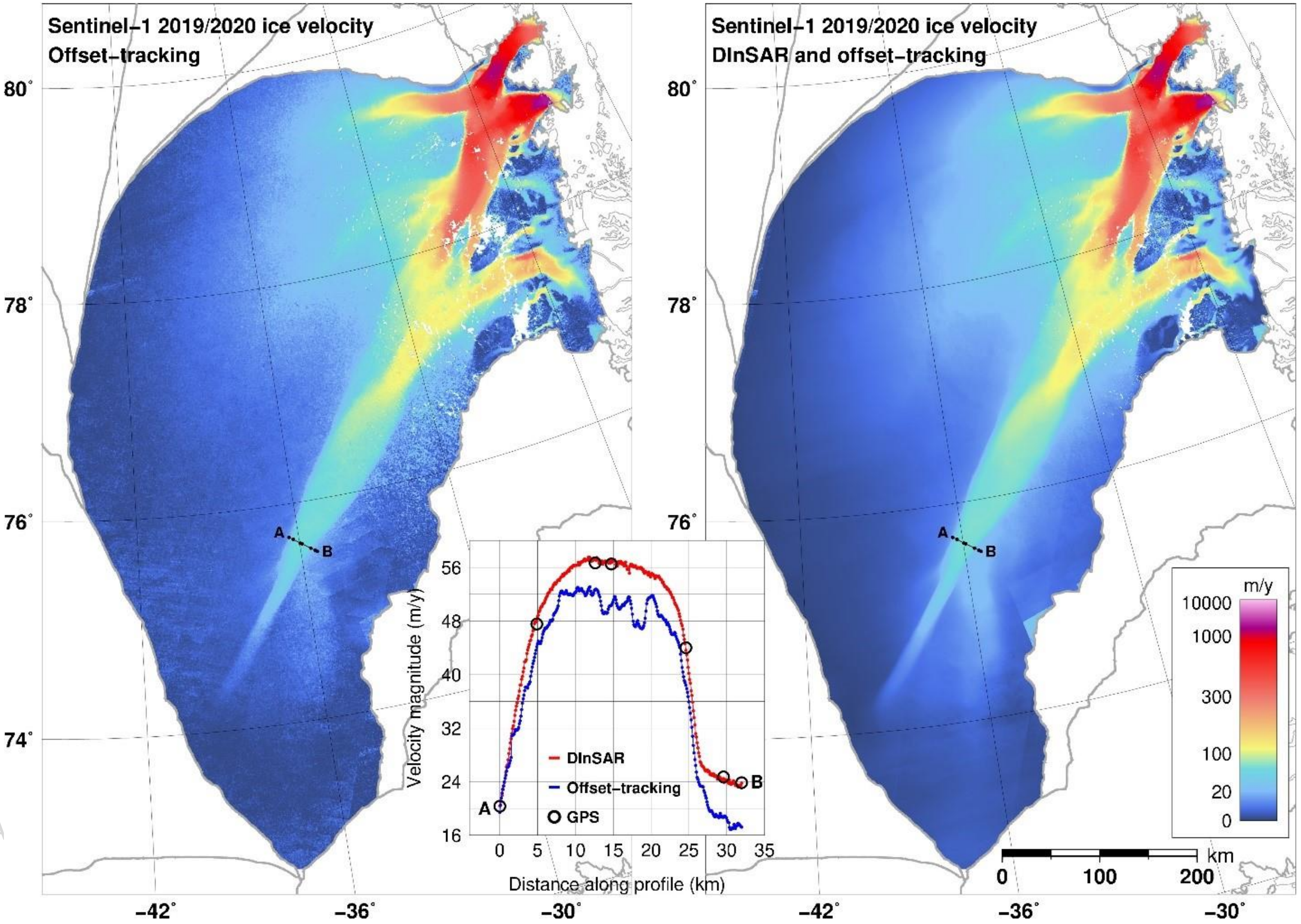
$$\sigma_{\phi_{topo}} = \frac{\partial \phi}{\partial h}\sigma_h = \frac{4\pi}{\lambda}\frac{b_{\perp}}{\rho \sin\theta}\sigma_h$$ Topographic Sensitivity Term

$$\sigma_{\phi_{disp}} = \frac{\partial \phi}{\partial \Delta\rho}\sigma_{\Delta\rho} = \frac{4\pi}{\lambda}\sigma_{\Delta\rho}$$ Displacement Sensitivity Term

Since $\frac{b}{\rho} << 1$ ==> $\frac{\sigma_{\phi_{disp}}}{\sigma_{\Delta\rho}} >> \frac{\sigma_{\phi_{topo}}}{\sigma_h}$

