Deliverable 4.1

Earth Observation Applications

Lectures hand-book

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1. Introduction to ESA Earth Observation and evolution – current and next generation missions

History of ESA

- **Early 1960s** - 6 European countries (Belgium, France, Germany, Italy, the Netherlands and the UK) formed the **European Launcher Development Organisation (ELDO)** to develop a heavy launcher (called 'Europa')
- Those same countries, plus Denmark, Spain, Sweden and Switzerland, established the **European Space Research Organisation (ESRO)**, soon after, to undertake mainly scientific satellite programmes.
- **1975** - a convention was drafted to set up one **'European space agency' (ESA),** and broadening the scope of the agency's remit to include operational space applications systems, e.g. telecommunications satellites
- → **30 May 1975 – signing of the ESA Convention**

Signing of ESA Convention

Source: https://www.esa.int/ESA_Multimedia/Images/2015/05/Signing_of_ESA_Convention

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

ESA facts

- Over 50 years of experience
- 22 Member States
- Eight establishments/facilities in Europe
- Approximately 2300 employees
- Over 80 satellites designed, tested and operated in flight

Source: https://www.esa.int/About_Us/Corporate_news/ESA_facts

ESA Membership

22 Member States

Austria	Italy
Belgium	Luxembourg
Czech Republic	Netherlands
Denmark	Norway
Estonia	Poland
Finland	Portugal
France	Romania
Germany	Spain
Greece	Sweden
Hungary	Switzerland
Ireland	United Kingdom

Associate Members

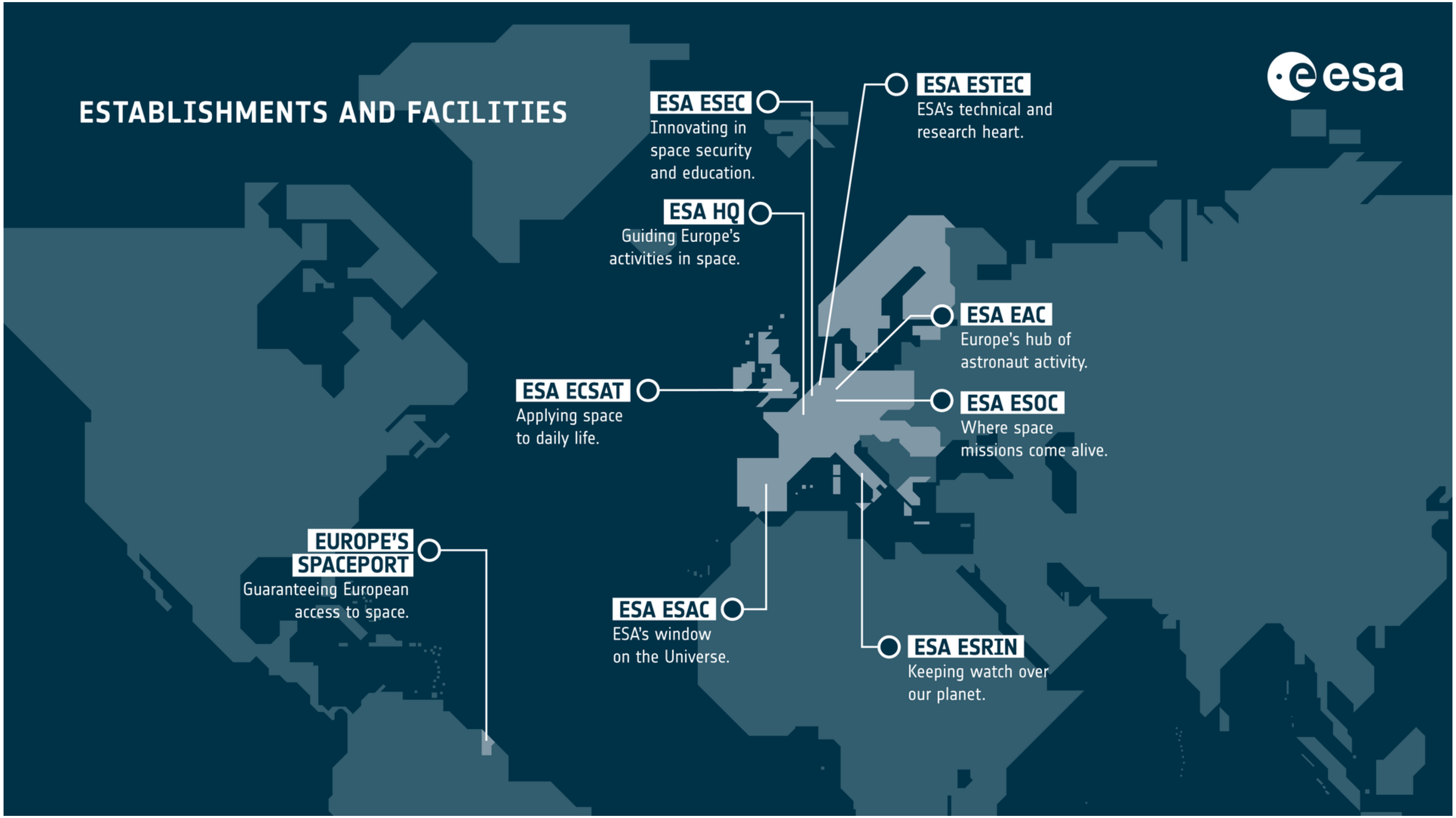
Slovakia, Latvia, Lithuania, Slovenia

Cooperation Agreements

Bulgaria, Croatia, Cyprus, Malta, Canada

Source: https://www.esa.int/About_Us/Corporate_news/Member_States_Cooperating_States

ESA's locations

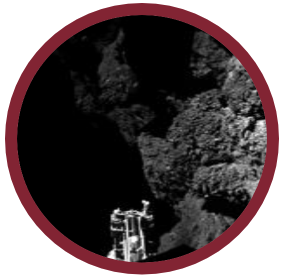


Source: https://www.esa.int/ESA_Multimedia/Images/2021/06/ESA_establishments_and_facilities

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

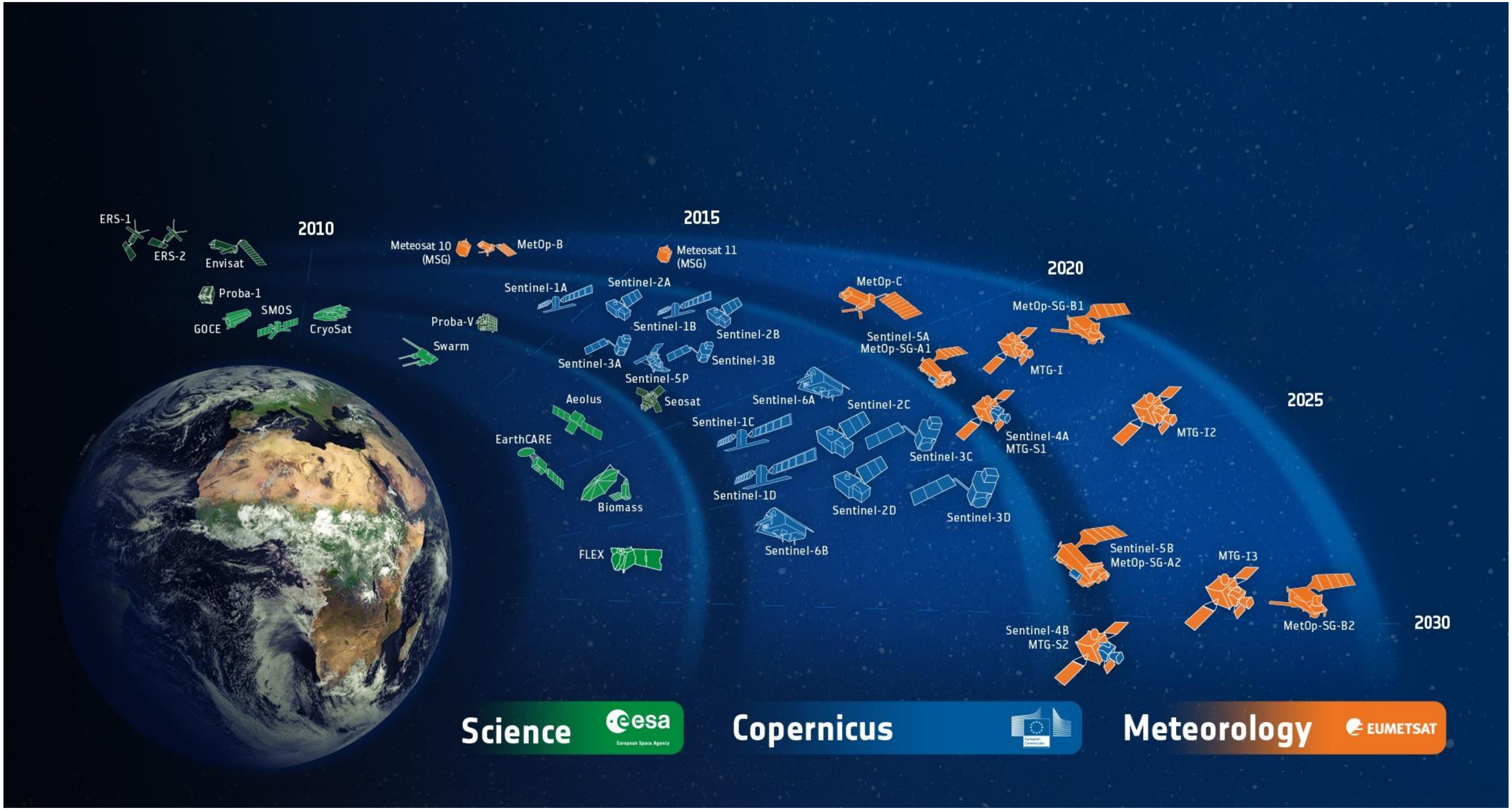
operations

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

Devising Earth Observation Missions

Member States	EU	EUMETSAT	Industry
Earth Explorers	Copernicus	Meteorology	InCubed
			

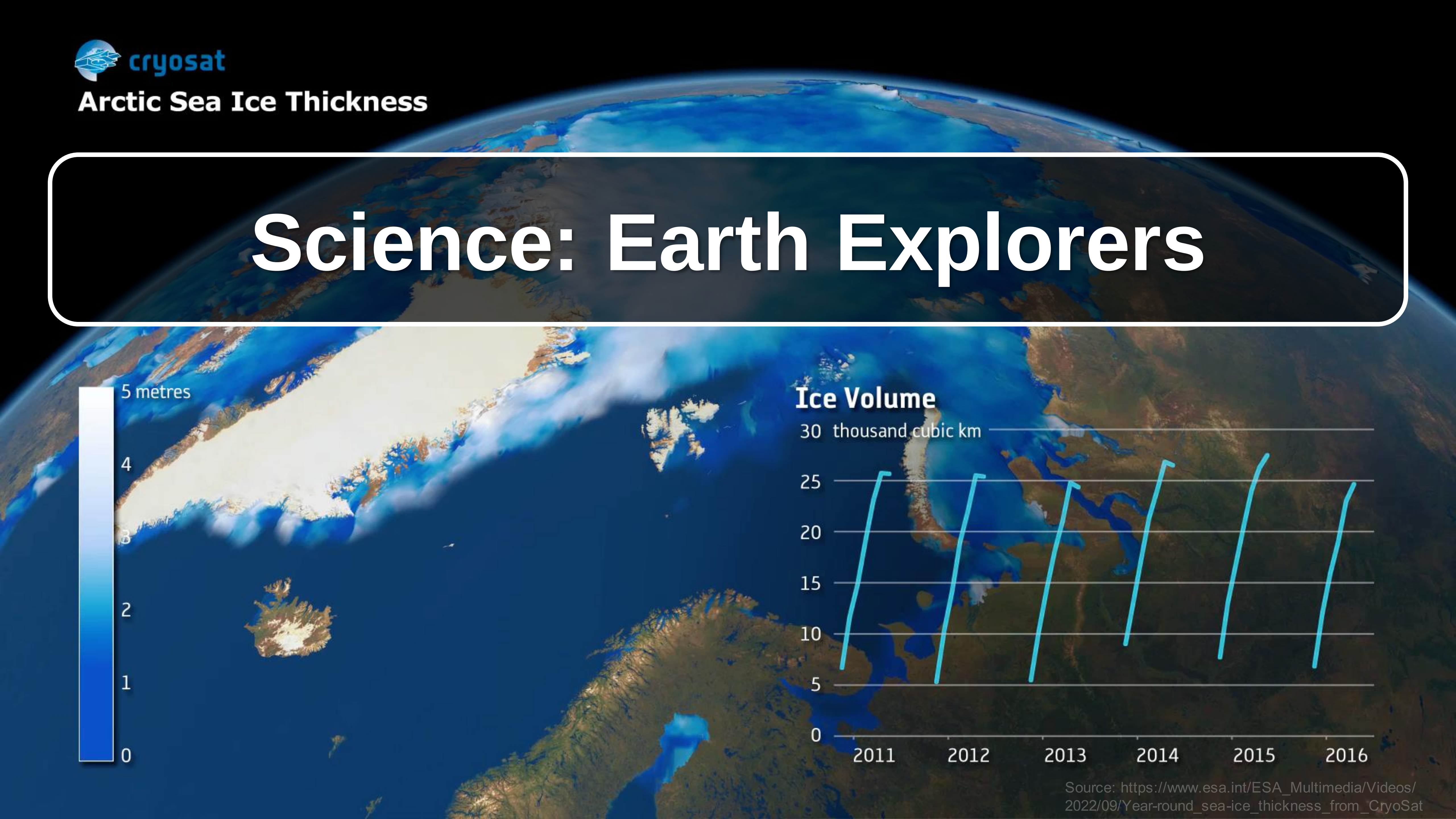
- Determined by scientific collaborators within Member States through Open Calls

- Goals are established by partners and industry stakeholders
- The mission's definition is a collaborative effort involving ESA, industry partners, and users

Inspired by https://esto.nasa.gov/wp-content/uploads/2020/07/Rosello-Plenary.pdf
Source: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Call_opens_for_ESA_s_twelfth_Earth_Explorer, https://www.esa.int/Space_in_Member_States/Austria/ESA_headquarters, https://www.eumetsat.int/about-us/our-facilities, https://www.esa.int/Applications/Observing_the_Earth/Strengthening_InCubed_s_role_in_commercial_Earth_observation,

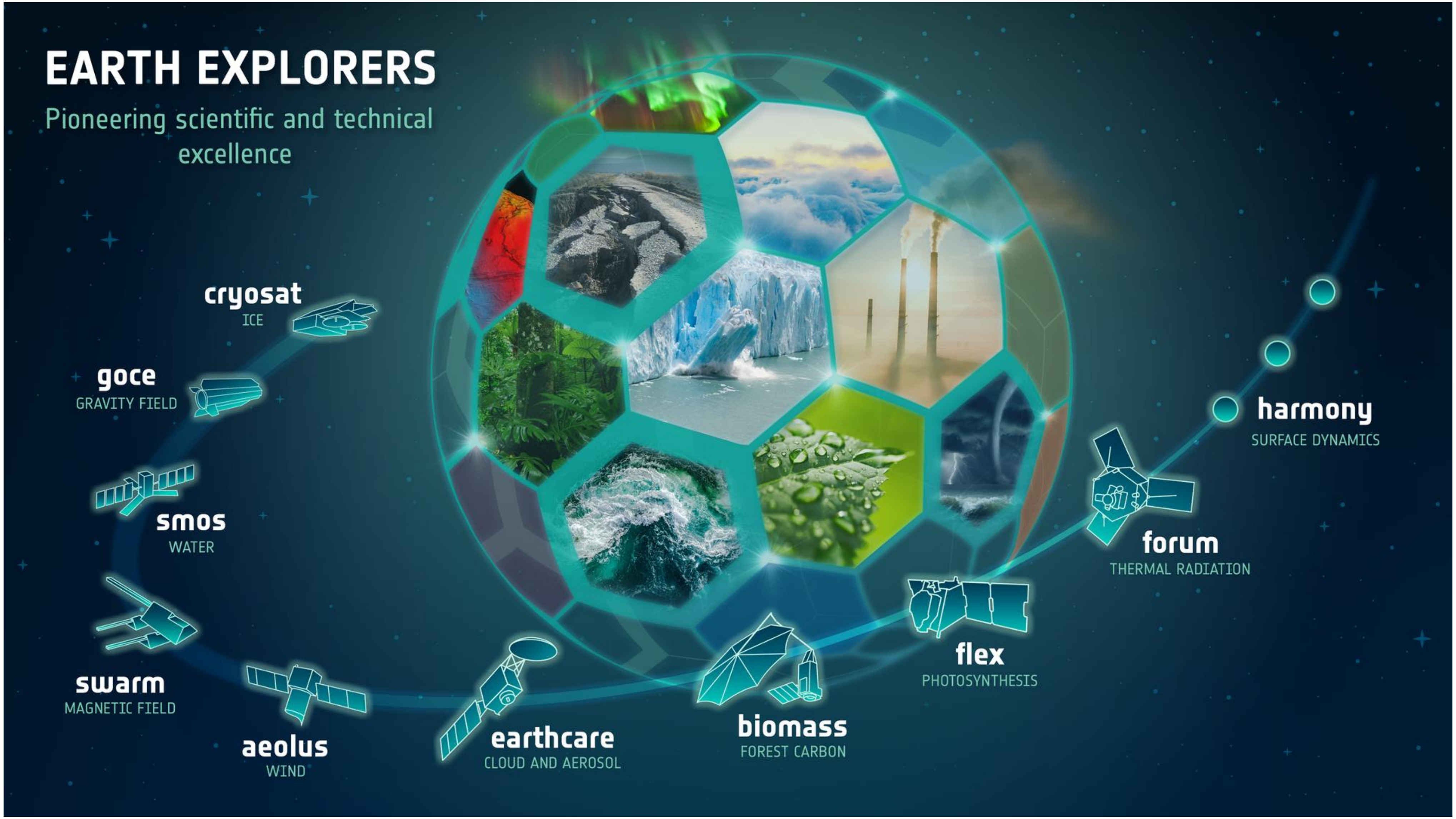
For more information, see the tutorial: 1. Introduction to ESA Earth Observation and evolution – ESA EO data on the web

Science: Earth Explorers



Source: https://www.esa.int/ESA_Multimedia/Videos/2022/09/Year-round_sea-ice_thickness_from_CryoSat

Science: Earth Explorers



Source: https://www.esa.int/ESA_Multimedia/Images/2022/08/ESA_s_Earth_Explorer_missions

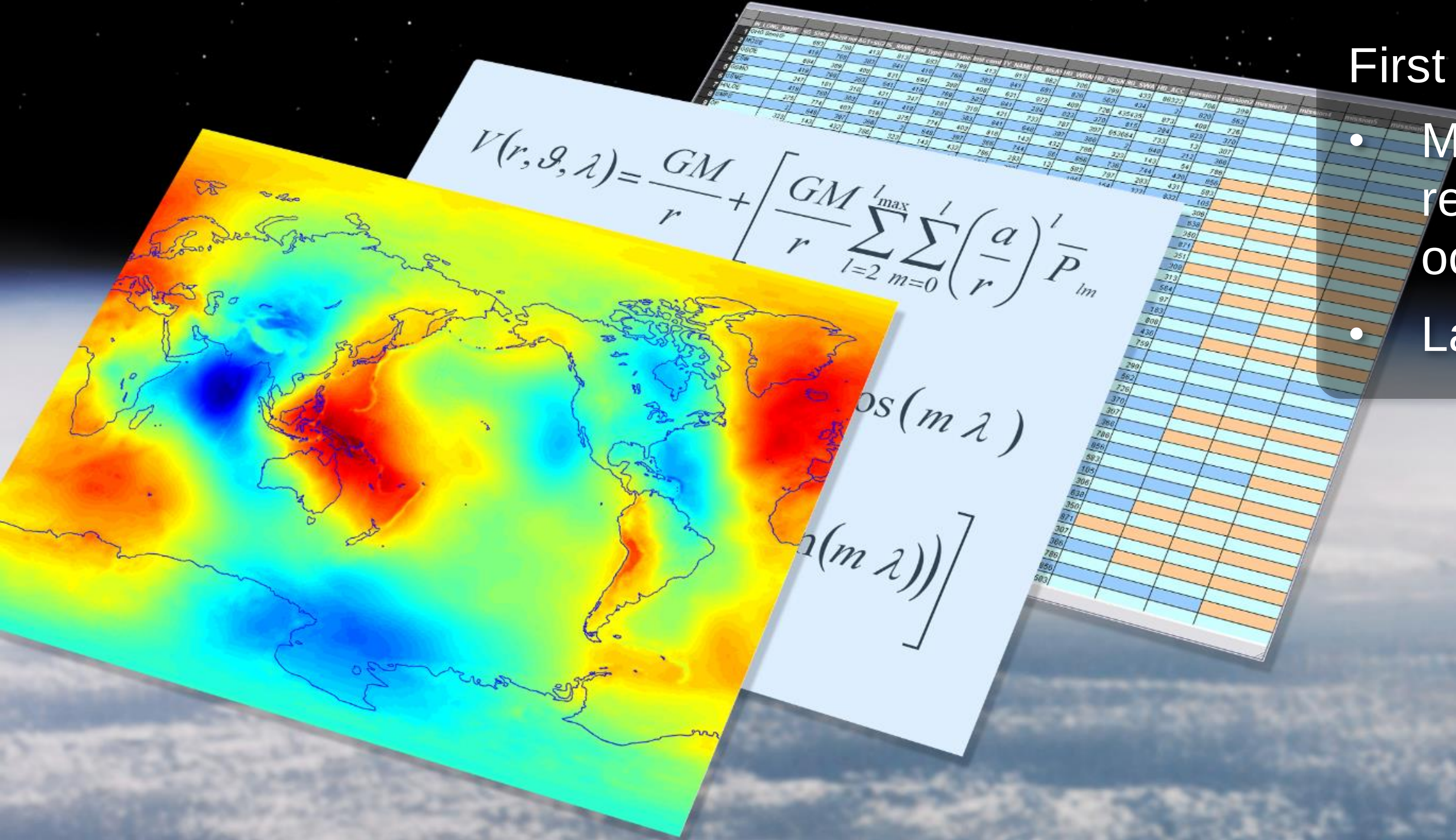
The Earth Explorers Missions

- Science driven programme
- Mission selection proposed by “Advisory Committee for Earth Observation”
- Financed through the Earth Observation Envelope Programme (EOEP)
- One mission every 2 years (on average)

Source: https://www.csun.edu/science/books/sourcebook/chapters/8-organizing/files/earth-systems-interactions.html

GOCE

(Gravity field and steady-state Ocean Circulation Explorer)

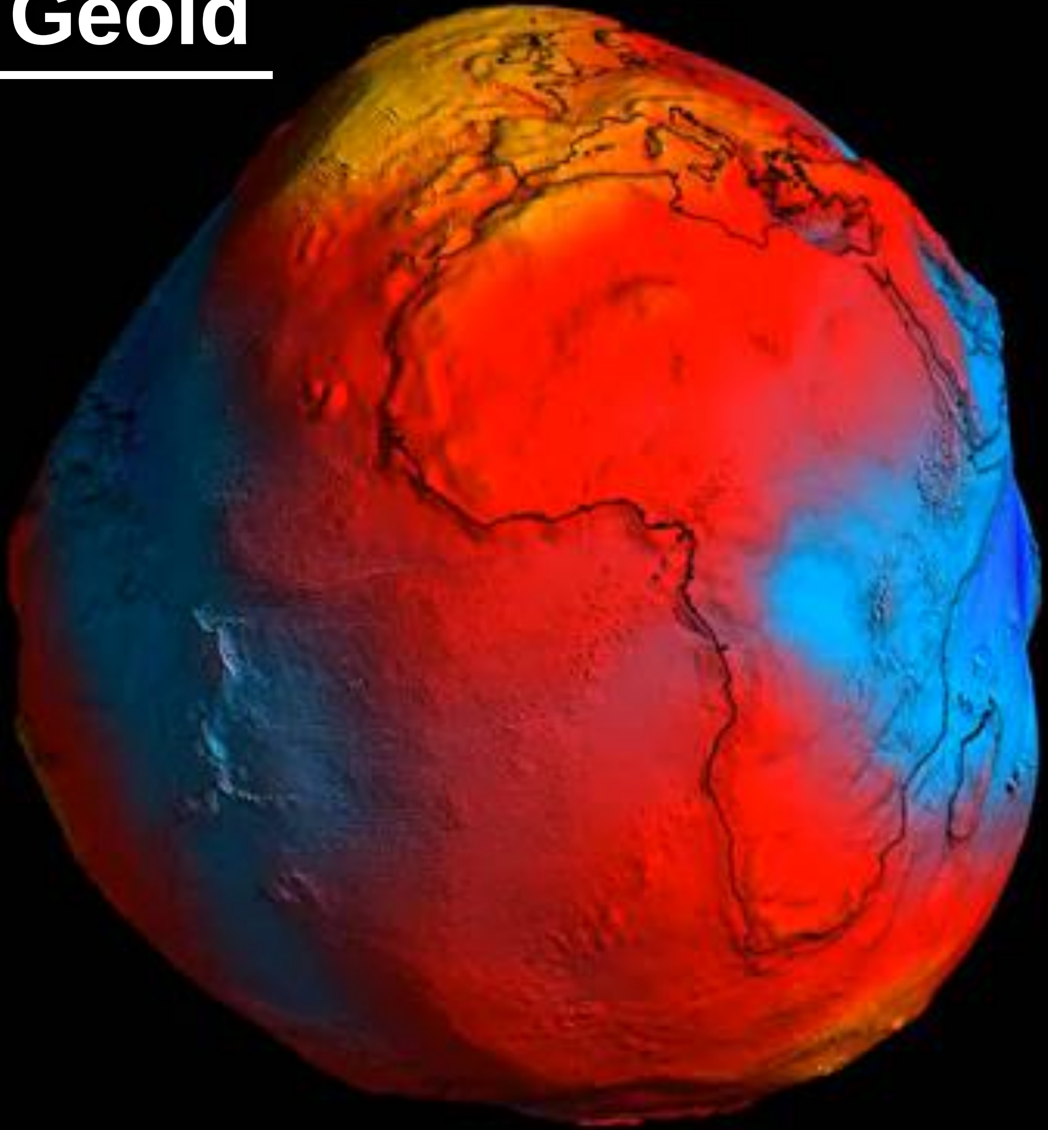


First Earth Explorer

- Mapping the gravity field to advance research in Earth-interior processes, oceanography and geodesy
- Launched 17 March 2009

Source: https://www.esa.int/ESA_Multimedia/Images/2008/04/GOCE_will_advance_many_fields_of_science

GOCE: Earth's Geoid

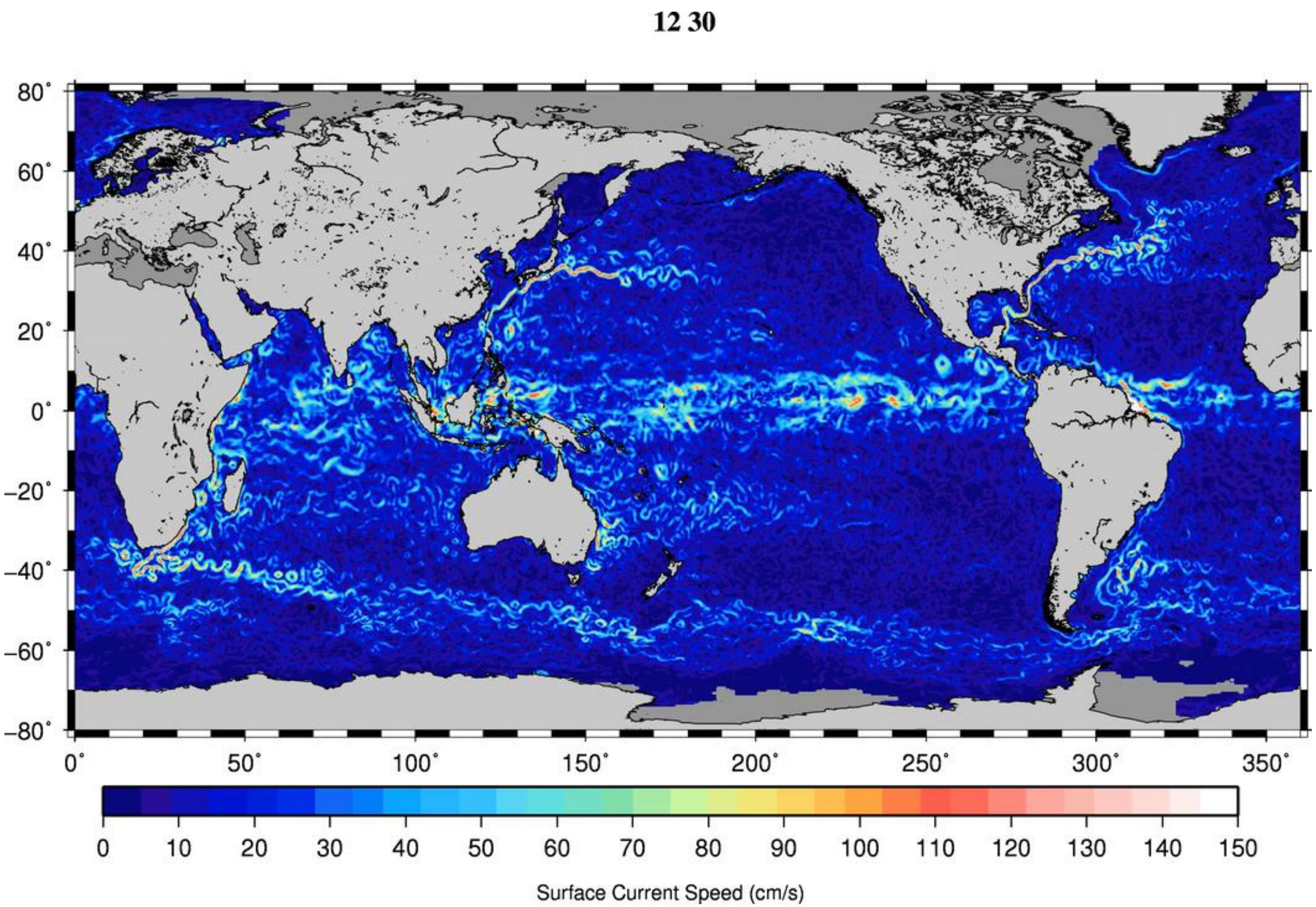


- Model of the 'geoid' with unprecedented accuracy and spatial resolution
- Crucial reference for measuring ocean circulation and sea-level change

https://visioterra.net/VtGsep/

Source: https://www.esa.int/ESA_Multimedia/Videos/2011/03/GOCE_Geoid/(lang)/en

GOCE: Ocean Currents



Weekly evolution of ocean surface currents from January 1993 to December 2011.

Gravity data from GOCE geoid & sea altimetry data

Source: https://www.esa.int/ESA_Multimedia/Images/2014/11/Ocean_currents_from_GOCE

SMOS

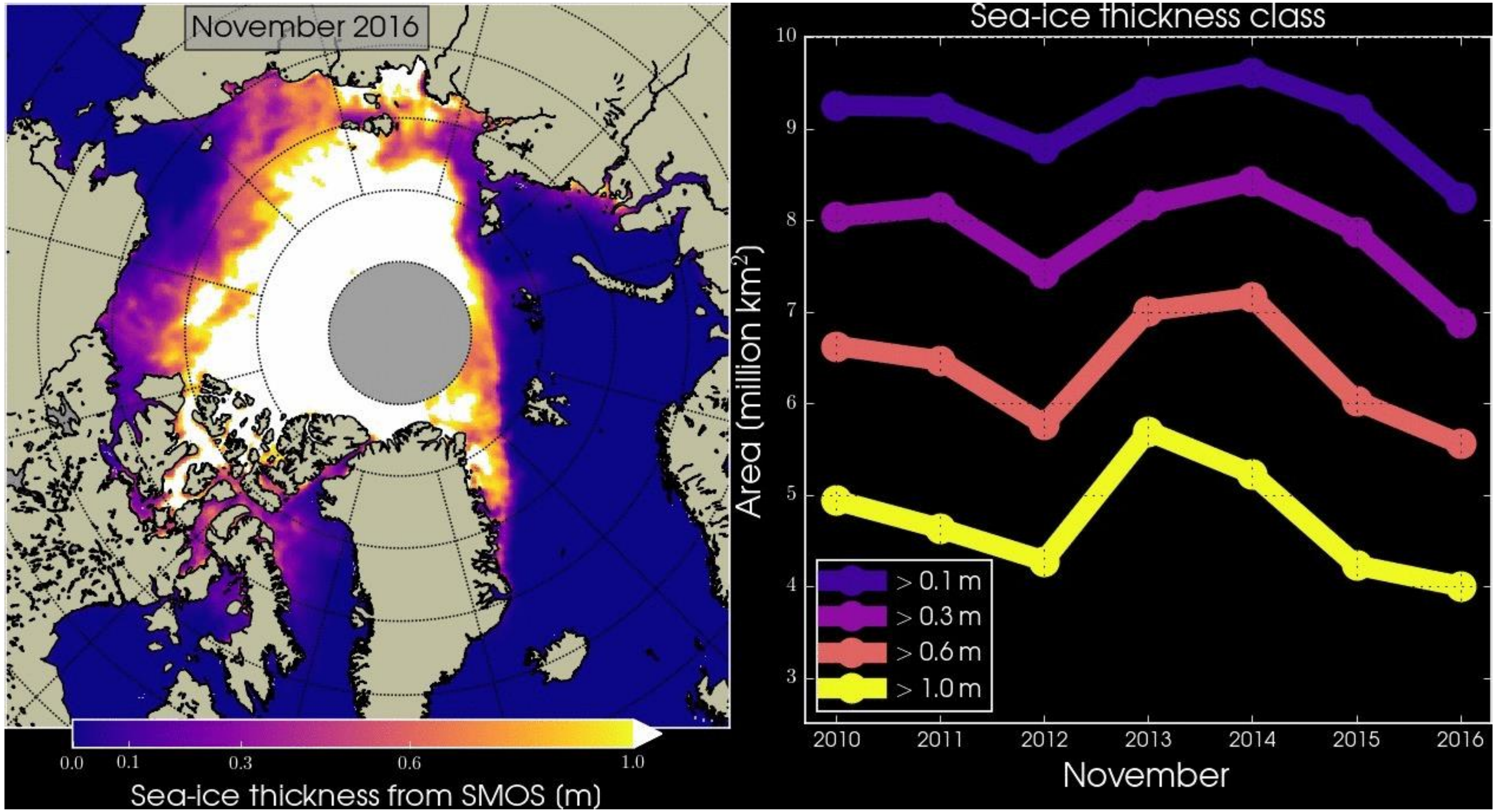
(Soil Moisture and Ocean Salinity)

Second Earth Explorer

- Launched 2 November 2009
- Global observations of soil moisture over landmasses and salinity over the oceans

Source: https://earth.esa.int/eogateway/news/esa-s-excellent-earth-explorer-missions-extended-to-2025/smos-in-orbit

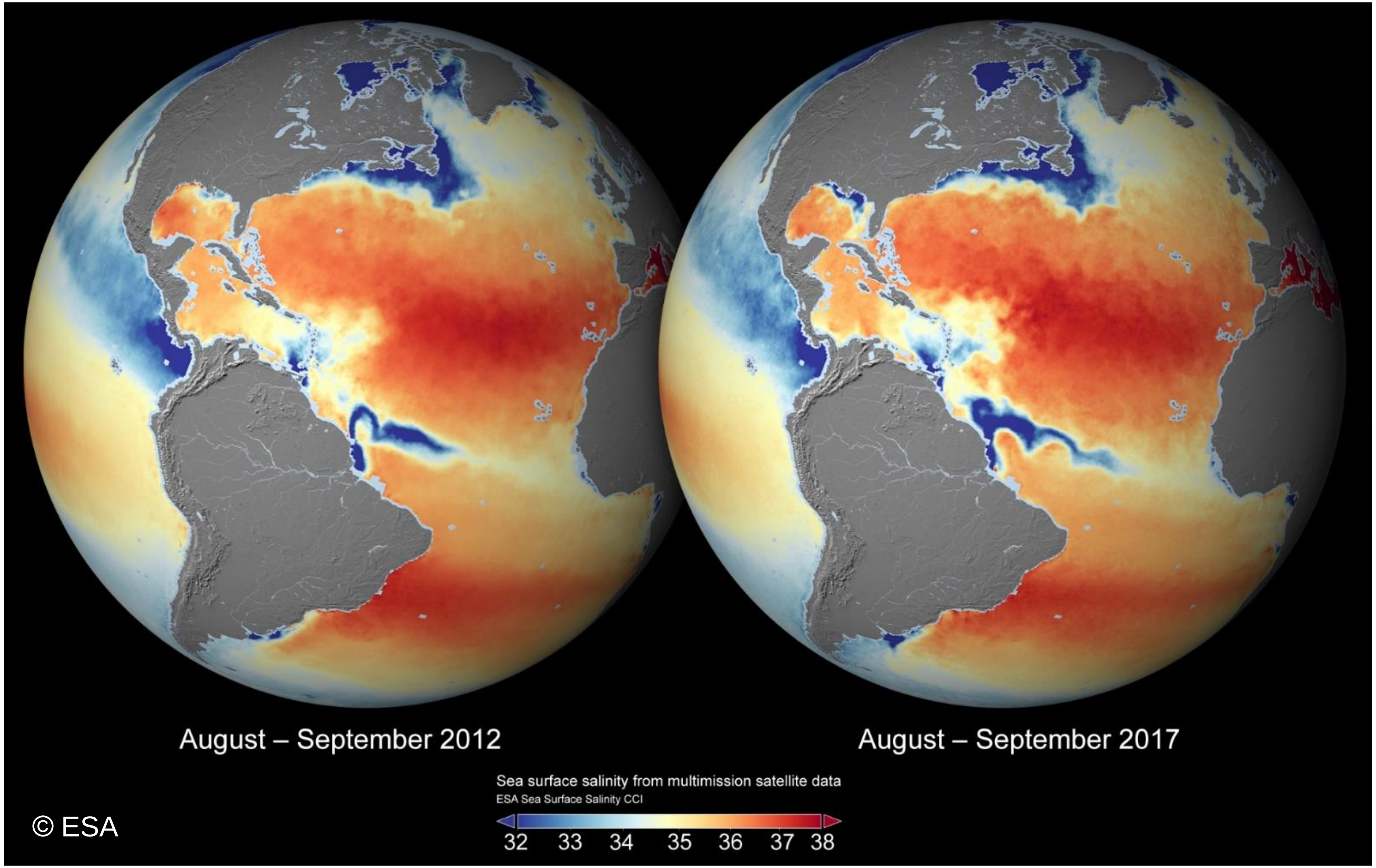
SMOS: Sea-ice change



Based on measurements from the SMOS mission, the animation shows changes in sea-ice thickness during November between 2010 and 2016. Although designed to improve our understanding of Earth's water cycle, SMOS is now being used to provide accurate measurements of thin sea-ice, complementing the CryoSat mission

Source: © University of Hamburg,

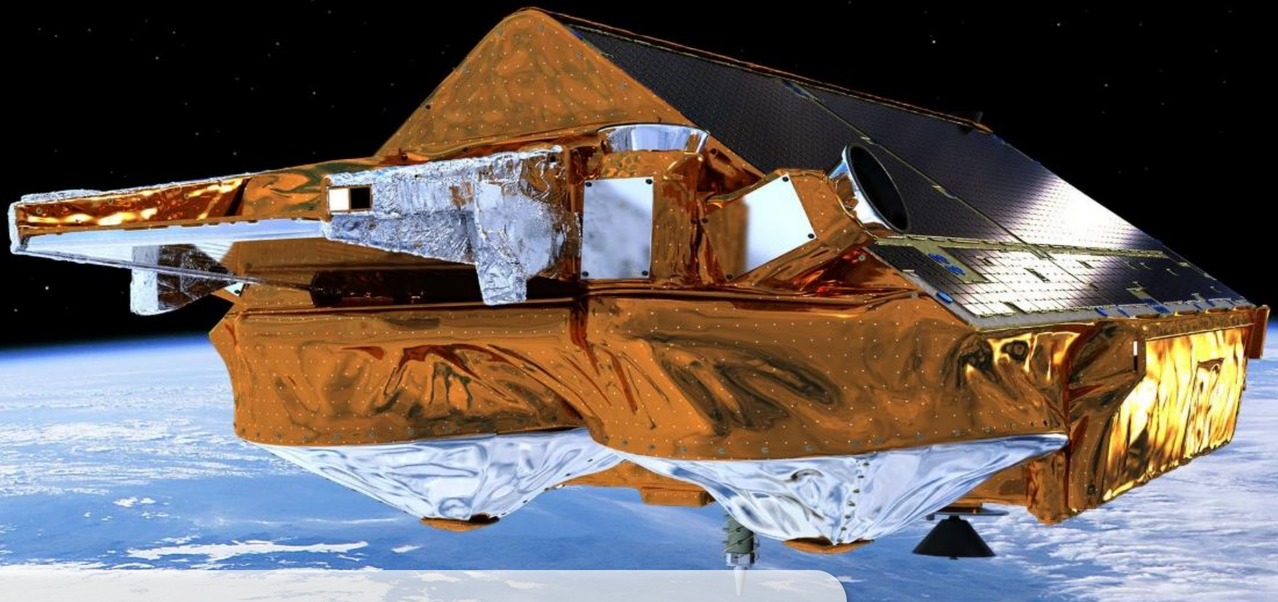
SMOS: Global sea-surface salinity



Source: https://www.esa.int/ESA_Multimedia/Images/2019/11/Global_sea-surface_salinity_2012_and_2017

Global sea-surface salinity maps from ESA's Climate Change Initiative showing the difference for the same period in 2012 and in 2017. Note the differences in the spreading of the Amazon and Mississippi River plumes.

CRYOSAT



Third Earth Explorer

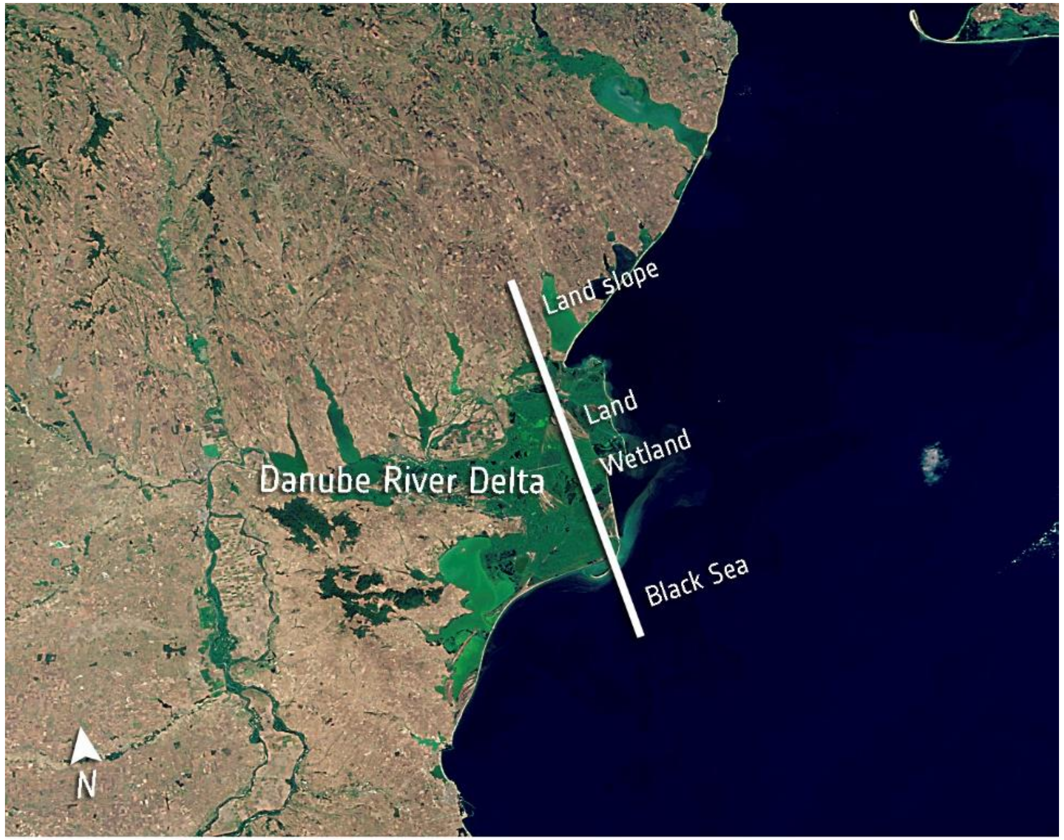
- Launched 8 Nov. 2010
- Precise monitoring of changes in the thickness of marine ice floating in the polar oceans
- Variations in the thickness of the vast ice sheets that blanket Greenland and Antarctica

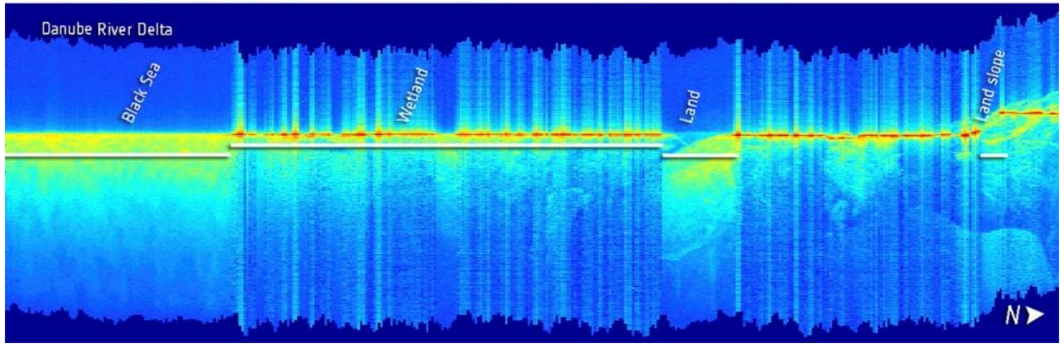
Source: https://www.eoportal.org/satellite-missions/cryosat, ESA

Greenland meltwater runoff

Extreme ice melting events in Greenland have become more frequent and more intense over the past 40 years, raising sea levels and the risk of flooding worldwide.