Meter Scale Topography Measurement - Millimeter Scale Topographic Change

Differential Interferometry - Sensitivities



A

https://eo4society.esa.int/wp-content/uploads/2021/05/icevelocity1.jpg

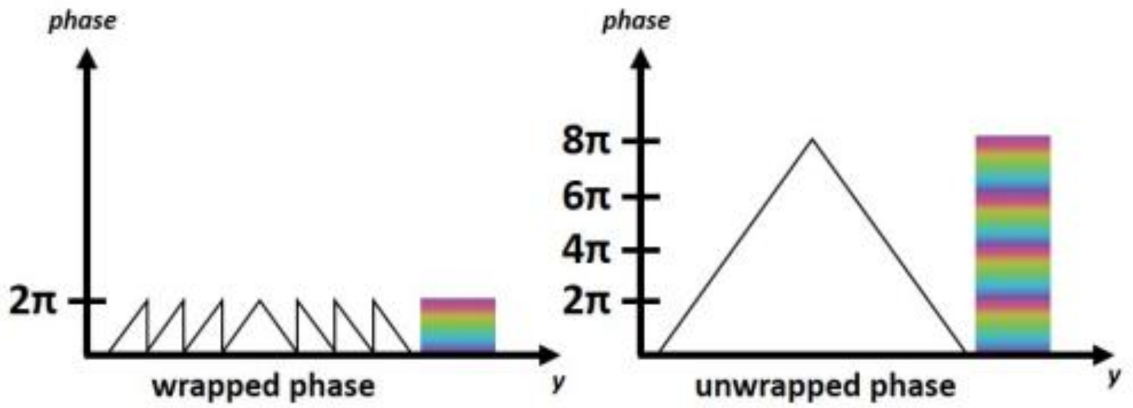
Phase unwrapping

- In order to correlate the interferometric phase with topographic height, the phase must undergo an unwrapping process
- Then, the proper 2p phase “ambiguity” must be determined
- The altitude of ambiguity refers to the altitude difference that causes a change in the interferometric phase
- Phase unwrapping resolves this ambiguity by integrating the phase difference between adjacent pixels

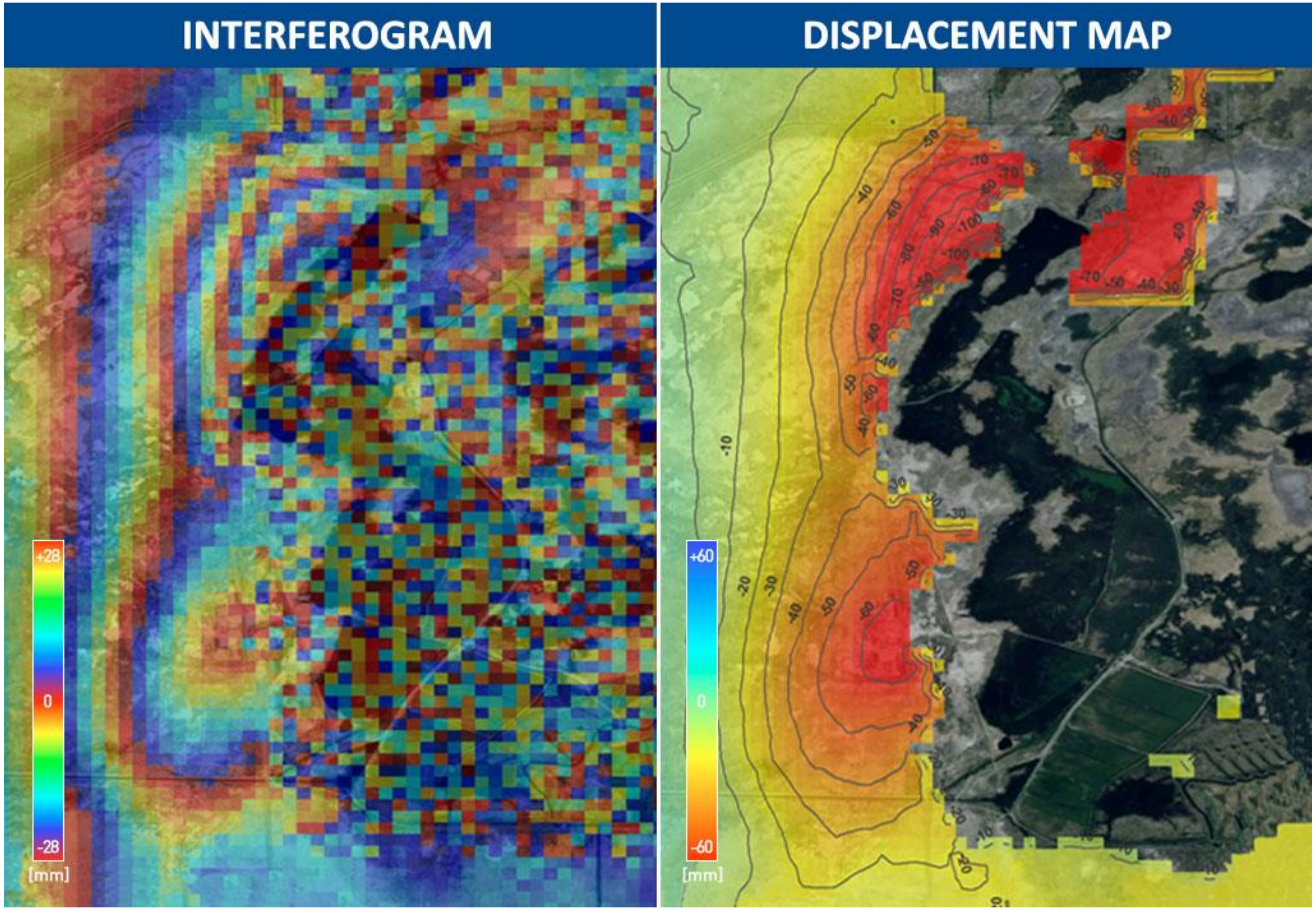
$$\Delta\phi_{topo} = \frac{2\pi p}{\lambda}\left(\rho_1 - \rho_2\right) = \frac{2\pi p}{\lambda}\vec{b} \bullet \vec{l}$$

$$\Delta\phi_{meas} = \mathrm{mod}\left(\Delta\phi_{topo}, 2\pi\right)$$

$$\Delta\phi_{unwrap}(s,\rho) = \Delta\phi_{topo}(s,\rho) + \Delta\phi_{const}$$



Phase unwrapping



https://site.tre-altamira.com/insar/

- Consequently, unwrapped results should be interpreted as relative height or displacement between pixels in two images.

Correlation Theory

Decorrelation

- InSAR signals decorrelate = become incoherent due to noise, scattering, rotation of viewing geometry, random motions over time
- Relates to the local phase standard deviation of the interferogram phase and affects:

  - height and displacement accuracy

  - ability to unwrap phase
- Correlation effects are multiplicative, unlike phase effects, which are additive
- When there is low coherence or decorrelation for any reason, it leads to a loss of information in that area.

$$\gamma = \gamma_v \gamma_g \gamma_t \gamma_c$$

where

γ_v is volumetric (trees)

γ_g is geometric (steep slopes)

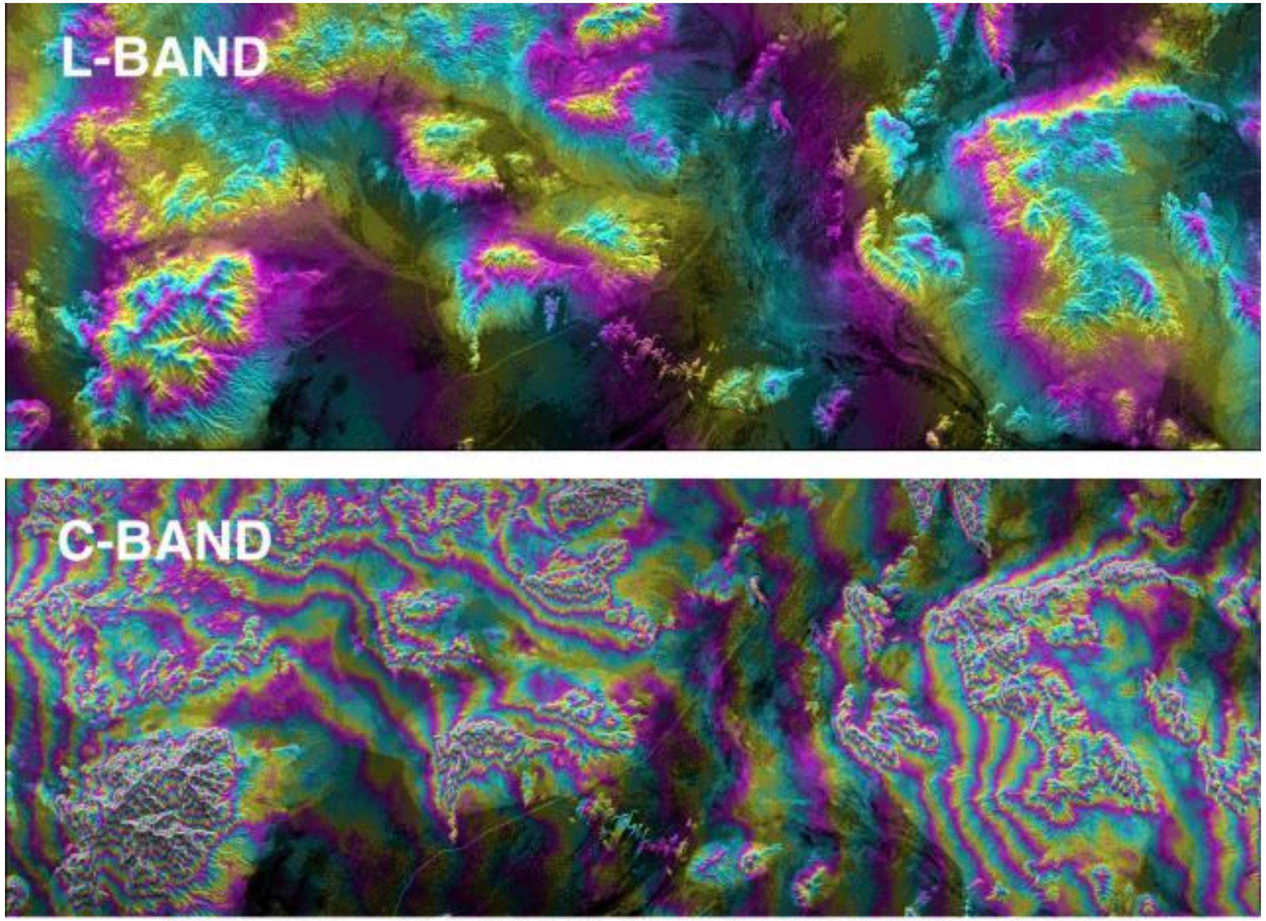
γ_t is temporal (gradual changes)