CRYOSAT: Altimeter readings





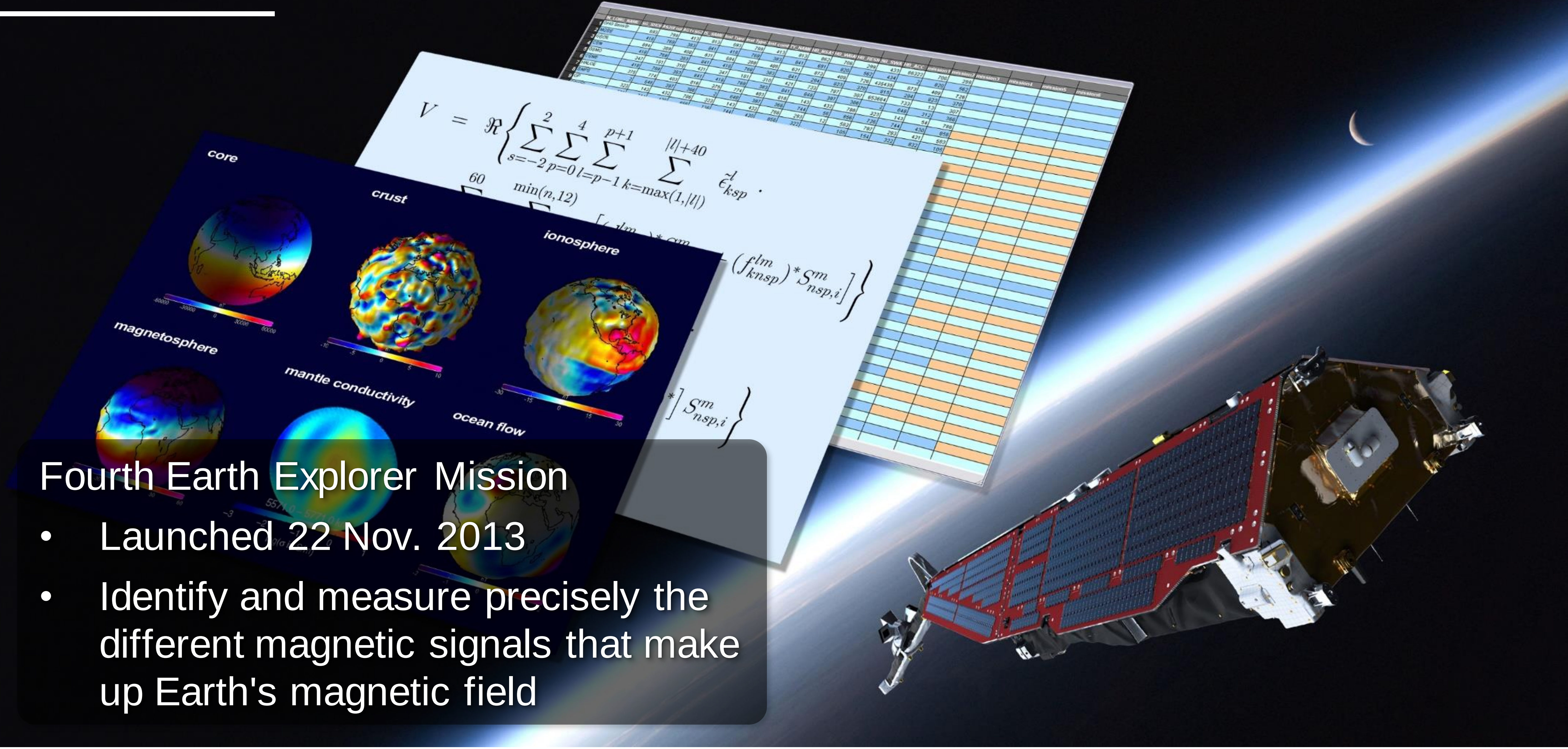
CryoSat altimeter readings over the Danube River delta in eastern Romania. The radar image shows different radar reflection intensities from the Black Sea, Danube Delta's wetland and elevated land.

Over wetlands, due to the to the standing waters, points of bright radar reflections are pictured in red, whereas over sea or land they appear yellow.

These readings are of unprecedented sharpness compared to previous altimeters.

Source: https://www.esa.int/ESA_Multimedia/Images/2019/11/Global_sea-surface_salinity_2012_and_2017

SWARM

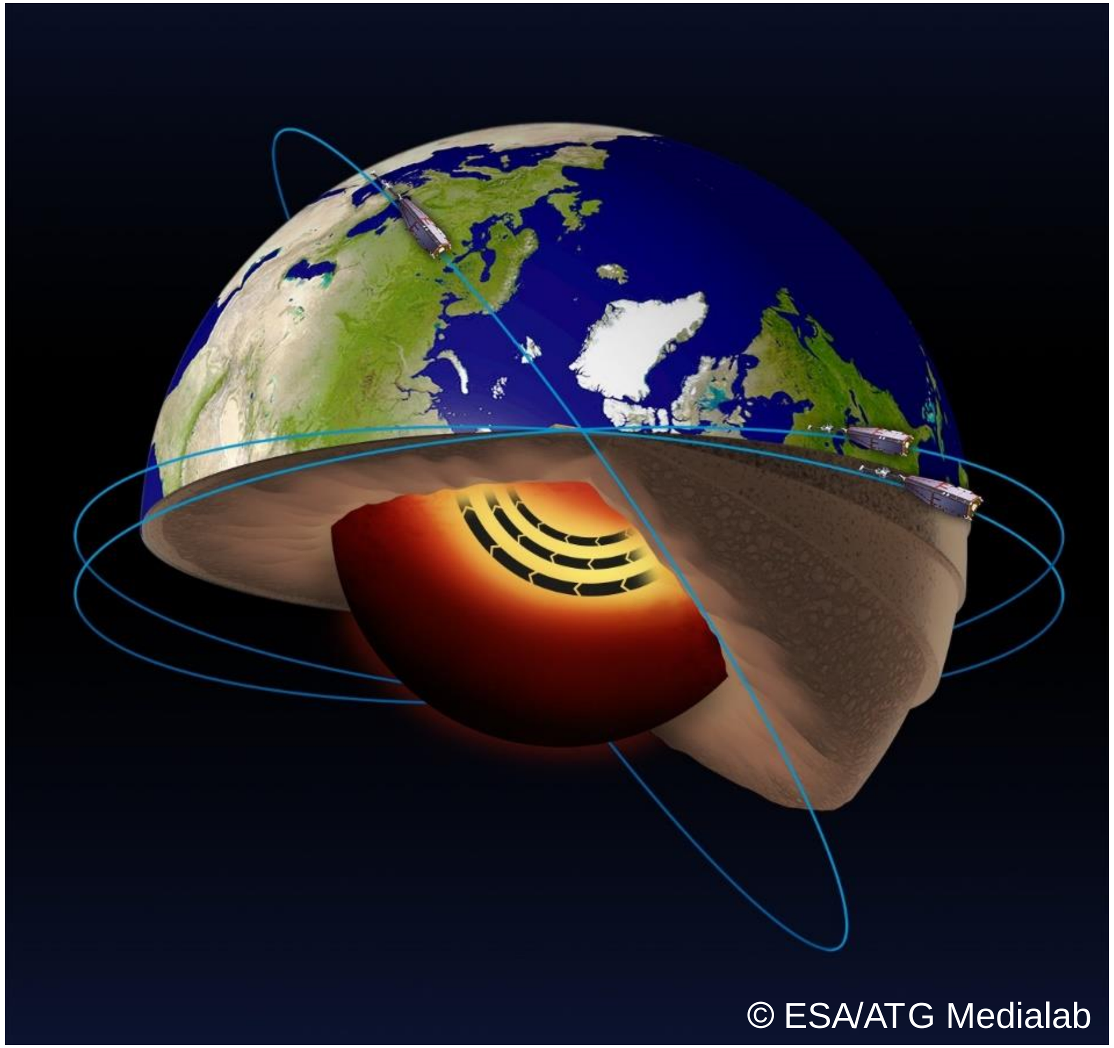


Fourth Earth Explorer Mission

- Launched 22 Nov. 2013
- Identify and measure precisely the different magnetic signals that make up Earth's magnetic field

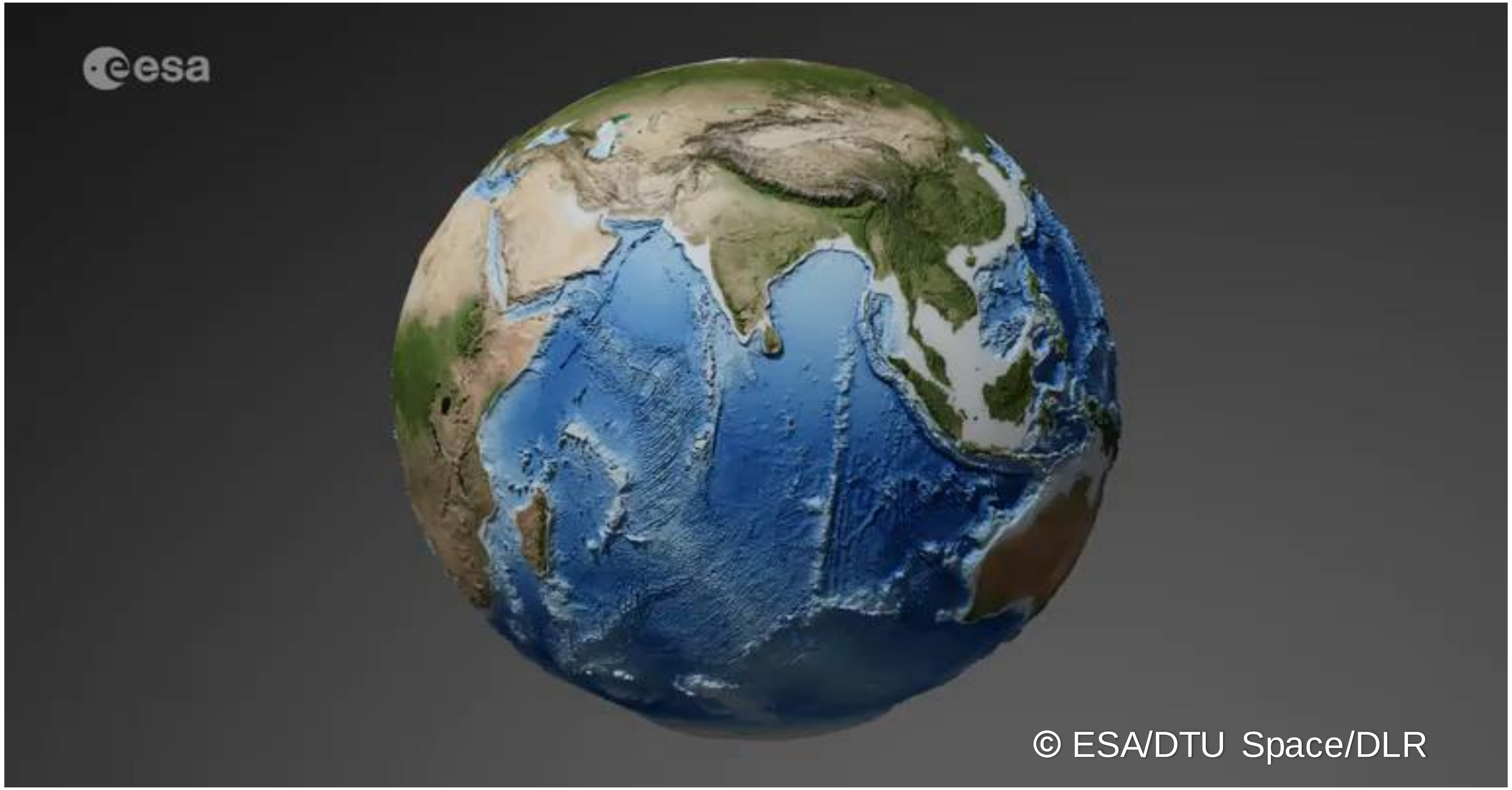
Source: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Swarm/Data_products

Swarm: Jet stream in Earth’s core



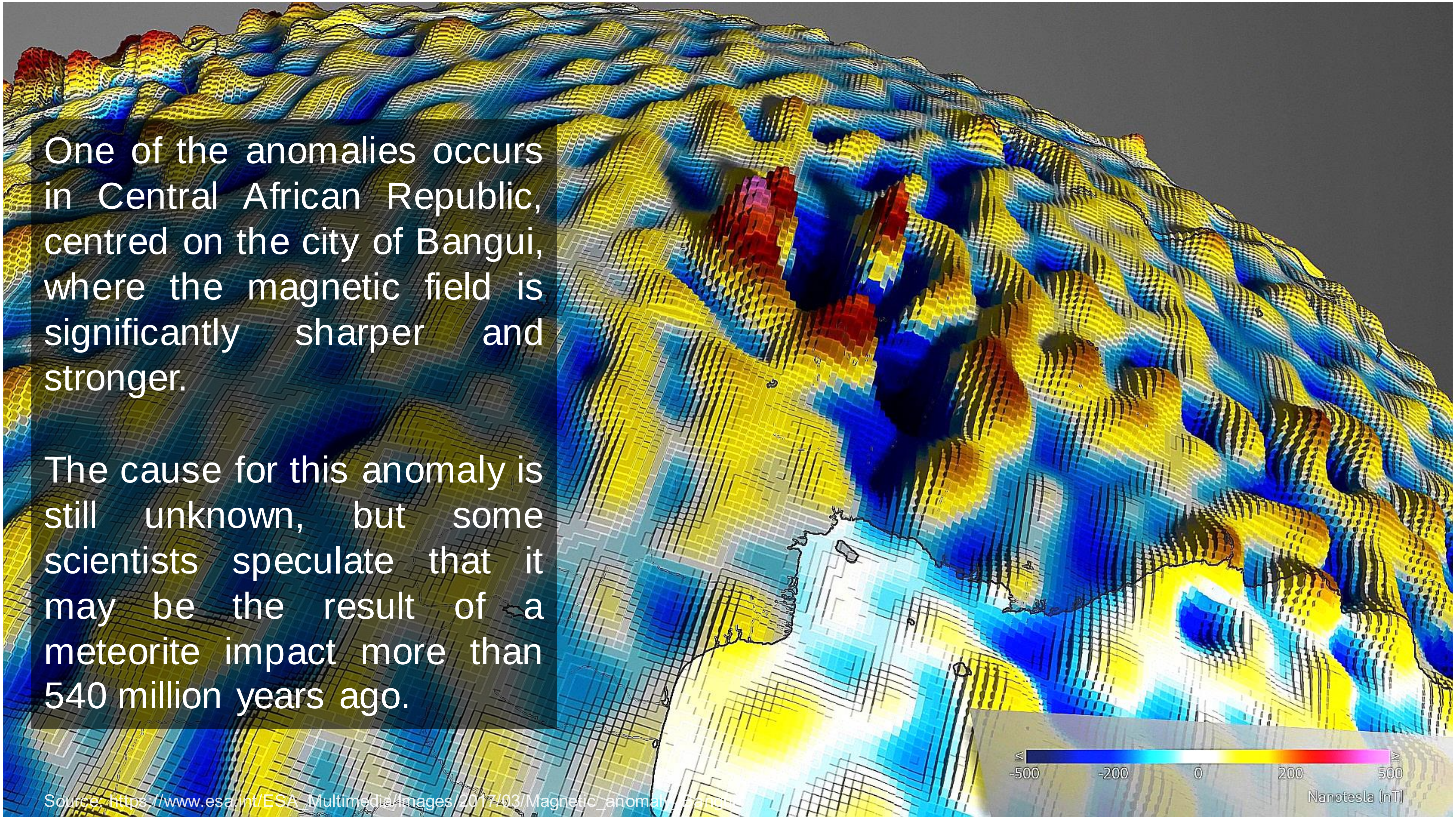
ESA’s Swarm satellites have led the discovery of a jet stream in the liquid iron part of Earth’s core 3000 km beneath the surface. In addition, Swarm satellite data show that this jet stream is speeding up.

SWARM (with CHAMP): Lithospheric Magnetic Field



The highest resolution map of Earth’s lithospheric magnetic field from space to date The dataset combines measurements from ESA’s Swarm satellites with historical data from the German CHAMP satellite using a new modelling technique that allowed scientists to extract tiny magnetic signals from Earth’s outer layer. Red represents areas where the lithospheric magnetic field is positive, while blue show areas where it is negative.

Magnetic anomaly: Bangui



One of the anomalies occurs in Central African Republic, centred on the city of Bangui, where the magnetic field is significantly sharper and stronger.

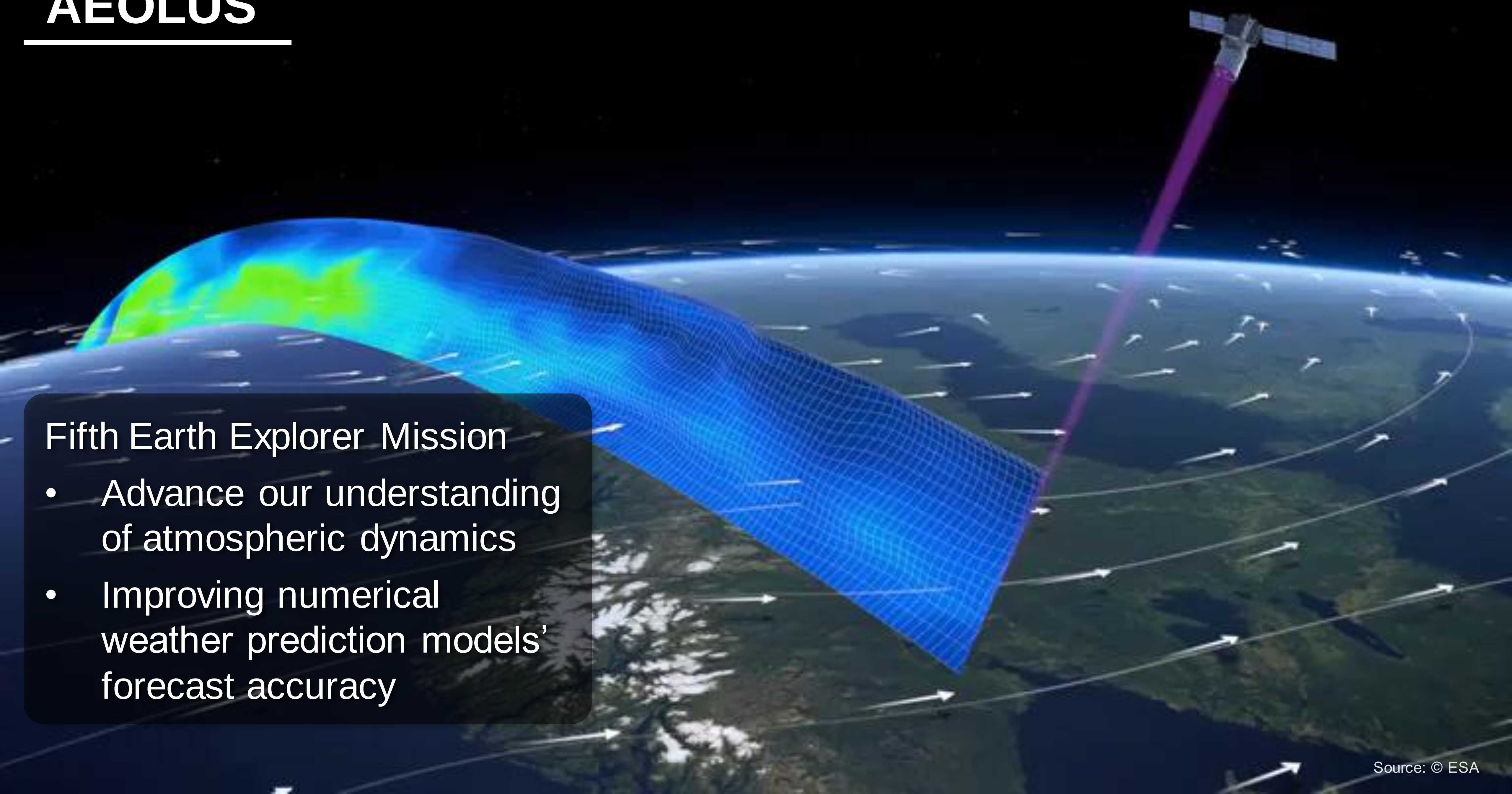
The cause for this anomaly is still unknown, but some scientists speculate that it may be the result of a meteorite impact more than 540 million years ago.

Source: https://www.esa.int/ESA_Multimedia/Images/2017/03/Magnetic_anomaly_Bangui

AEOLUS

Fifth Earth Explorer Mission

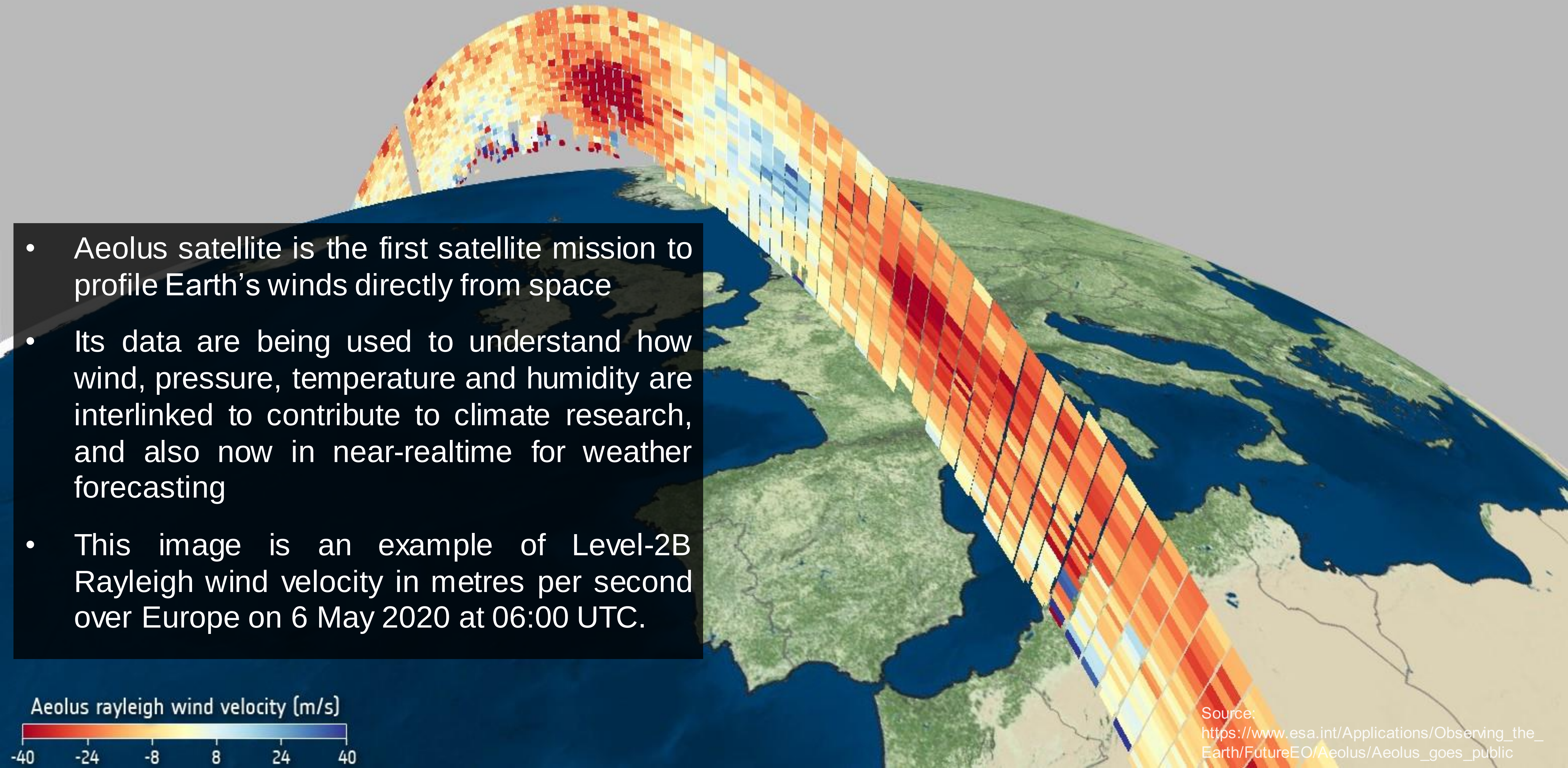
- Advance our understanding of atmospheric dynamics
- Improving numerical weather prediction models' forecast accuracy



Source: © ESA

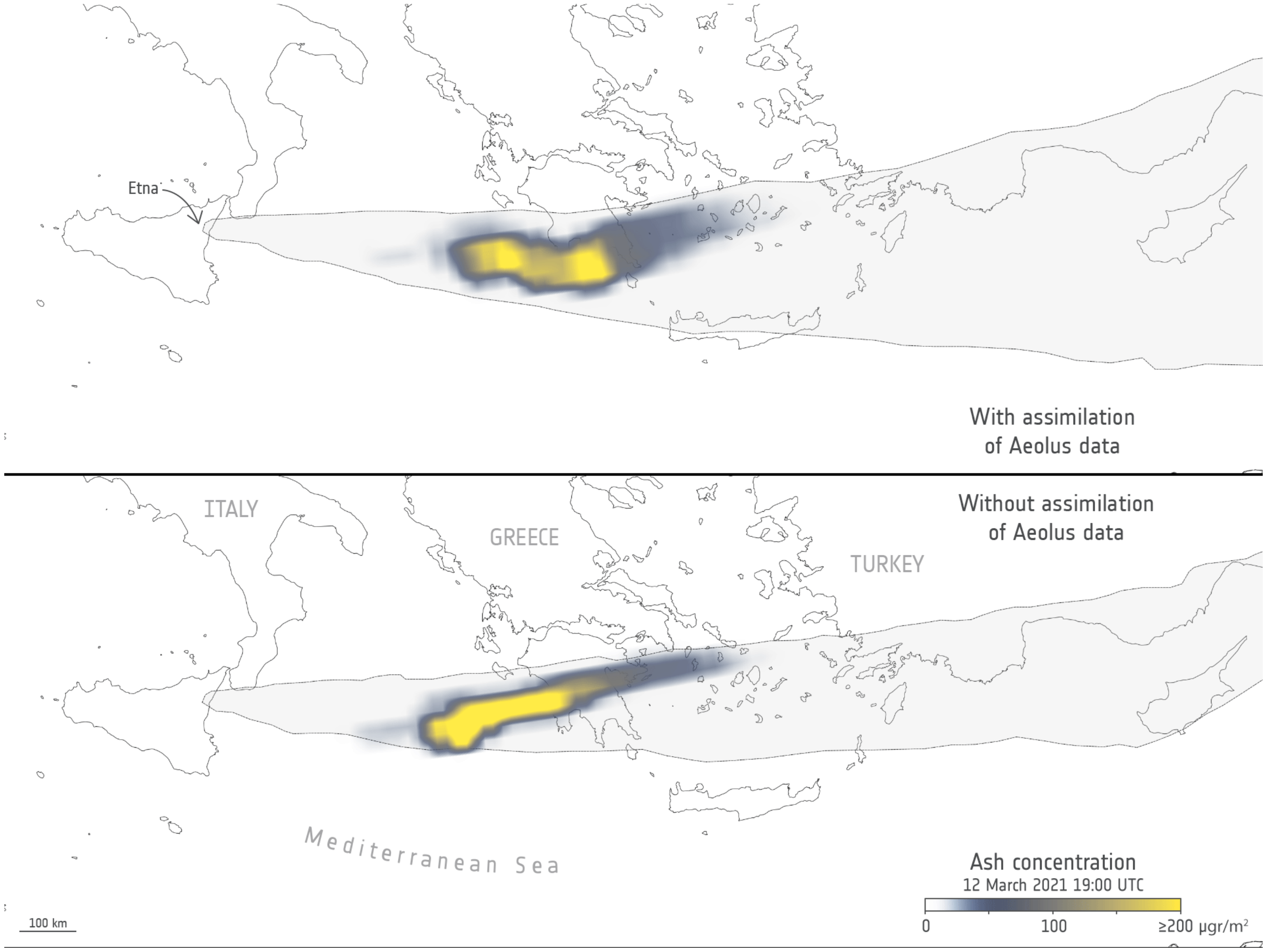
AEOLUS: Wind profiles

- Aeolus satellite is the first satellite mission to profile Earth’s winds directly from space
- Its data are being used to understand how wind, pressure, temperature and humidity are interlinked to contribute to climate research, and also now in near-realtime for weather forecasting
- This image is an example of Level-2B Rayleigh wind velocity in metres per second over Europe on 6 May 2020 at 06:00 UTC.



Source: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Aeolus/Aeolus_goes_public

AEOLUS: Ash plumes

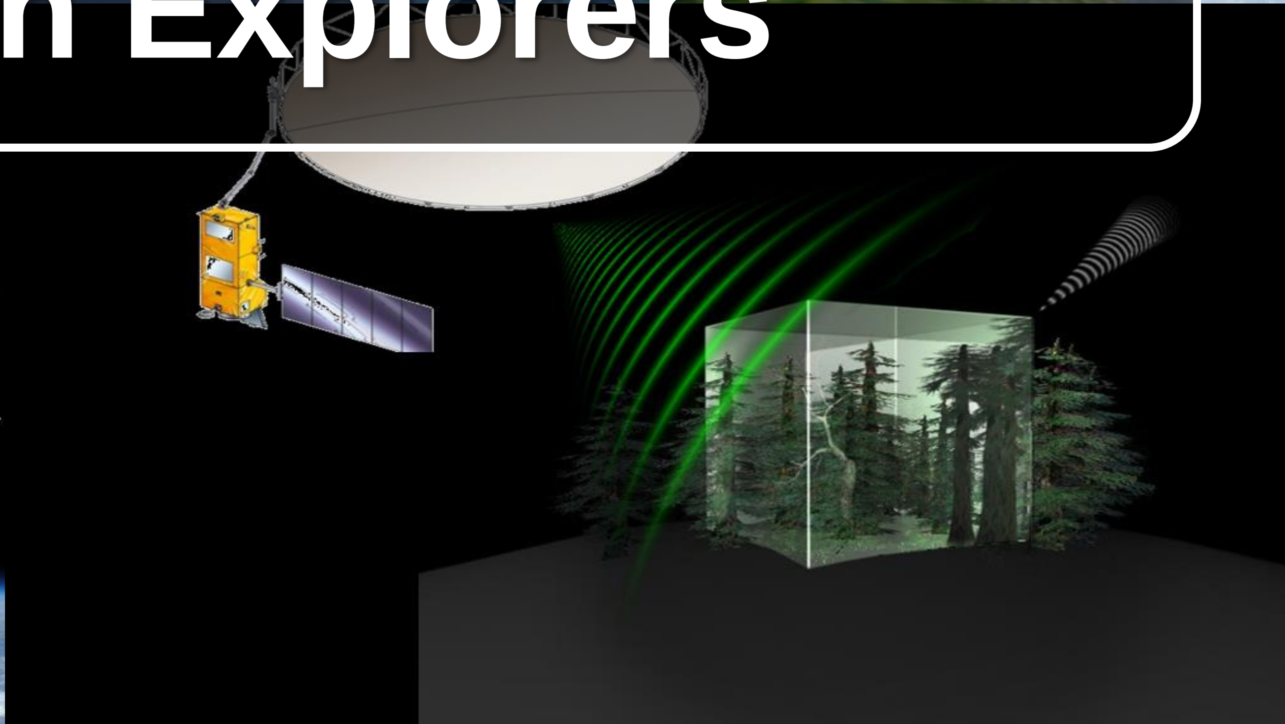


Source: https://www.esa.int/ESA_Multimedia/Images/2023/05/Flights_crossing_the_Mount_Etna_volcanic_ash_plume

The ash plume after an eruption at Mount Etna on 12 March 2021 travelling over Greece, with and without Aeolus data assimilation.

Forecasting volcanic ash in the atmosphere is crucial for aviation

Future Earth Explorers



Source: ESA artist's concept by P. Carril, ESA/ATG medialab,
https://www.esa.int/ESA_Multimedia/Images/2013/12/Artist_s_view_of_EarthCARE2,
https://casi.ca/resources/Documents/AERO/2019/Abstracts%20Submitted/2019-06-ESA-EO-ASTRO.pdf

Upcoming Earth Explorers

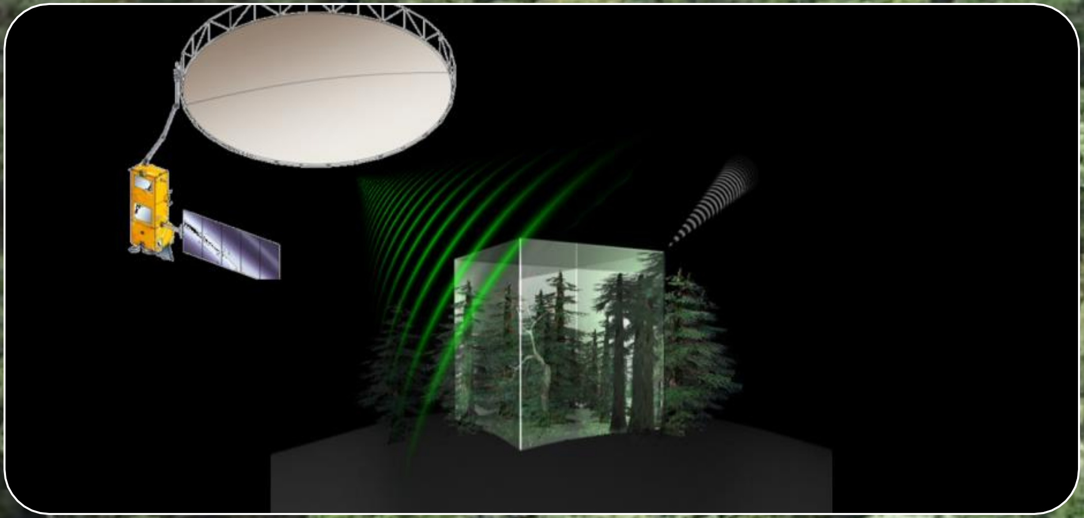
6

EarthCARE

- Clouds, aerosols & radiation
- High preformance lidar tech.
- Partnership JAXA
- Launch planned 2021

Source:ESA, JAXA, https://earthcare-val.esa.int/, https://amsweatherband.org/index.cfm/weatherband/articles/may-15-2022-mammatus-and-lightning-story-the-war-of-the-worlds/

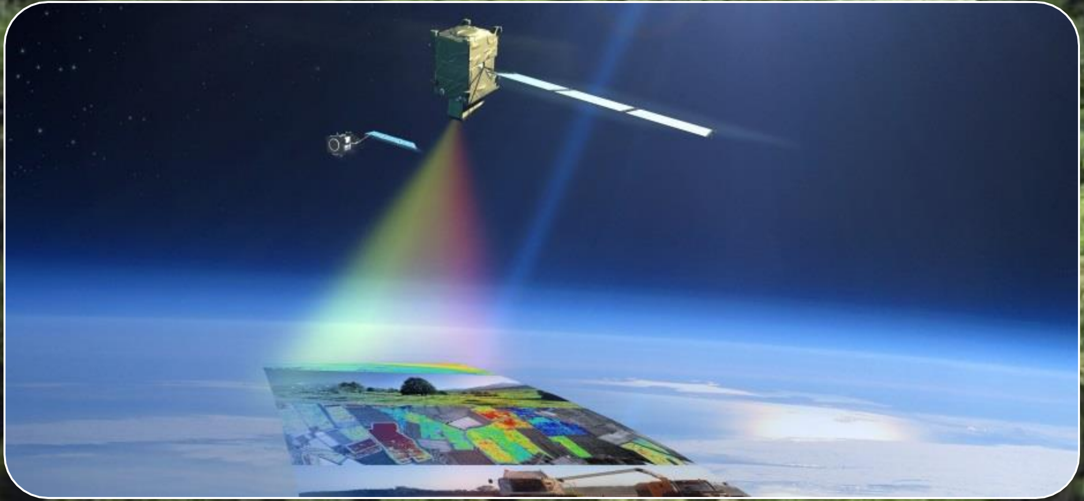
Upcoming Earth Explorers



7

Biomass

- Biomass estimates
- First P-band SAR in space
- Launch planned 2022



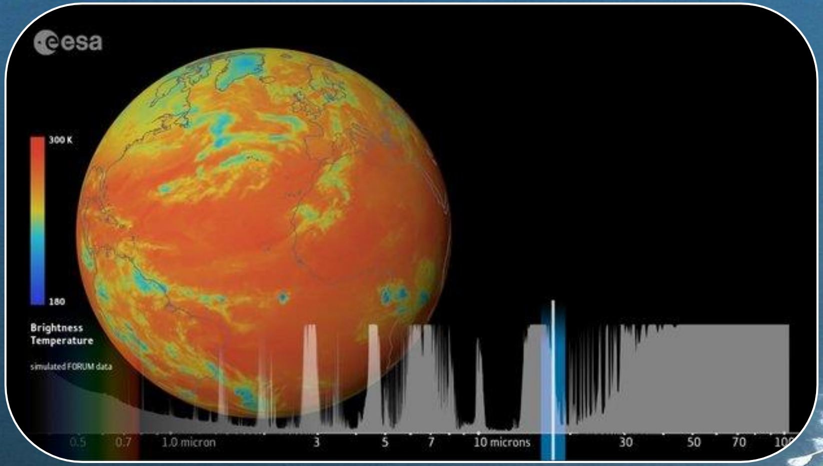
8

FLEX

- Vegetation fluorescence, indicator of photosynthesis
- Launch planned 2022

Source:ESA, https://casi.ca/resources/Documents/AERO/2019/Abstracts%20Submitted/2019-06-ESA-EO-ASTRO.pdf /, ESA/ATG medialab, https://education.nationalgeographic.org/resource/rain-forest/

Future missions



9

FORUM

- Planet’s radiation budget
- improve climate models
- Launch planned 2027

10

Harmony

- High-resolution observations of motion occurring at or near Earth’s surface
- Launch planned 2029

Source:https://www.forum-ee9.eu/the-forum-mission-is-selected/, https://www.esa.int/Applications/Observing_the_Earth/FutureEO/ESA_selects_Harmony_as_tenth_Earth_Explorer_mission, https://www.esa.int/ESA_Multimedia/Images/2022/03/Flying_over_the_Wadden_Sea_for_Harmony

Future missions

11

Earth Explorer 11

- Four mission ideas were selected to enter pre-feasibility study in June 2021:
- **Cairt** (changing-atmosphere IR tomography),
- **Nitrosat** (measuring NO2 and NH3),
- **Wivern** (measuring wind in clouds, delivering profiles of rain, snow and ice water)
- **Seastar** (providing ocean surface current and surface wind vectors at 1 km resolution for all the coastal ocean, shelf seas and marginal ice zones)
- Launch planned 2031-2032

Source:https://eo4society.esa.int/event/earth-explorer-11-user-consultation-meeting/

Future missions

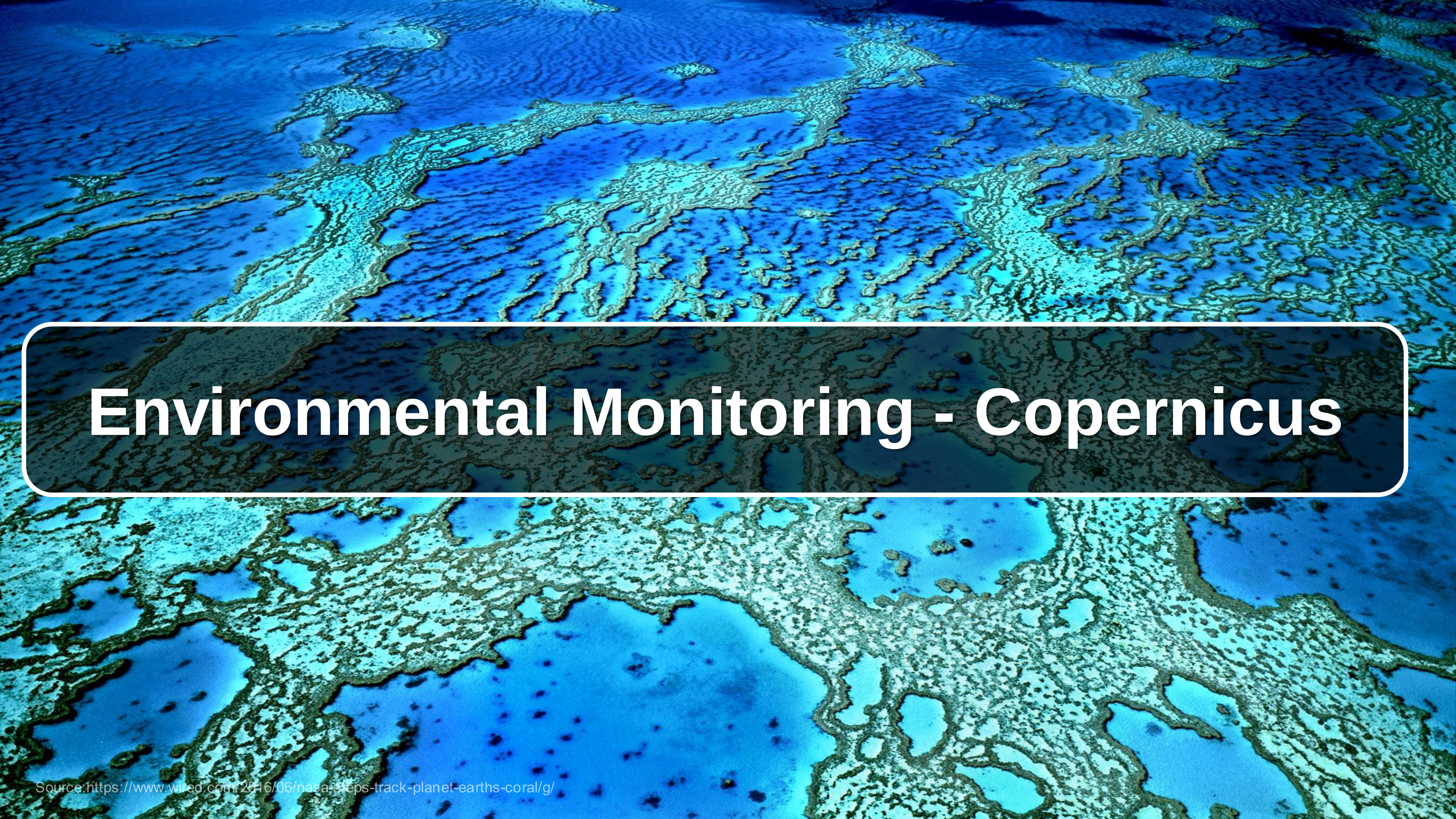
12

Earth Explorer 12

- A Call for Ideas was issued on 20 February 2023. The deadline to submit a full proposal is 29 September 2023

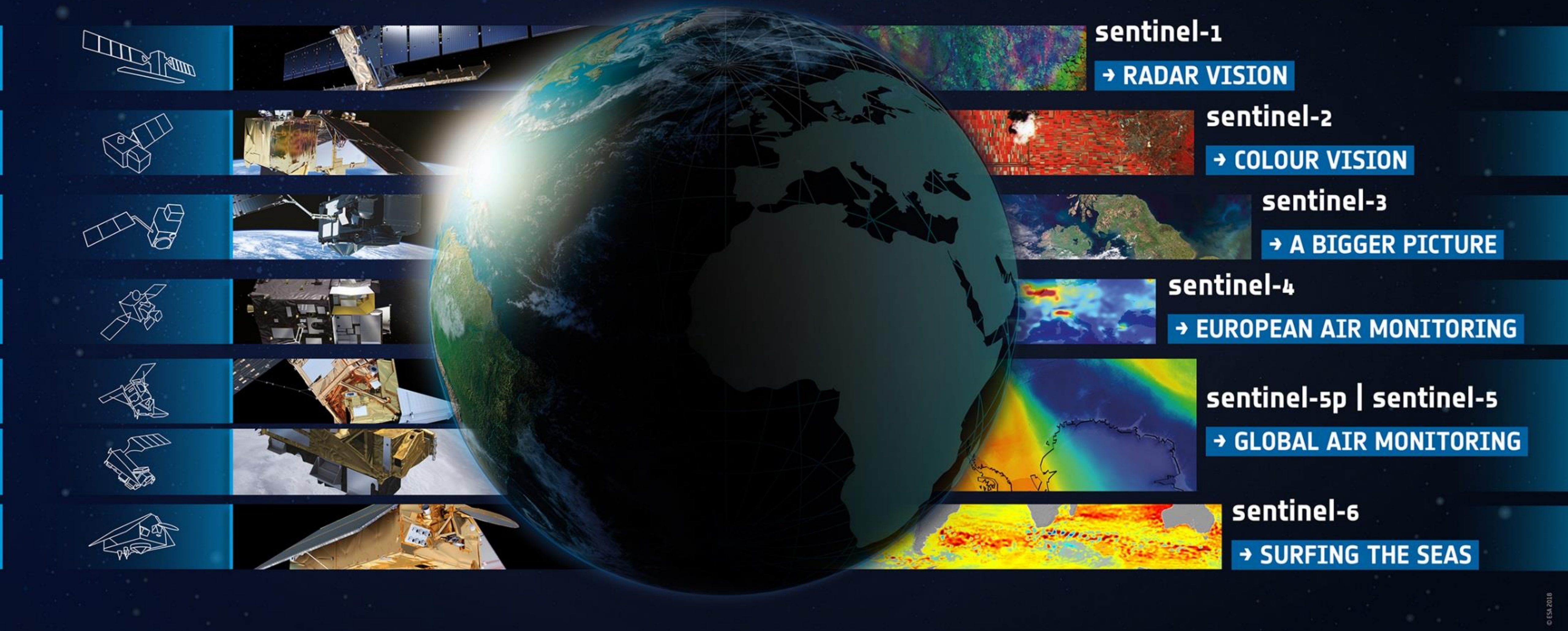
Source:https://eo4society.esa.int/event/earth-explorer-11-user-consultation-meeting/

Environmental Monitoring - Copernicus



Source:https://www.wired.com/2016/06/nasa-steps-track-planet-earths-coral/g/

Environmental Monitoring: Copernicus Sentinels



Source:ESA

Copernicus – a new Phase in EO

European response to global needs:

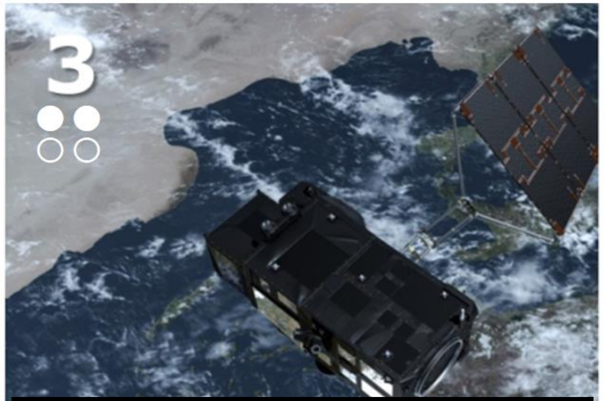
- to manage the environment
- to mitigate the effects of climate change
- to ensure civil security

European independence, contribution to global system (GEOSS)

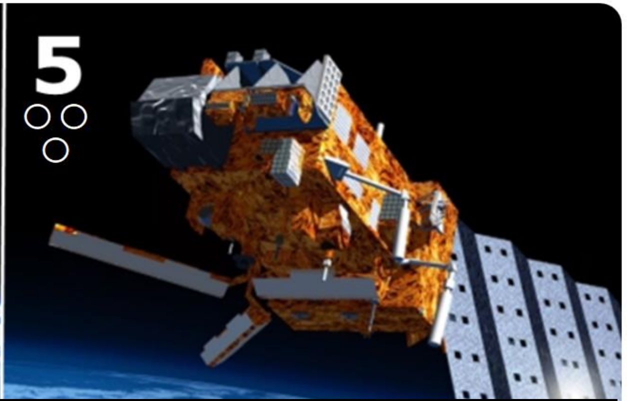
Source: https://sentinels.copernicus.eu/web/sentinel/videos

Copernicus - the largest producer of EO data in the world

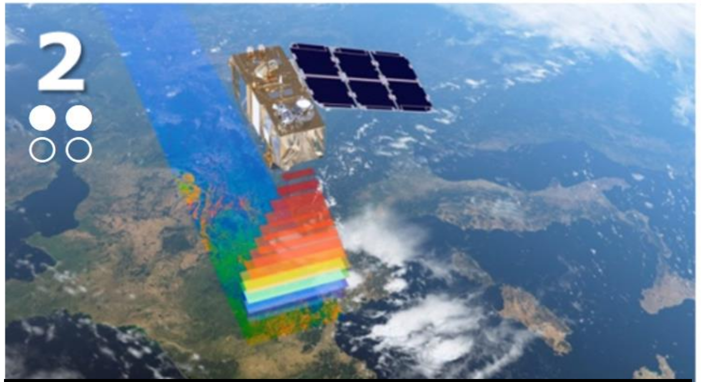
Sentinel-1 (A/B) – SAR imaging
All weather, day/night applications, interferometry