γ_c is sudden changes

Coherent Change Detection

SIR-C L and C-band Interferometry

- Simultaneous C and L band
- InSAR experiments have shown good correlation at L-band

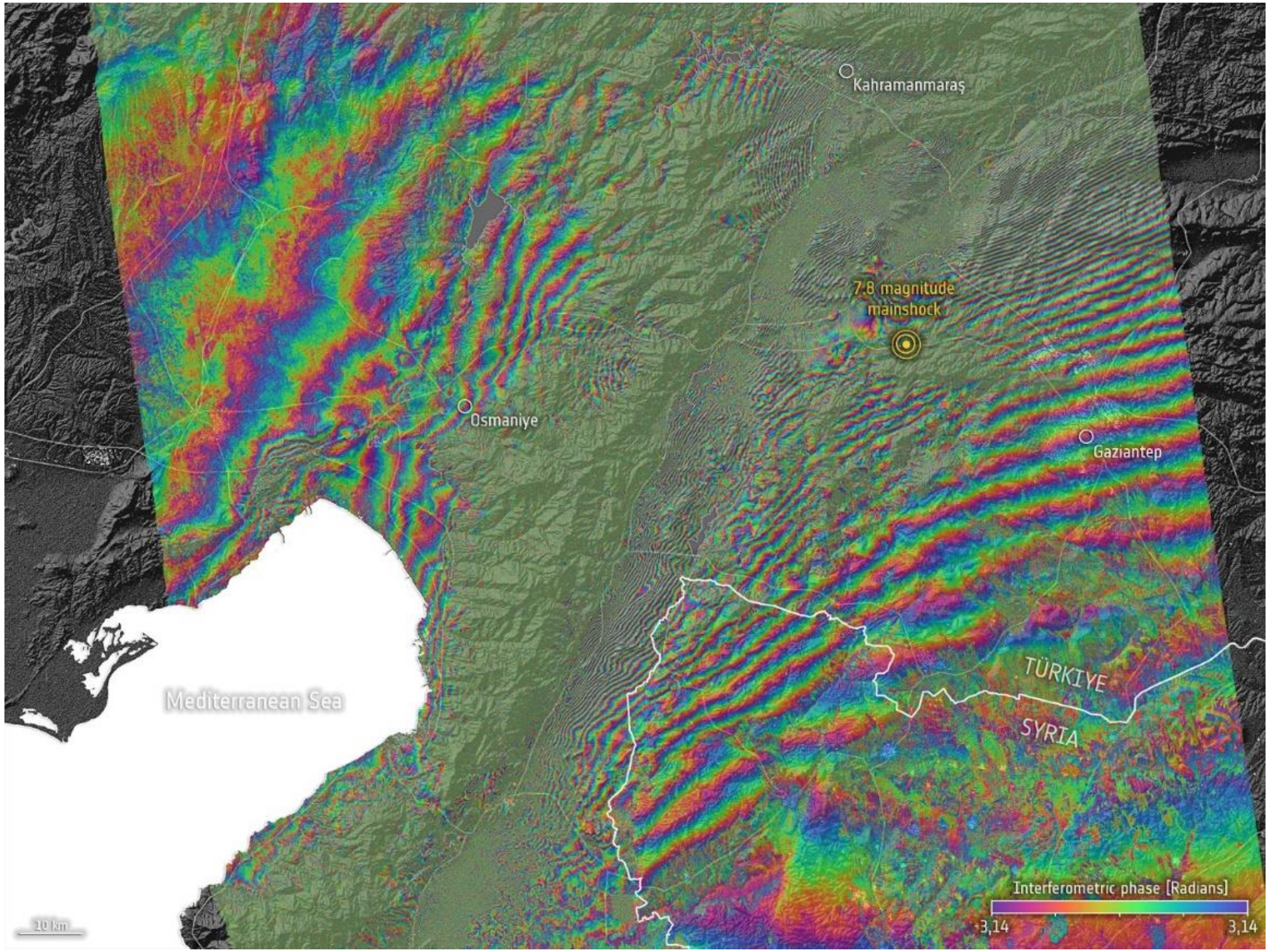


SIR-C L, C BAND INTERFEROGRAMS
FT. IRWIN, CALIFORNIA

https://upload.wikimedia.org/wikipedia/commons/3/32/L_C_band_topo_interferograms.jpg

Applications

Türkiye–Syria interferogram

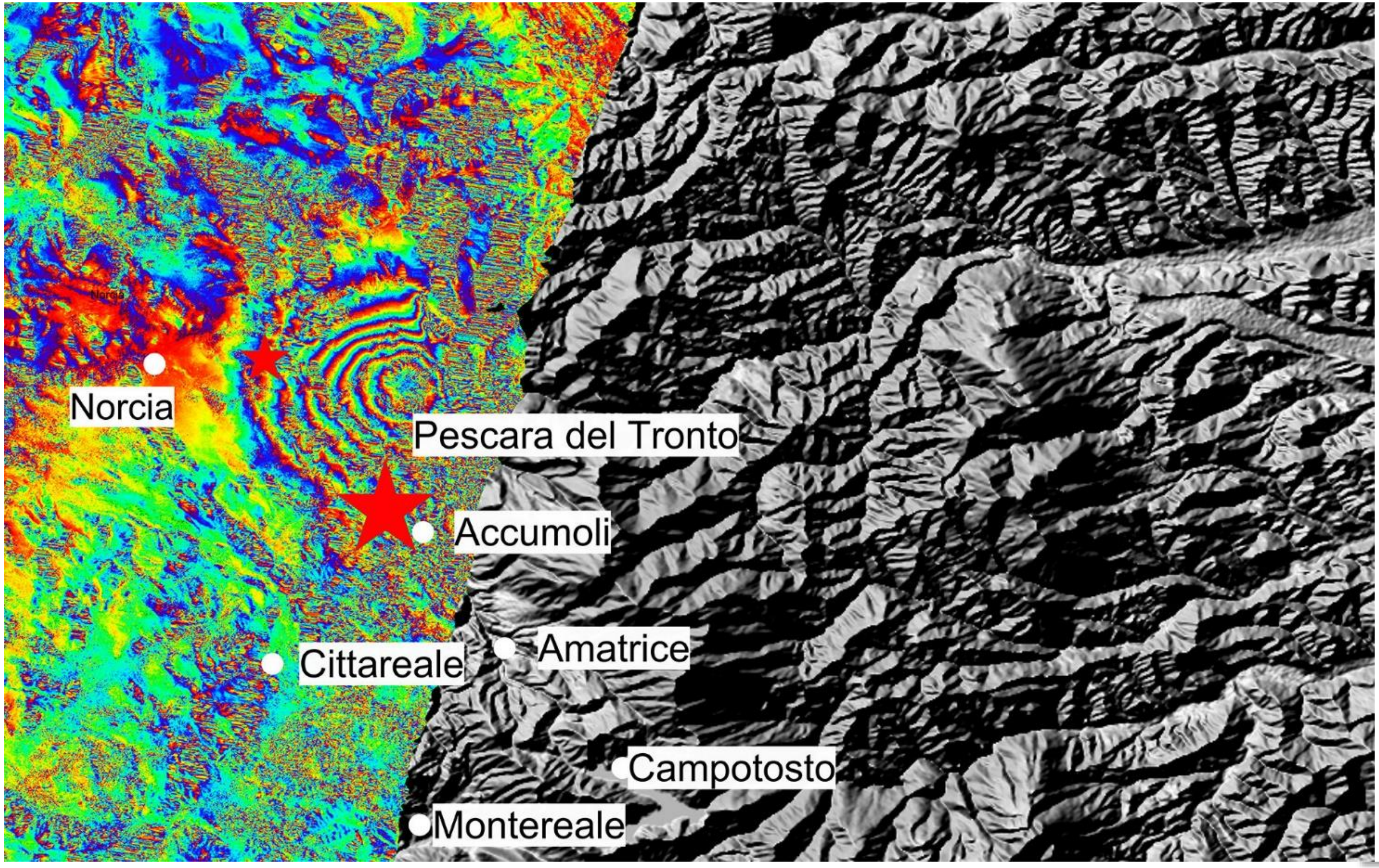


Interferogram showing the coseismic surface displacement in the area near Gaziantep, generated from multiple Copernicus Sentinel-1 scans – before and after the earthquakes.

Source:https://www.esa.int/ESA_Multimedia/Images/2023/02/Tuerkiye_Syria_interferogram