Sentinel-3 (A/B) – Ocean and global land monitoring

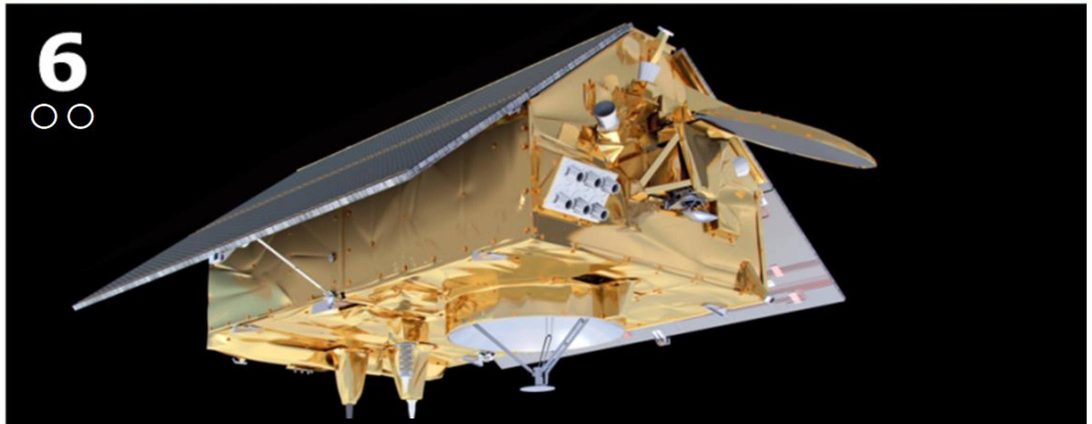


Sentinel-5 precursor/ Sentinel-5 (A/B) – Low Earth-orbit Atmospheric composition monitoring



Sentinel-2 (A/B) – Multi-spectral imaging, Land applications: urban, forest, agriculture,…

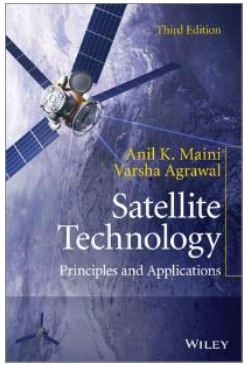
Sentinel-4 (A/B) – Geostationary atmospheric



Sentinel 6 - Jason-CS (A/B) – Low inclination Altimetry
Sea-level, wave height and marine wind speed

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

Further reading



Satellite Technology: Principles and Applications, 3rd Edition

Fully updated edition of the comprehensive, single-source reference on satellite technology and its applications Covering both the technology and its applications, Satellite Technology is a concise reference on satellites for commercial, scientific and military purposes. The book explains satellite technology fully, beginning by offering an introduction to the fundamentals,

www.wiley.com

- https://www.wiley.com/en-us/Satellite+Technology:+Principles+and+Applications,+3rd+Edition-p-9781118636459

VŠ učebnica - EO-ESA

Earth Observations with ESA missionje projekt, ktorý je riešený na základe zmluvy Contact No.4000133959/21/NL/SC medzi Európskou vesmírnou agentúrou ESA, inštitúciou ESTEC – The European Space Research and Technology Centre a Technickou univerzitou v Košiciach, Fakultou baníctva, ekológie, riadenia a geotechnológií, v rámci 5. projektovej výzvy programu PECS – Plan for European Cooperating States.

eo-esa.fberg.tuke.sk

https://eo-esa.fberg.tuke.sk/vysokoskolska-ucebnica/

History of Europe in space

www.esa.int

https://www.esa.int/About_Us/ESA_history/History_of_Europe_in_space

2. ESA EO Data Access and resources, including Third Party missions, applications of Copernicus Earth Observation data

ESA EO Data Access and resources

Sourcehttps://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

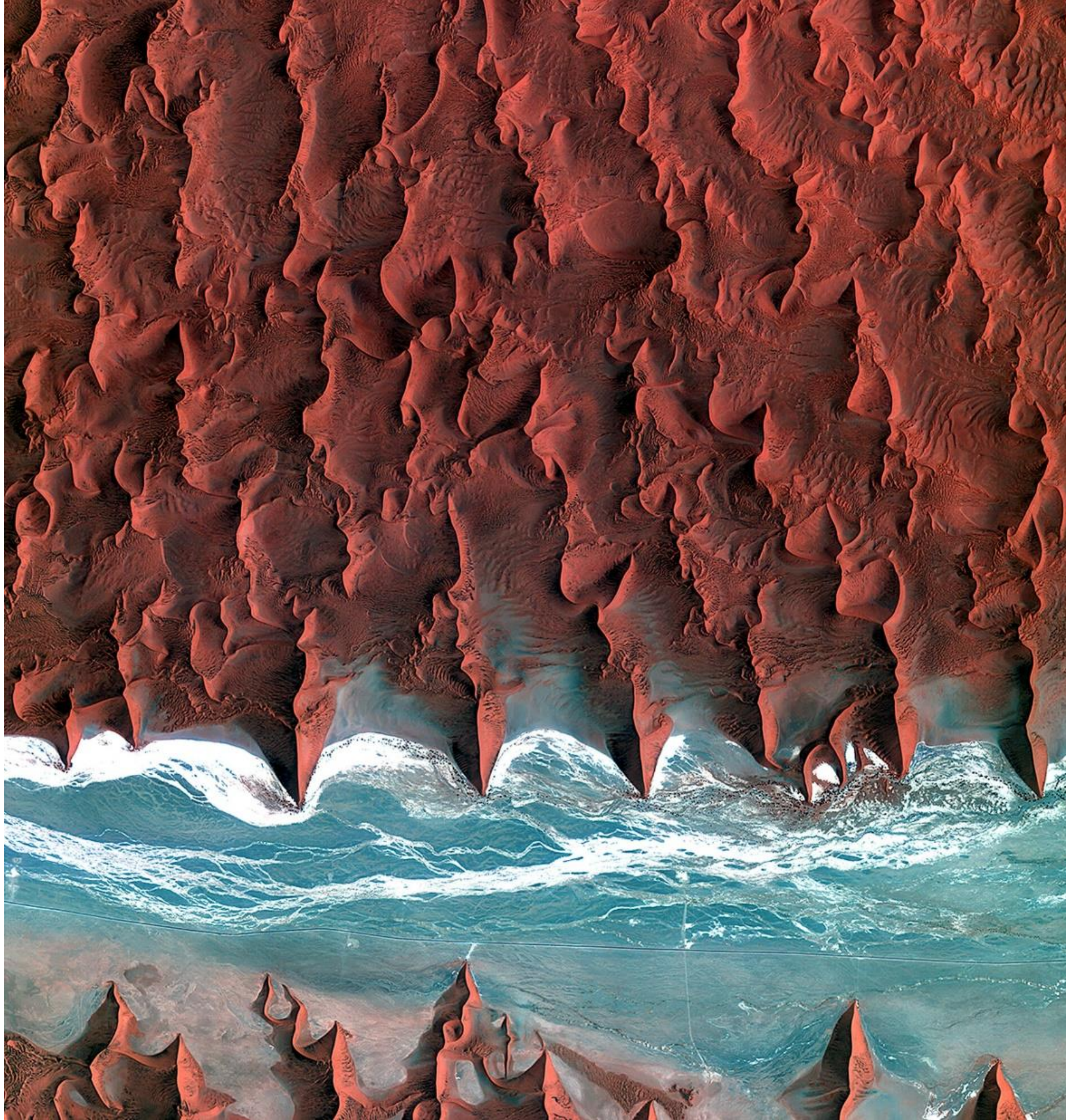
Source: https://www.esa.int/Applications/Observing_the_Earth/Envisat/ESA_declares_end_of_mission_for_Envisat, https://earth.esa.int/eogateway/news/esa-s-excellent-earth-explorer-missions-extended-to-2025/esa-s-ice-mission , https://www.esa.int/ESA_Multimedia/Images/2012/12/Pleiades#.XoNYGqecnA8.link

EO data access

Free open source platforms

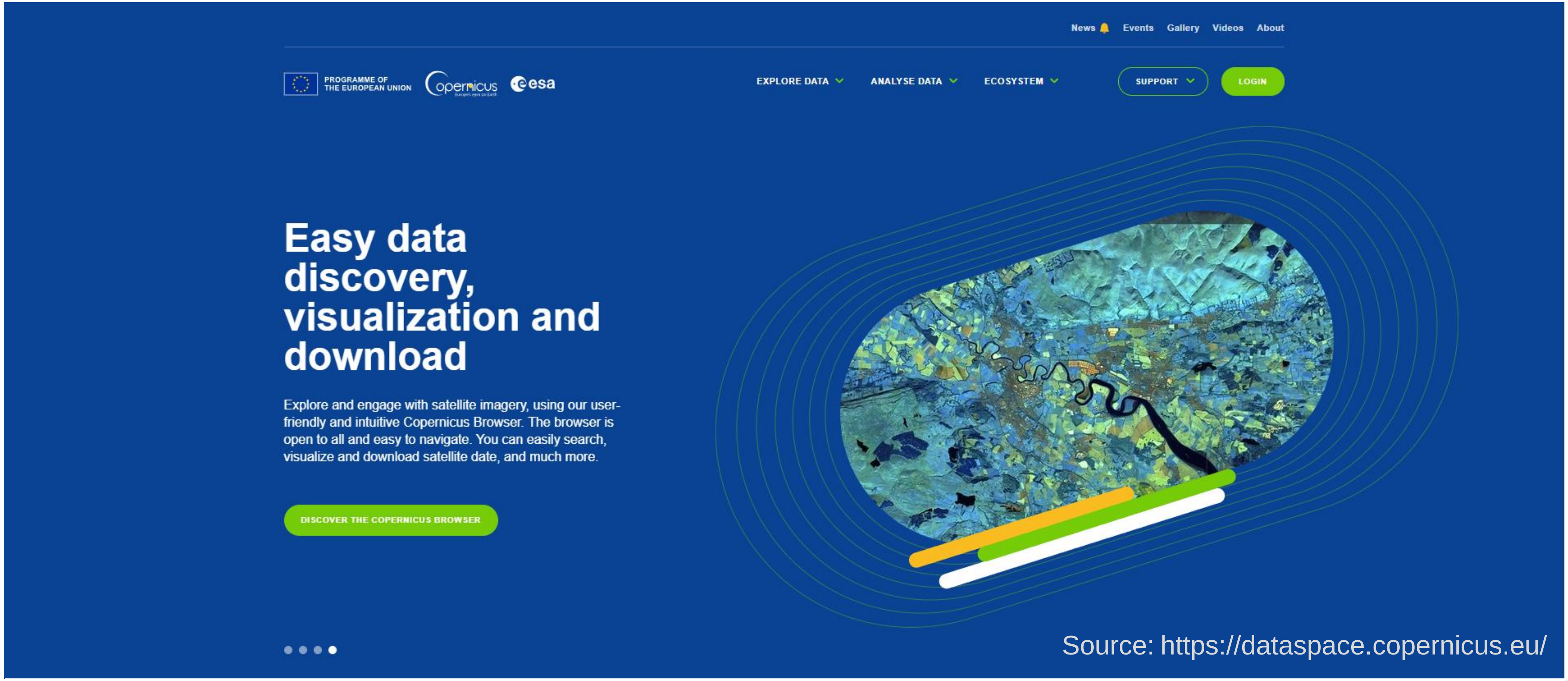
- **Copernicus Open Access Hub**
- Earth System Lab
- ESA Thematic Exploitation Platforms
- Alaska Satellite Facility
- Copernicus Global Land Service
- **Copernicus Data Space Ecosystem**
- **Sentinel Data Access Service**
- USGS Earth Explorer
- Sentinel Application Platform software
- Open Data Cube

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/

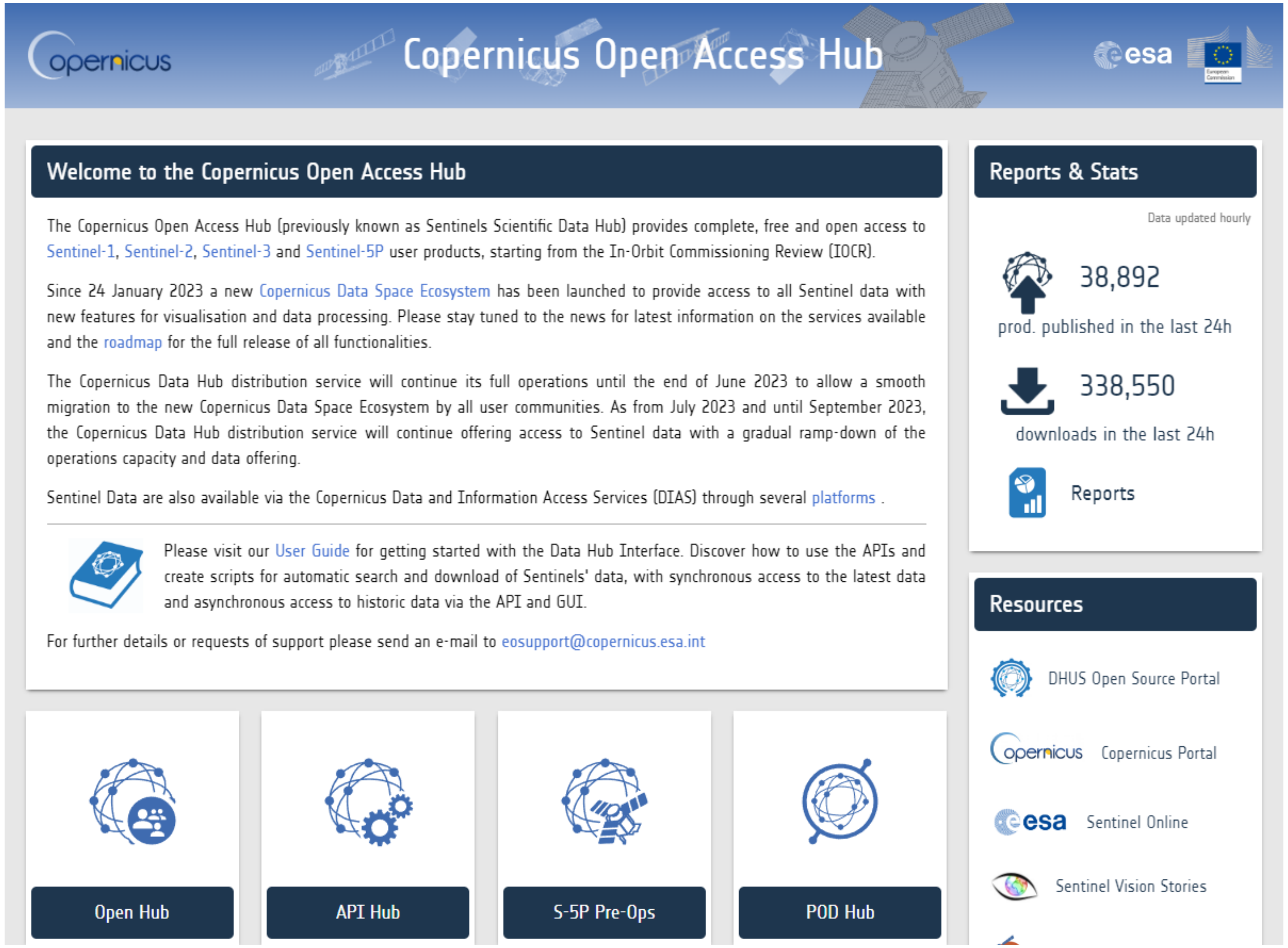


Source: https://dataspace.copernicus.eu/

- 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/

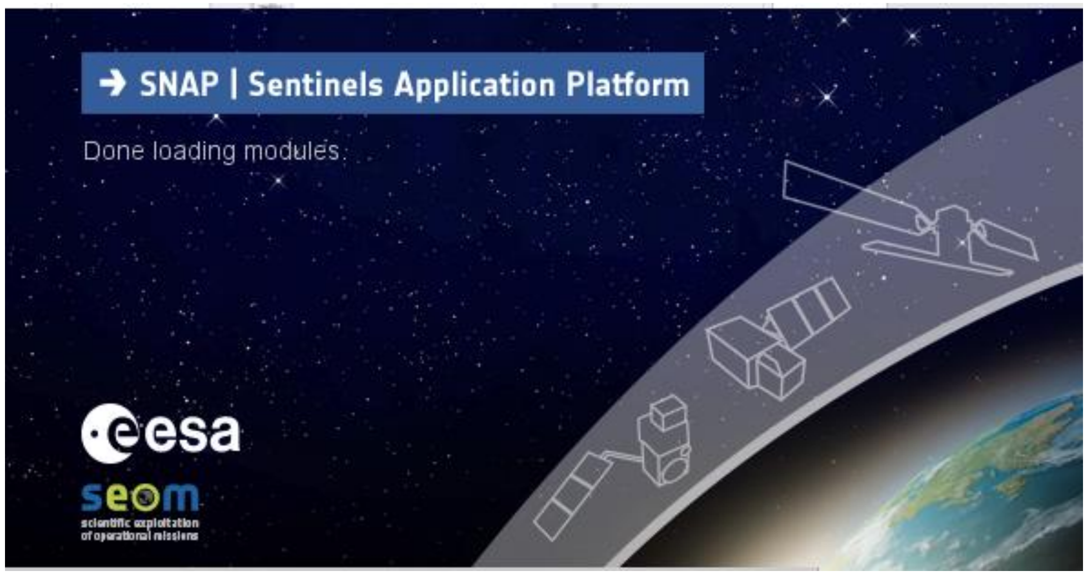


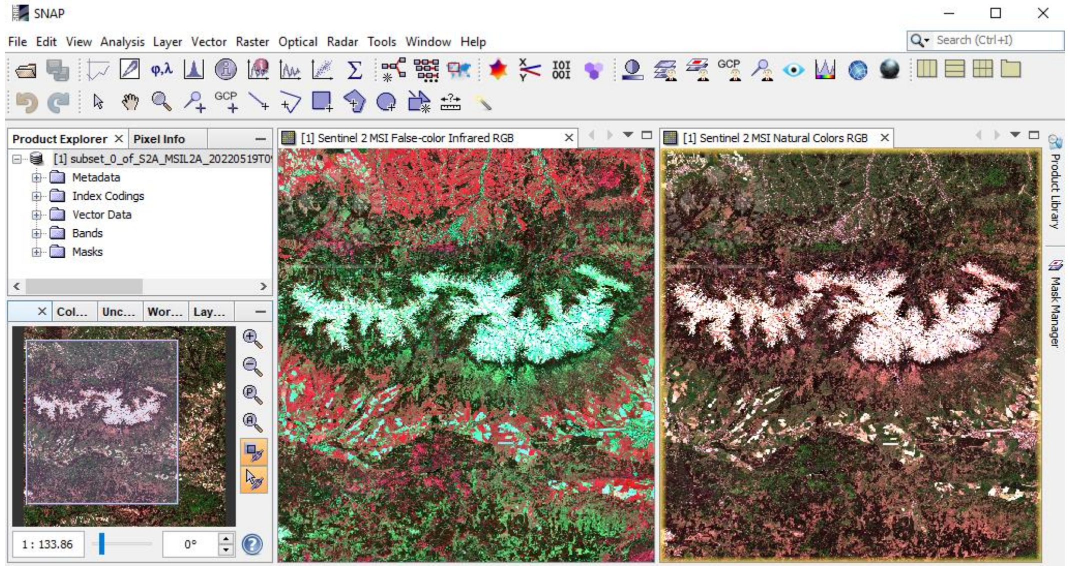
Source: https://scihub.copernicus.eu

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

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

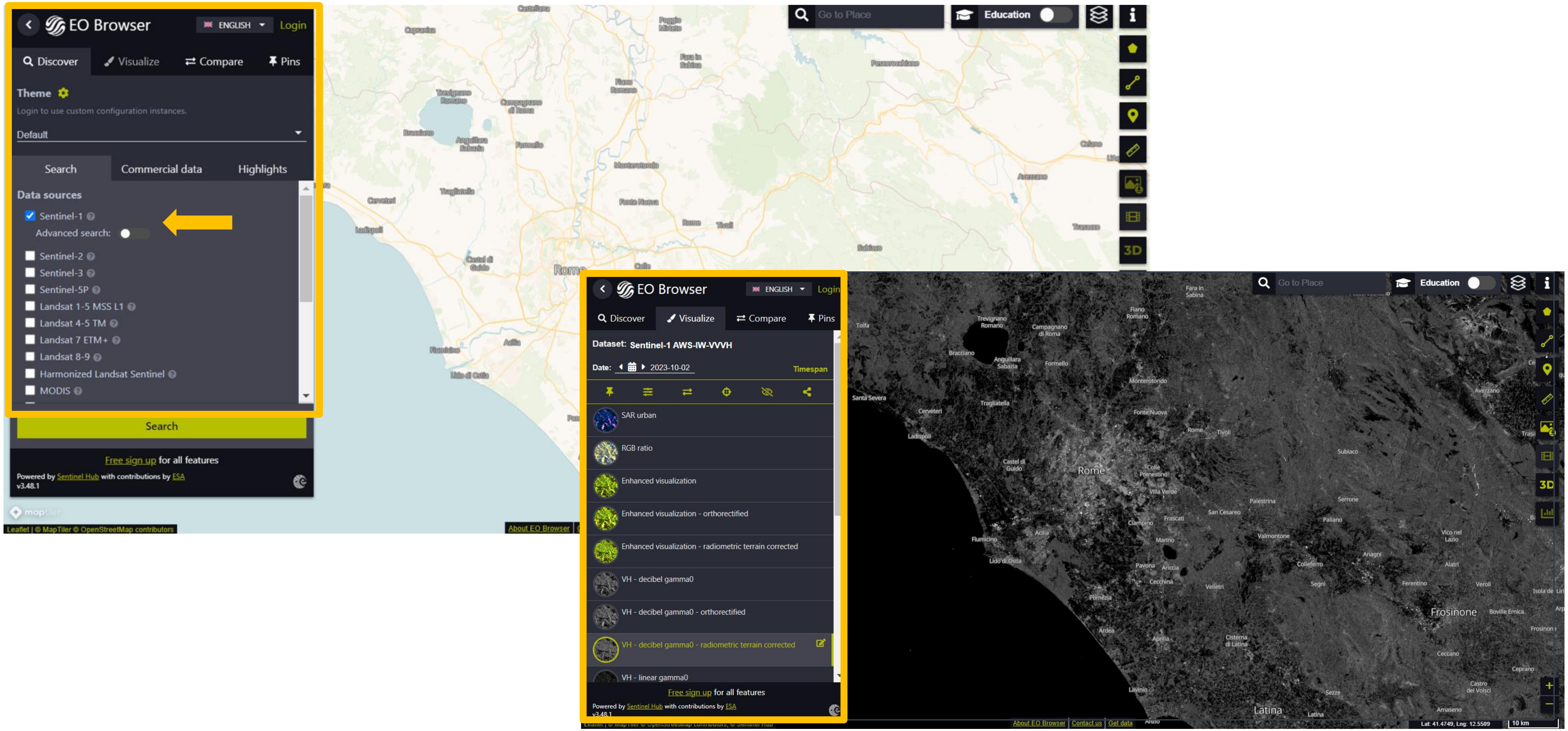
- **EO Browser Sentinel Hub**
- DIAS - Copernicus Data & Information Access Services
- Google Earth Engine
- Earth on AWS

For more information, see the tutorial: [2. ESA EO Data Access and Selection, applications of Copernicus Earth Observation data]

Source: https://www.esa.int/ESA_Multimedia/Images/2017/03/The_Karavasta_Lagoon_in_Albania_looks_spectacular/

EO Browser - SENTINEL Hub

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

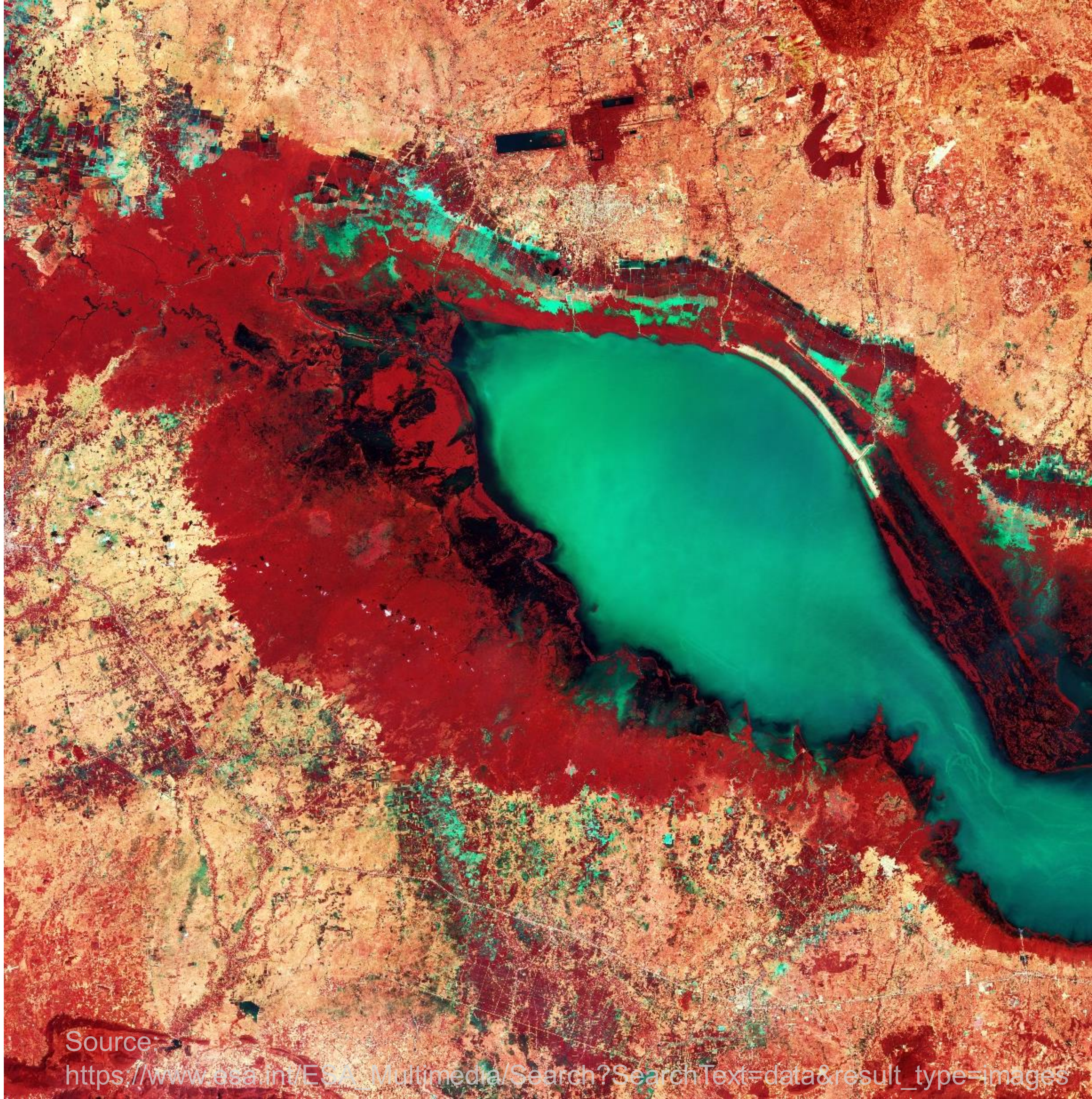


Source: https://apps.sentinel-hub.com/eo-browser

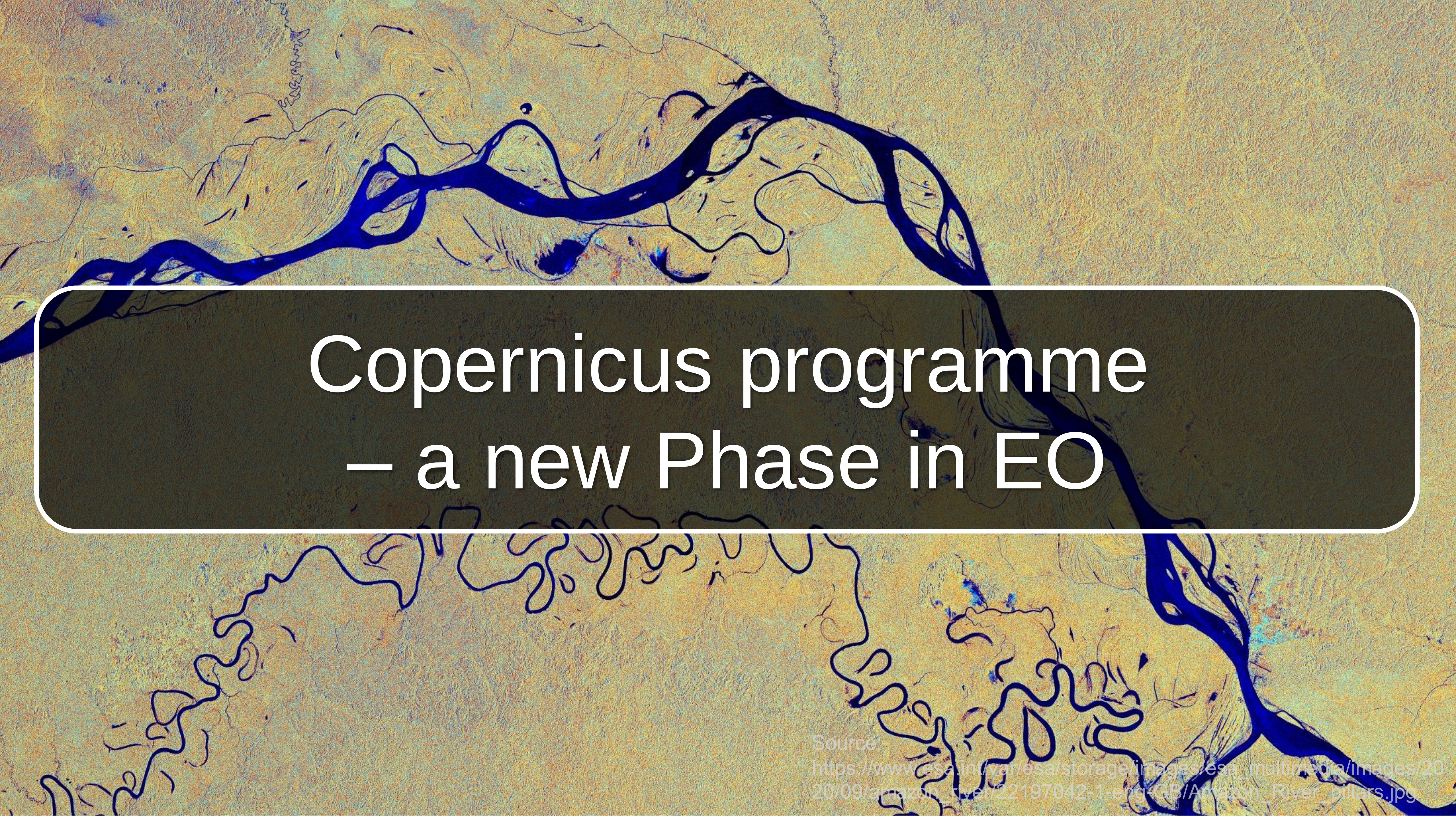
EO data access

Commercial EO platforms

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



Copernicus programme – a new Phase in EO

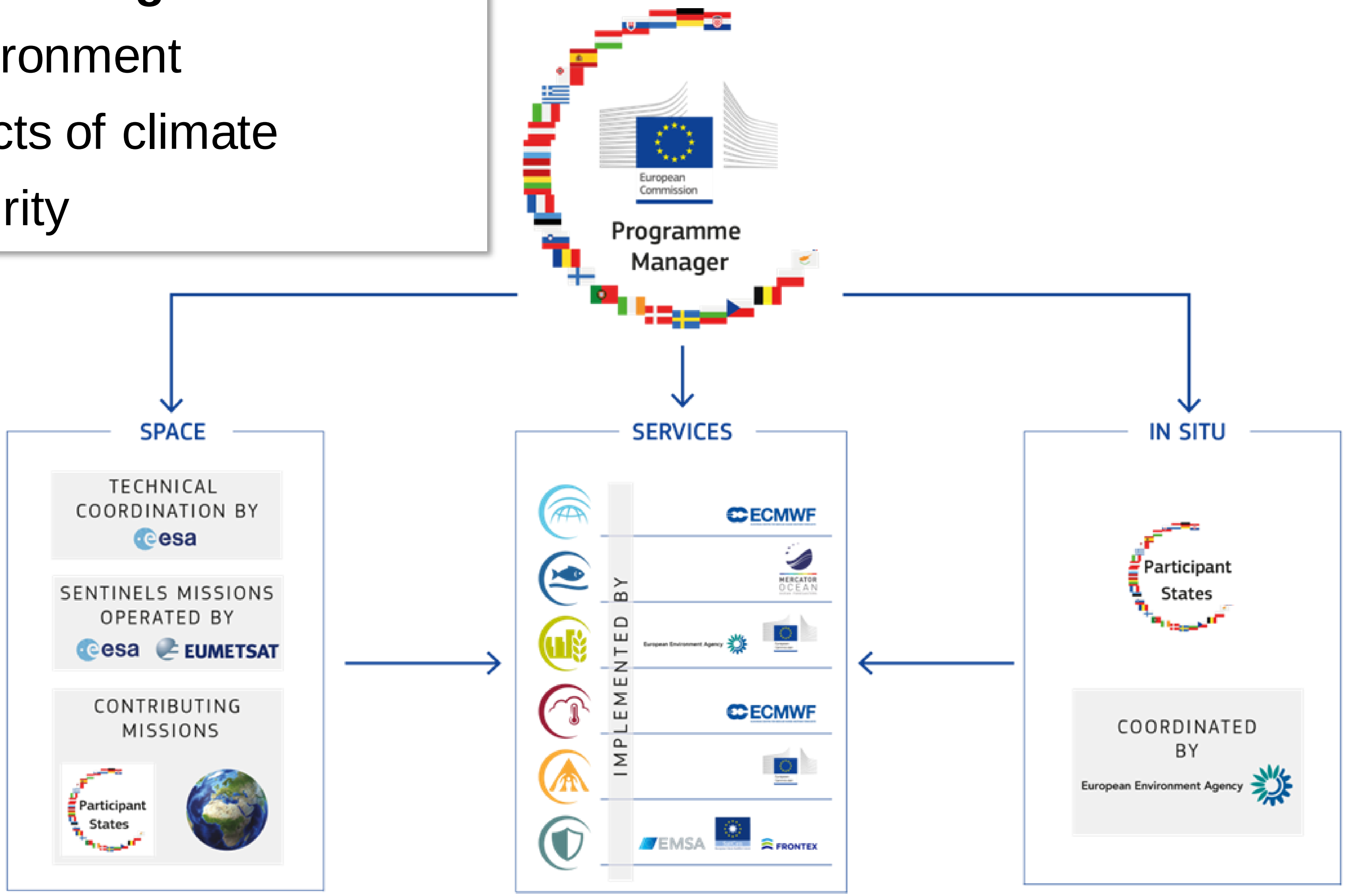


Source: https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2020/09/amazon_river/22197042-1-eng-GB/Amazon_River_pillars.jpg

Copernicus purpose and architecture

→ European response to global needs:

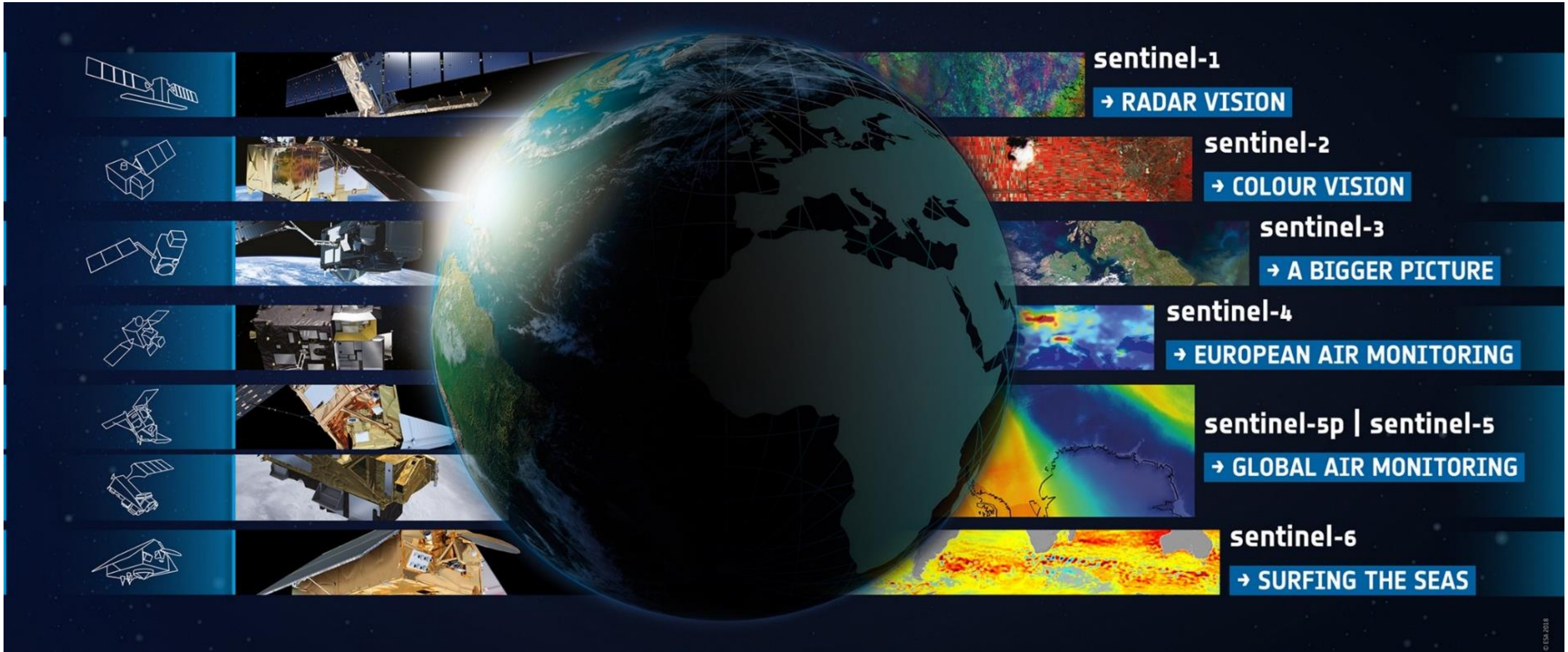
- to manage the environment
- to mitigate the effects of climate
- to ensure civil security



Space component

The Earth observation satellites which provide the data exploited by the Copernicus services are split into two groups of missions:

- Sentinels - developed for the specific needs of the Copernicus programme
  - Sentinel-1, -2, -3, -5P, -6, - Sentinel-4, -5



Space component

- Contributing Missions
  - operated by National, European or International organisations
  - already provide a wealth of data for Copernicus services

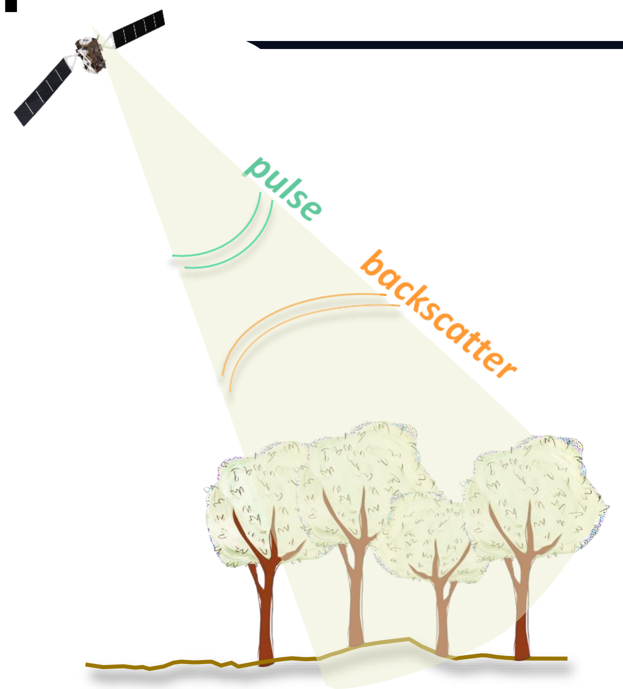
Sentinel-1 – Radar vision

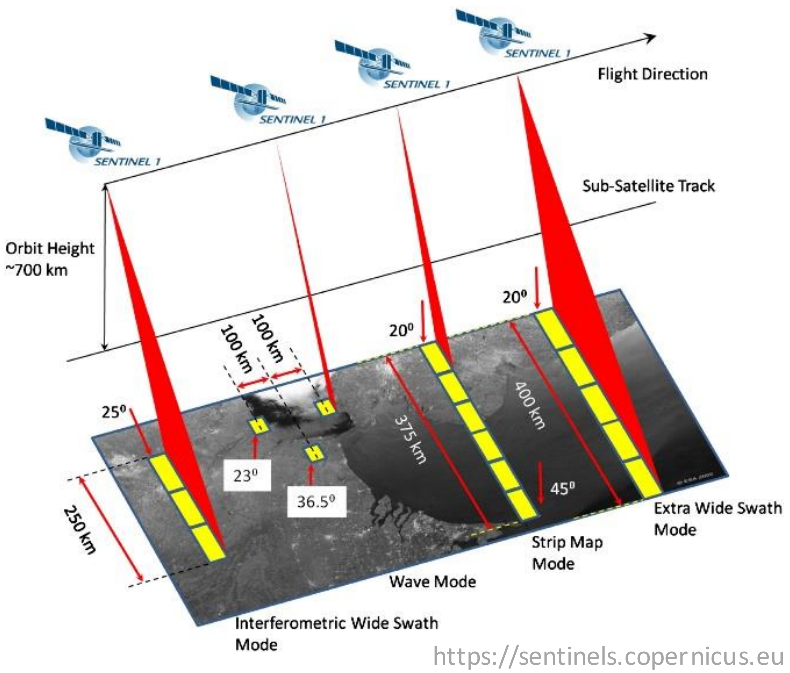
Mission objectives:

- Marime and land monitoring
- Emergency management

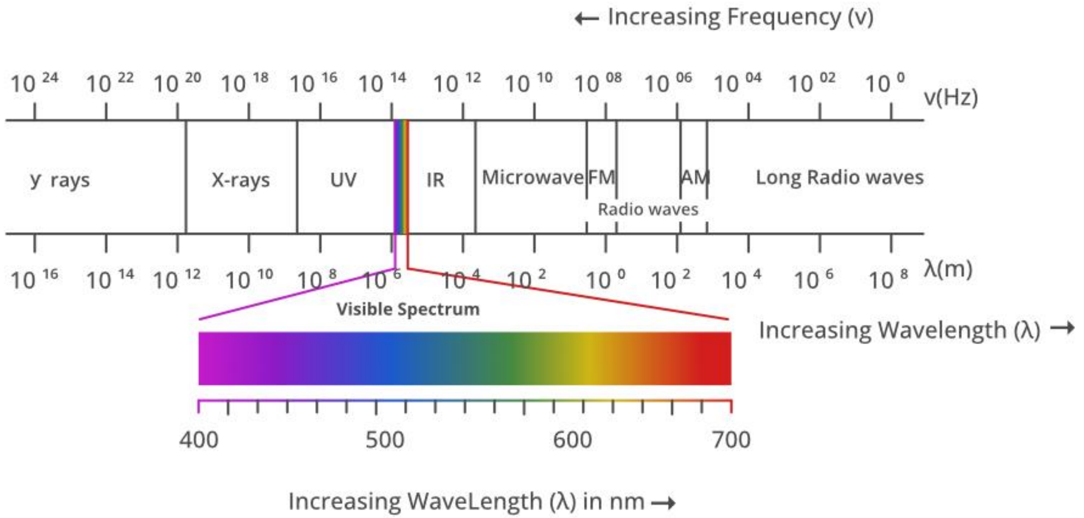
Mission profile:

- 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



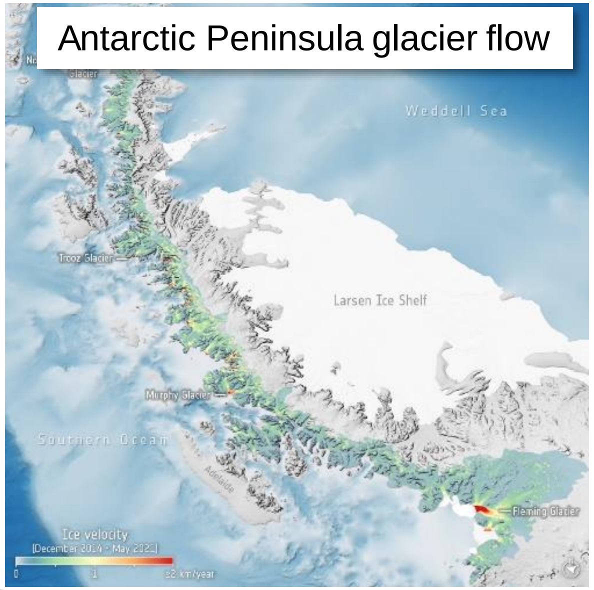


https://sentinels.copernicus.eu

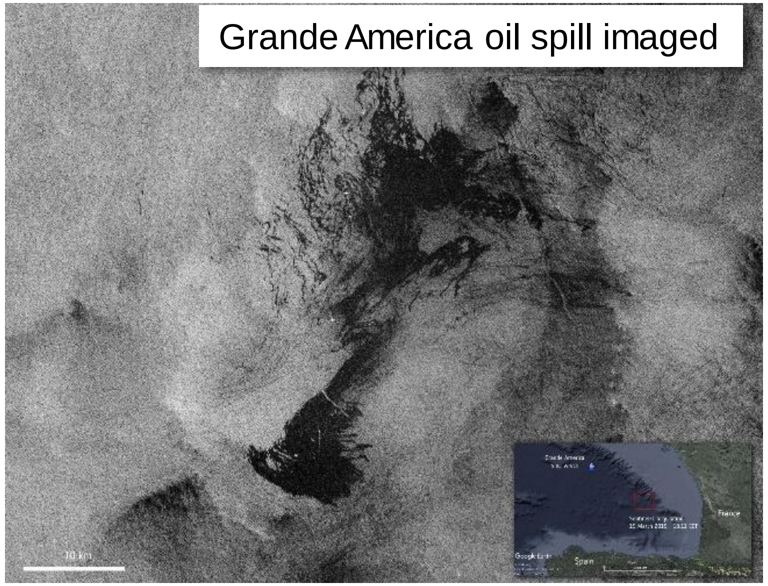


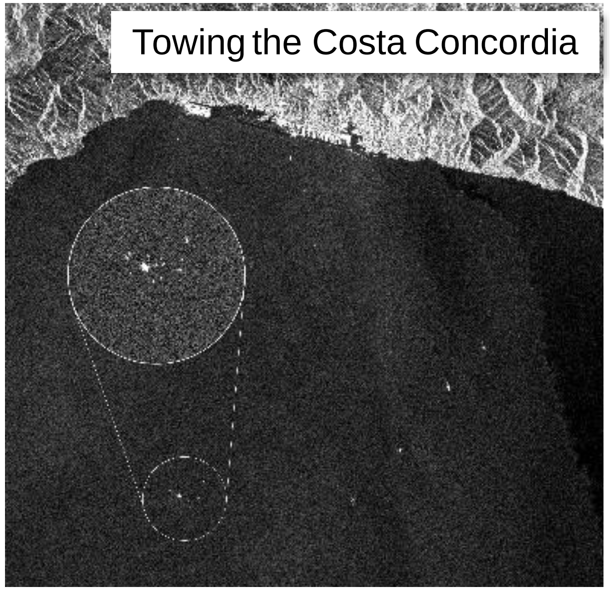
Sentinel-1 – Applications

Maritime surveillance:
- Ice Monitoring
- Oil Spill Monitoring
- Ship Detection
- Marine Winds, Etc.

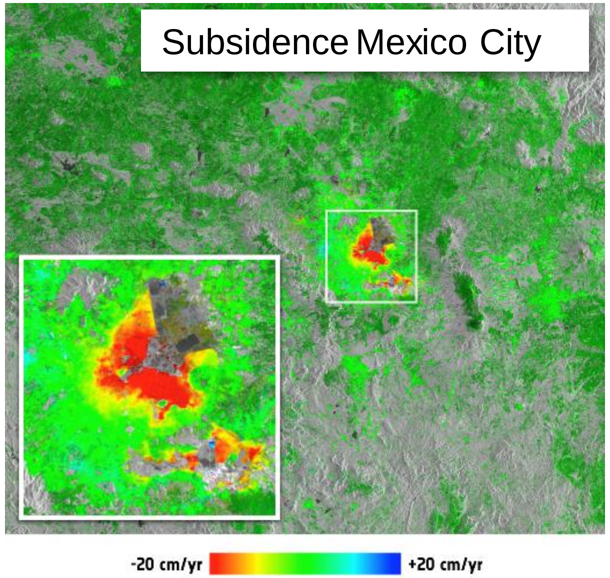


Antarctic Peninsula glacier flow


Grande America oil spill imaged

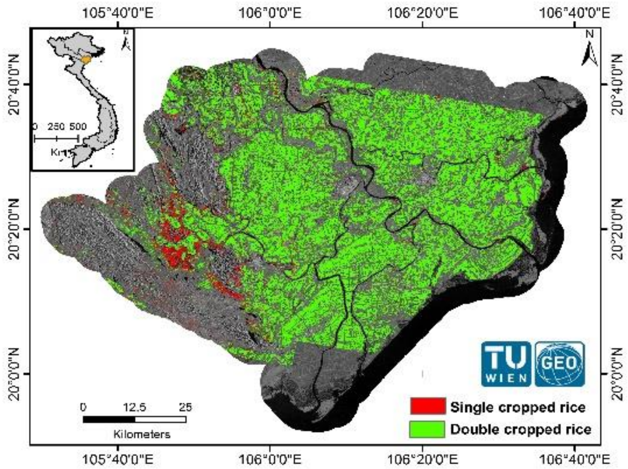

Towing the Costa Concordia

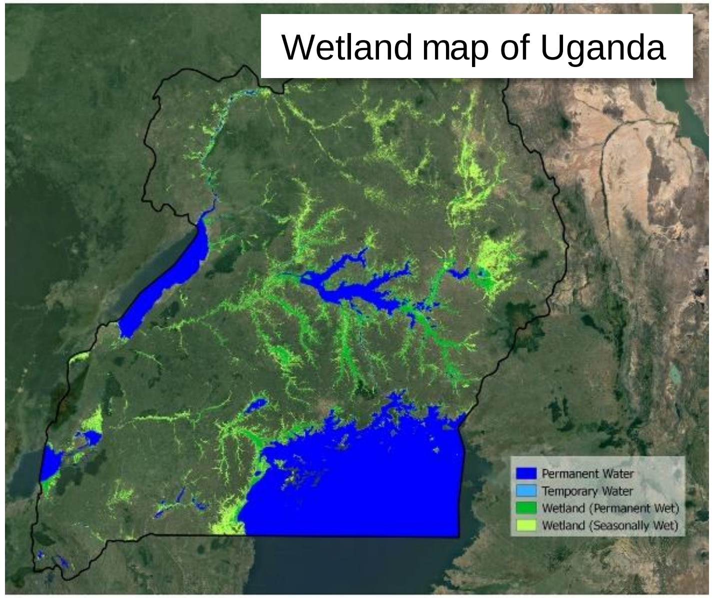
Land monitoring
- Forestry
- Agriculture
- Ground deformation
- Urban planning
- Soil Moisture, Etc.



Subsidence Mexico City

Rice-cropping systems in Vietnam's Red River Delta



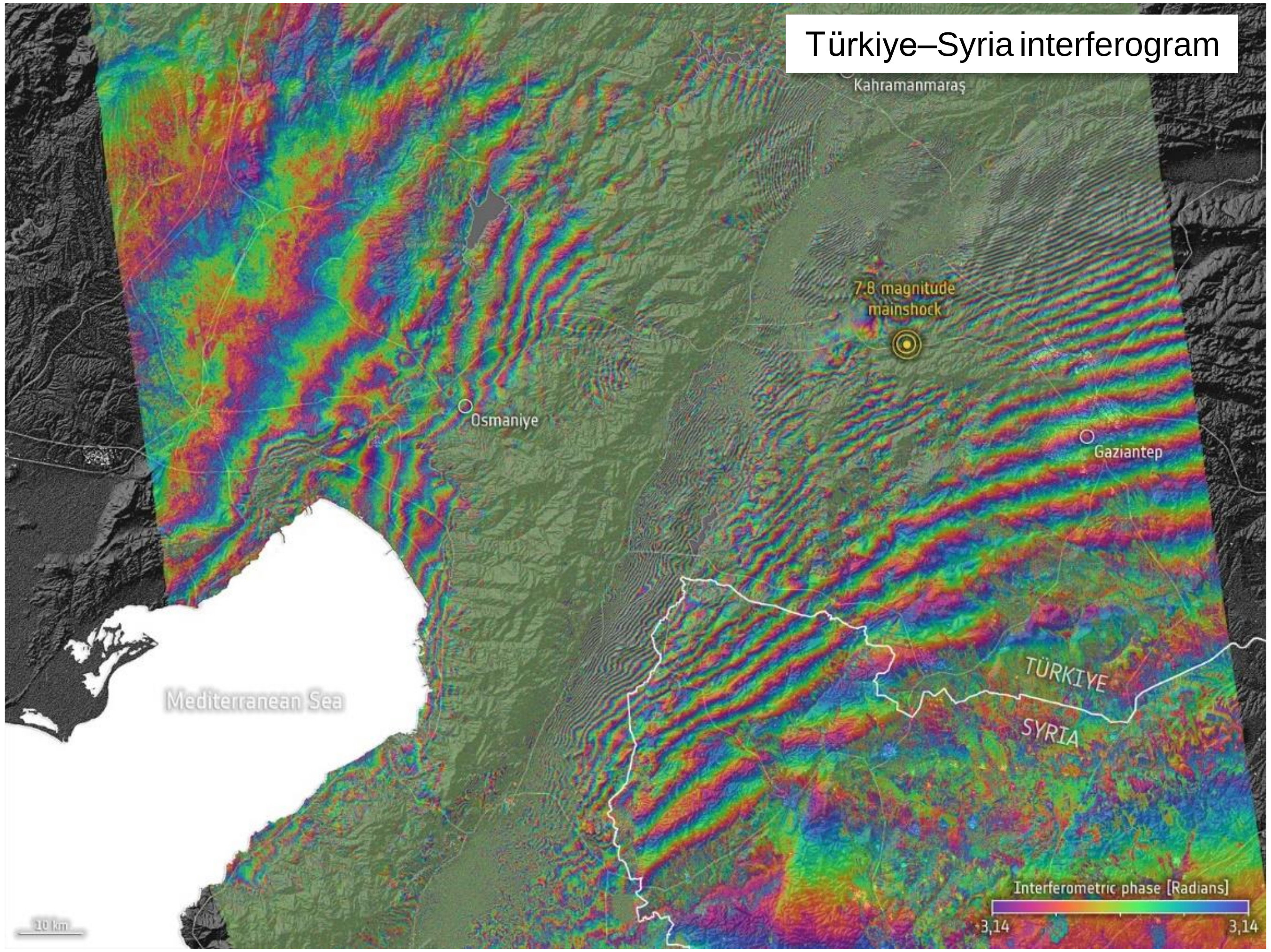


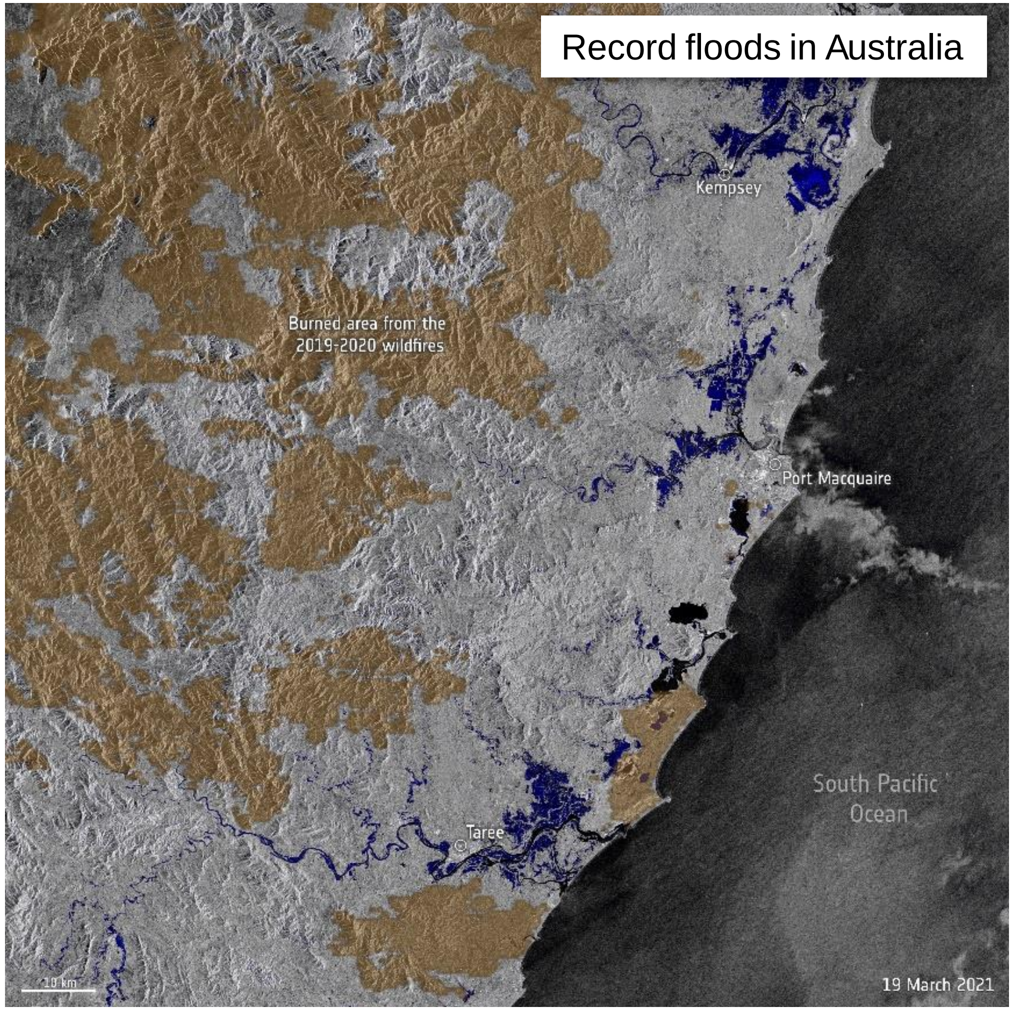
Wetland map of Uganda

Sentinel-1 – Applications

Emergency management:

- Flood Monitoring
- Earthquake Analysis
- Landslide and volcano monitoring, etc.





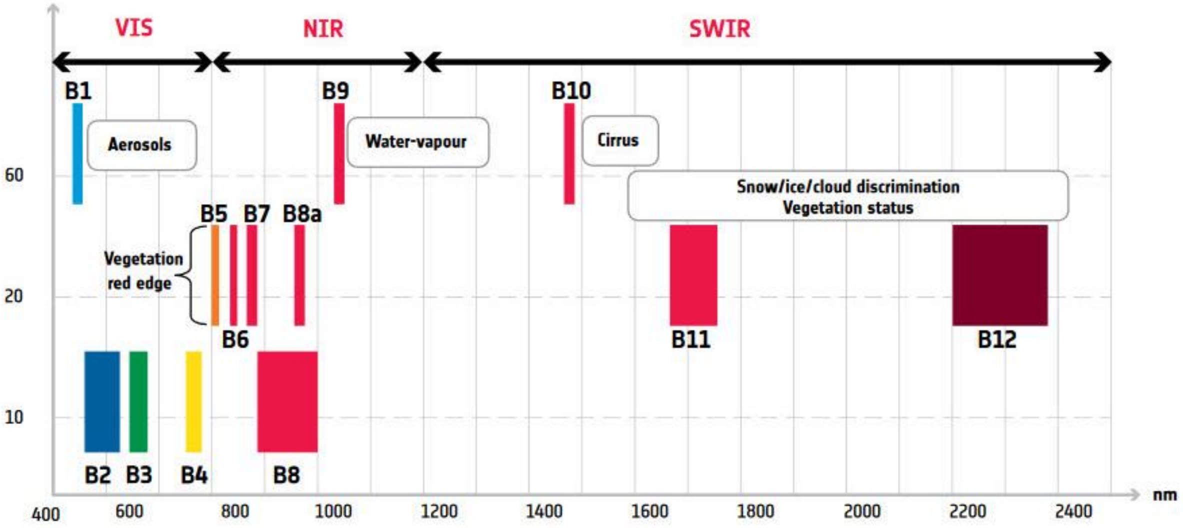
Sentinel-2 – Color vision

Mission objectives:

- Land management
- Agriculture
- Forestry
- Humanitarian relief operations
- Risk mapping and security concerns

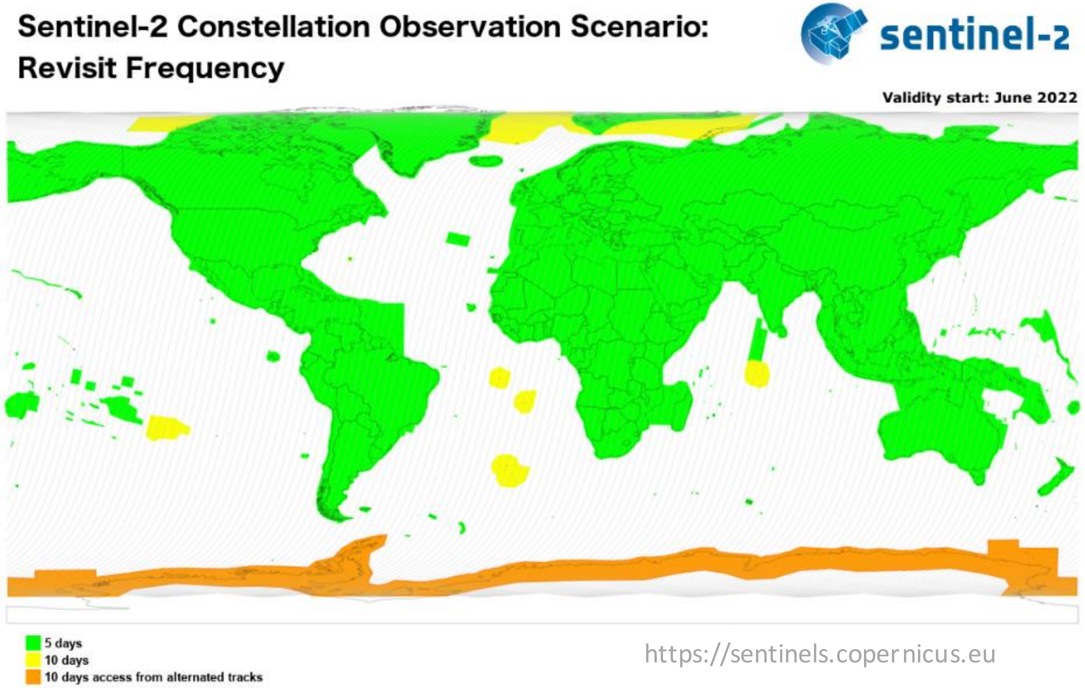
Mission profile:

- 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



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

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

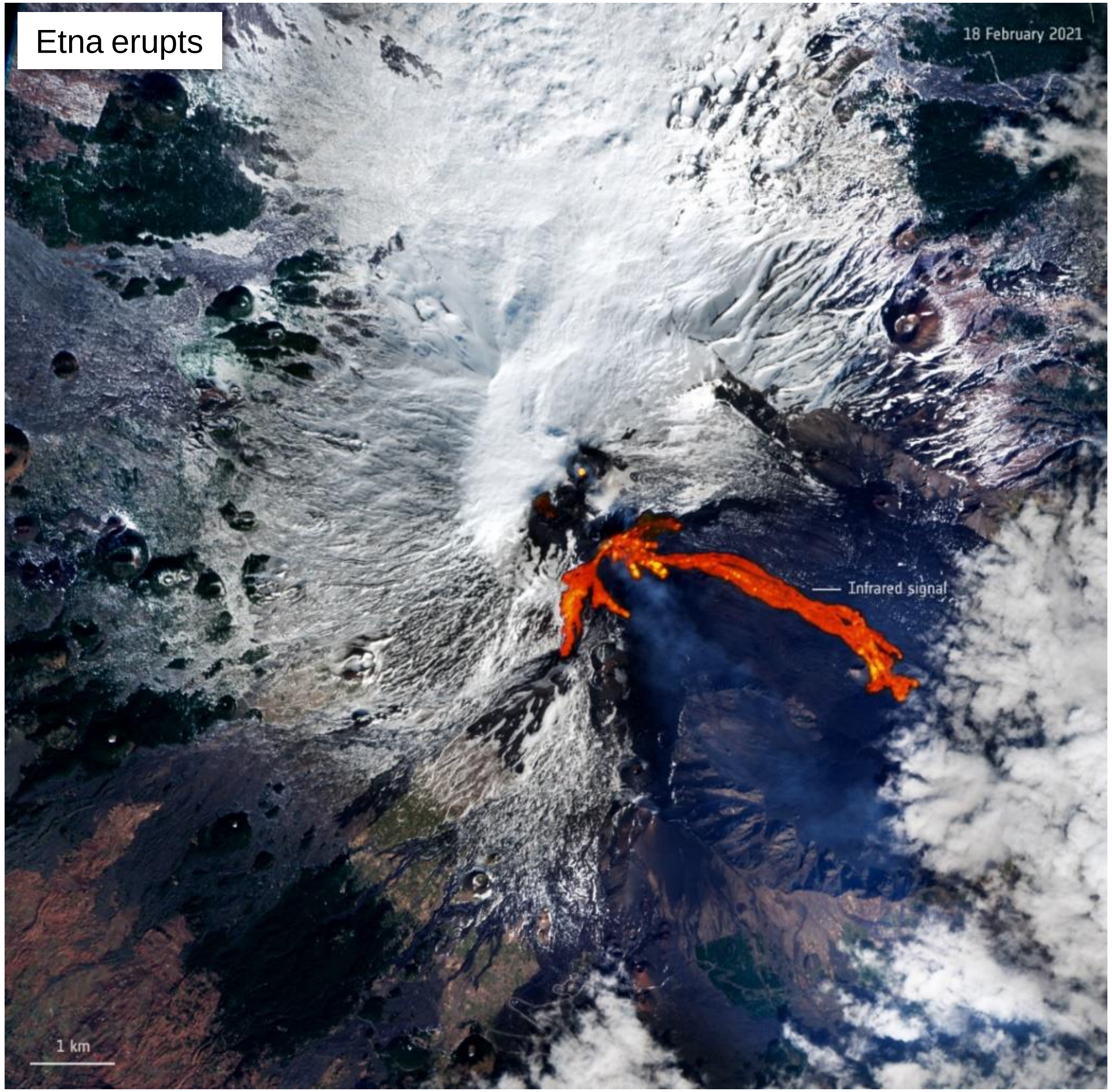


https://sentinels.copernicus.eu

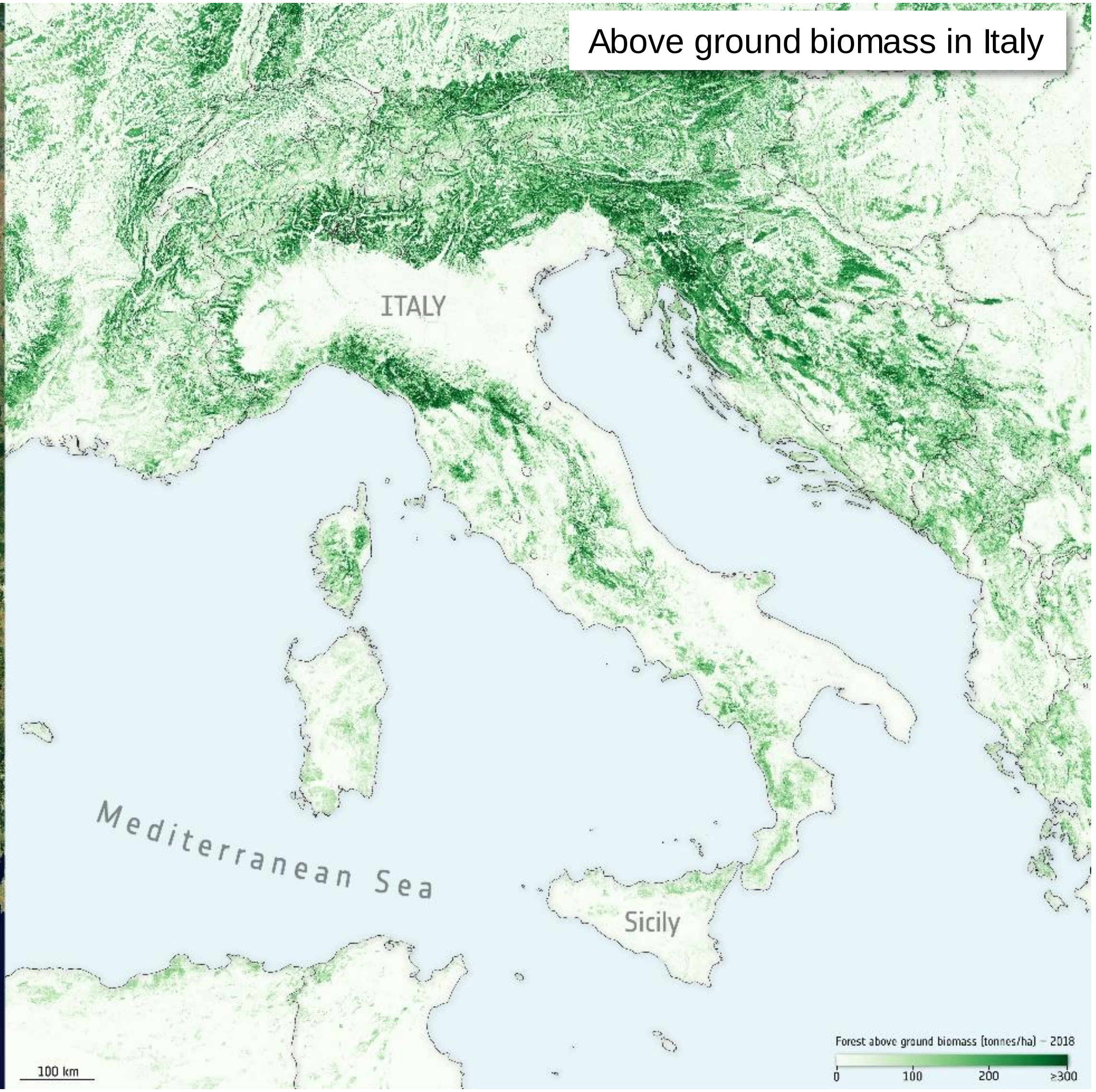
Sentinel-2 – Applications

Europe land-cover mapped in 10 m resolution

Etna erupts

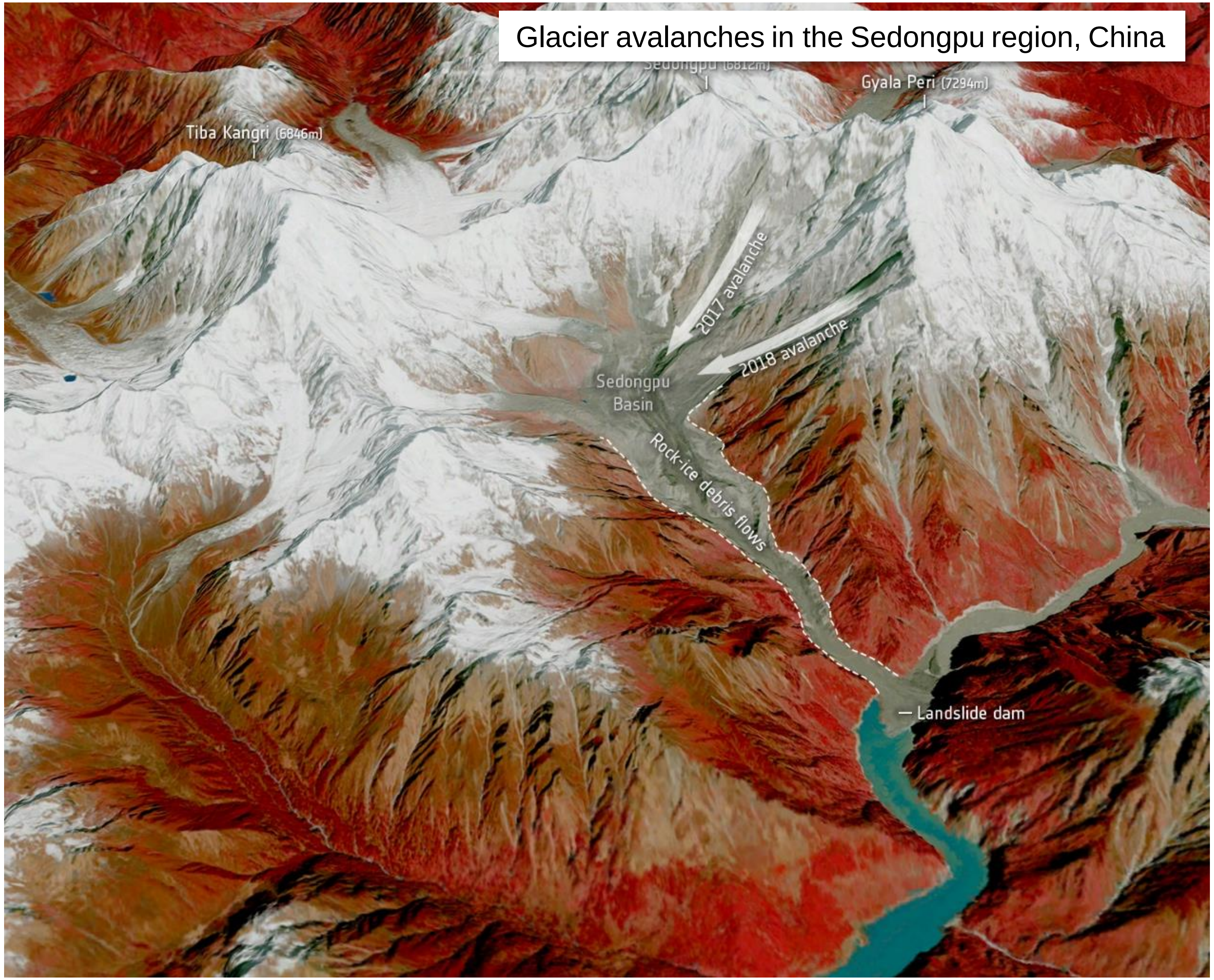


Sentinel-2 – Applications



Sentinel-2 – Applications

Rhodes wildfire forces thousands to flee



Glacier avalanches in the Sedongpu region, China

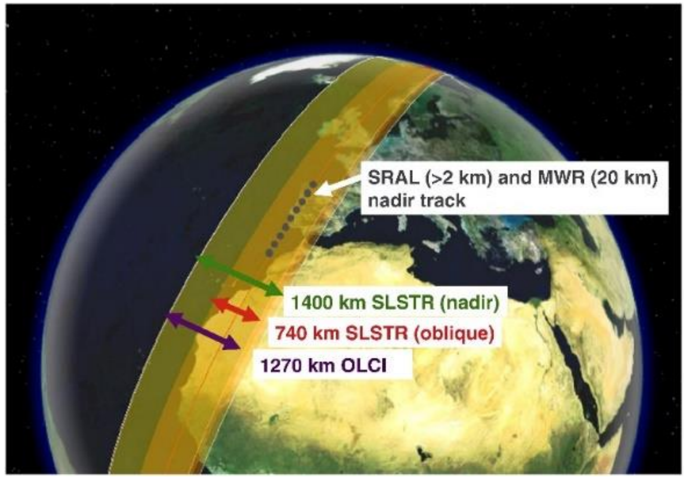
Sentinel-3 – A bigger picture

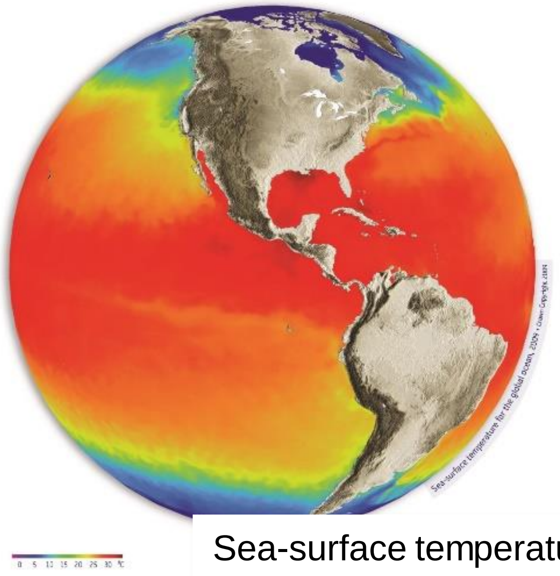
Mission objectives:

- Ocean, inland sea, coastal zone colour measurements
- Sea surface temperature measurements
- Sea surface topography measurements

Mission profile:

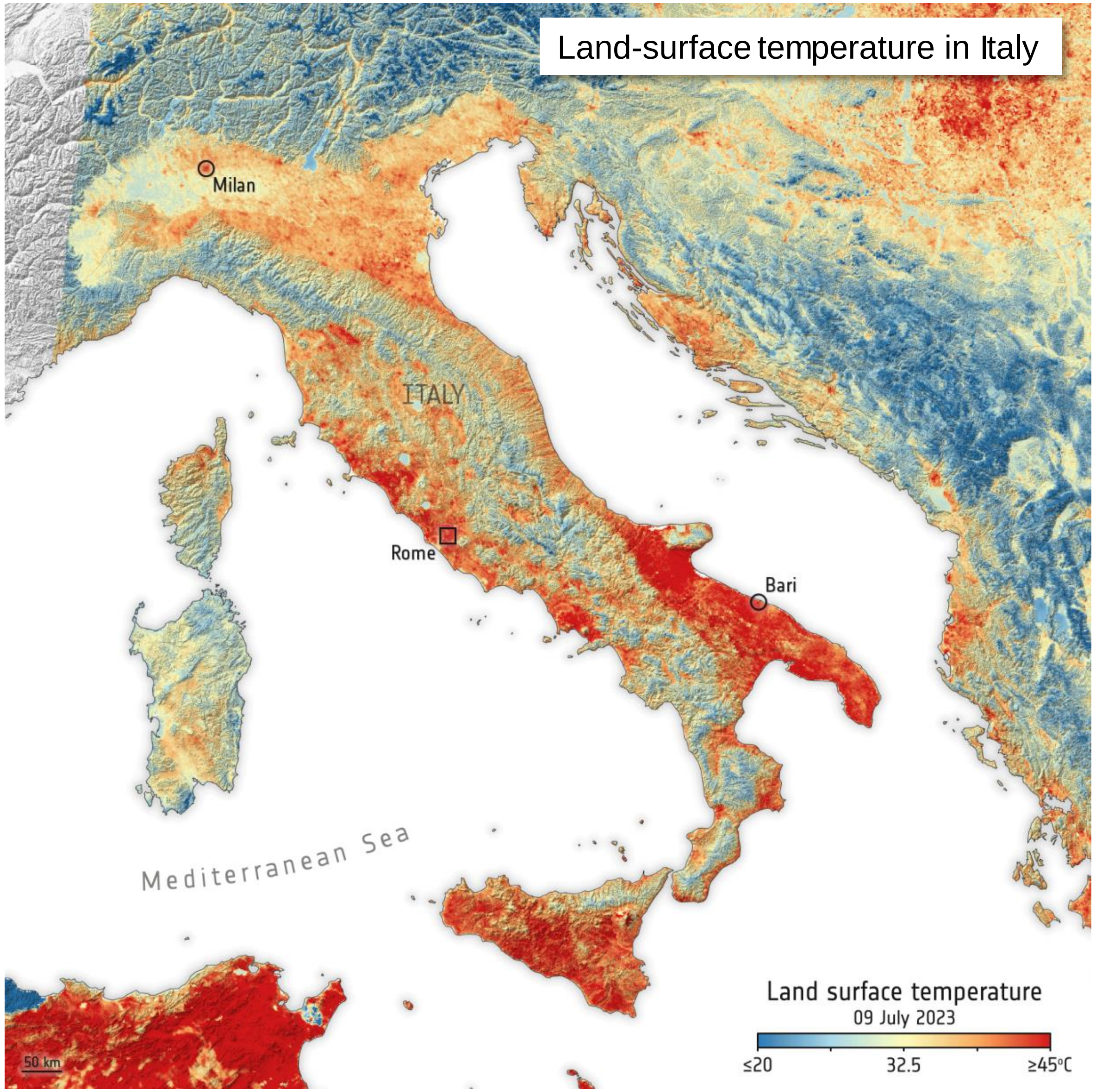
- Operational mission in high-inclination, low Earth orbit
- Orbital cycle is 27 days
- Ocean and Land Colour Instrument (OLCI),
  Sea and Land Surface Temperature Radiometer (SLSTR),
  SAR Radar Altimeter (SRAL),
  MicroWave Radiometer (MWR)
  and Precise Orbit Determination (POD) instruments
- Full performance achieved with 2 satellites in orbit

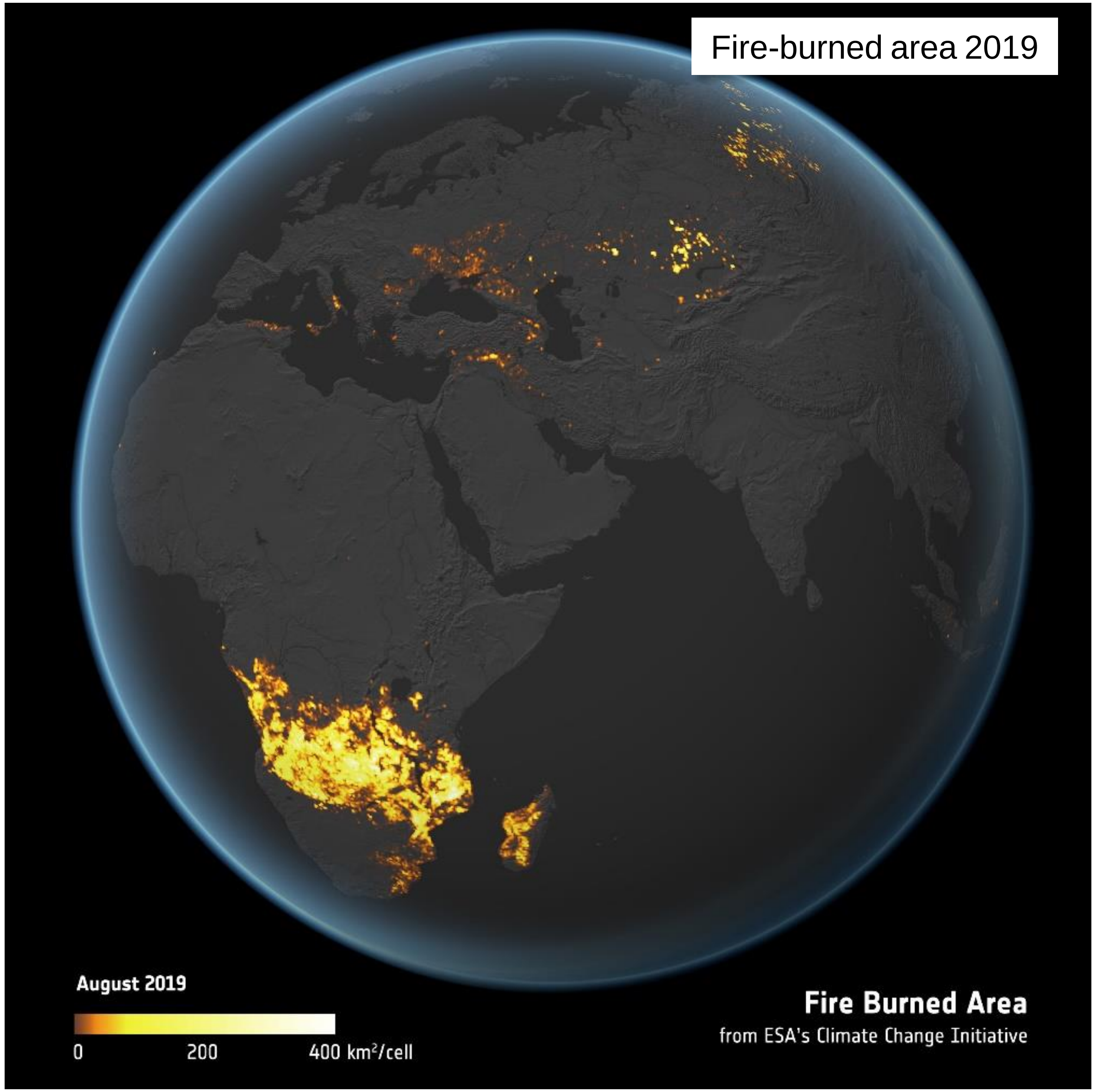




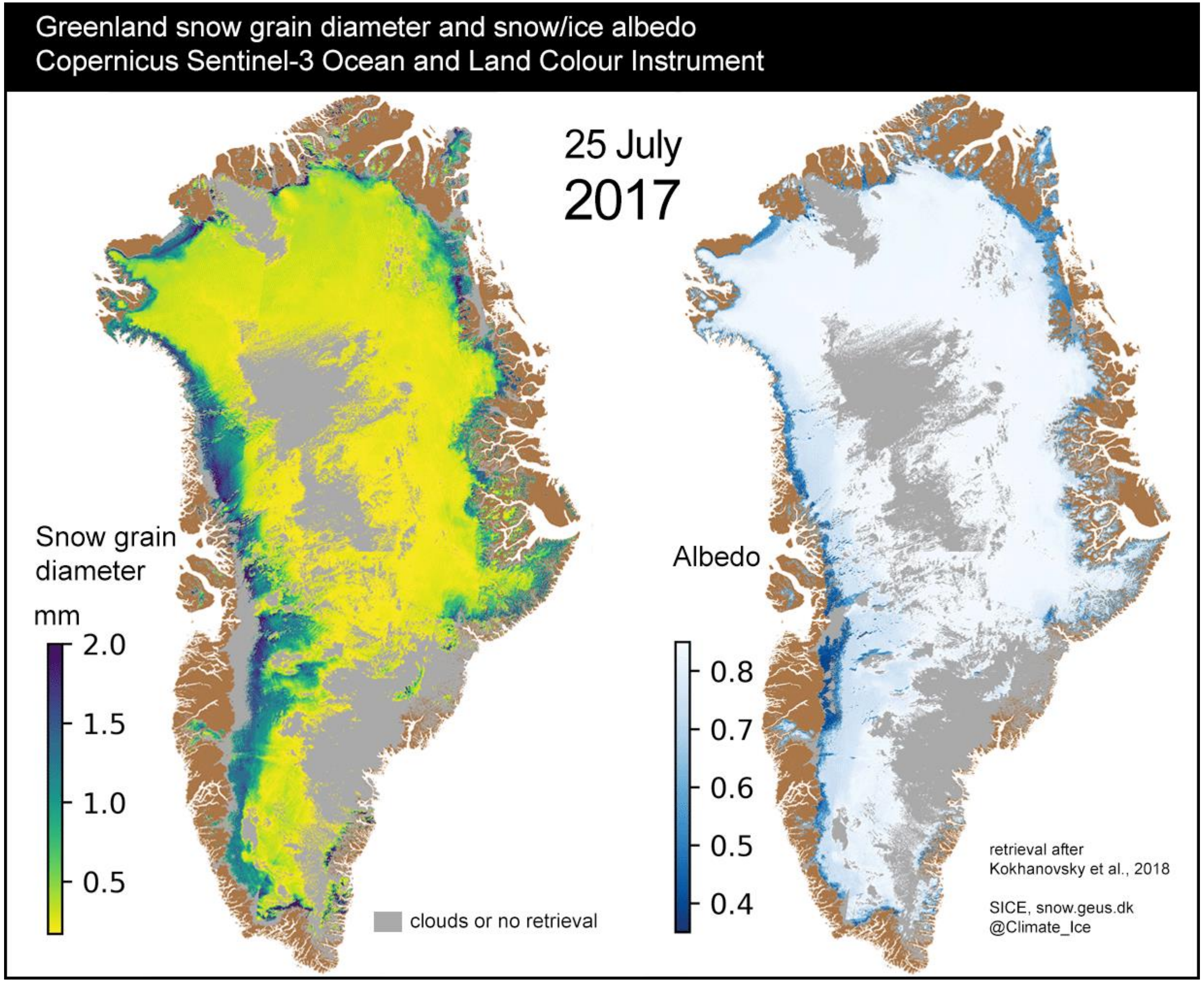
Sea-surface temperature

Sentinel-3 – Applications





Sentinel-3 – Applications



Greenland snow grain and albedo

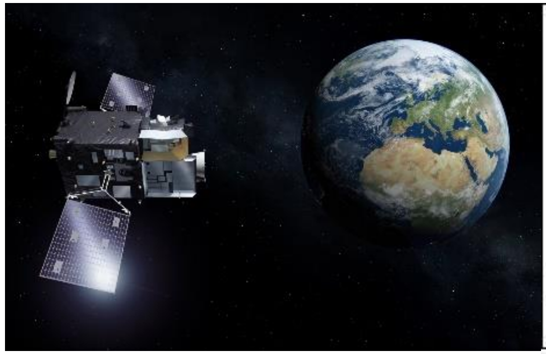
Sentinel-4 – European air monitoring

Mission objectives:

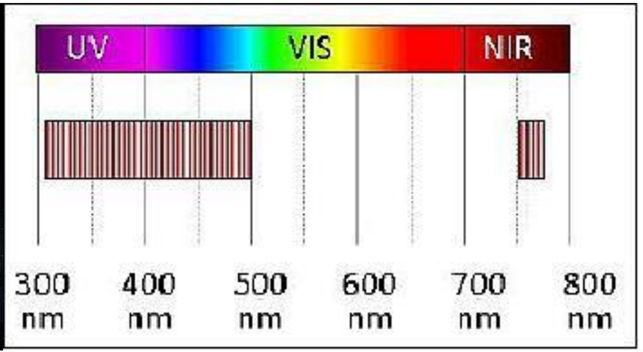
- Observing the diurnal cycle of the tropospheric composition over Europe and North Africa
- Monitoring in particular key air quality trace gases like O_3, NO_2, SO_2, HCHO, CHOCHO, as well as aerosol and cloud properties

Mission profile:

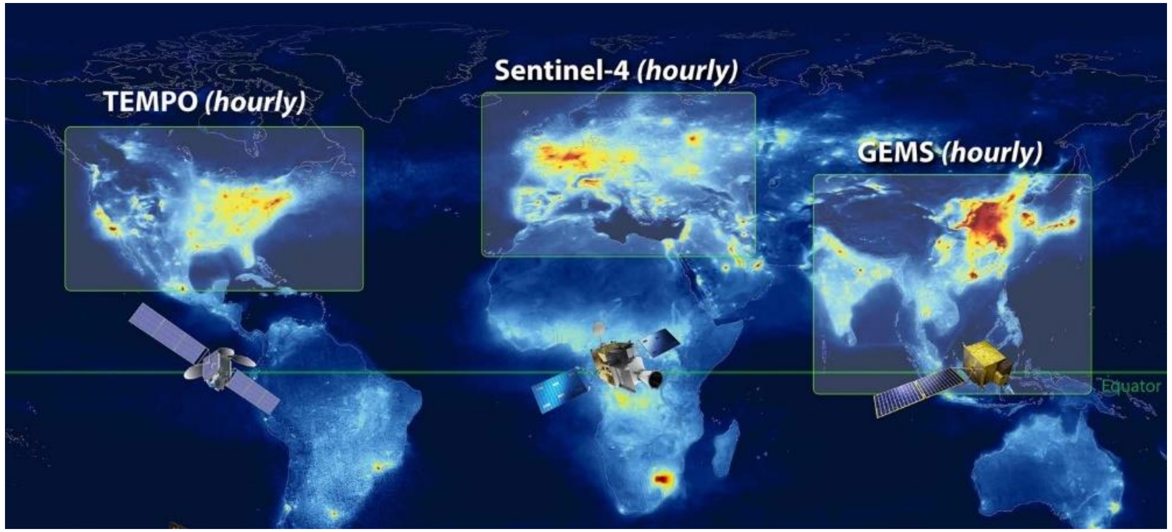
- Passive imaging spectrometer
- Three spectrometric bands: UV (305-400 nm), VIS (400-500 nm) and NIR (750-775 nm)
- Push-broom scanning (scan - E/W direction)
- Spatial resolution: 8x8 km^2
- Revisit time: about 60 min



Sentinel-4. Credits: ESA



Spectral coverage of the UVN Sounder. Credits: ESA



A pioneering new constellation of three space-based instruments has started to take shape to advance global air quality science and monitoring. Credits: NASA

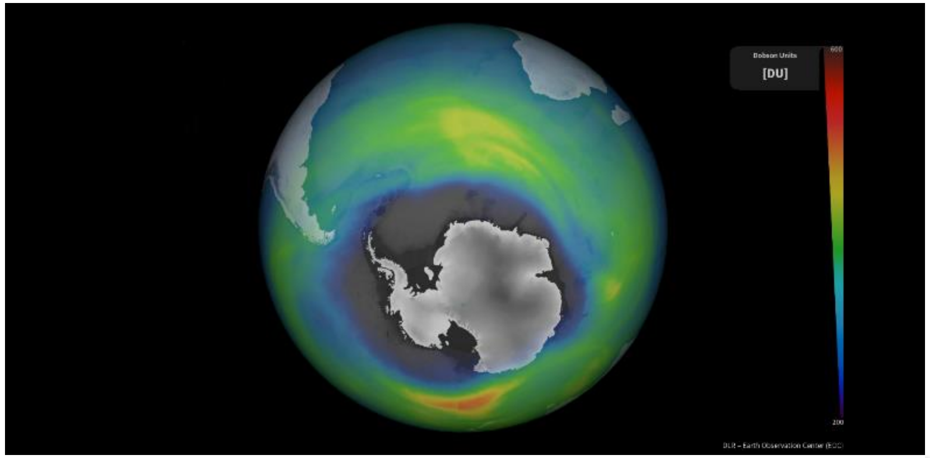
Sentinel-5P - Sentinel-5 – Global air monitoring

Mission objectives:

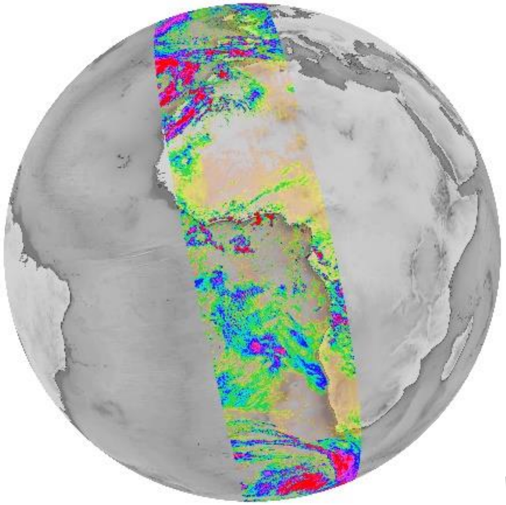
- Measuring, at the Top Of Atmosphere (TOA), the solar radiation reflected by and radiated from the earth
- Monitoring air quality, stratospheric ozone layer and climate change monitoring + forecasting

Mission profile:

- TROPOMI - space-borne, nadir-viewing, imaging spectrometer covering UV and SWIR bands
- Push-broom configuration (non-scanning), with a swath width of ~2600 km on the Earth's surface
- The typical pixel size (near nadir) will be 7x3.5 km^2 for all spectral bands, with the exception of the UV1 band (7x28 km^2) and SWIR bands (7x7 km^2).