Applications

Italy earthquake displacement

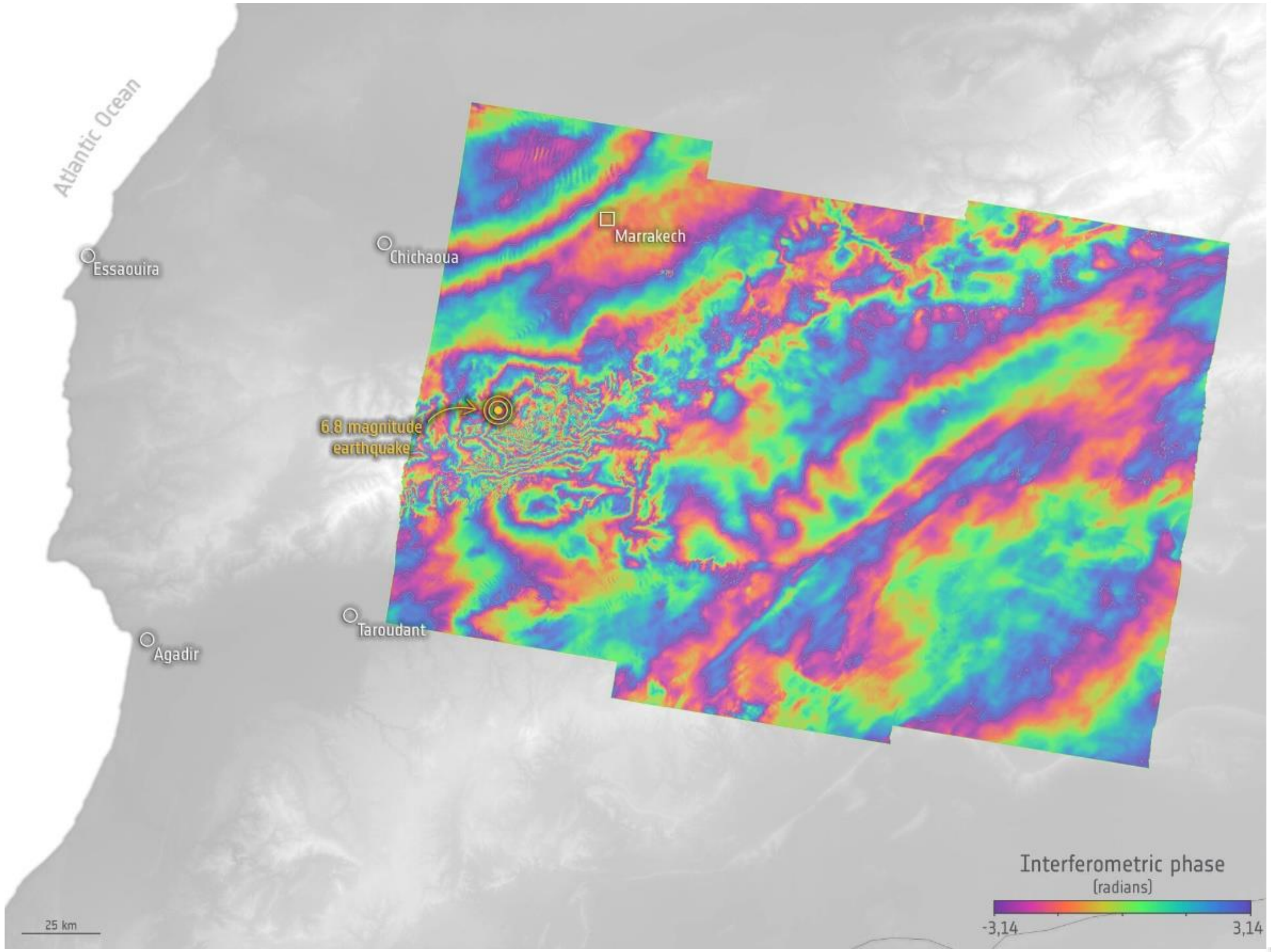


Combining two Sentinel-1 radar scans from 20 August (Sentinel-1B) and 26 August 2016 (Sentinel-1A), this interferogram shows changes that occurred during the 24 August earthquake that struck central Italy.

The seven interferometric 'fringes' correspond to about 20 cm of surface deformation in the radar sensor line of sight. Each fringe (which is associated to a colour cycle) corresponds to approximately 2.8 cm of displacement.

Applications

Morocco earthquake fringes

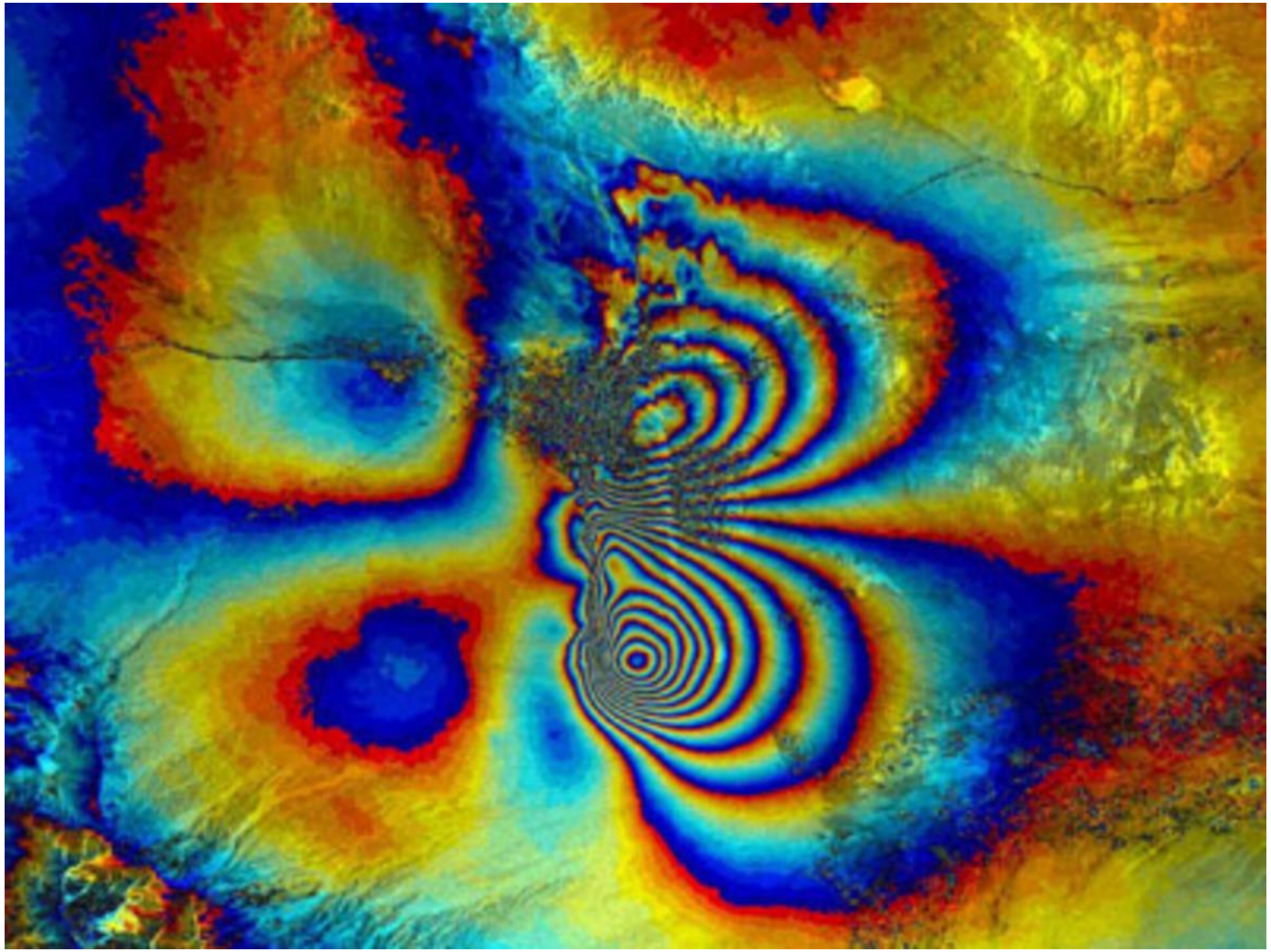


Following the devastating earthquake that struck Morocco on 8 September 2023, radar measurements from Europe's Copernicus Sentinel-1 satellite mission are being used to analyse how the ground has shifted as a result of the quake. This will not only help in planning the eventual reconstruction but will also further scientific research into the effects of earthquakes. Sentinel-1 acquisitions from 30 August 2023 and 11 September were combined to produce this interferogram, the coloured fringe pattern shows surface displacement.

•**CREDIT**: contains modified Copernicus Sentinel data (2023), processed by Aristotle University of Thessaloniki and the DIAPASON InSAR service of CNES integrated by TRE Altamira on the Geohazard Exploitation Platform GEP/ESA

Applications

Interferogram of Bam earthquake

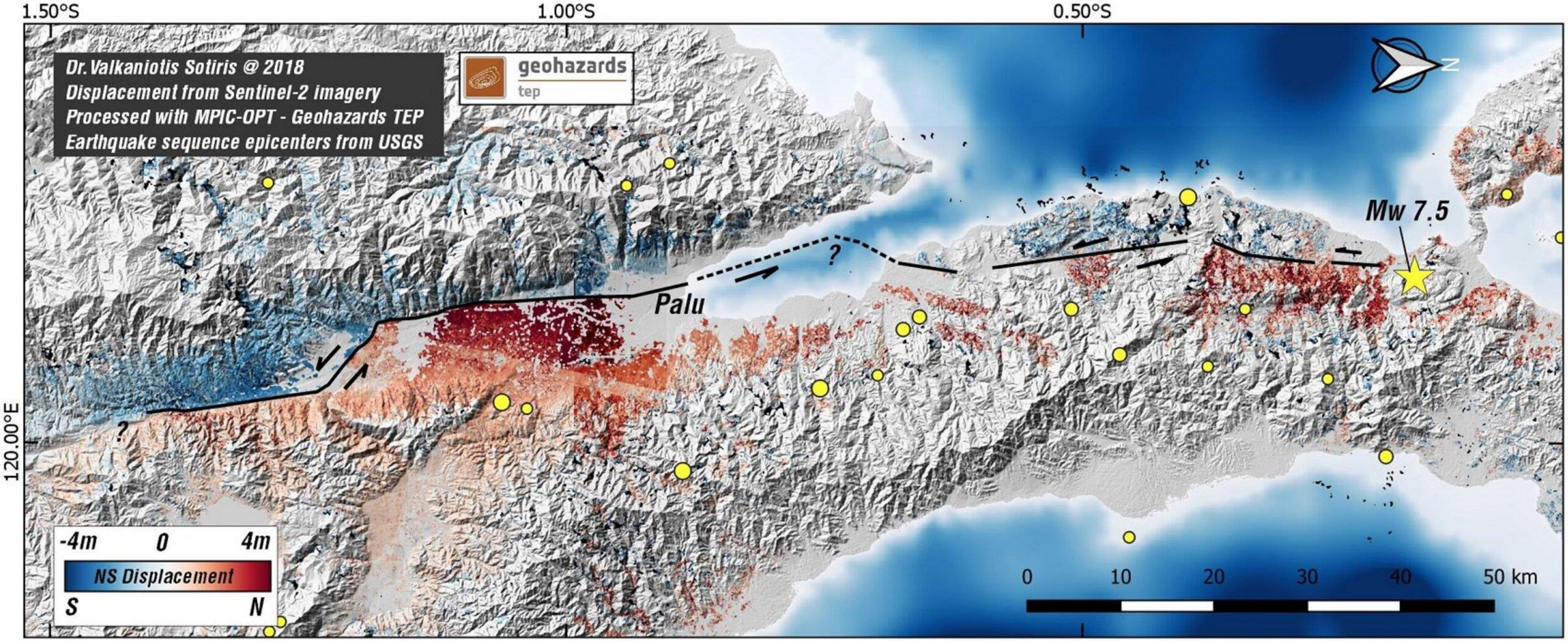


This interferogram, created by using Envisat's Advanced Synthetic Aperture Radar (ASAR) data, shows ground motion associated with the 26 December 2003 earthquake at Bam in Iran. CREDIT: Polimi/Poliba