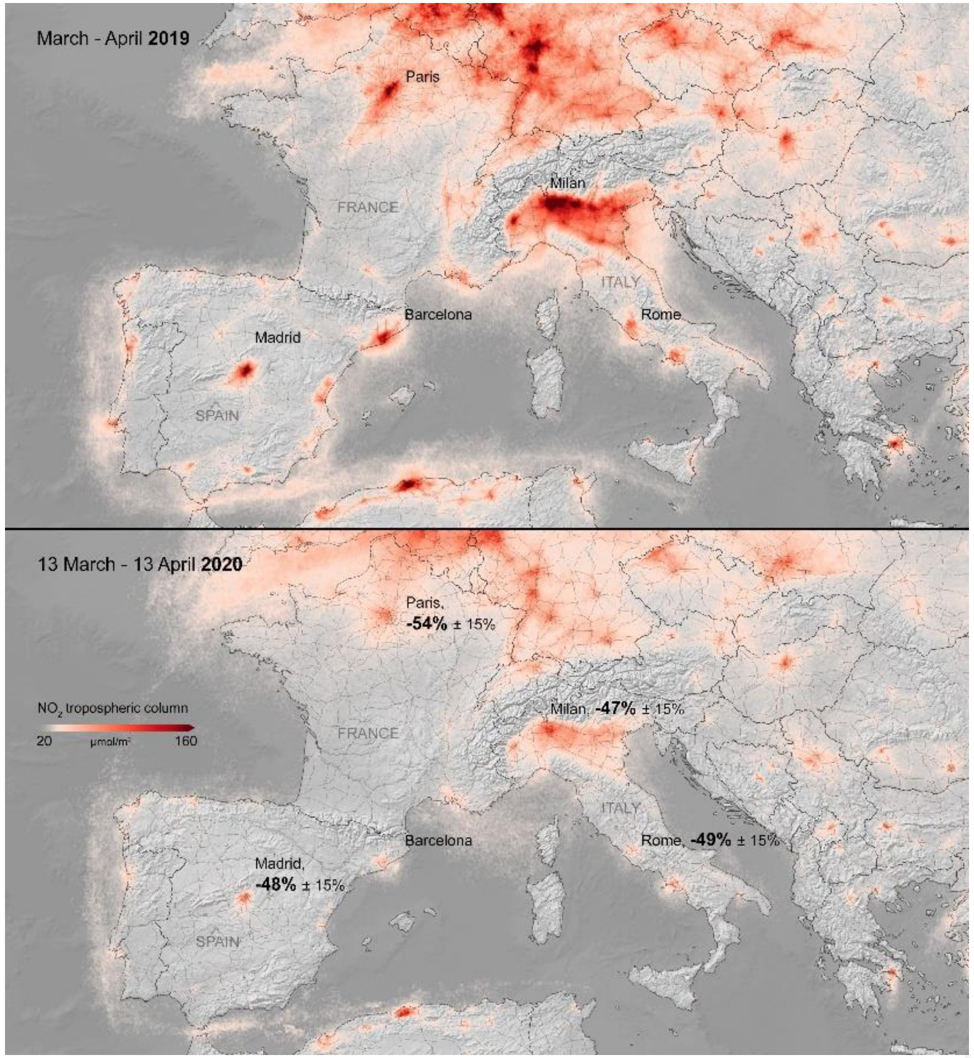
Ozone hole extension 2022. Credits: ESA



Cloud coverage seen in high resolution with Sentinel-5P. Credits: ESA

Sentinel-5P - Sentinel-5 – Applications

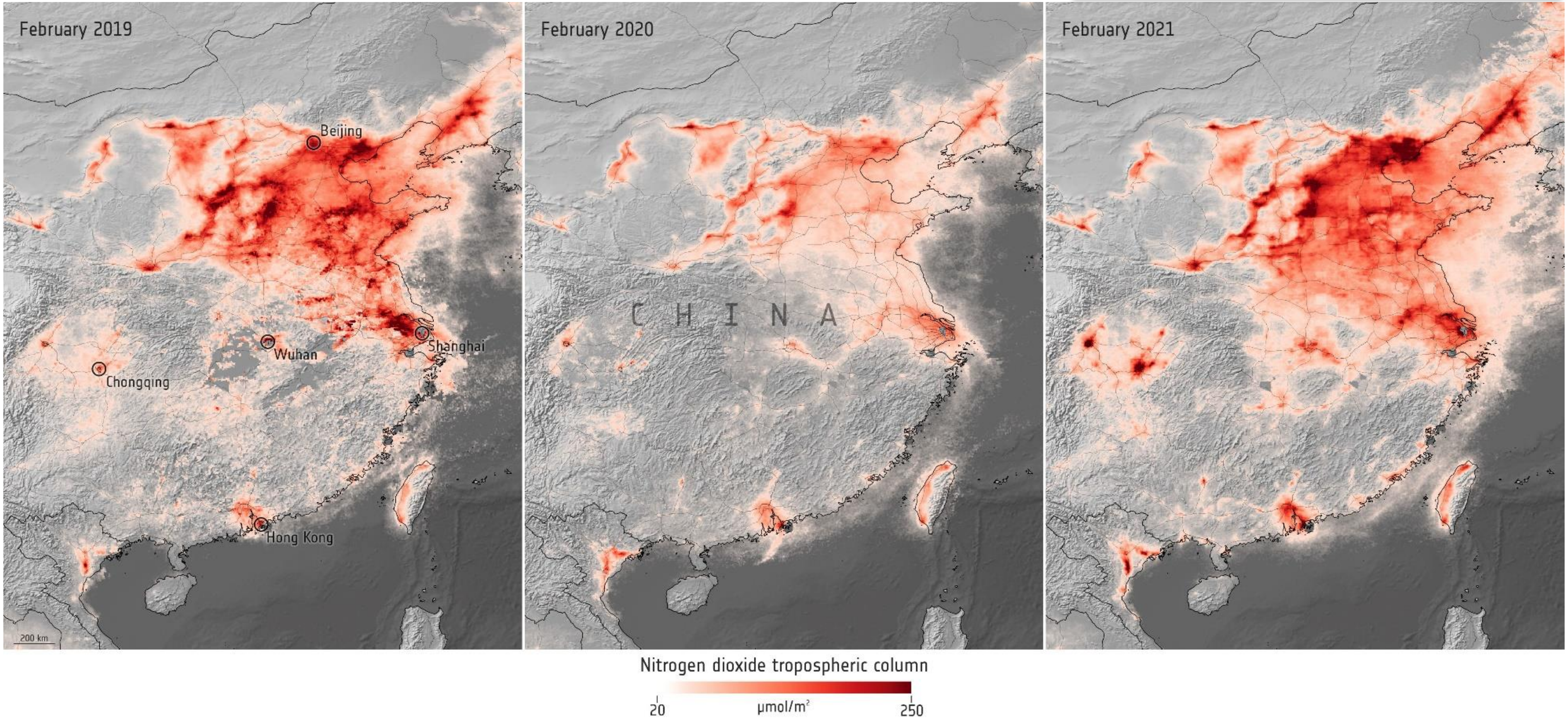
Methane enhancement over Libya



Nitrogen dioxide concentrations over Europe

Sentinel-5P - Sentinel-5 – Applications

Nitrogen dioxide concentrations over China



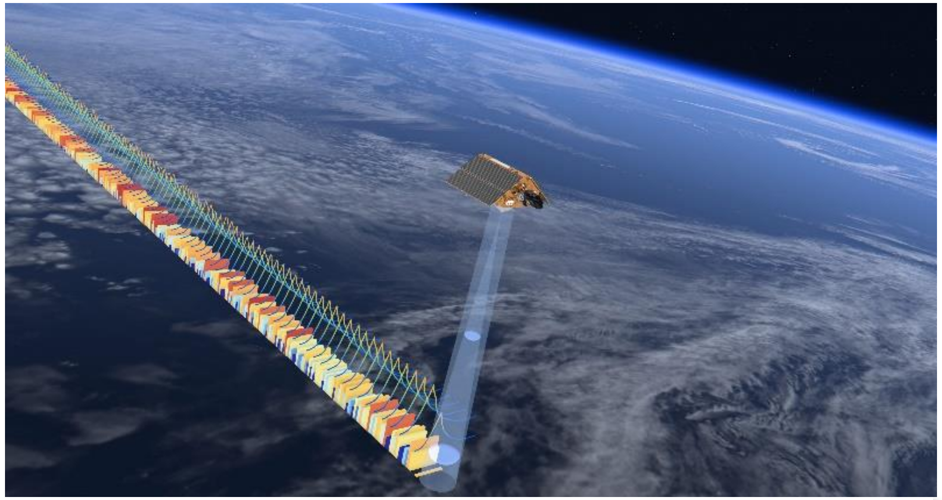
Sentinel-6/Jason-CS – Surfing the seas

Mission objectives:

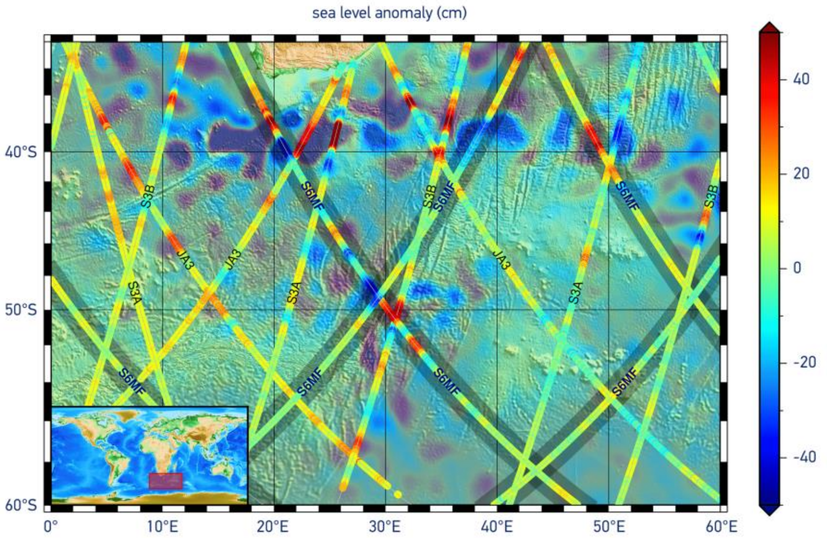
- Provide continuity of satellite altimetry measurements
- The mission will extend this measurement time series to ~2030+
- Reference mission in the CEOS-coordinated virtual constellation of ocean surface topography missions

Mission profile:

- High Resolution altimetry based on unfocused SAR (Synthetic Aperture Radar) processing combined with the conventional Low Resolution Mode (LRM) altimetry;

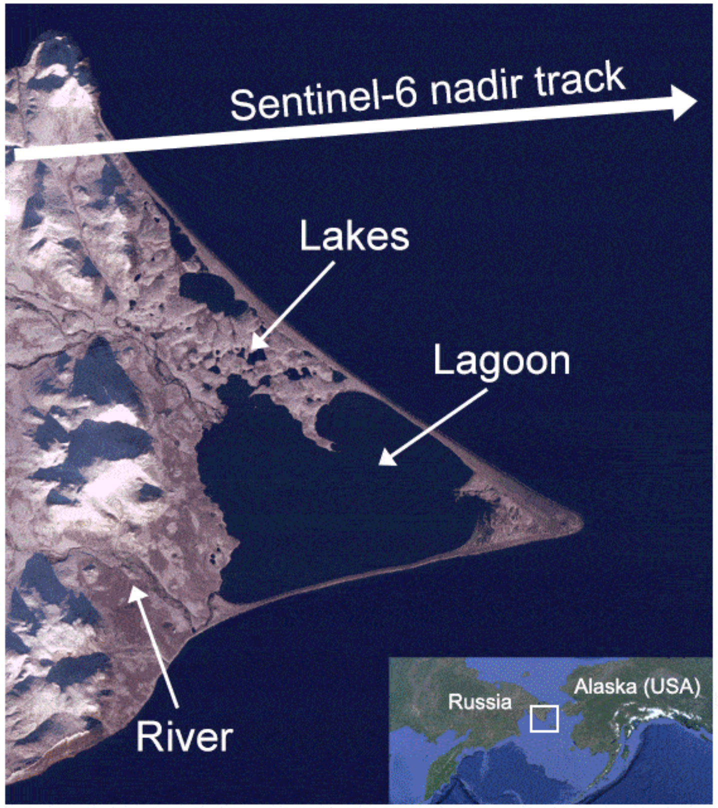


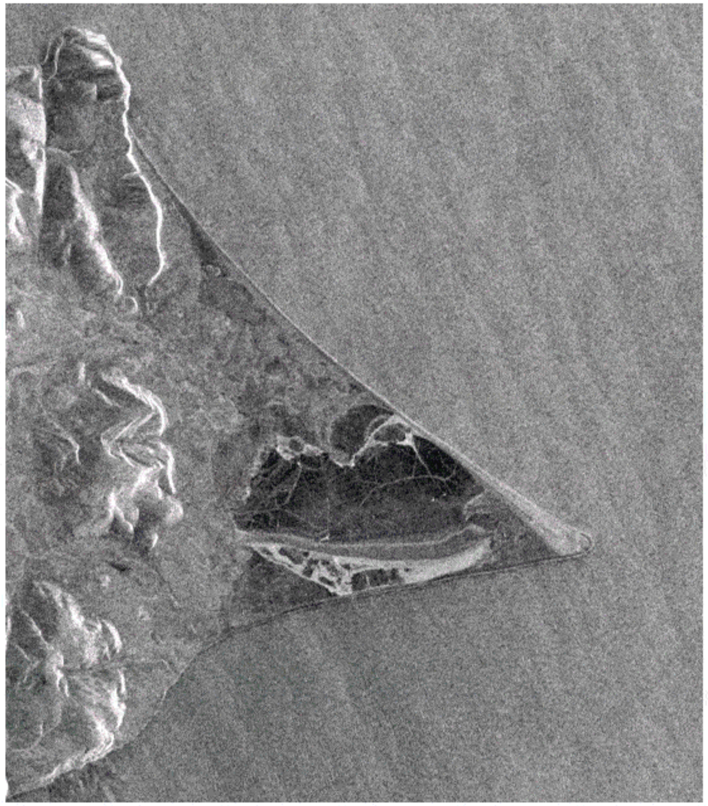
Copernicus Sentinel-6 radar altimeter. Credits: ESA

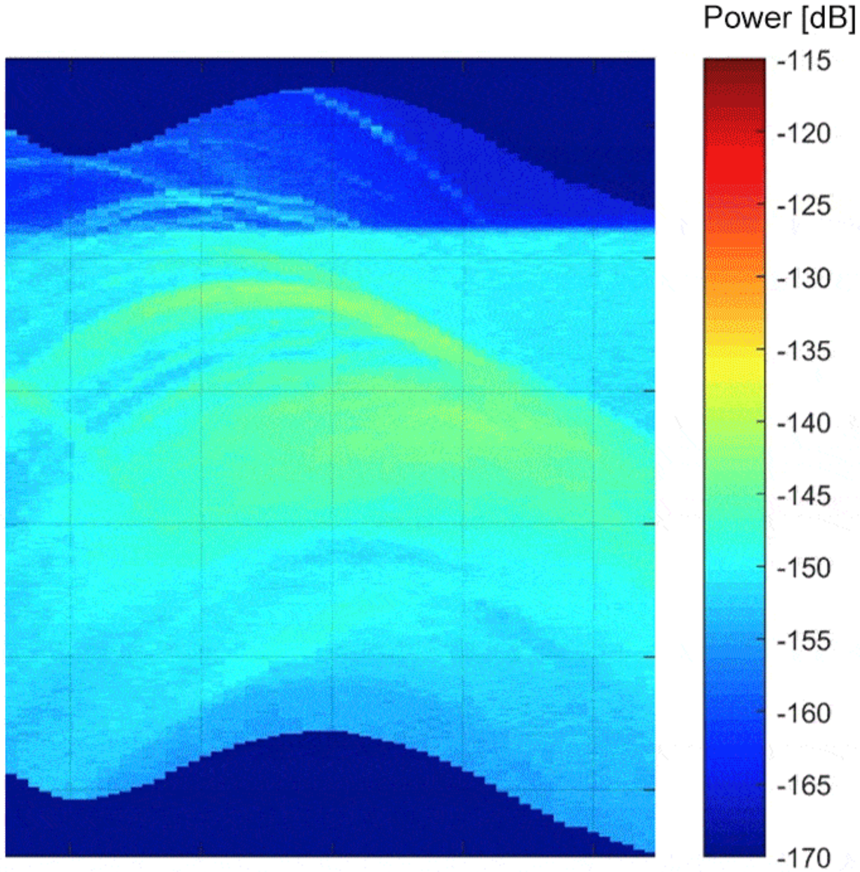


First sea-level height results from Copernicus Sentinel-6. Credits: ESA

Sentinel-6/Jason-CS – Applications



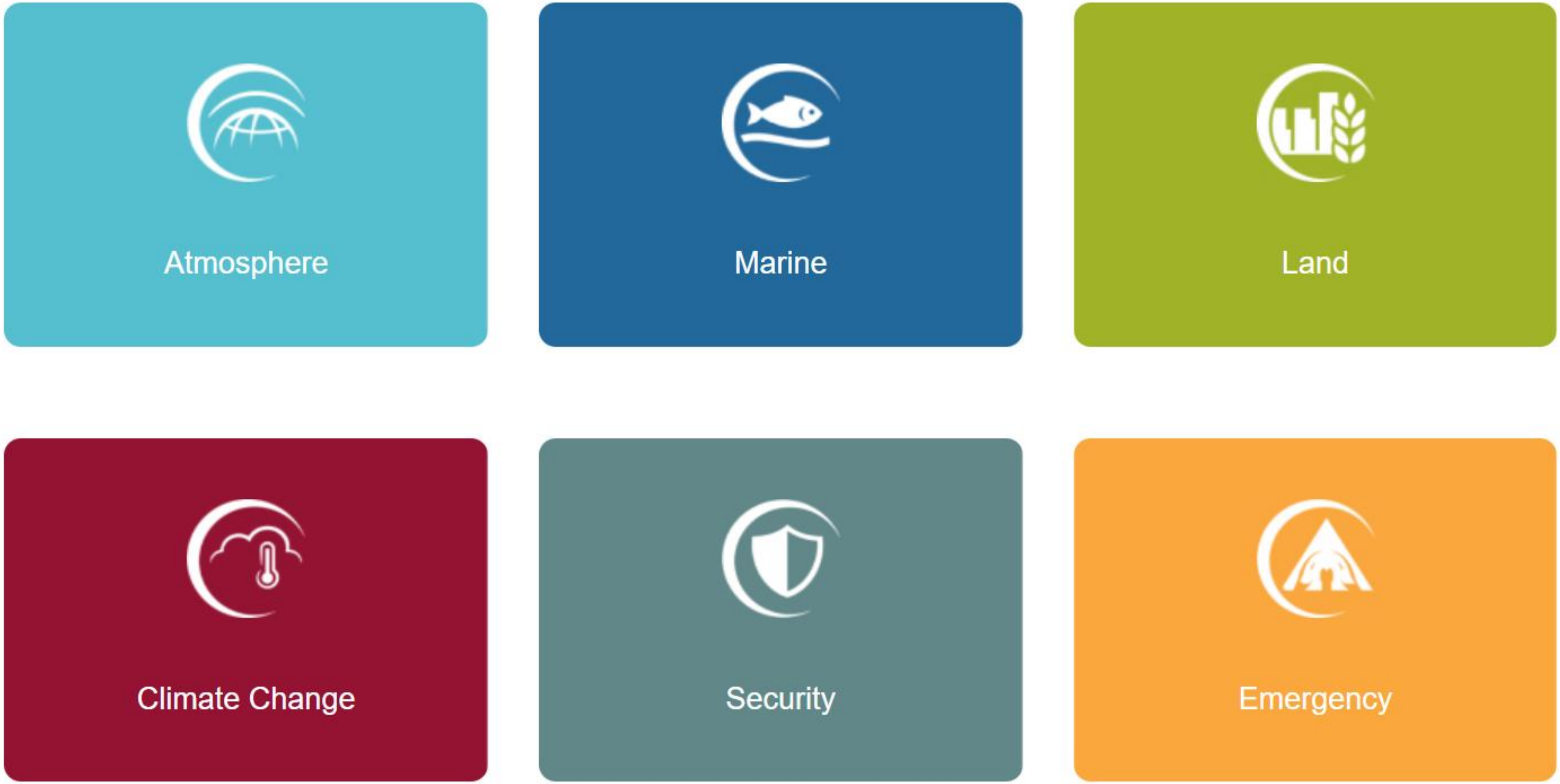




The images of Russia's Ozero Nayval Lagoon and surrounding rivers show multiple views from Copernicus satellites. The first is a 10-m resolution 'camera-like' image captured on 29 October 2020 by Copernicus Sentinel-2. The image is marked with the ground track of Copernicus Sentinel-6 as it crosses the region. The second is a radar image captured on 29 November 2020 by Copernicus Sentinel-1 in interferometric wide swath mode and processed to 10 m resolution. The lagoon has frozen over and numerous cracks are visible in the ice. Ocean swell and wind sea roughness are also seen in the ocean with some wave reflection and refraction on the southern coastal areas. The next image uses Copernicus Sentinel-6 pulse-limited low-resolution mode data for the same area. In this mode, similar to Jason-3, the strongest radar reflections appear as overlapping parabola features, but no discrimination of the ground can be made. Overlying the third image, the Copernicus Sentinel-6 Poseidon-4 fully-focused synthetic aperture radar image reveals features of the Ozero Nayvak Peninsular in fine detail. Credits: ESA

Service component

Copernicus services – provided free of charge for users:

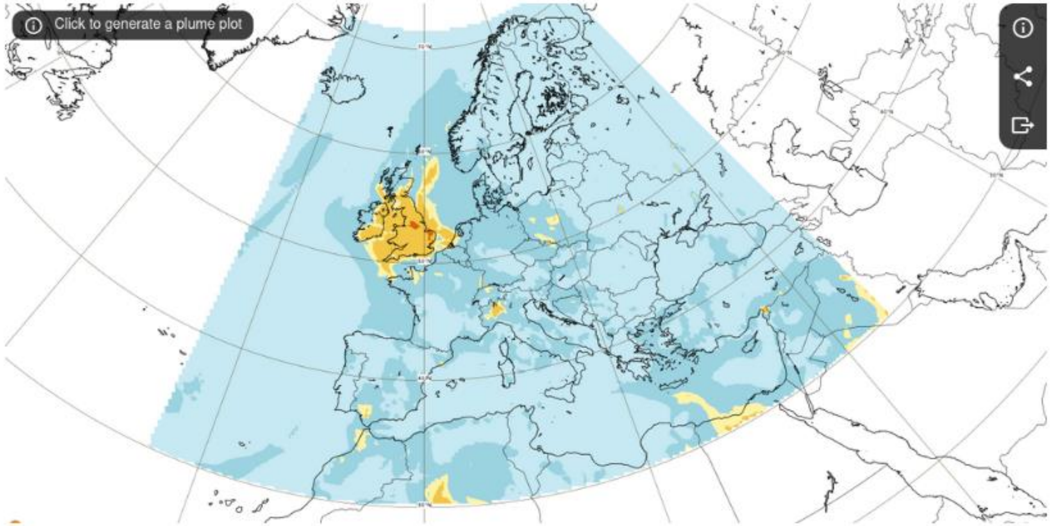


Service component - Atmosphere

The service focuses on five main areas:

- Air quality and atmospheric composition;
- Ozone layer and ultra-violet radiation;
- Emissions and surface fluxes;
- Solar radiation;
- Climate forcing.:

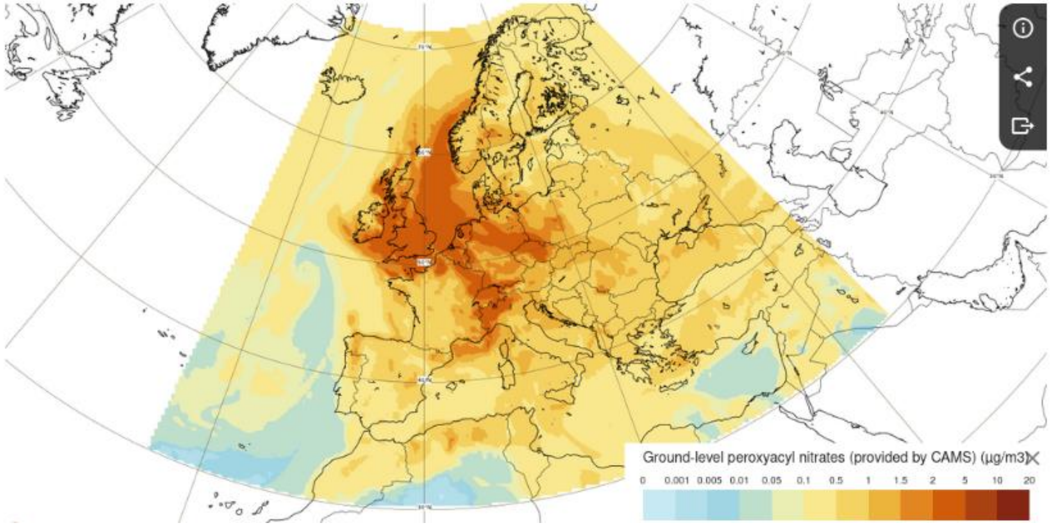
Service component - Atmosphere



Regulated pollutants

Forecasts of the five main air pollutants regulated by the European Union and the World Health Organization air quality standards: nitrogen dioxide (NO2), ozone (O3), coarse particulate matter (PM10), fine particulate matter (PM2.5) and sulphur dioxide (SO2).

Access the charts >



Other air quality pollutants

European forecasts for other air quality pollutants: ammonia, carbon monoxide, formaldehyde, glyoxal, nitrogen monoxide, non-methane VOCs, peroxyacyl nitrates.

Access the charts >

European air quality forecast plots. Credits: ESA

Service component - Marine

Provides free, regular and systematic authoritative information on the state of the Blue (physical), White (sea ice) and Green (biogeochemical) ocean, on a global and regional scale.

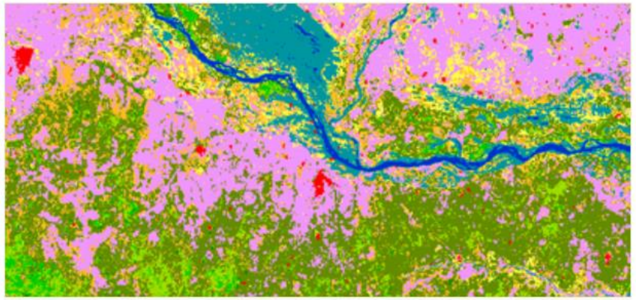
- combating pollution
- marine protection
- maritime safety and routing
- sustainable use of ocean resources
- developing renew. marine energy resources
- supporting blue growth
- climate monitoring, forecasting, etc.

Support to coral reef protection: Coral Guardian.


Rheticus Marine for Water and Food Security Planning and Investments in Indonesia

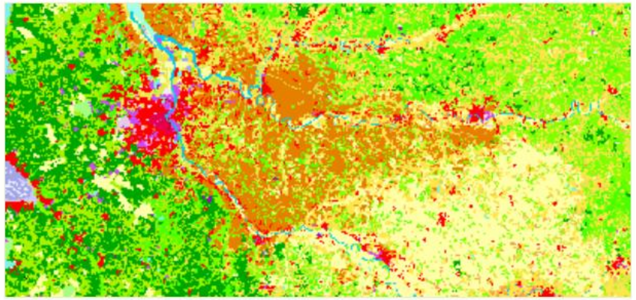
Service component - Land

- The systematic monitoring of biophysical parameters
- Land cover and land use mapping
- Thematic hot-spot mapping
- Imagery and reference data
- Ground motion



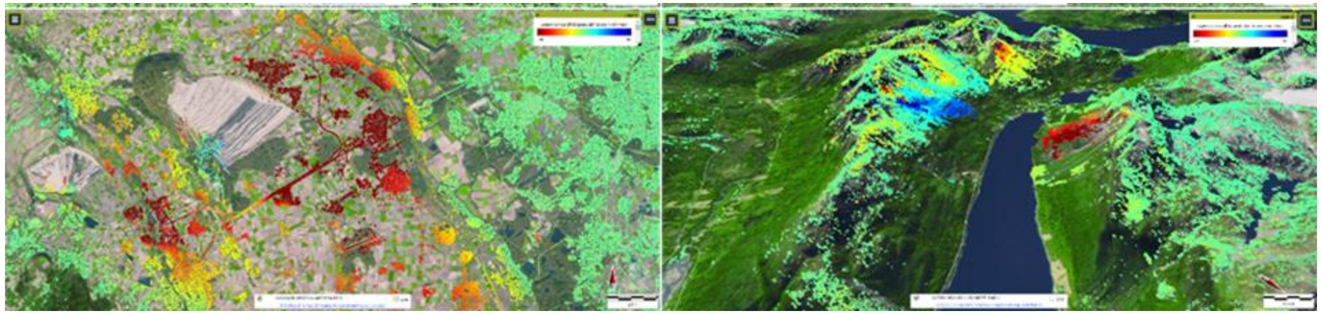
Dynamic Land Cover

The Dynamic Land Cover product provides a primary land cover scheme at three classification levels with class definitions according to the Land Cover Classification System (LCCS) scheme. The product is produced annually, and the actual version of the product (V3.0) is available for the 2015-2019 reference years.



CORINE Land Cover

CORINE Land Cover is a pan-European land cover inventory with 44 thematic classes. Initiated in 1985 (the 1990 reference year) the inventory is available for the 1990, 2000, 2006, 2012 and 2018 reference years including change layers 1990-2000, 2006-2012 and 2012-2018.

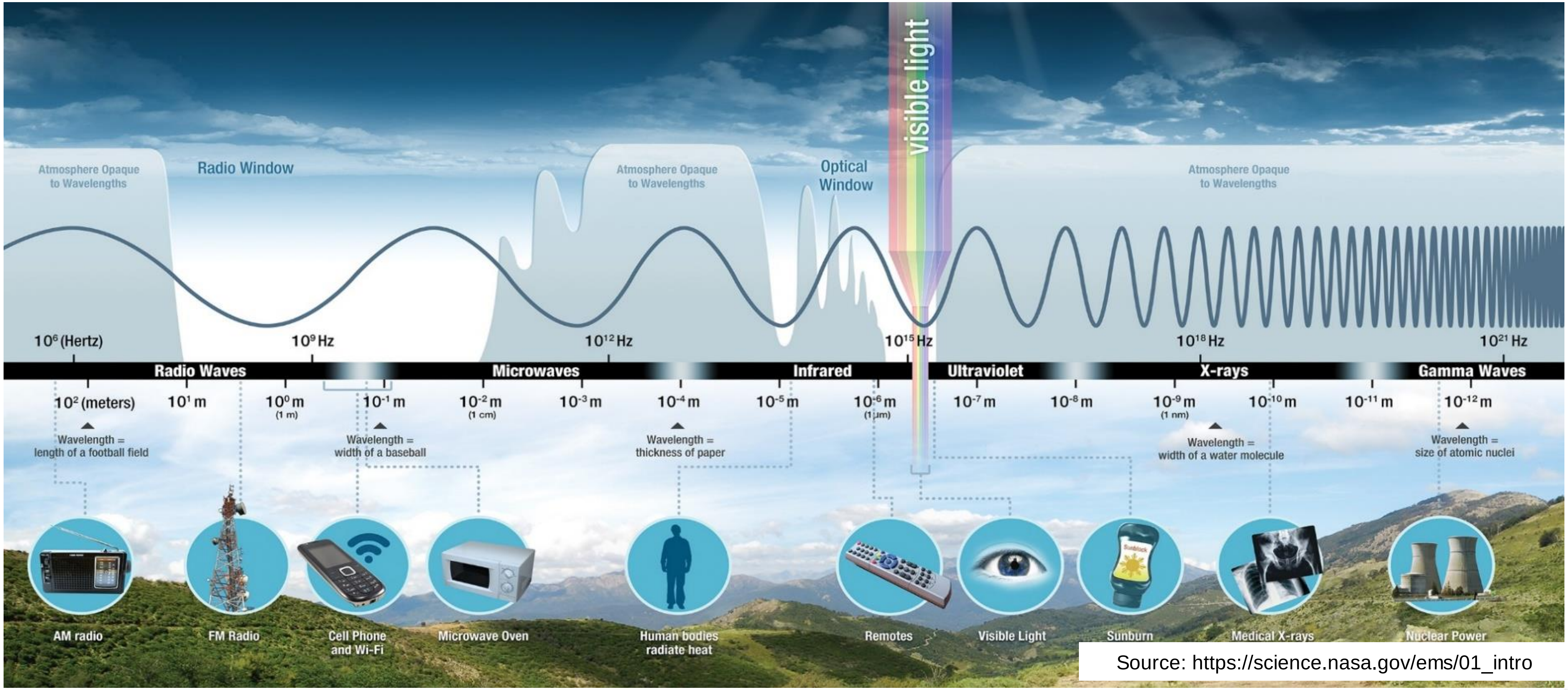


Lower left, ground motion in the surroundings of the Hambach surface mine in Germany; lower right, landslides in the slopes of a fjord near Tromsø (Norway).

3. Key concepts and physical principles of remote sensing methods: electromagnetic energy, its properties, spectral behaviour and interaction with the environment

Principle of Remote Sensing

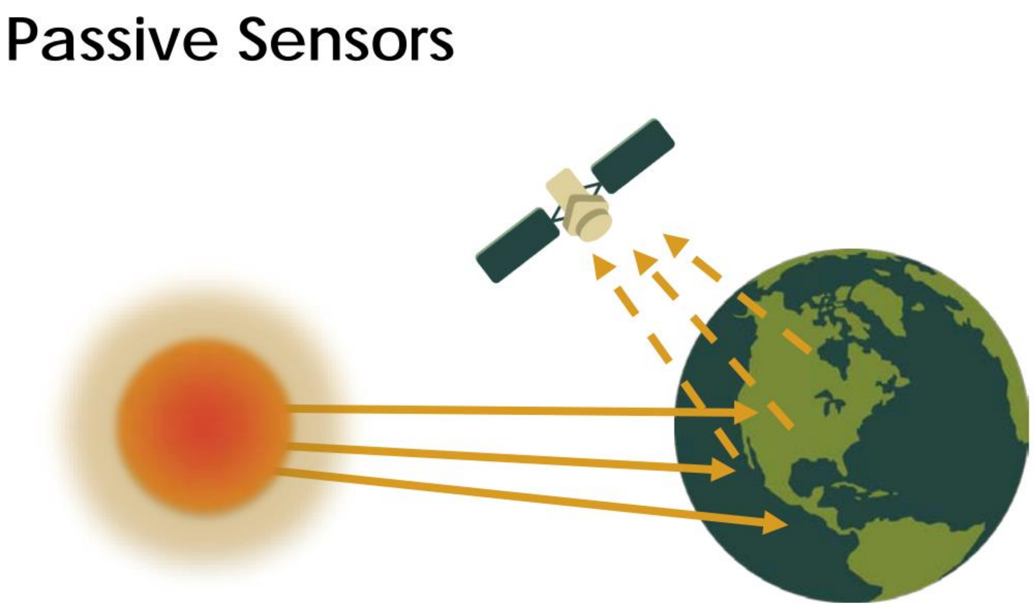
Detection and discrimination of objects or surface features = detecting and recording of electromagnetic radiation reflected or emitted by objects or surface material



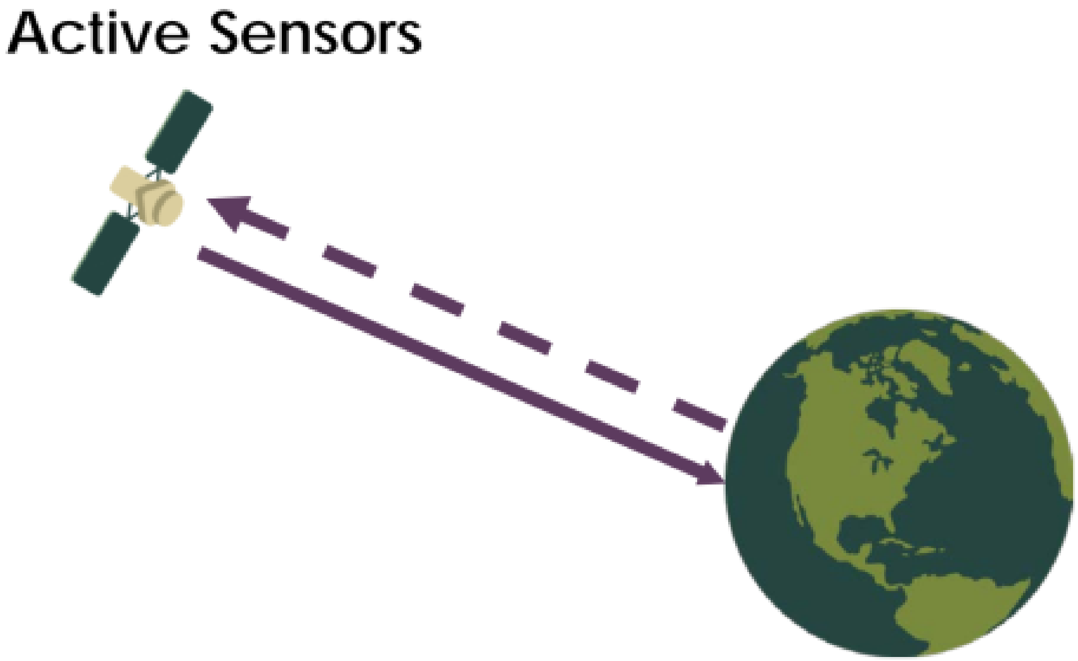
Source: https://science.nasa.gov/ems/01_intro

Different objects return different amount and kind of energy in different bands of the EMG spectrum.

Remote Sensing Sensors



- Dependent on a natural source (e.g. Sun, Earth) to provide energy
- The satellite sensor records primarily the radiation that is reflected from the target

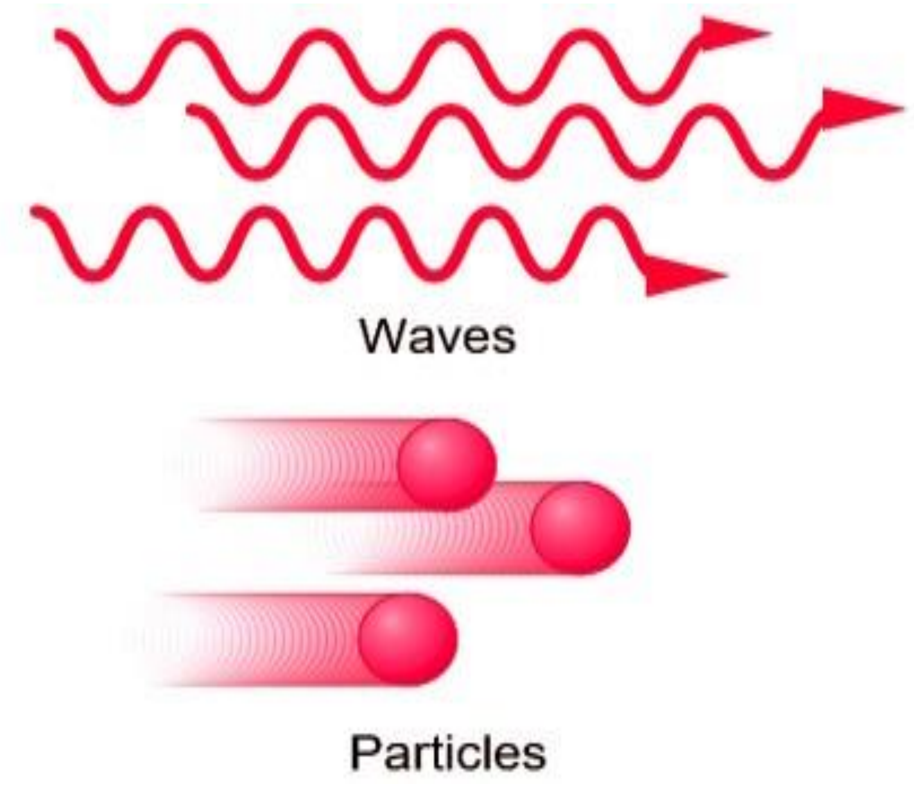


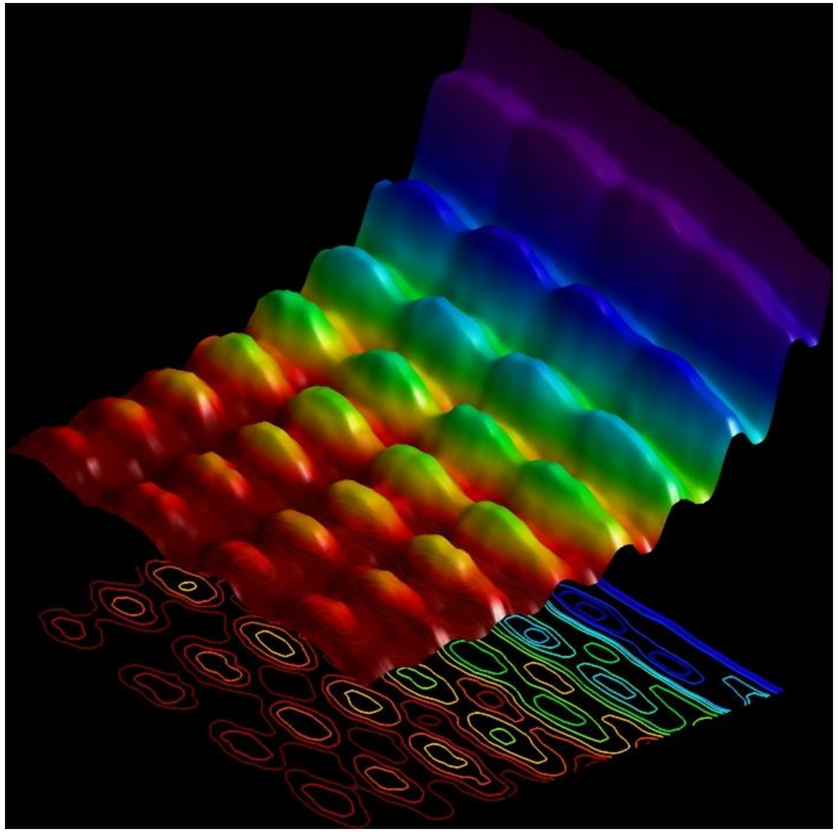
- Use an artificial source for energy
- The satellite itself can send a pulse of energy which can interact with the target
- Can be carried out during day and night and in all weather conditions

Source: https://www.earthdata.nasa.gov/learn/backgrounders/passive-sensors, https://www.earthdata.nasa.gov/learn/backgrounders/active-sensors

Properties of Electromagnetic radiation

Electromagnetic radiation has properties of **waves** but also can be thought of as a **stream of particles (quantum).**





Source: https://m.sciencecalculators.org/optics/light/, https://conciencia2.es/la-doble-naturaleza-de-la-luz/

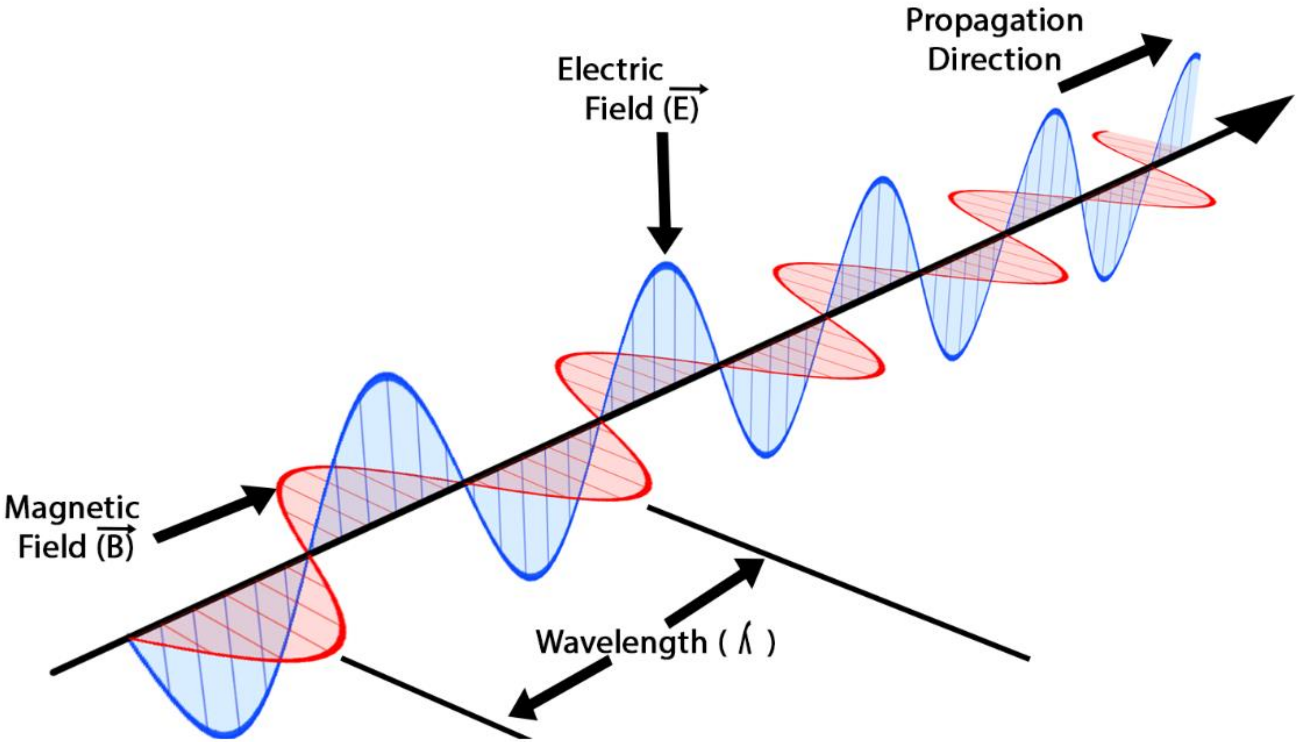
Electromagnetic wave

According to Maxwell's EM wave theory, light waves are related to changing electric fields and magnetic fields. The change within the electrical and magnetic field leads to the propagation of electromagnetic waves or light waves (c = 299 792 458 m.s^{-1})

$$c = \lambda \cdot f$$

$$f = \frac{c}{\lambda}$$

$$\lambda = \frac{f}{c}$$



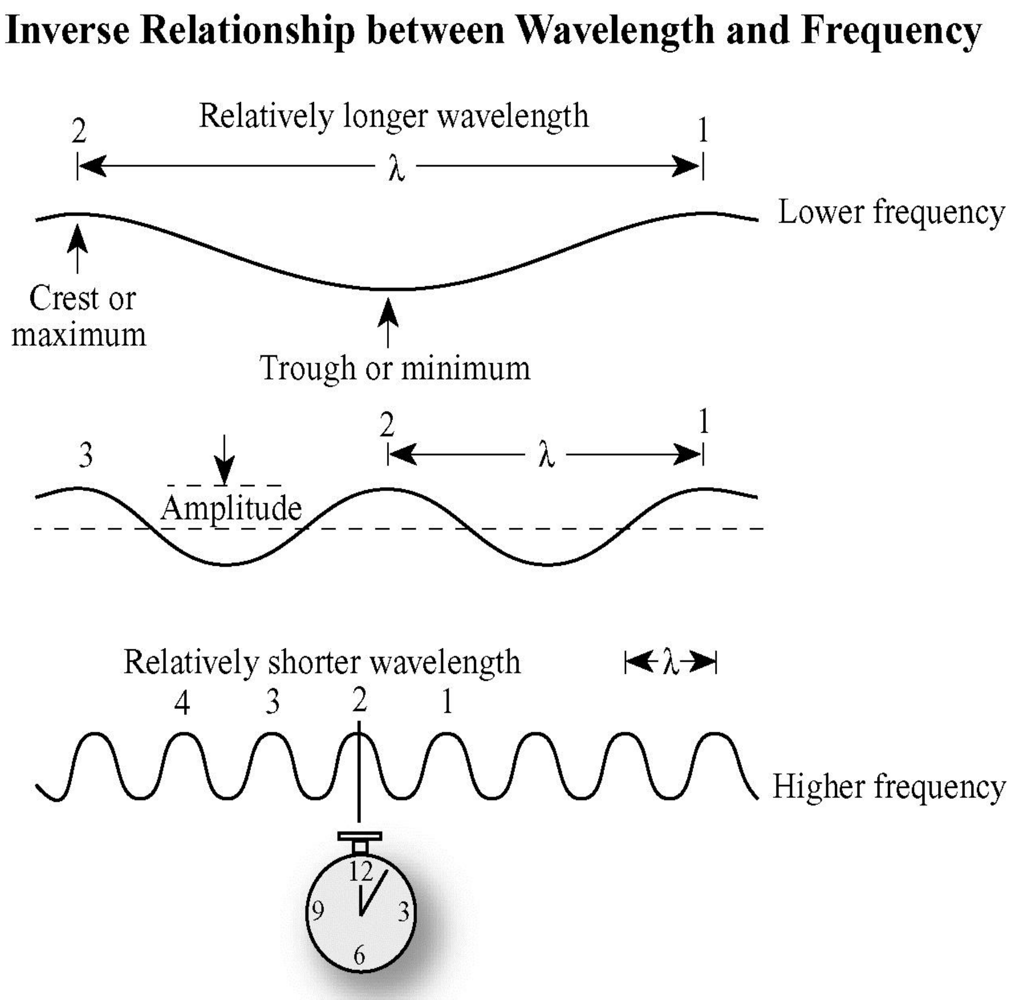
Source: https://www.mdpi.com/2075-5309/13/7/1729/

Relationship between Wavelenght and Frequency

- Wavelength and frequency have an inverse relationship, as indicated by the equation. If wavelength increases, then frequency decreases and vice versa.

- Wavelength is the distance between identical points (adjacent crests) in the adjacent cycles of a waveform signal propagated in space or along a wire.

- The amplitude of an electromagnetic wave is the height of the wave crest above the undisturbed position. This frequency is measured in cycles per second, or hertz

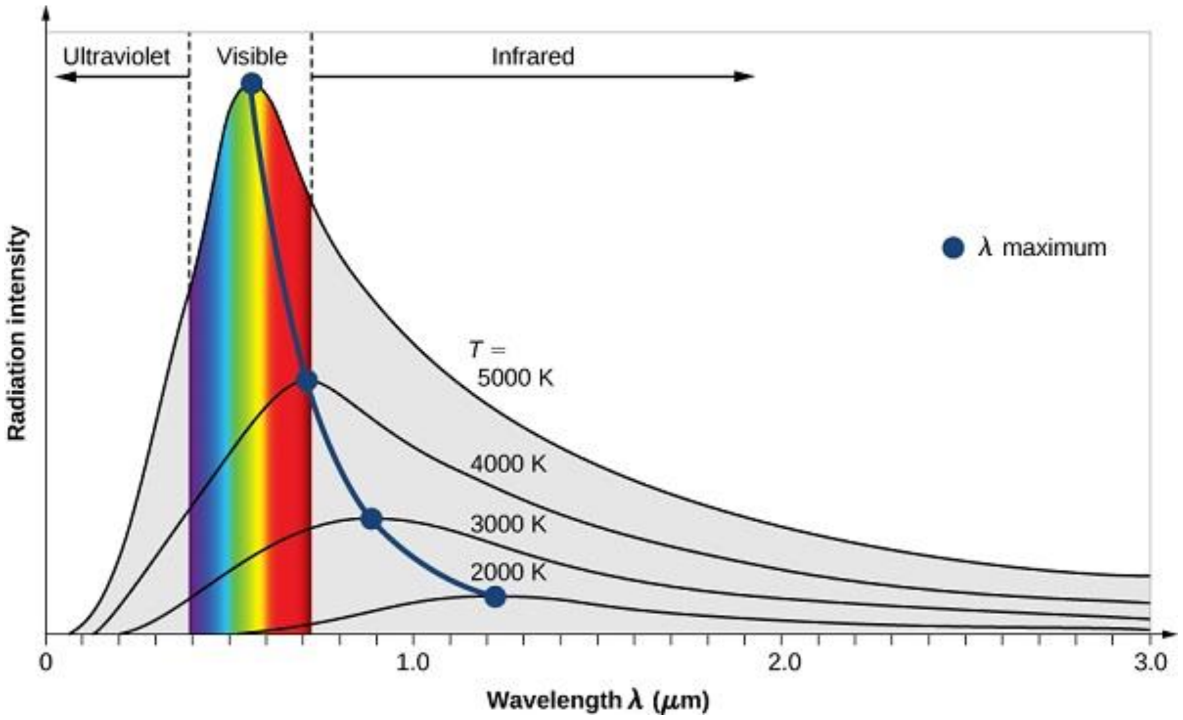


Source: Jensen (2008)

Relationship between Wavelenght and Frequency

Blackbody radiation

- Object or system which absorbs all radiation incident upon it and re-radiates energy
- All matter with a temperature above absolute zero (k) radiates energy in the form of EM waves of various wavelenghts
- By measuring the blackbody emission curves at different temperatures, it was able to construct two phenomenological Laws: Stefan-Boltzmann's Law and Wien's Displacement Law



Source: Jensen (2008)

Relationship between Wavelenght and Frequency

Blackbody radiation

Energy of a photon

We can measure the energy of a photon using Einstein´s equation:

$$E = hf = \frac{hc}{\lambda}$$

$h = 6.63 \times 10^{-34}$ Js → Planck constant

f = frequency of photon/electromagnetic radiation

$c = 3 \times 10^{8}$ m/s → speed of light in a vacuum

λ = wavelength of photon/electromagnetic radiation

Stefan–Boltzmann law

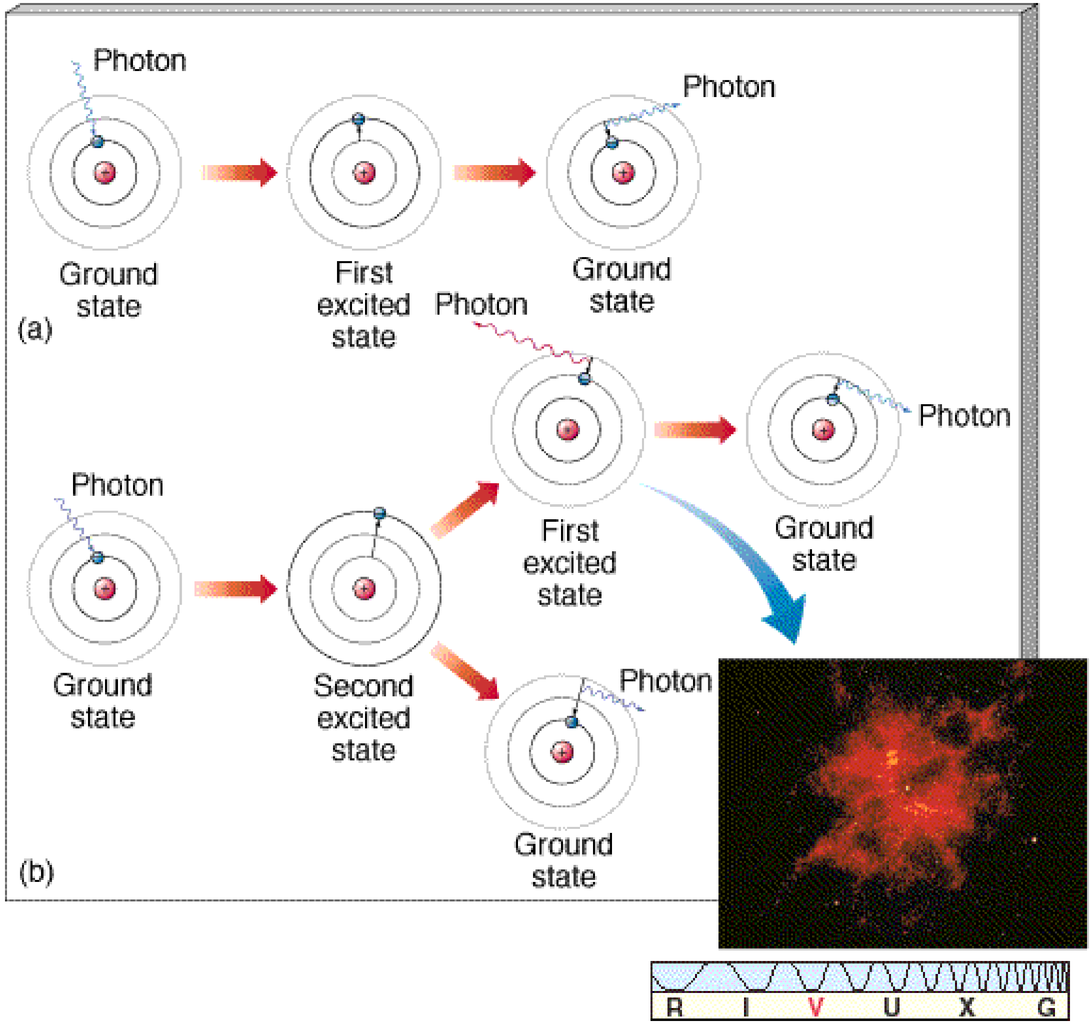
We can measure the energy of a photon using Einstein´s equation:

$$I = \sigma T^4$$

I is the intensity of emitted em radiation in W/m^2

σ (lower case sigma) is the Stefan-Boltzmann constant 5.67×10^{-8} W m^{-2} K^{-4}

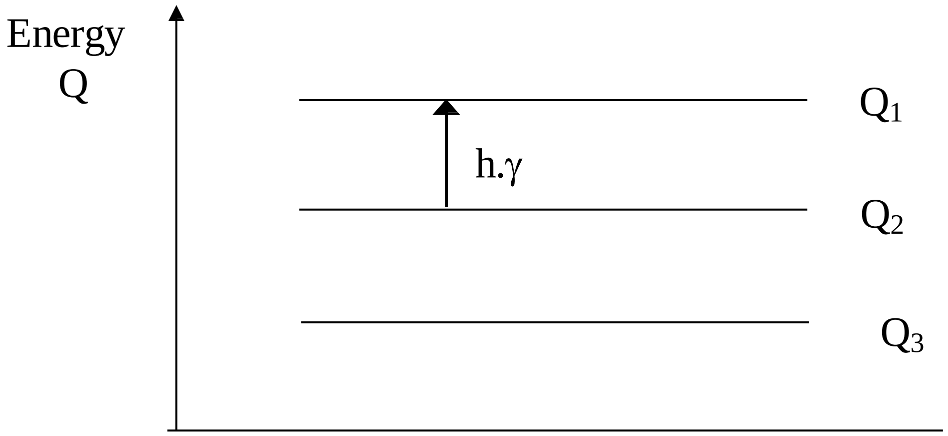
T is the temperature in kelvin, K

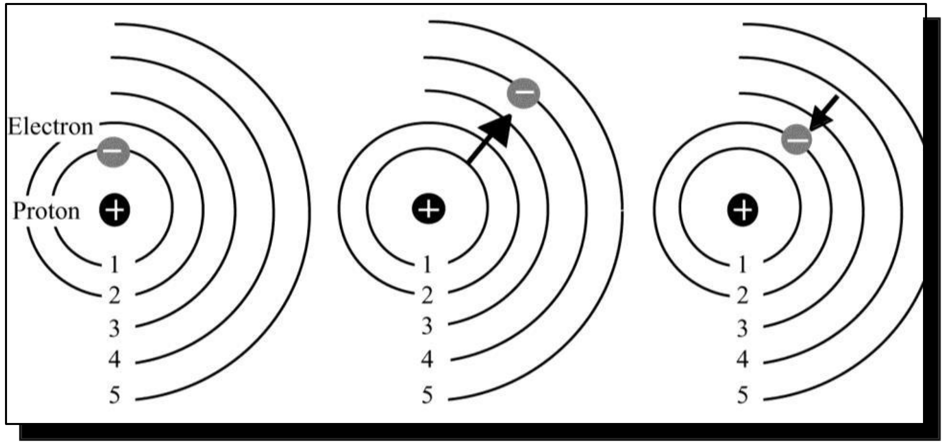


Source:http://lifeng.lamost.org/courses/astrotoday/CHAISSON/AT304/HTML/AT3040 2.HTMBAk

Relationship between Wavelenght and Frequency

Blackbody radiation





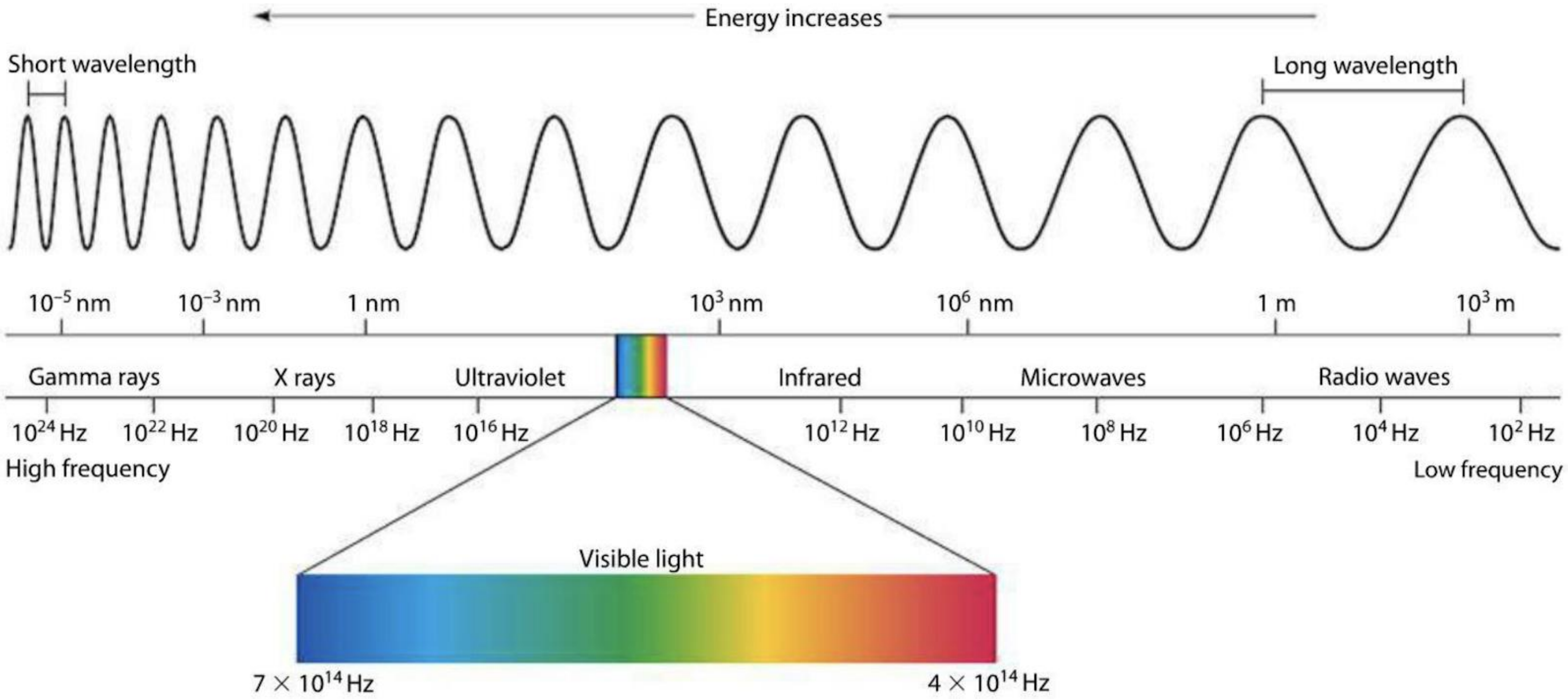
$$\Delta Q = Q_m - Q_n = h.\gamma$$

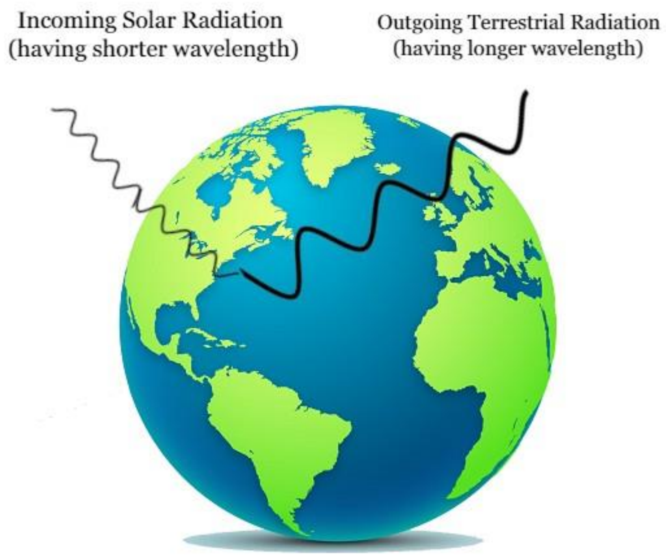
γ – $frequency(ní)$

Planck constant $h = 6{,}625.10^{-34}$ J.s

Source: Jensen (2005)

Electromagnetic bands used in Remote Sensing

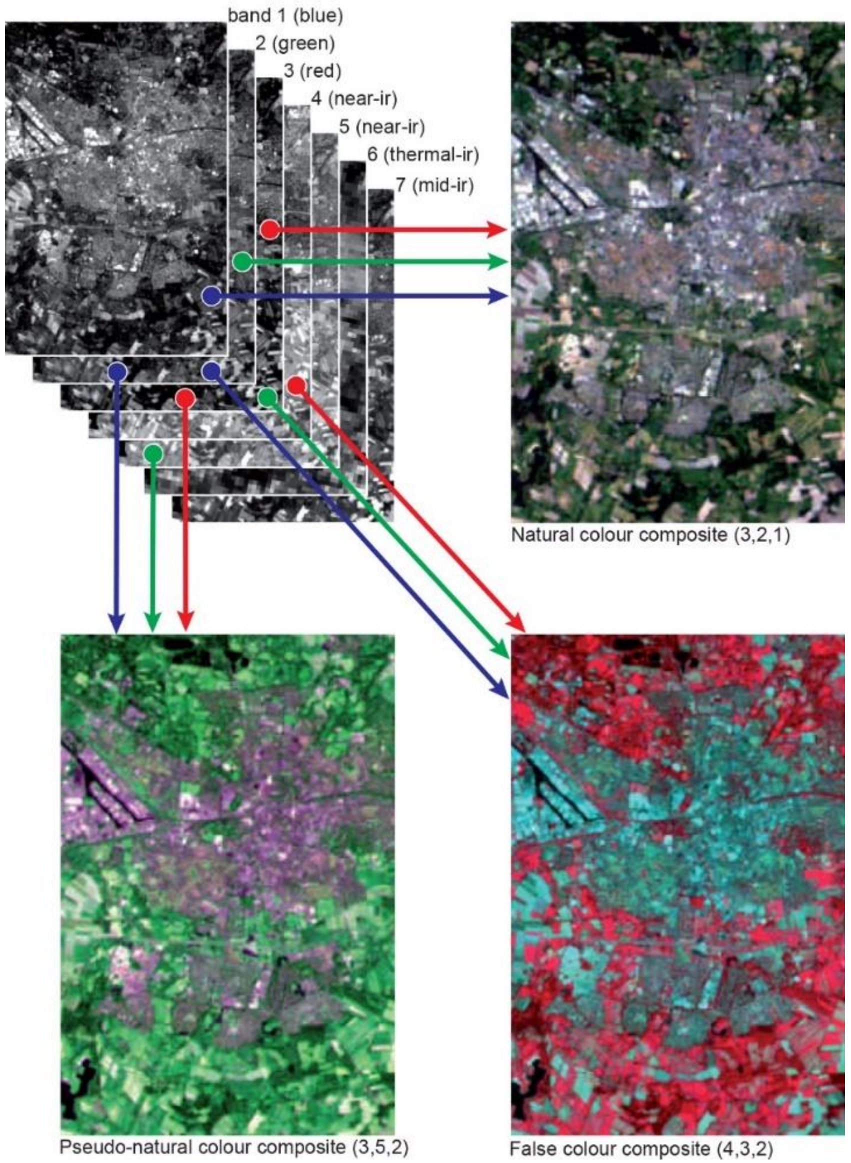


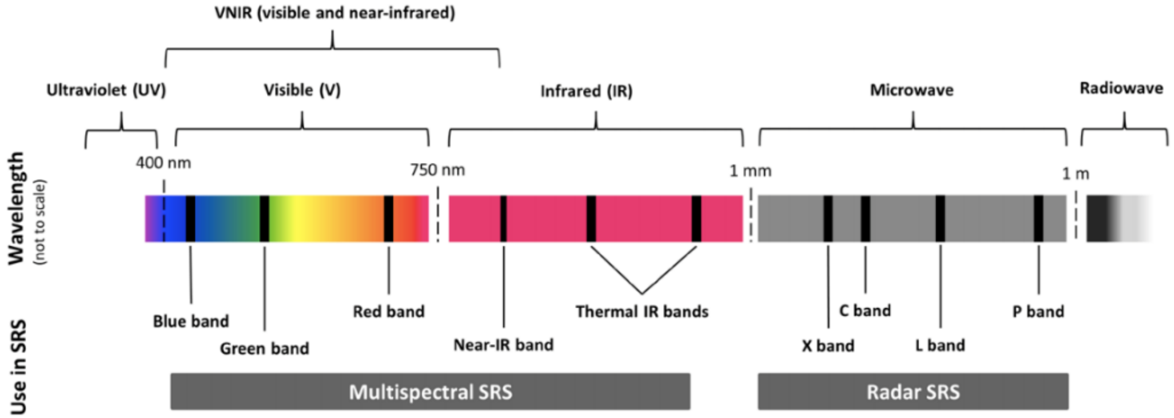


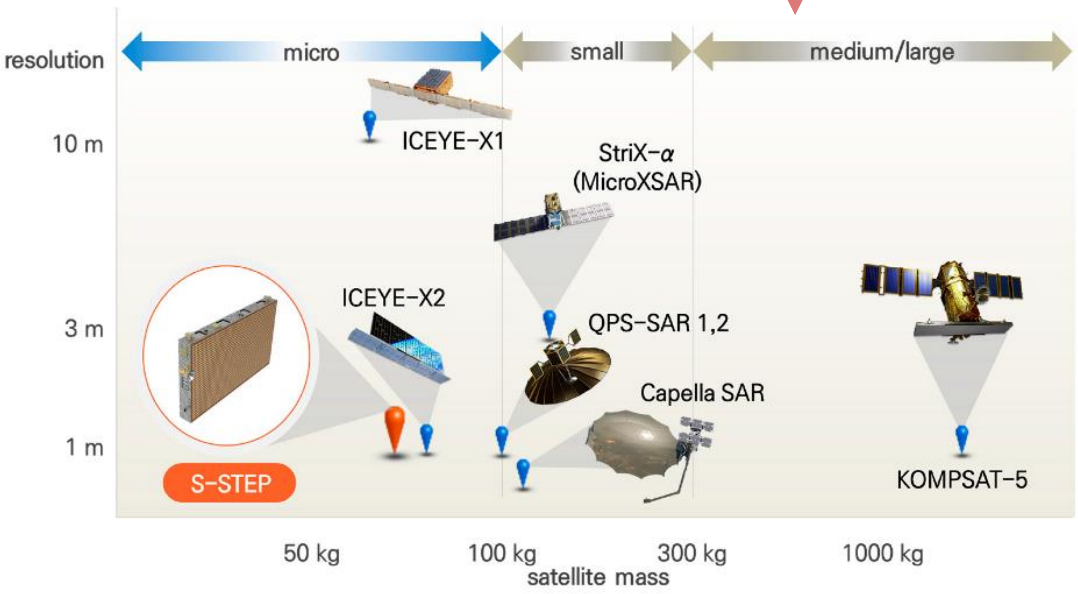
- The Sun produces a *continuous spectrum* of energy from gamma rays to radio waves that continually bathe the Earth in energy.
- The portion of the spectrum may be measured using wavelength, frequency or electron volts (eV). All units are interchangeable.

Source: https://www.researchgate.net/publication/326025281_Review_on_Material_Processing_Through_Microwave_Energy,
https://www.iasnotes.in/2022/10/insolation-and-heat-budget-vision-ias-notes-upsc-classnotes.html

Electromagnetic bands used in Remote Sensing







Source: https://ltb.itc.utwente.nl/498/concept/81525, https://rpubs.com/GeospatialEcologist/RS, https://www.mdpi.com/2226-4310/9/4/213

Electromagnetic bands used in Remote Sensing

Commonly used bands in remote sensing

Visible (400-700 nm)

Commonly used in satellite and aerial imaging, to provide detailed information about land cover, vegetation health, urban development, etc.

Near-infrared (700-1300 nm)

One of the most powerful ways to classify healthy vegetation and water. This is because, healthy plants reflect more energy in the NIR, while water absorbs it.

Mid-infrared (1300-3000 nm)

Used for vegetation monitoring, geological mapping, fire detection, urban heat island detection, and atmospheric studies.

Thermal infrared (3000-14000 nm)

Useful in understanding surface temperature, environmental monitoring, fire detection, and volcanic activity monitoring.

Microwave (1 mm-1m)

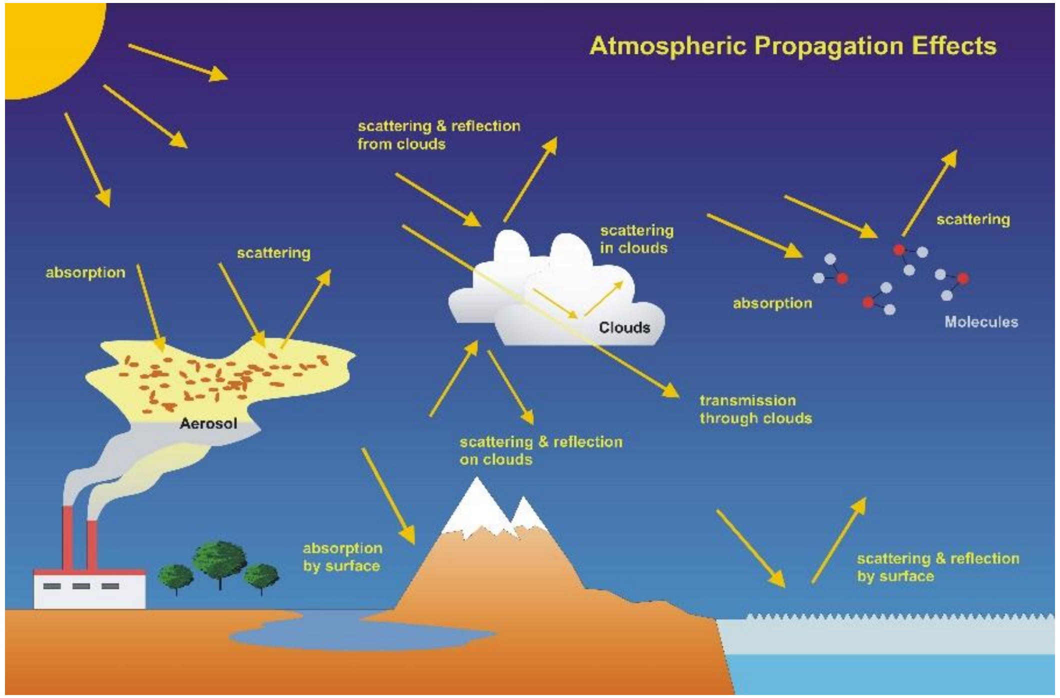
The microwave band is used for penetrating clouds and vegetation, monitoring soil moisture, studying oceans and ice, radar imaging, atmospheric studies.

Source:https://gisgeography.com/spectral-signature/

Interaction of EMR with atmosphere

- Energy recorded by RS systems undergoes fundamental interactions that should be understood to properly interpret the remotely sensed data. For example, if the energy comes from the Sun, the energy:

- propagates through the vacuum of space at the speed of light
- interacts with the Earth's atmosphere
- interacts with the Earth's surface
- interacts with the Earth's atmosphere once again
- finally reaches the remote sensor where it interacts with various optical systems, etc.

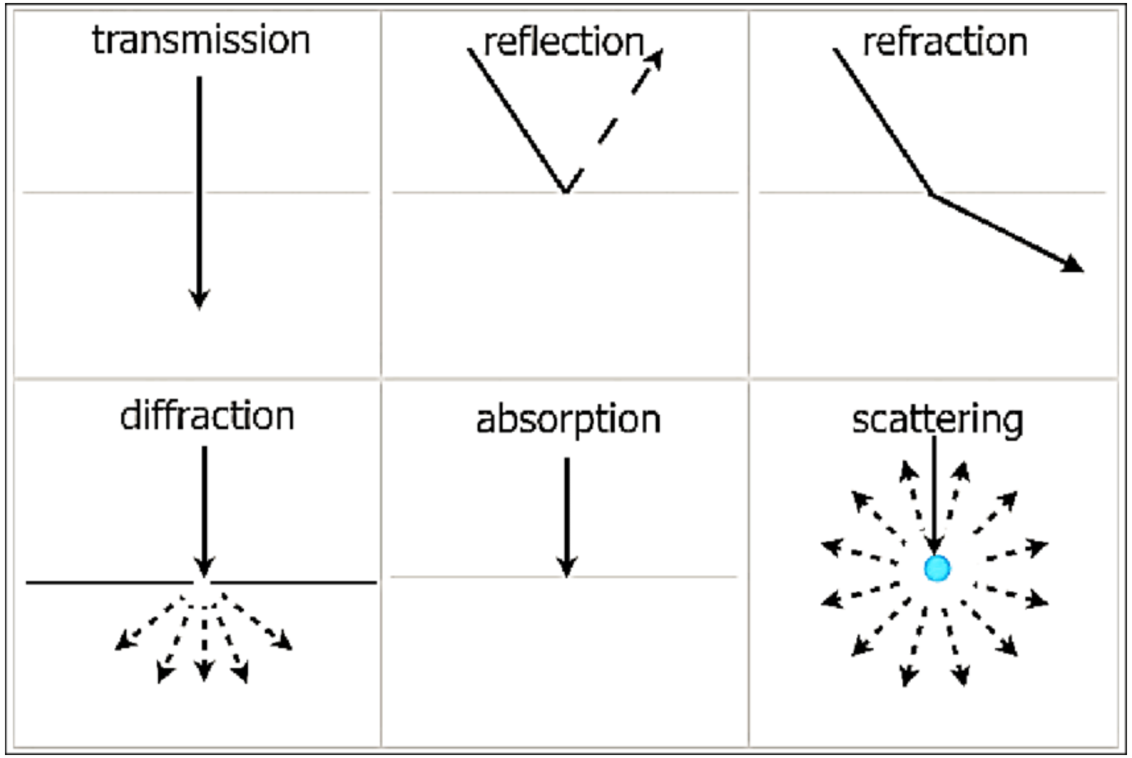


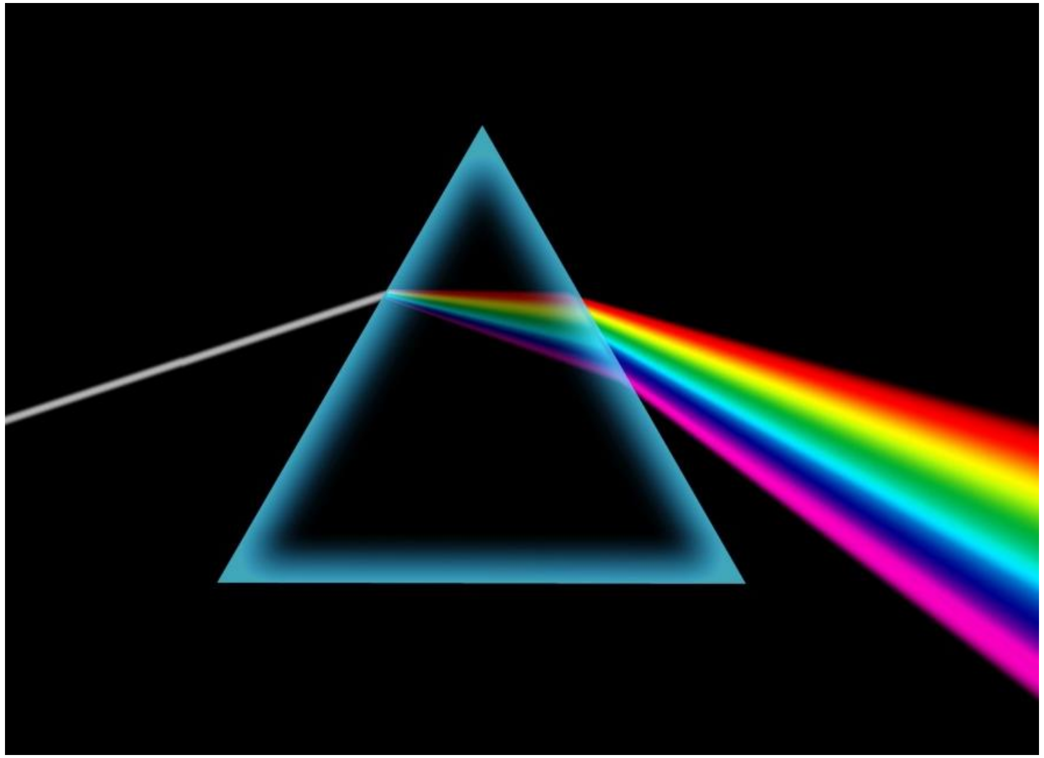
Source:https://atmos.eoc.dlr.de/projects/scops/sciamachy_book/sciamachy_book_figures_springer/chapter_7/fig_7_1.jpg

For more information, see the tutorial: 3. Key concepts of remote sensing data processing,converting DN values to radiance and reflectance, using SNAP software

Interaction of EMR with atmosphere

- Upon interaction with matter, EMR can undergo transmission, reflection, refraction, diffraction, adsorption and scattering





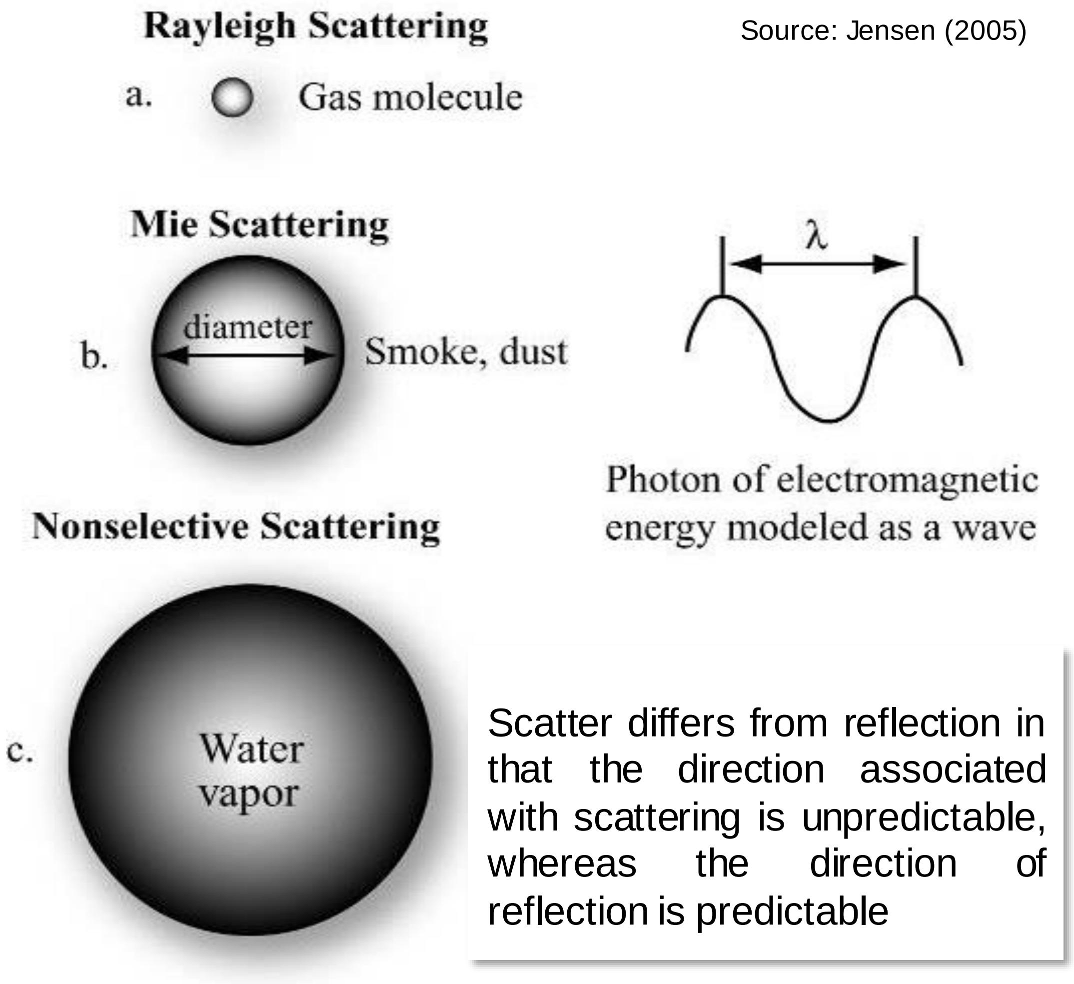
Source: Robinson and Dean, 2017, https://socratic.org/questions/how-can-refraction-make-a-rainbow-1

Interaction of EMR with atmosphere - Scattering

- **There are essentially three types of scattering:**
    - Rayleigh
    - Mie
    - Non-selective

- **Type of scattering is a function of:**
    1) the wavelength of the incident radiant energy, and
    2) the size of the gas molecule, dust particle, and/or water vapor droplet encountered

Source: Jensen (2005)



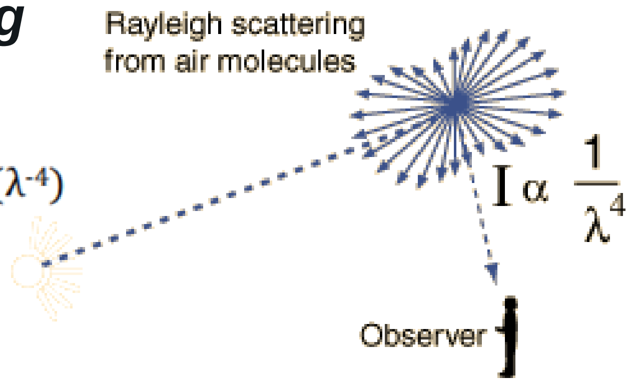
Scatter differs from reflection in that the direction associated with scattering is unpredictable, whereas the direction of reflection is predictable

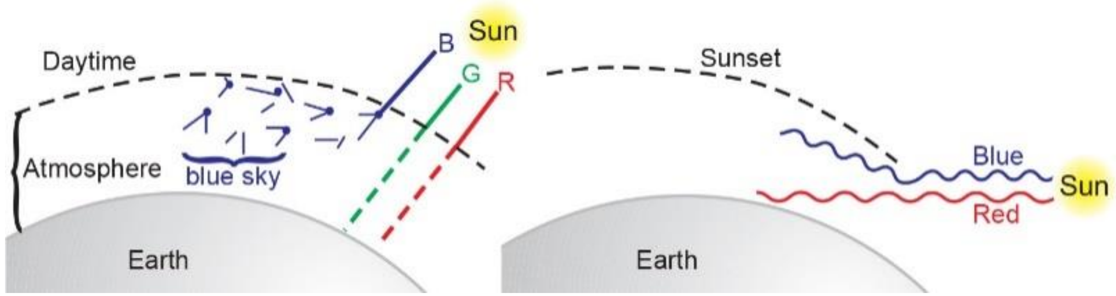
Interaction of EMR with atmosphere - Scattering

Rayleigh scattering

$\varnothing < \lambda$

Stronger effect at shorter λ (λ^{-4})



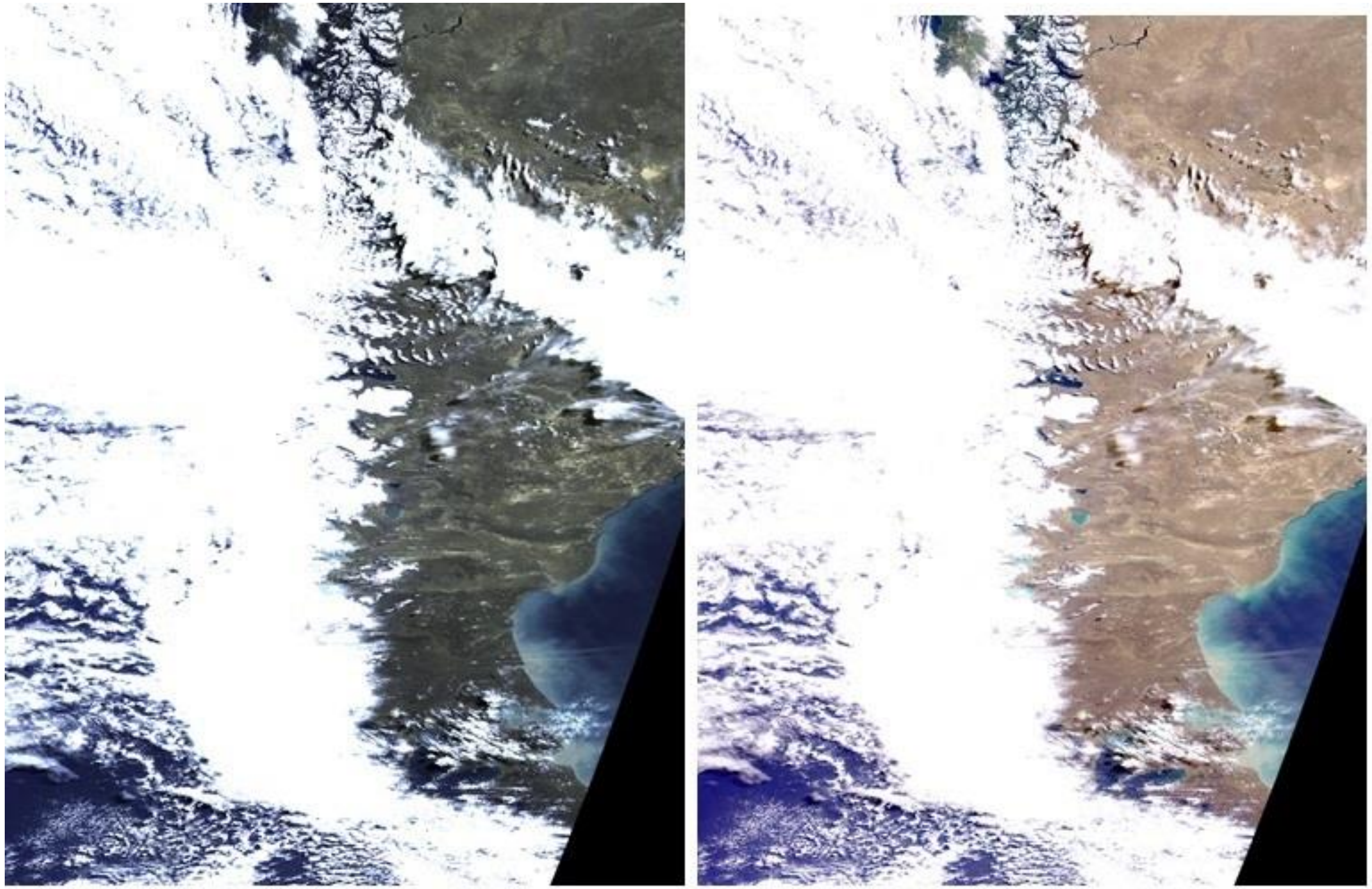


- The Rayleigh scattering effect in the atmosphere causes greater reflection of shorter wavelengths (blue color) – blue color of clear sky
- Involves particles smaller than the wavelength of incident light

Source: http://hyperphysics.phttps://www.researchgate.net/figure/Rayleigh-scattering-causes-us-to-perceive-a-blue-sky-during-daytime-and-a-red-sky-at_fig15_233793398, hy-astr.gsu.edu/hbase/atmos/blusky.html, https://fineartamerica.com/featured/red-sunset-jasna-buncic.html, https://theconversation.com/explainer-why-is-the-sky-blue-10821,

Interaction of EMR with atmosphere - Scattering

Rayleigh scattering



Before Rayleigh correction

After Rayleigh correction

Source: https://forum.step.esa.int/t/still-a-strong-rayleigh-signal-after-rayleigh-correction/7006/8:

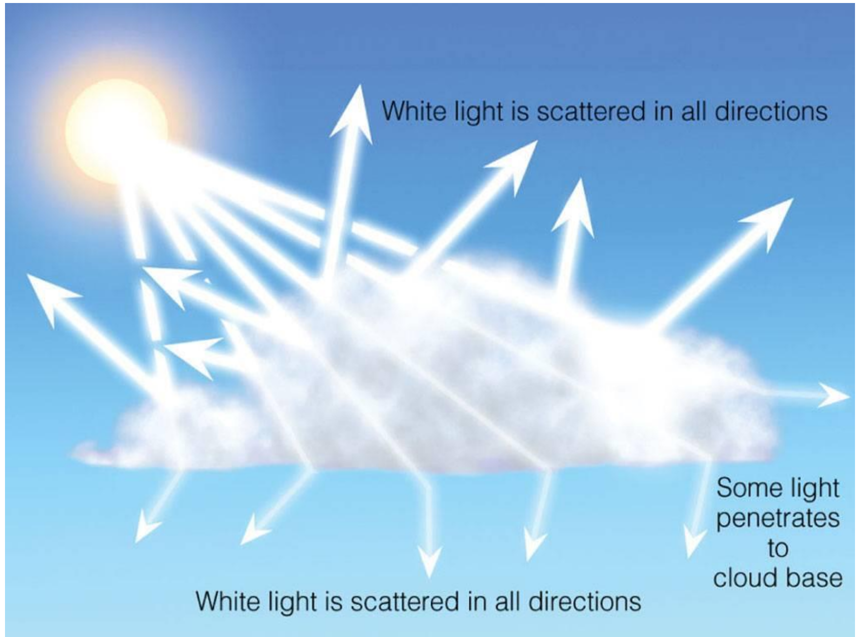
Interaction of EMR with atmosphere - Scattering

Mie scattering

$\varnothing \approx \lambda$

Clearer effect at longer λ

- Predominates for particle sizes equal or larger than a wavelength (0.1 - 10 times the wavelength)
- Occurs below 4.5 km in the atmosphere - more spherical particles with diameters approx. equal to the size of the wavelength of the incident energy (aerosols, pollution, dust particles, etc.)
- Produces almost white glare around the sun when a lot of particulate material is present in the air
- White light from mist and fog
- Contributes to the reddish sunsets



Source: http://www.china.org.cn/travel/2017-07/06/content_41165327.htm, https://medium.com/@elif_erkk/the-color-of-clouds-and-the-color-of-the-sky-a-dance-of-light-and-scattering-acbf2e66fe22

Interaction of EMR with atmosphere - Scattering

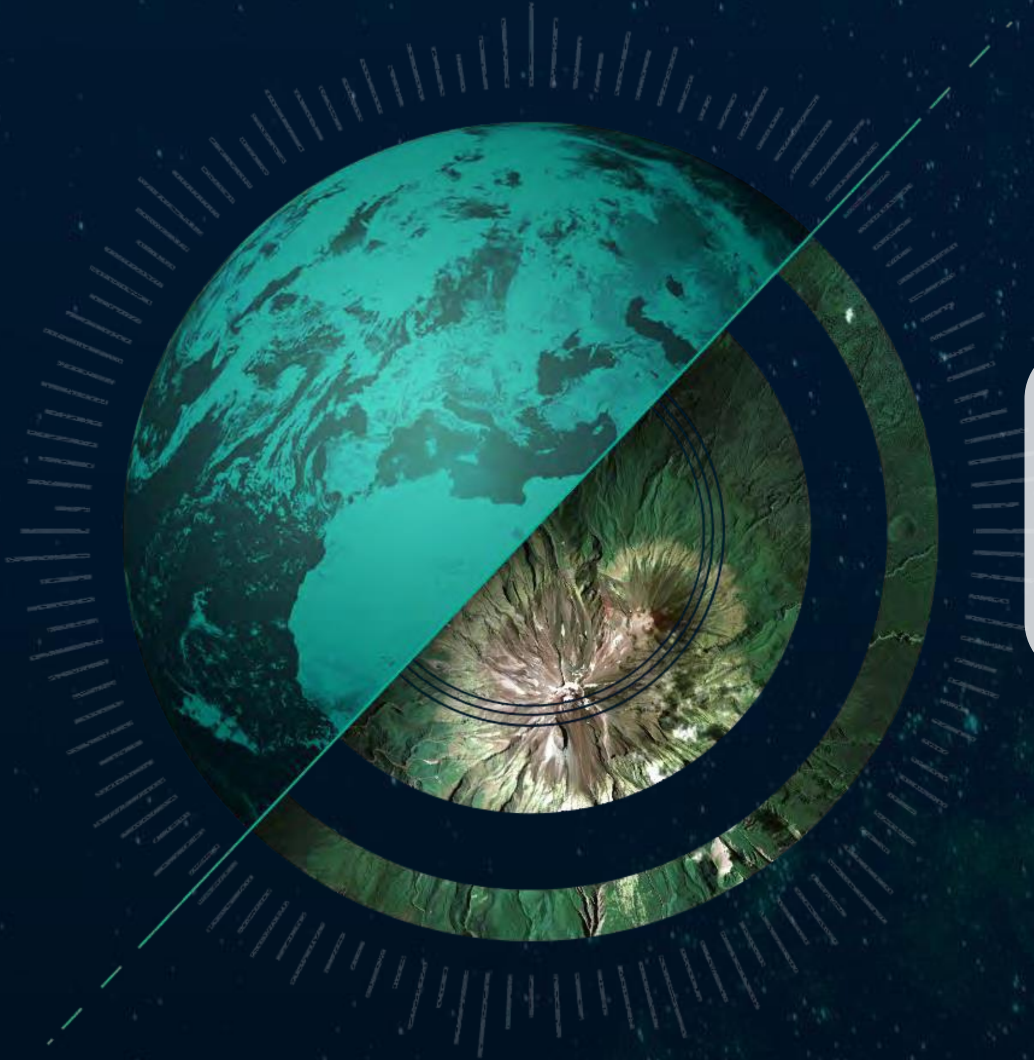
Non-selective scattering

$\varnothing > \lambda$

Similar at different λ: clouds.