For more information, see the tutorials:
13. Earthquake deformation with Sentinel-1 using the SNAP software

Applications

Indonesia earthquake displacement map

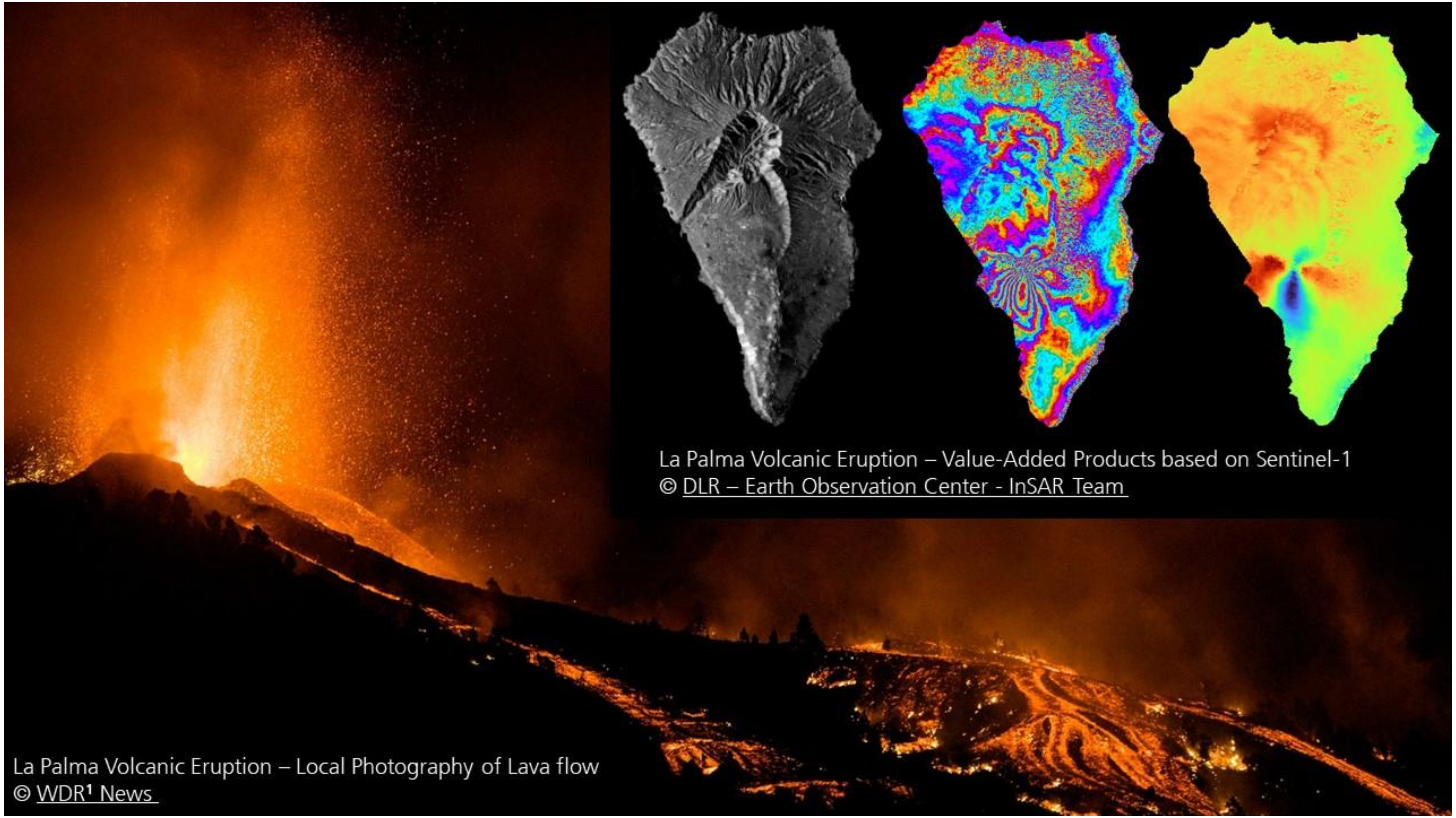


Thematic experts from the Corinth Rift Laboratory in Greece have generated a displacement map using Copernicus Sentinel-2 acquisitions from 17 September and 2 October, showing the impact of the 7.5-magnitude earthquake that hit Indonesia on 28 September 2018. The earthquake and subsequent tsunami have destroyed homes and are thought to have claimed at least 1400 lives according to the most recent reports. It has been estimated that up to 1.5 million people will be affected by these events.

CREDIT: Contains modified Copernicus Sentinel data (2018), processed by the Corinth Rift Laboratory

Applications

Volcano monitoring



La Palma Volcanic Eruption – Value-Added Products based on Sentinel-1
© DLR – Earth Observation Center - InSAR Team

La Palma Volcanic Eruption – Local Photography of Lava flow
© WDR¹ News

https://www.esa.int/gsp/ACT/images/coffee/SCAnsari.jpg

esa space solutions

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