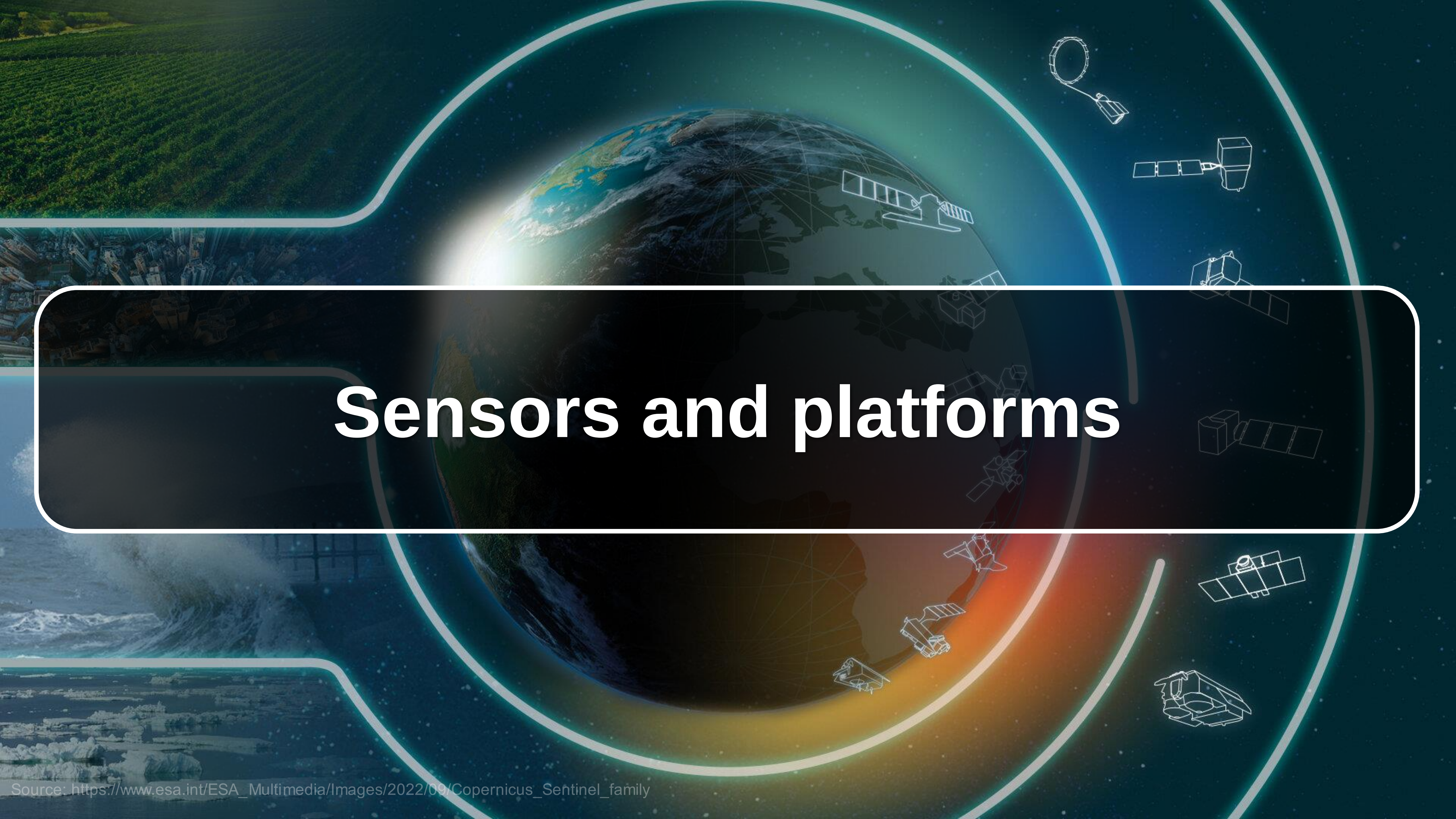
- Takes place in the lower parts of the atmosphere where the particles are larger than 10 times the wavelength of the incident radiation
- Here, any wavelength can be scattered equally effectively, hence the clouds appear white, for example

Source: https://depositphotos.com/cz/photos/poprad-tatry.html, https://backcountrymagazine.com/stories/hillary-nelson-and-james-morrison-make-first-full-descent-of-27940-foot-lhotse/



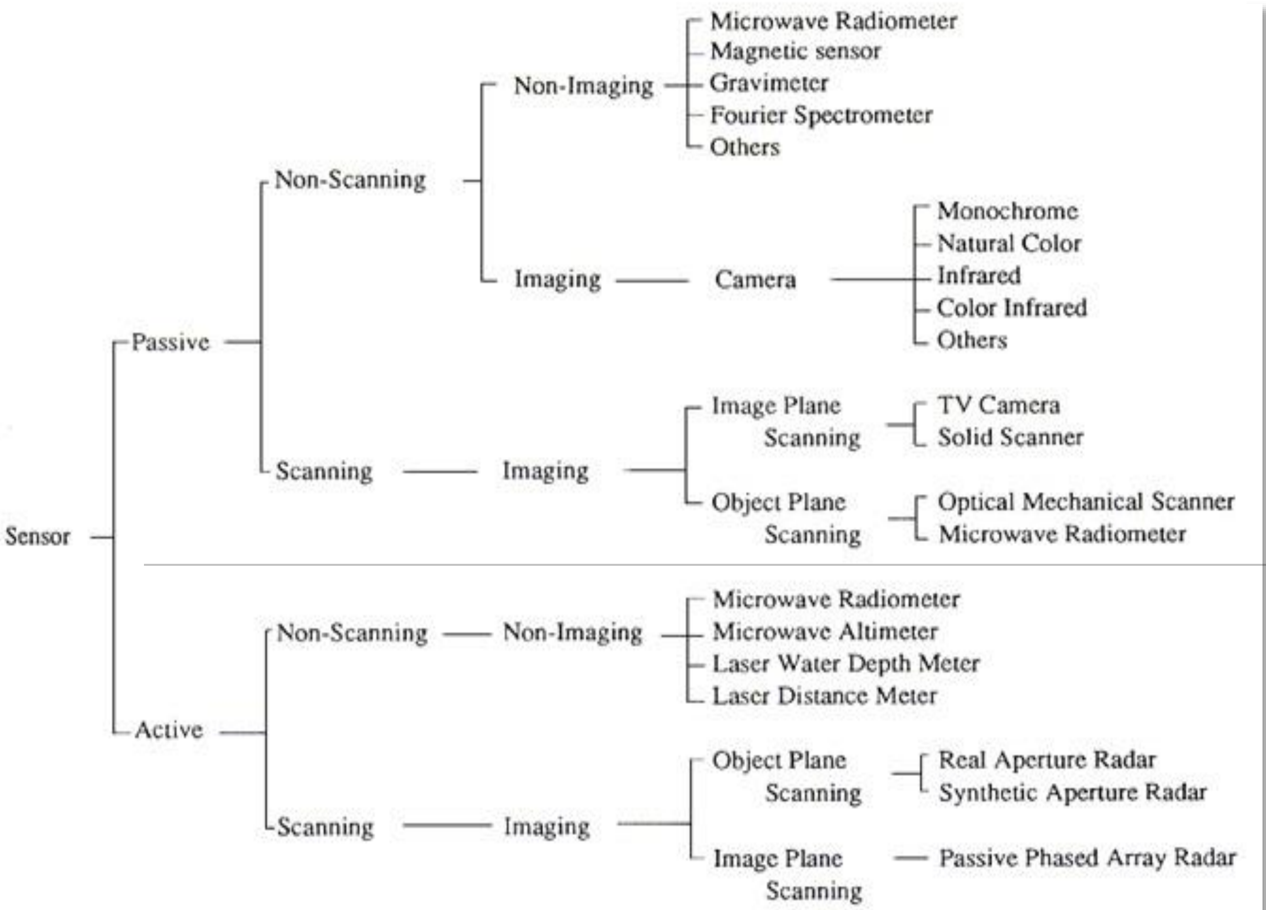
4. Optical remote sensing using ESA Copernicus´ data: sensors and platforms, image metadata, image resolution (spectral, spatial, temporal and radiometric resolution)

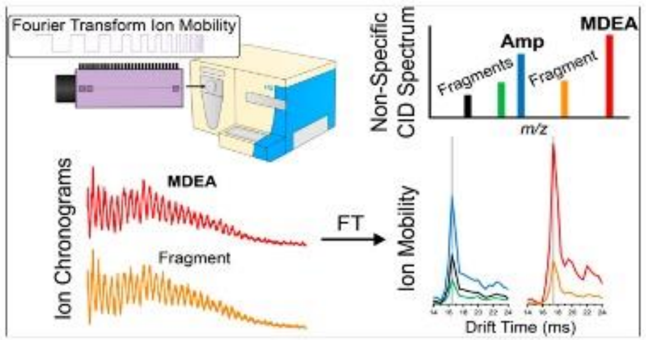
Sensors and platforms

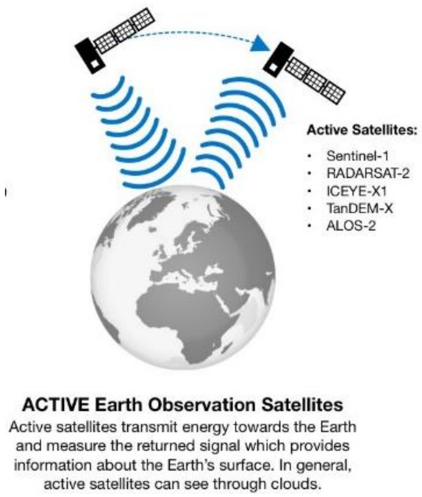


Source: https://www.esa.int/ESA_Multimedia/Images/2022/09/Copernicus_Sentinel_family

Types of sensors







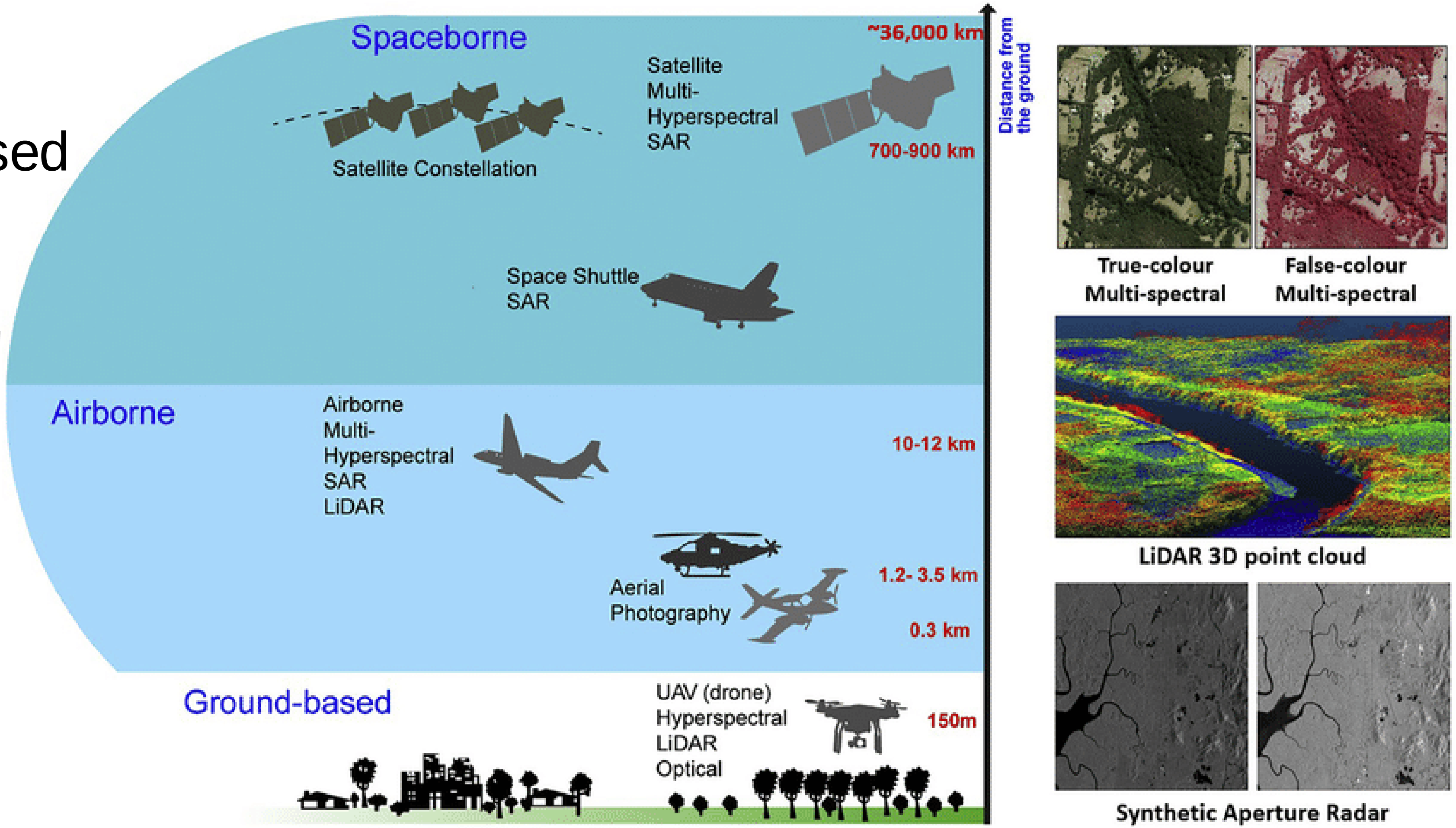
Source: https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2022/09/copernicus_sentinel_family/24451531-1-engGB/Copernicus_Sentinel_family_pillars.jpg?fbclid=IwAR0Fj0JjjxucGiN6ICSRwqPmvLd1T1F5eGgv6pr7kNp53_T3XFHfv8Hojk4, https://www.geospatialworld.net/blogs/observing-the-earth-fueling-global-development-solutions/, https://www.geospatialworld.net/blogs/observing-the-earth-fueling-global-development-solutions/, https://www.researchgate.net/publication/224136559_The_Soil_Moisture_Active_and_Passive_SMAP_mission/figures?lo=1, https://www.iqservices.eu/sk/novinky/faro-focus-core.html

Types of platforms

Platforms = the vehicles or carriers for remote sensing devices

3 main platforms:

- Terrestrial/ground based
- Airborne
- Spaceborne



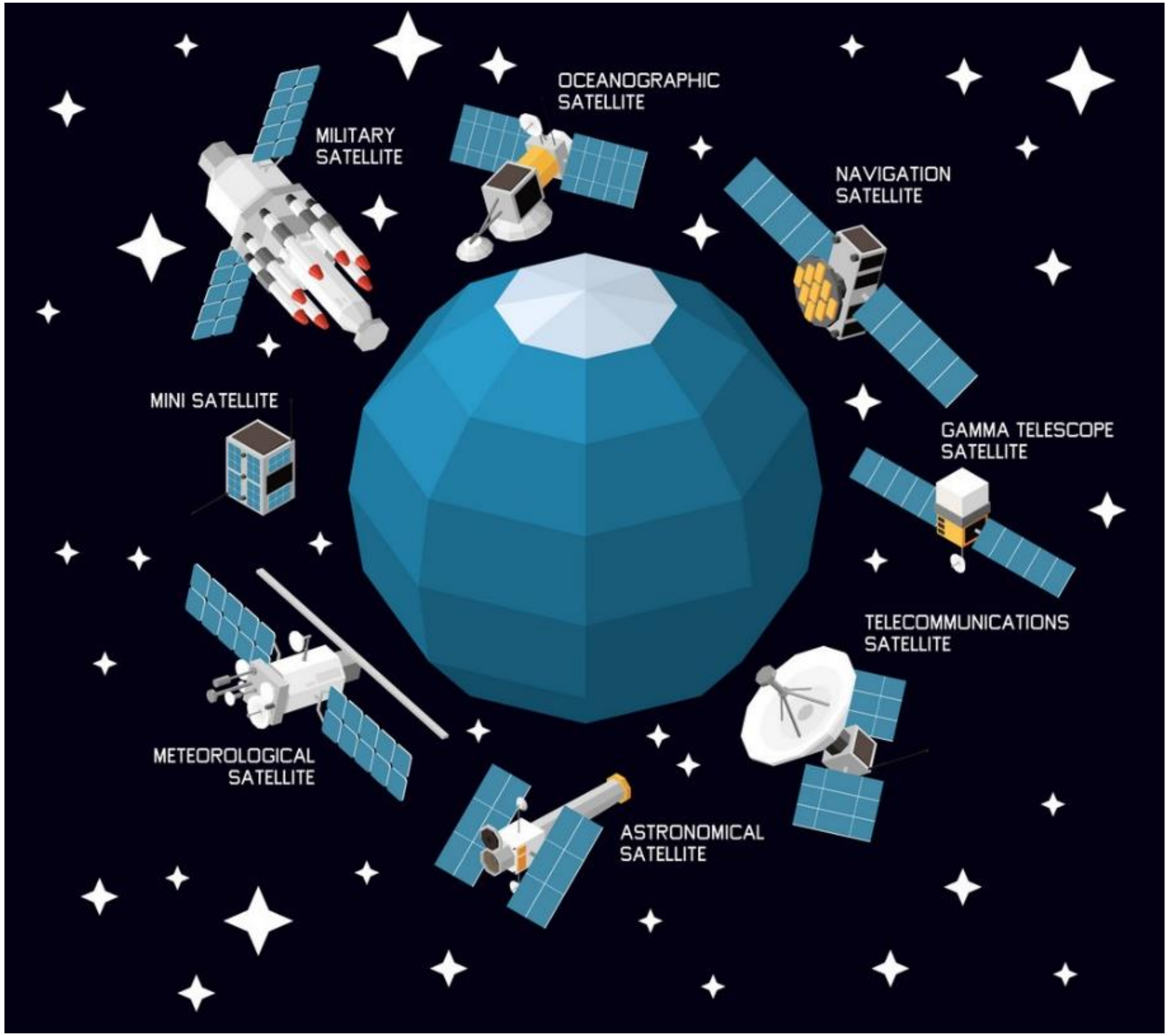
Source: https://l.facebook.com/l.php?u=https%3A%2F%2Fleclab.wixsite.com%2Fspatial%2Fpost%2Fapplications-in-remote-sensing-to-forest-ecology-and-management%3Ffbclid%3DIwAR2FmvF9puHnHJ2uK9nkkn2M17rsHxPN2oAvmXsTpJs9ALWnUSEoGwXVPw&h=AT03SEz8ODeTVHYAj5_j0w1yhRDd7_5GJQGRn5FLIgfUYVaXrZsOSK3E7IwfOd78qB94URBYG7IDfCtM0MRpRfEd7rBDDowQZTLJ4Gu8gk9IdpkxlYSKzHH1JZbM4LadoKg

Types of satellites

Today man-made or artificial satellites are widely used for a large number of purposes.

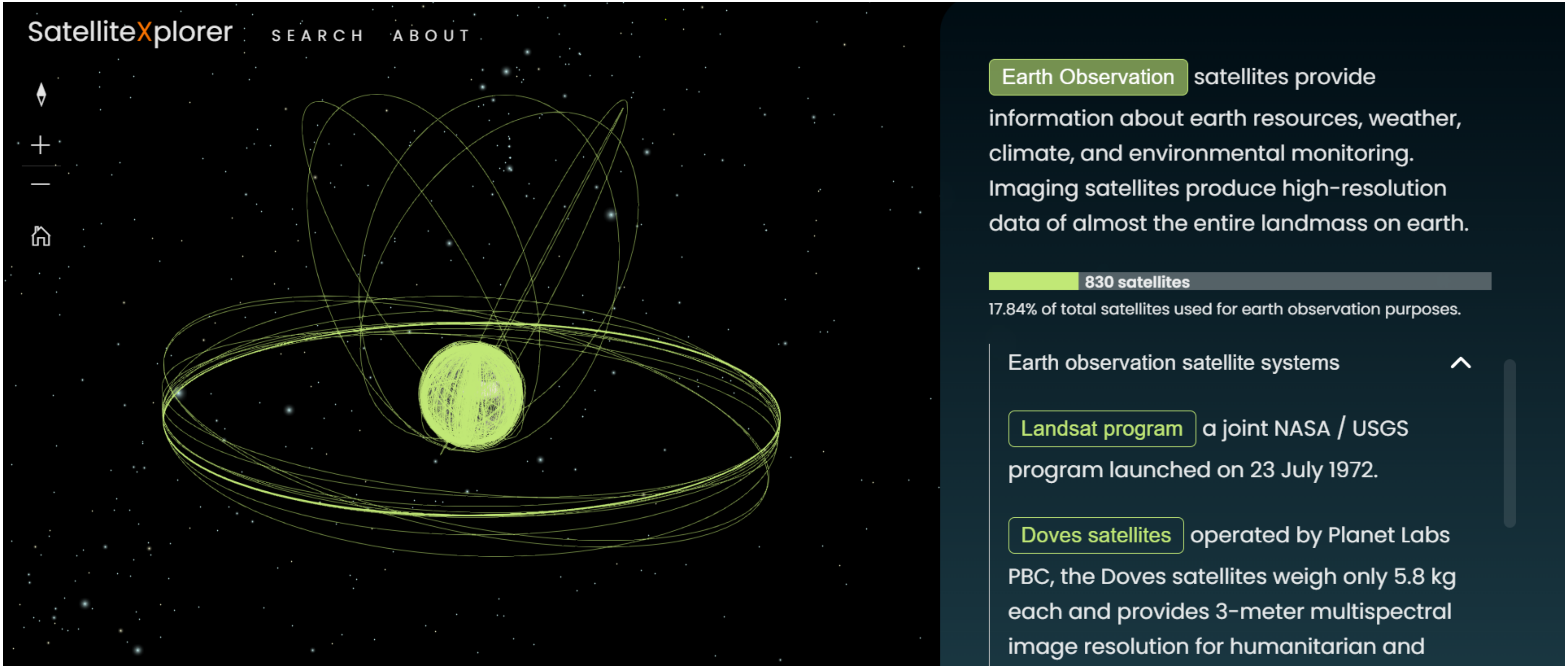
Hence such satellites are classified into six major types:

- Astronomical
- Communication
- Weather
- Remote sensing
- Navigation
- Reconnaissance satellites



Source: https://www.vectorstock.com/royalty-free-vector/satellites-types-composition-vector-45762172

Types of satellites



Source: https://geoxc-apps.bd.esri.com/space/satellite-explorer/

Image metadata

Source: https://tees.tamu.edu/global/deep-tech-entrepreneurship-program.html

Metadata

- In the Earth observation domain, metadata is the descriptive information about the data
- Metadata provides the user information about the content, source, quality, condition for use, lineage, and other relevant characteristics

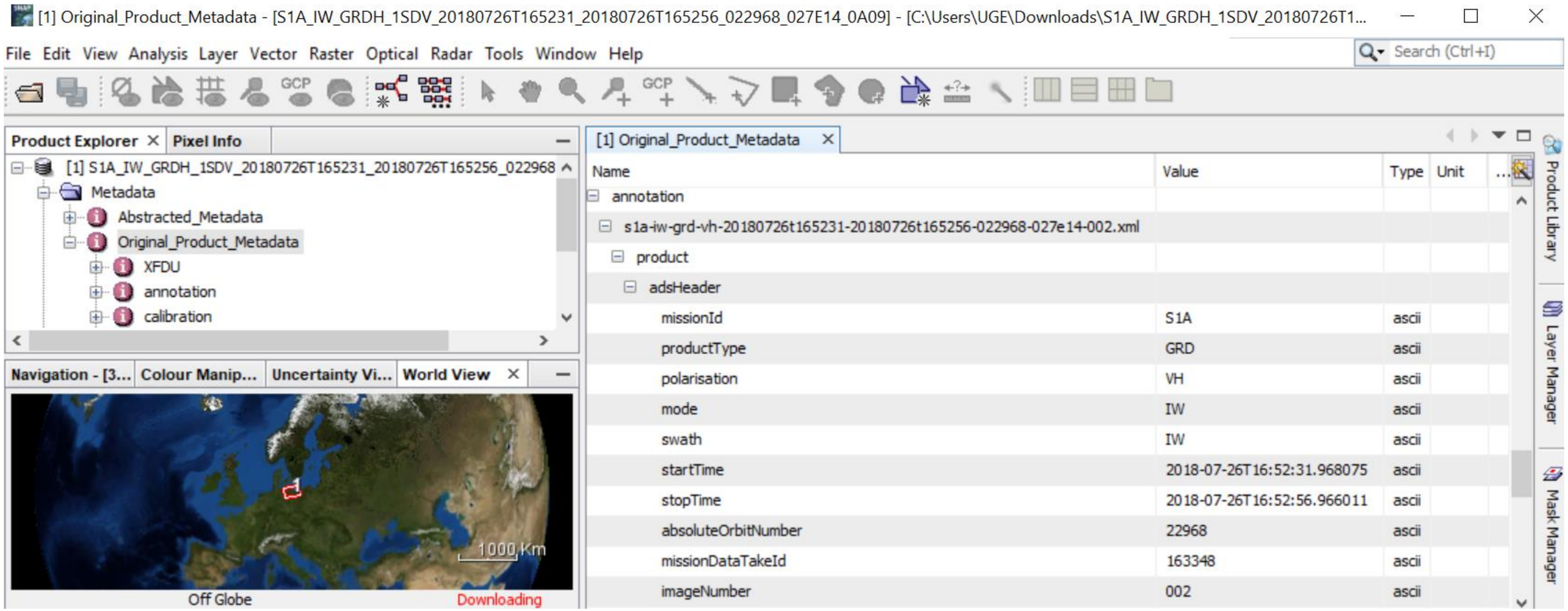
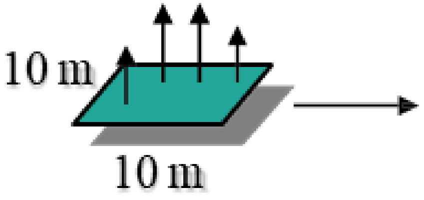
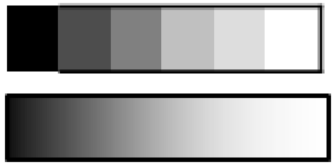


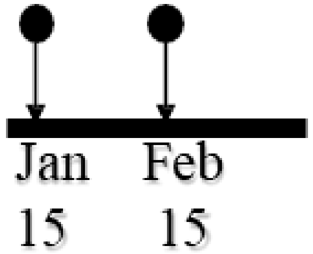
Image resolution

Source: https://www.earthdata.nasa.gov/learn/backgrounders/remote-sensing

Image Resolution





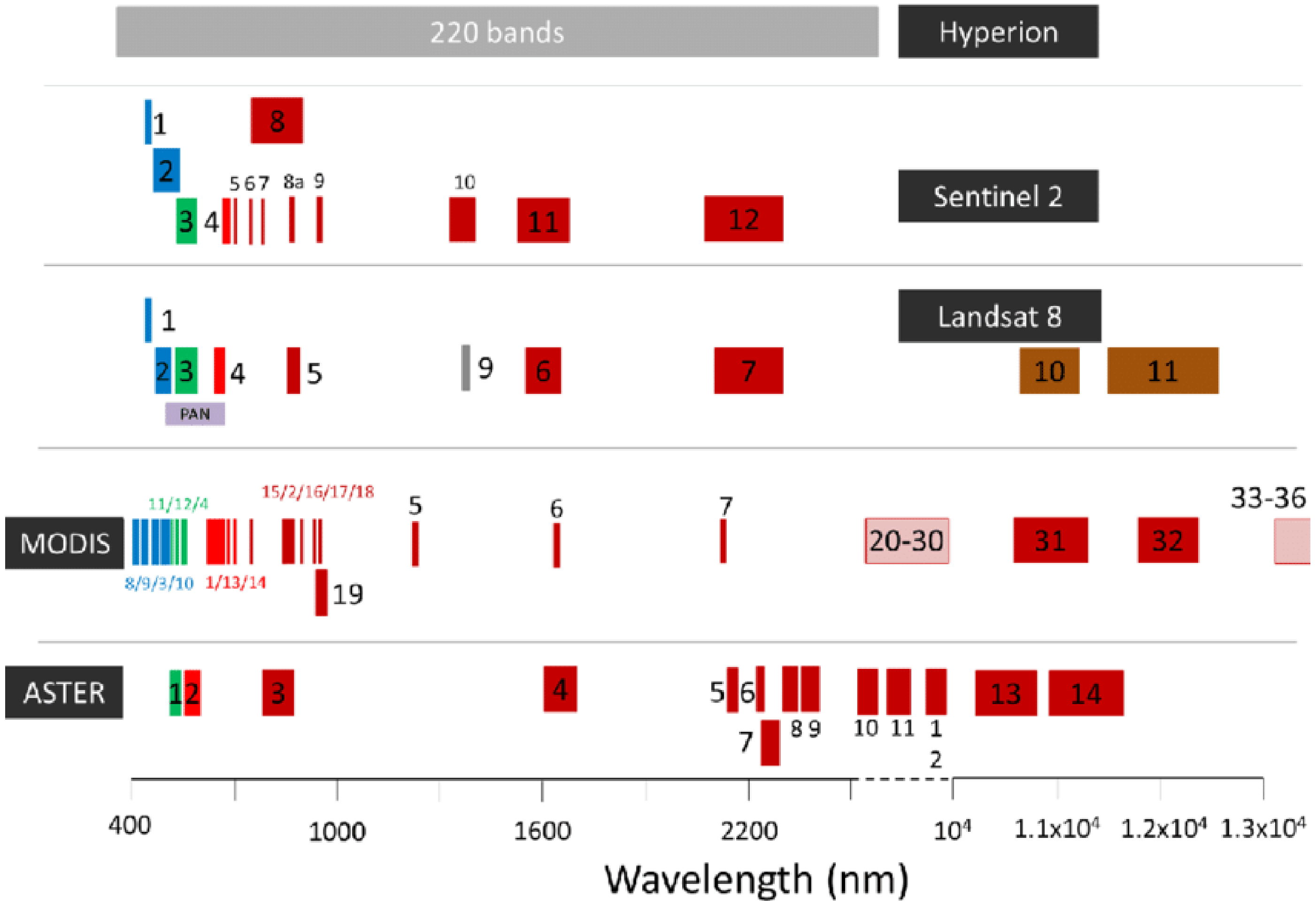


- **Spatial** - the size of the field-of-view per pixel, e.g. 10 x 10 m
- **Spectral** - the number and size of spectral regions the sensor records data in, e.g. blue, green, red, near-infrared, thermal infrared, microwave (radar).
- **Radiometric** - the sensitivity of detectors to small differences in electromagnetic energy. (8bit, 16bit)
- **Temporal** - how often the sensor acquires data, e.g. every 30 days

Jensen, 2007

Spectral resolution

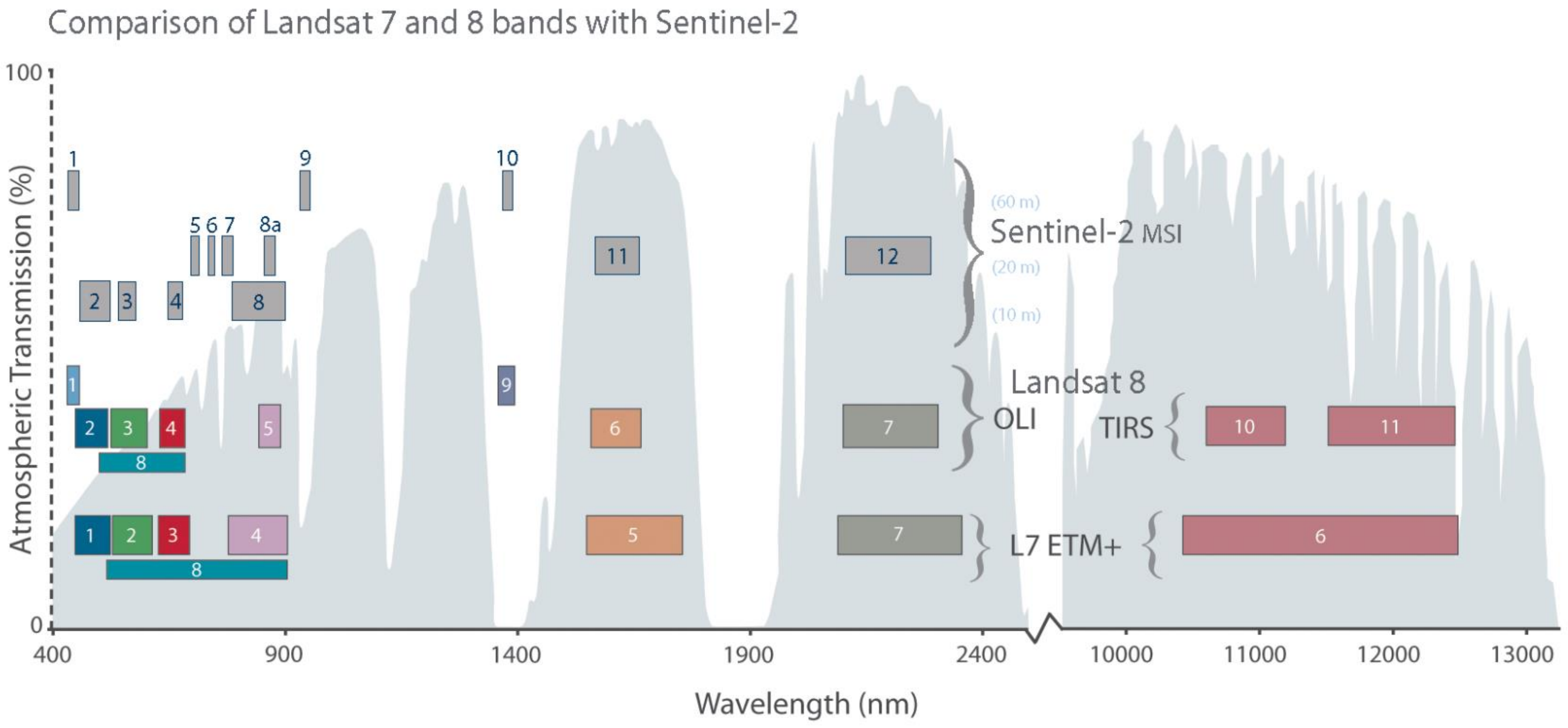
- The bandwidth (width), number, and position of specific wavelength bands that a sensor system can record



Source: https://www.researchgate.net/publication/324537528_Conservation_Technology_Series_Issue_4_SATELLITE_REMOTE_SENSING_FOR_CONSERVATION/figures?lo=1/

Spectral resolution

- The bandwidth (width), number, and position of specific wavelength bands that a sensor system can record



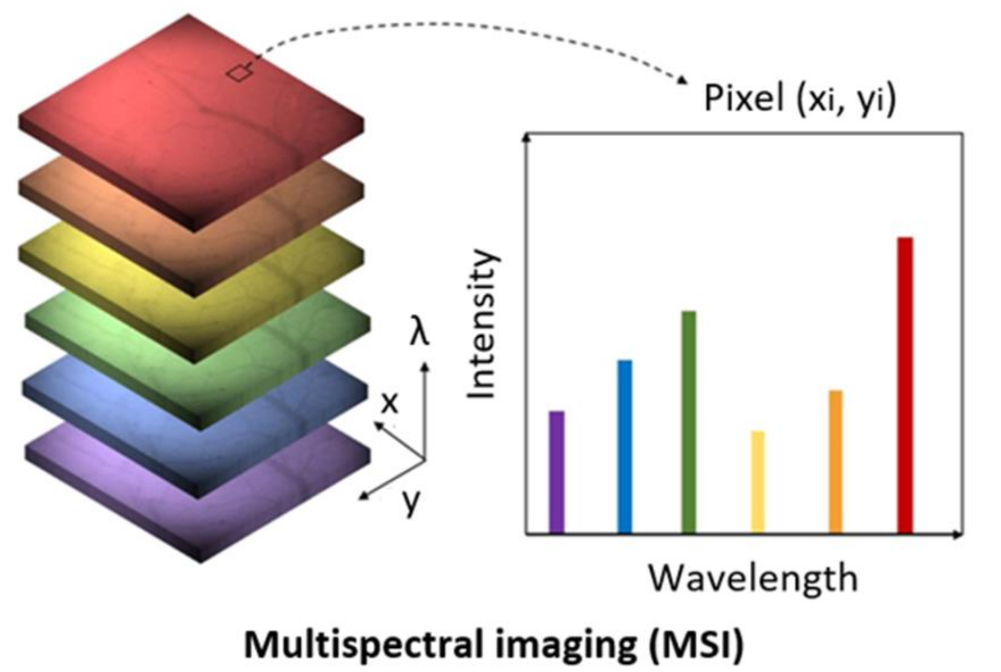
Source: https://digital-geography.com/landsat-8-how-not-to-plan-a-mission-part-2-the-sensors//

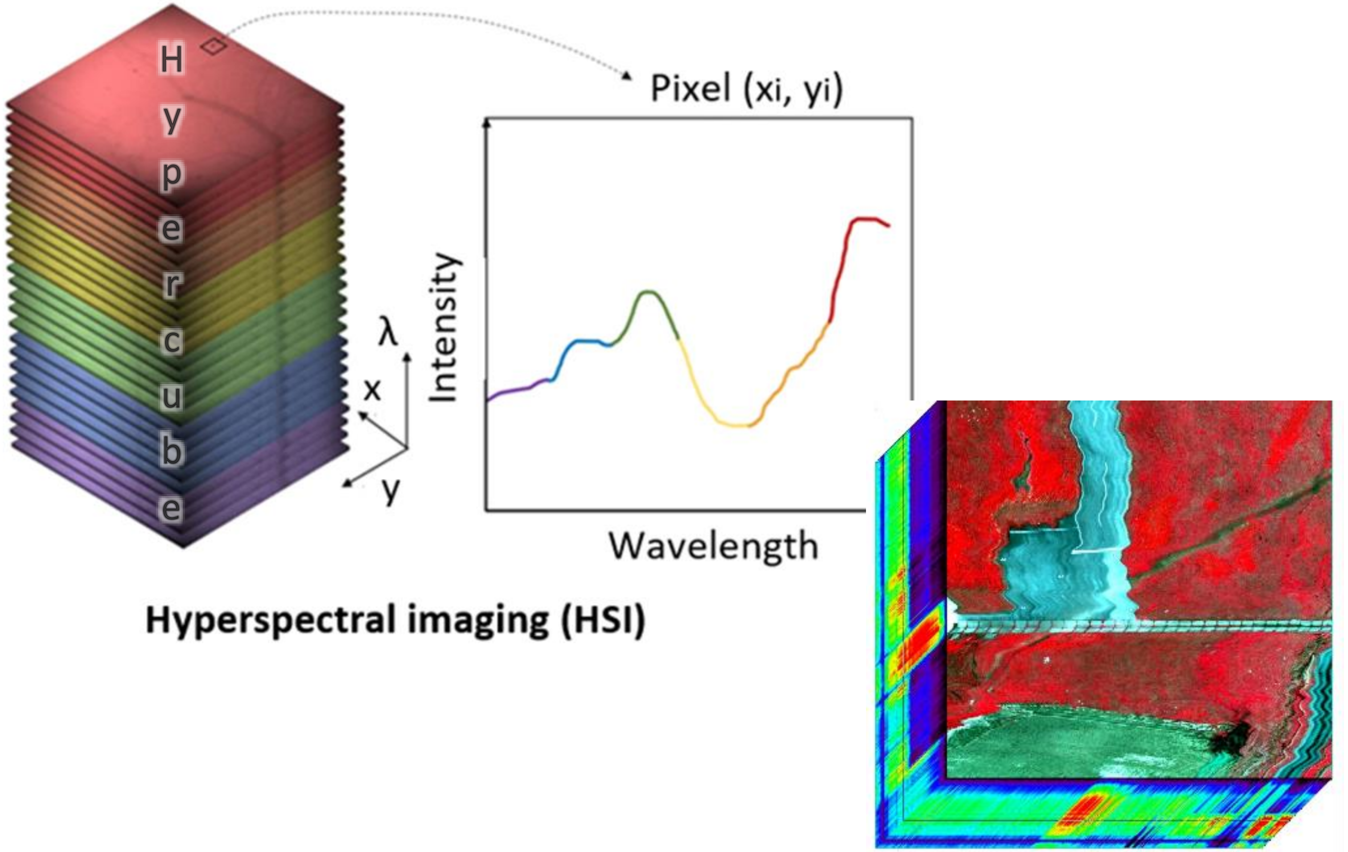
Spectral resolution

	Sentinel-2A MSI			Landsat 8 OLI		
Band	Spectral region	Wavelength range (nm)	Resolution (m)	Spectral region region	Wavelength range (nm)	Resolution (m)
B1				Blue	435–451	30
B2	Blue	458–523	10	Blue	452–512	30
B3	Green peak	543–578	10	Green	533–590	30
B4	Red	650–680	10	Red	636–673	30
B5	Red edge	698–713	20	NIR	851–879	30
B6	Red edge	733–748	20	SWIR1	1566–1651	30
B7	Red edge	773–793	20	SWIR2	2107–2294	30
B8	NIR	785–899	10			
B8A	NIR narrow	855–875	20			
B11	SWIR	1565–1655	20			
B12	SWIR	2100–2280	20			

Source: https://bg.copernicus.org/articles/15/5455/2018/

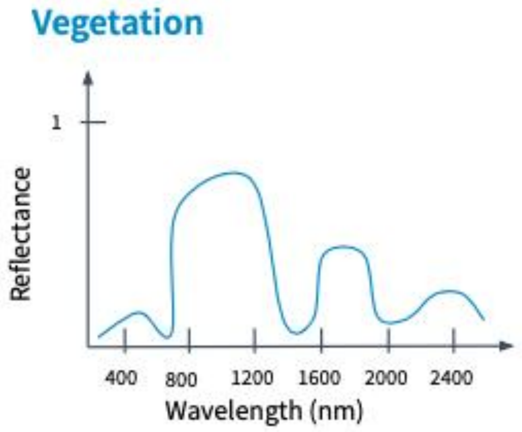
Spectral resolution

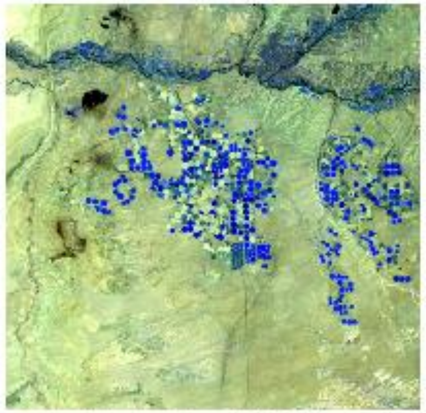




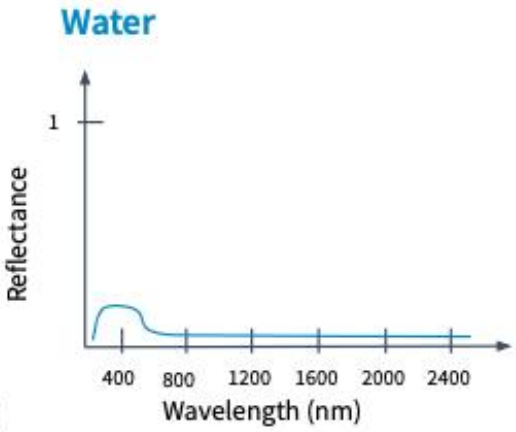
Source: https://www.pyroistech.com/hyperspectral-and-multispectral-imaging/, Institute of geography

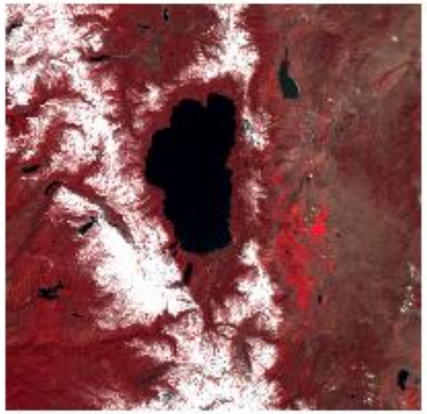
Spectral resolution vs. spectral curve



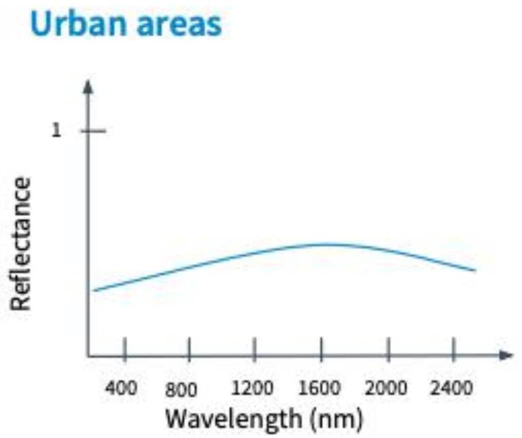


Center pivot irrigation, NASA Landsat, 2020
swir2 - swir1 - nir

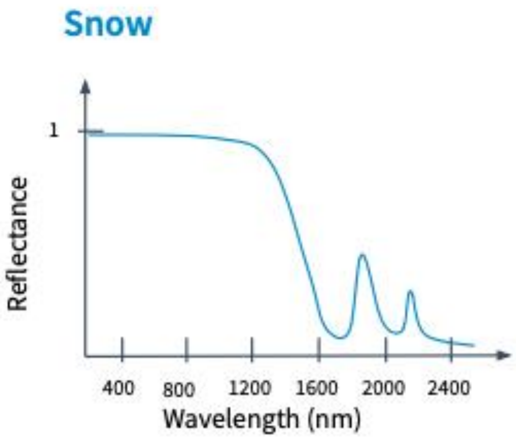


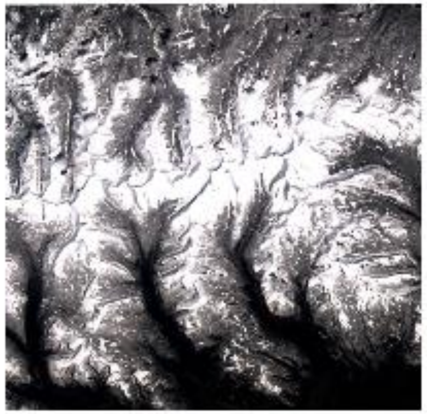


Lake Tahoe, NASA Landsat, 2020
nir - red - green



Los Angeles, NASA Landsat, 2020
red - green - blue





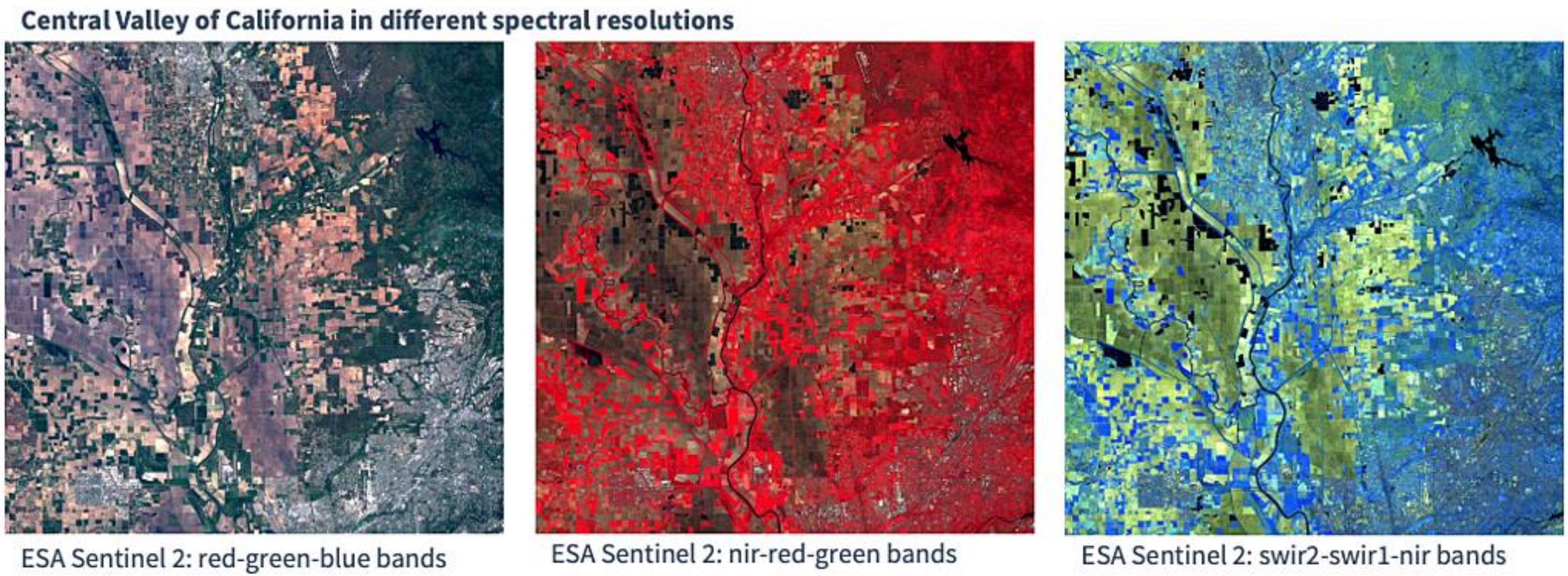
The Uintas, NASA Landsat, 2020
red -green - blue

*Note: spectral signatures have been generalized

Satellites can observe objects using different frequency bands all at once. You can choose different combinations of bands – color compositions to emphasize specific features.

Source: https://kb.descarteslabs.com/knowledge/introduction-to-remote-sensing

Spectral resolution vs. spectral curve

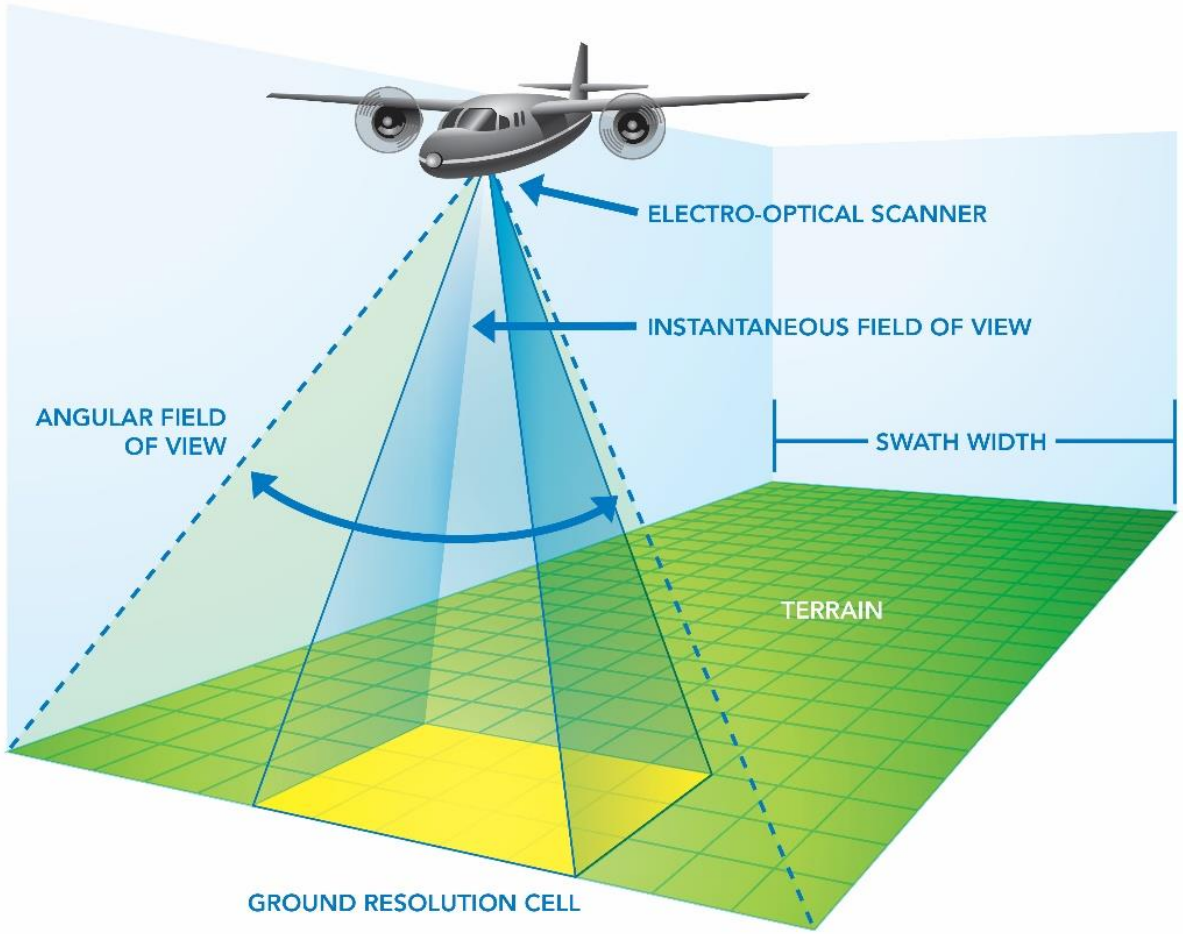


- *The first image shows red, green, and blue bands; this is the visible range and appears the same as what it would look like out the window of an airplane.*
- *The middle image is looking at near infrared, red, and green bands, where we see all the vegetation popping out strongly as a red color, since near infrared radiation is being reflected very strongly.*
- *The final image displays the two short wave infrared bands and near infrared. Agricultural fields emitting very strongly in the infrared bands, and are seeing more detail in the soil properties in yellow and brown.*

Source: https://blog.descarteslabs.com/a-look-into-the-fundamentals-of-remote-sensing

Spatial resolution

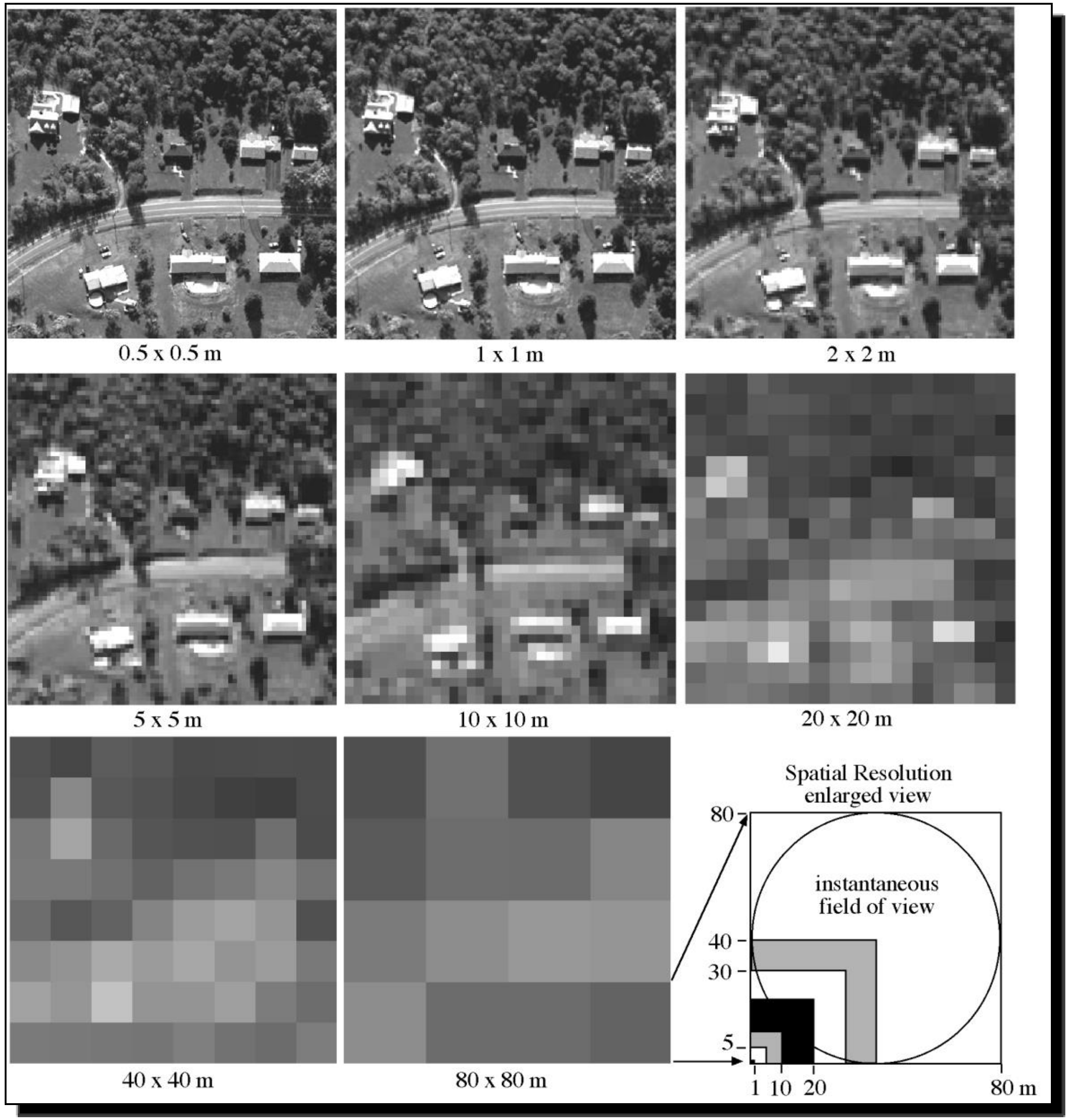
- The size of the smallest object that can be detected by a satellite – pixel size
- Pixel: smallest unit of an image
- Instantaneous field-of-view (IFOV)
- Distance on the ground that corresponds to one side of one pixel in image



Spatial Resolution: Comparison

Source: Jensen 2000

Spatial resolution



Example of different spatial resolutions

Source: Jensen 2000

Spatial resolution

Source: https://skywatch.com/what-resolution-do-i-need-when-using-satellite-earth-observation-data/

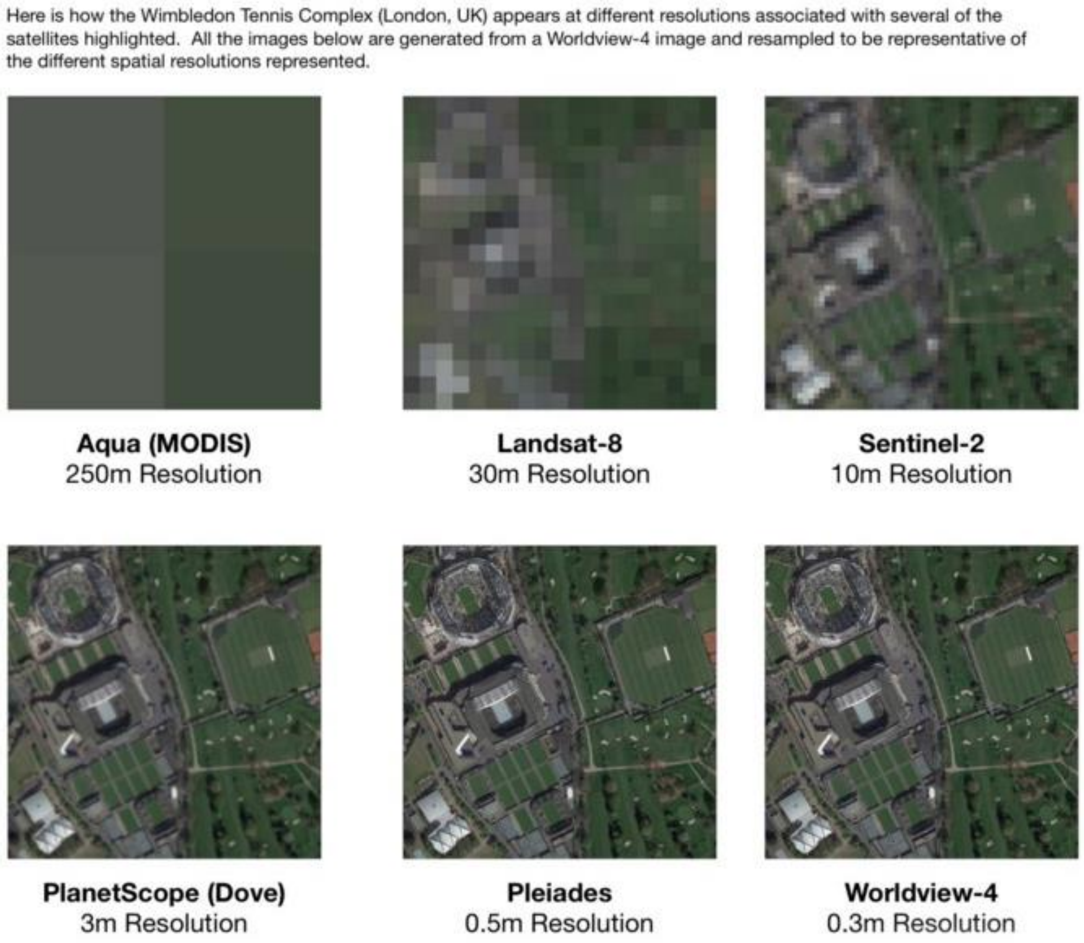
Spatial resolution

Source: https://www.earthdata.nasa.gov/learn/backgrounders/remote-sensing/

Spatial resolution

Main scales

- < 1 meter = Very high resolution: fine details in urban context, roofs, cars, small boats … Ikonos, Pleiades, QuickView
- 1 m < … < 5 m = High resolution: urban structures, houses, streets, individual trees, railway & road networks … SPOT 5
- 5 m < … < 30 m = Middle resolution: fine landcover, coarse urban structure: dense urban, residential or commercial areas, … Landsat, Spot 1-3
- > 30 m = low resolution: global landcover



Spatial Resolution: Sensor Comparison

Source: https://www.agridico.com/l/radiantearthinsight/

Spatial resolution

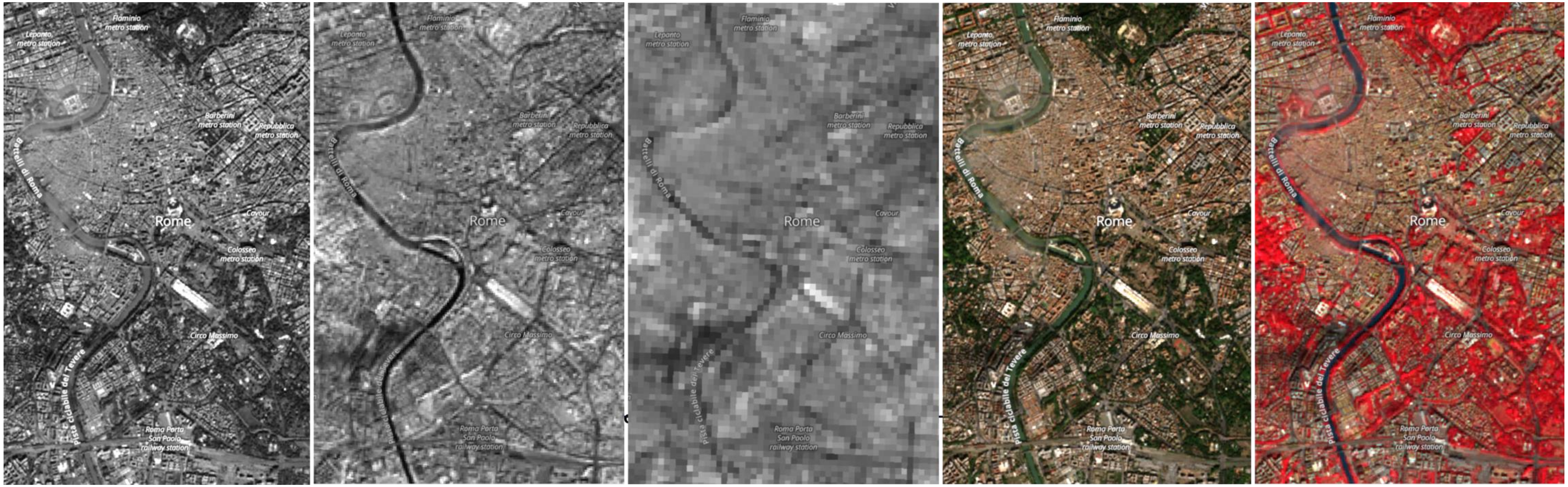


Image from the Sentinel 2A satellite, display in bands B-3 (10m), B-8a (20m), B-9 (60m) and in the true color composition B-4-3-2 (10m) and false color composition B-8A-4-3

Source: Institute of geography, PF UPJŠ, Košice

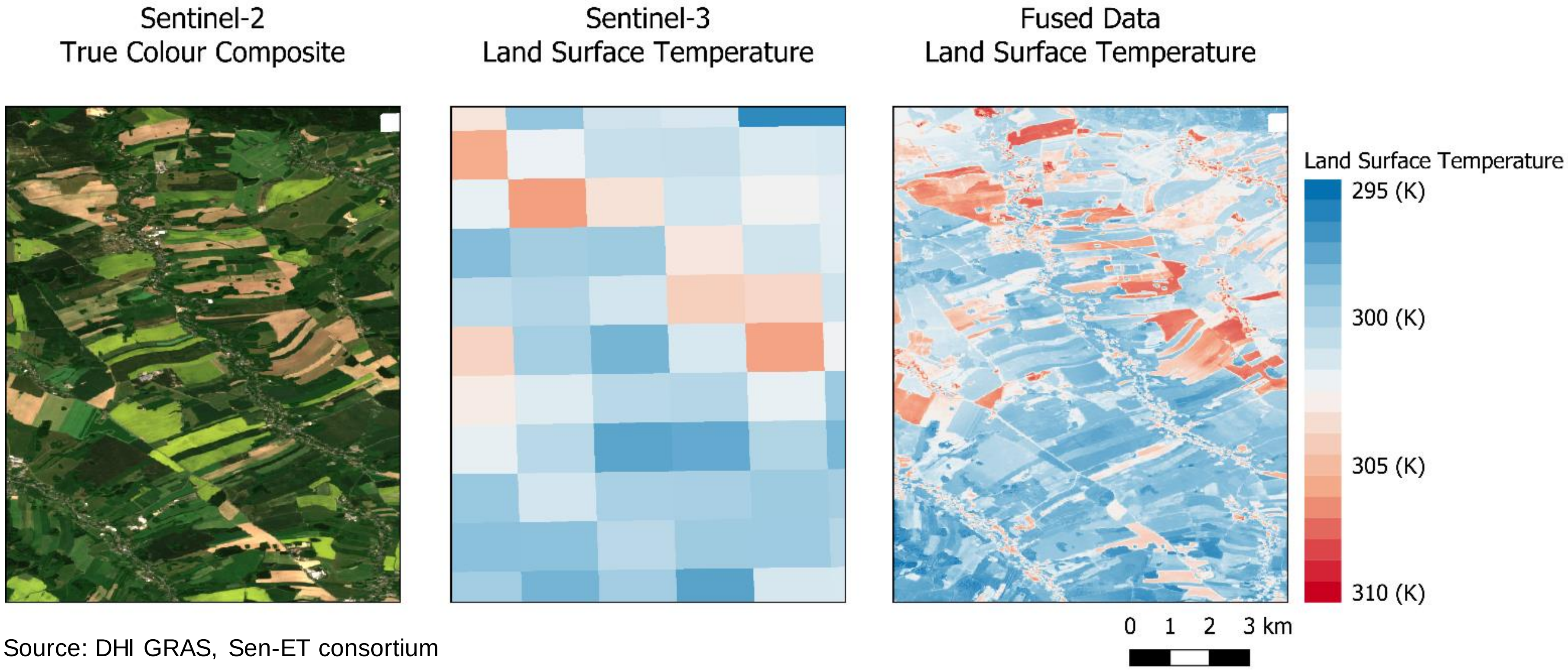
Spatial resolution

Comparison of spatial resolution: Sentinel-2, Landsat-8 and SPOT-5

Sentinel-2 MSI		Landsat-8 OLI		SPOT-5 HRG		
Band [m]	Range [nm]	Band [m]	Range [nm]	Band [m]	Range [nm]	Name
B1 * (60)	443 ± 10	B1 (30)	440 ± 10			Aerosol
B2 (10)	490 ± 32.5	B2 (30)	480 ± 30			Blue
B3 (10)	560 ± 17.5	B3 (30)	560 ± 30	B1 (10)	545 ± 45	Green
B4 (10)	665 ± 15	B4 (30)	650 ± 20	B2 (10)	645 ± 35	Red
		B8 * (15)	590 ± 45	PAN (5)	595 ± 115	PAN
B5 (20)	705 ± 7.5					Red-edge 1
B6 (20)	740 ± 7.5					Red-edge 2
B7 (20)	783 ± 10					Red-edge 3
B8 (10)	842 ± 57.5			B3 (10)	835 ± 55	NIR_{wide}
B8A (20)	865 ± 10	B5 (30)	865 ± 15			NIR_{narrow}
B9 * (60)	945 ± 10					Cirrus
B10 * (60)	1375 ± 15	B9 (30)	1370 ± 10			Water Vapor
B11 (20)	1610 ± 45	B6 (30)	1610 ± 40	B4 (20)	1665 ± 85	SWIR 1
B12 (20)	2190 ± 90	B7 (30)	2200 ± 90			SWIR 2
		B10 * (100)	$10,895 \pm 295$			Thermal 1
		B11 * (100)	$12,005 \pm 505$			Thermal 2

Source: https://www.semanticscholar.org/paper/Sentinel-2's-Potential-for-Sub-Pixel-Landscape-Radoux-Chom%C3%A9/a9d3e039e7645eb3c1e1586077fae34e7bbea396/figure/1

Spatial resolution



Source: DHI GRAS, Sen-ET consortium

The images show an agricultural area in southern Germany in late May 2017. The Copernicus Sentinel-2 image (left) was acquired at 20 m spatial resolution. This allows agricultural parcels and other landscape features such as roads to be distinguished. The Copernicus Sentinel-3 image (centre) captures the land-surface temperature, which is essential for estimating evapotranspiration, but here with a pixel size of around 1 km. By using advanced machine-learning algorithms, data from the two sensors can be fused, thus obtaining a 20 m representation of land-surface temperature (right) which can then be used to produce 20 m evapotranspiration maps.

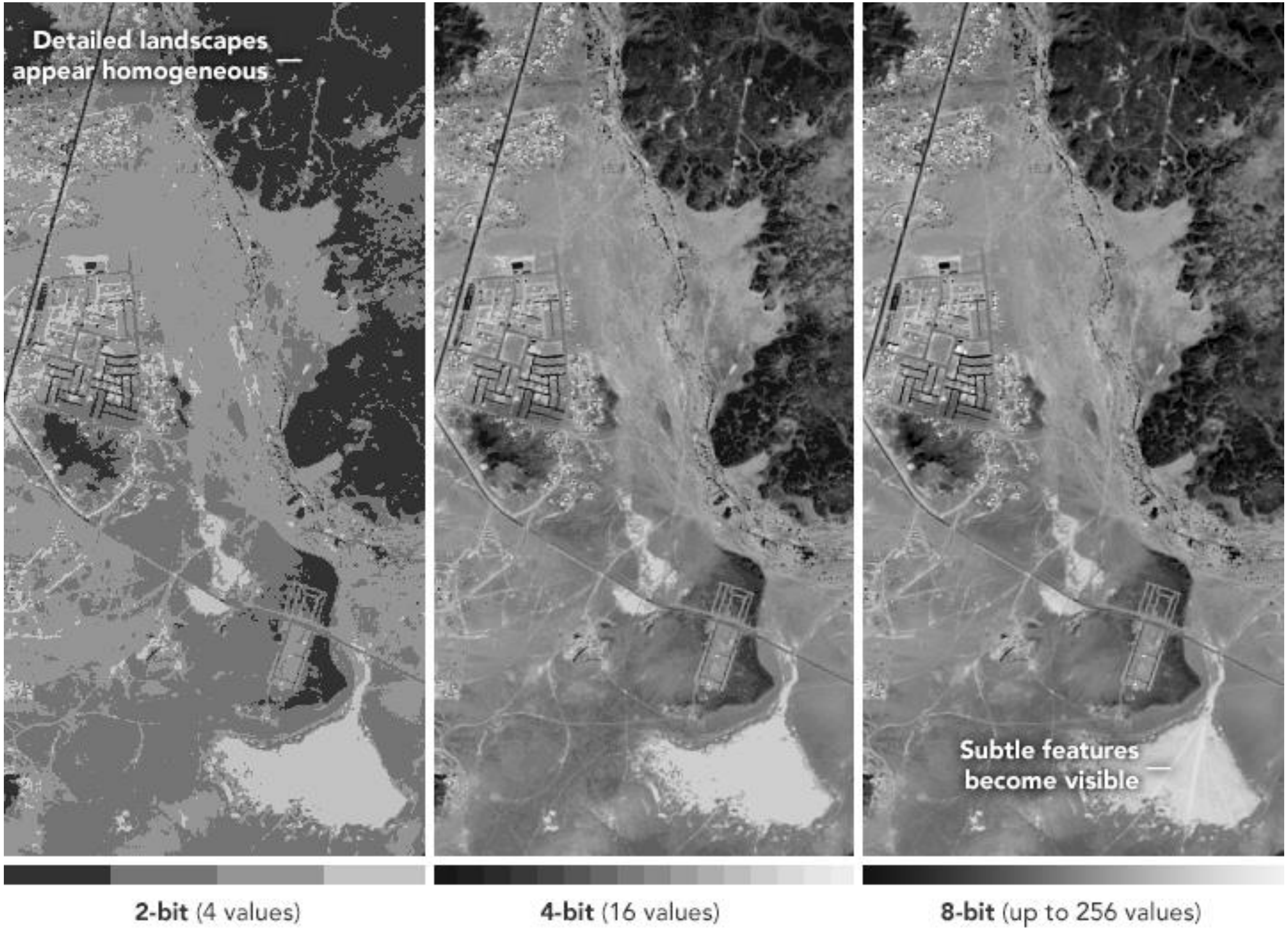
Radiometric resolution

- The sensitivity of detectors to small differences in electromagnetic energy
- Measured in bits (a number to the exponential power of 2)
- The higher the number, the finer the radiometric resolution

Number of bits	Range of quantisation levels
1	0-1
2	0-3
3	0-7
4	0-15
5	0-31
6	0-63
7	0-127
8	0-255
9	0-511
10	0-1023

Source: http://jukebox.esc13.net/untdeveloper/RM/Stats_Module_4/mobile_pages/Stats_Module_410.html, https://www.bu.edu/earth/faqs-rsgs/

Radiometric resolution



Source:
https://landsat.visibleearth.nasa.gov/view.php?id=91071

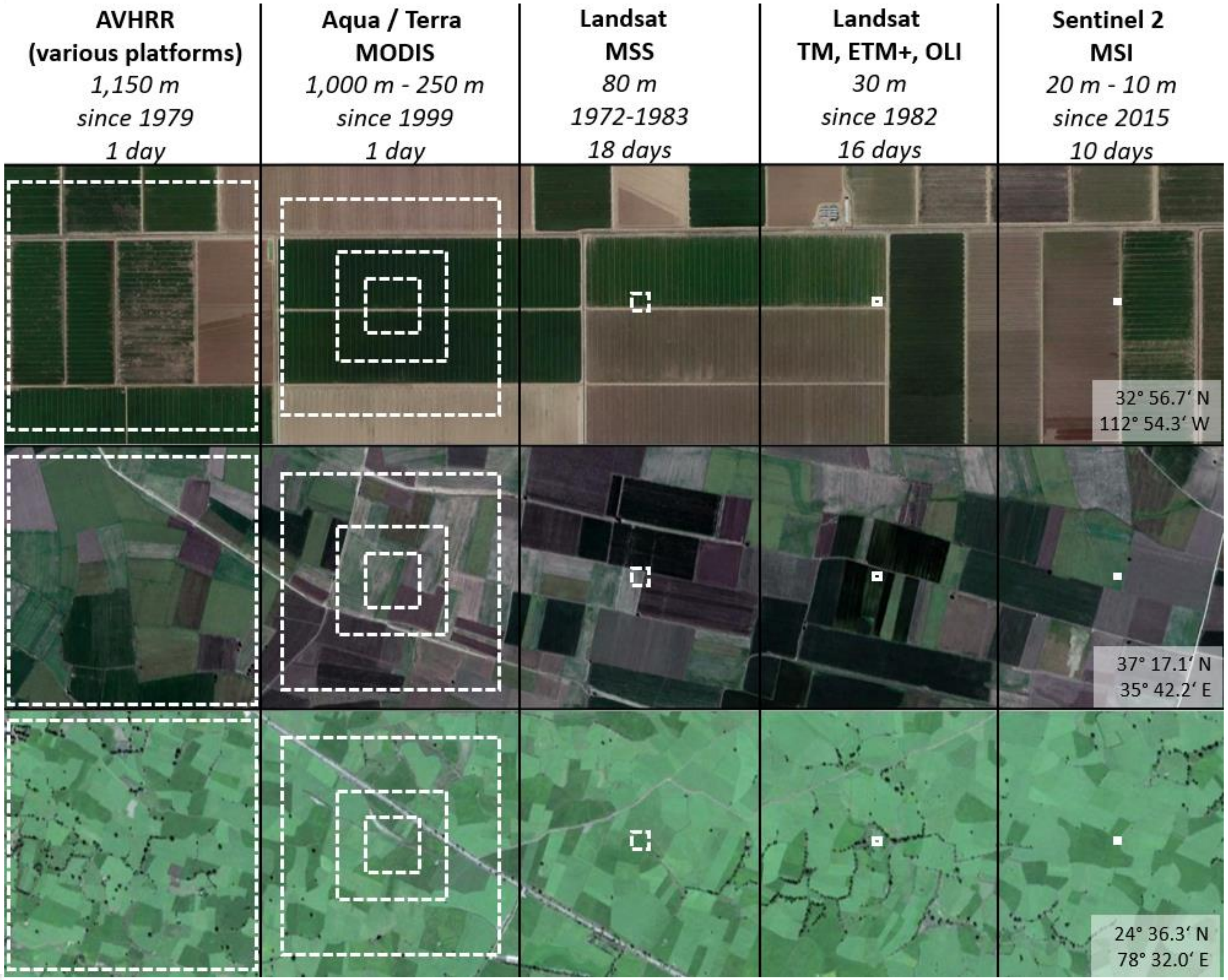
Temporal resolution

- Refers to the frequency at sensor collects imagery over a specific area

Depends on:

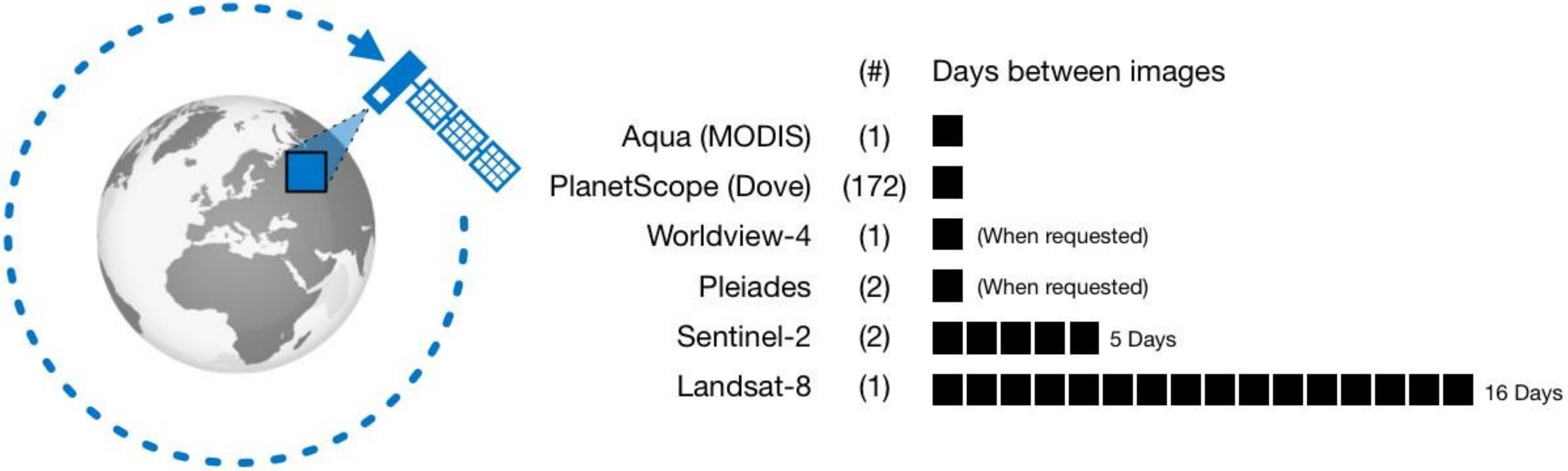
- Orbital characteristics
- Image swath width / footprint
- Off-nadir viewing capabilities
  (i.e., pointable optics)
- Number of satellites in the family

Source: https://pages.cms.hu-berlin.de/EOL/geo_rs/S11_Time_series.html



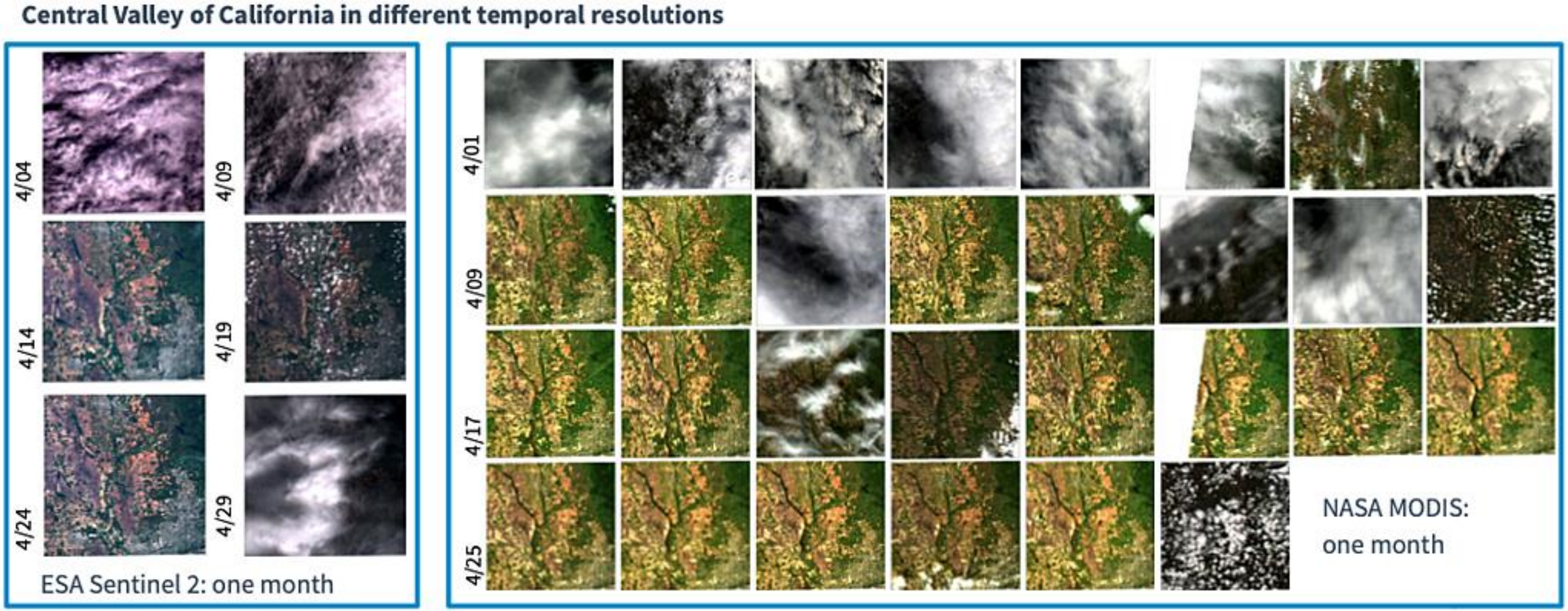
Temporal resolution

Temporal resolution varies by satellite and describes the time it takes for an individual satellite to orbit and revisit a specific area. Some satellites operate as a constellation with multiple satellites working together to increase their global coverage daily.



Source: https://twitter.com/MyanmarWitness/status/1492082733794959386/photo/1

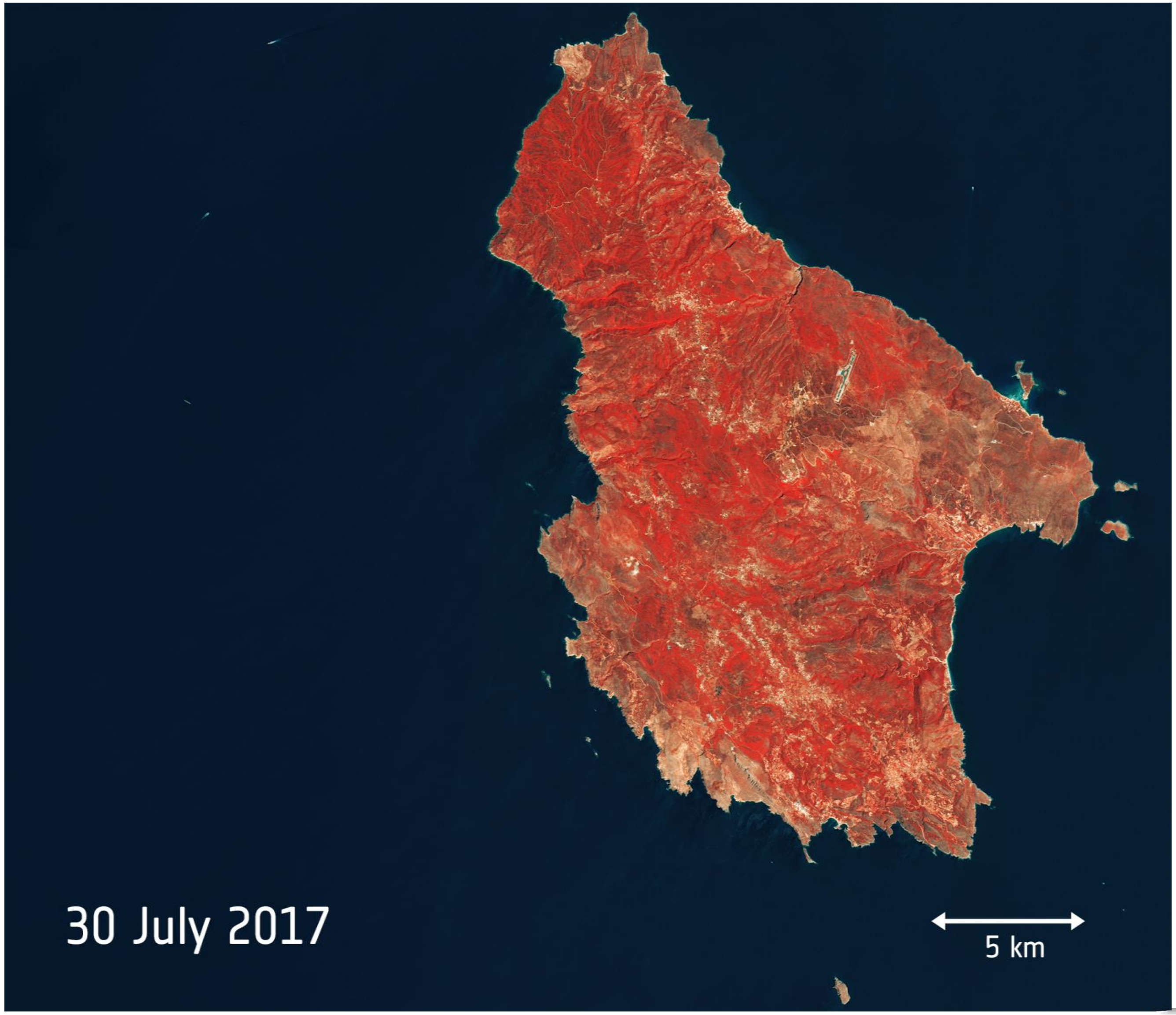
Temporal resolution



- *Temporal resolution refers to how often images are collected for any given location on earth. For Sentinel-2 imagery, we're getting about six images per month, whereas for MODIS we're getting an image every day. However, there is tradeoff: the coarser the spatial resolution, the higher the temporal resolution, and vice versa. If we're getting very fine spatial resolution data, we're not getting it as often.*

Source: https://kb.descarteslabs.com/knowledge/introduction-to-remote-sensing

Temporal resolution



- *The Copernicus Sentinel-2 satellite pair captured the start of a fire on the Greek island of Kythira on 4 August 2017. Five days later, a huge burn scar is visible across the western part of the island.*

- *Carrying a high-resolution multispectral optical imager, Sentinel-2 is used to monitor changes in vegetation (in this 'false-colour' image, vegetation is in red). The mission offers key information to optimise crop yield, thereby helping to improve food security. It can be used to measure leaf area, leaf chlorophyll and leaf water content to monitor plant growth, which is particularly important during the growing season.*

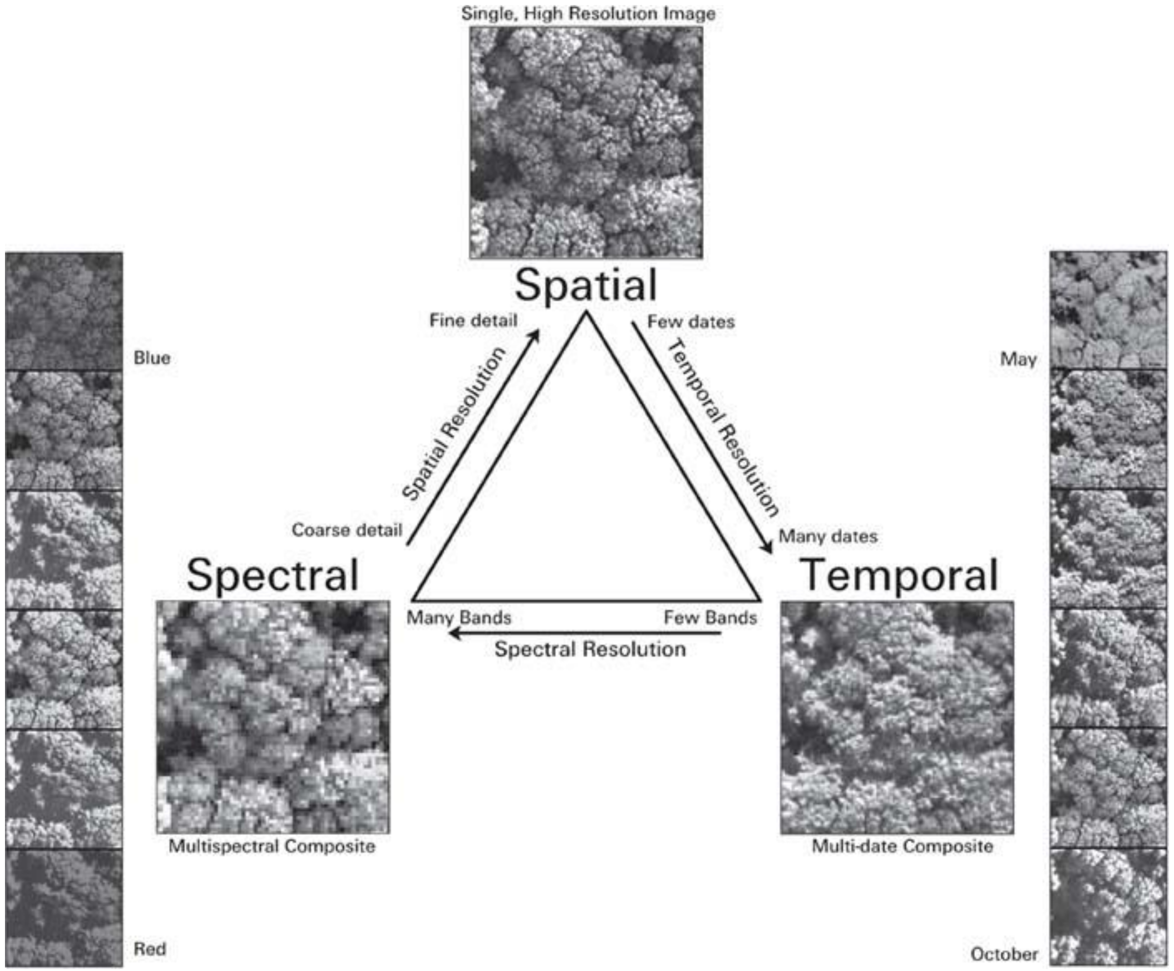
Source: ESA

Sensor Characteristics

Sensor	Number of Bands	Spatial Resolution	Temporal Resolution	Radiometric Resolution	Swath width/Footprint
MODIS	36	250 m, 500 m, 1000 m	*1 day	4096	2330 km swath width
Sentinel-2	13/1	10 m, 20 m, 60 m	*5 days	4096	290 km swath width
Landsat 5 & 7/Pan	7/1	30 m/15 m	*8 days	256	34,225 km^2 footprint
Landsat 8/Pan	10/1	30 m/15 m	16 days	4096	34,225 km^2 footprint
SPOT 5/Pan	3/1	20 m/10 m	*2-3 days	256/256	3600 km^2 footprint
IKONOS/Pan	4/1	4 m/1 m	~3 days	2048/2048	11.3 km swath width
QuickBird/Pan	4/1	2.4 m/0.6 m	2-11 days	2048/2048	16.4 km swath width

Resolution Tradeoffs

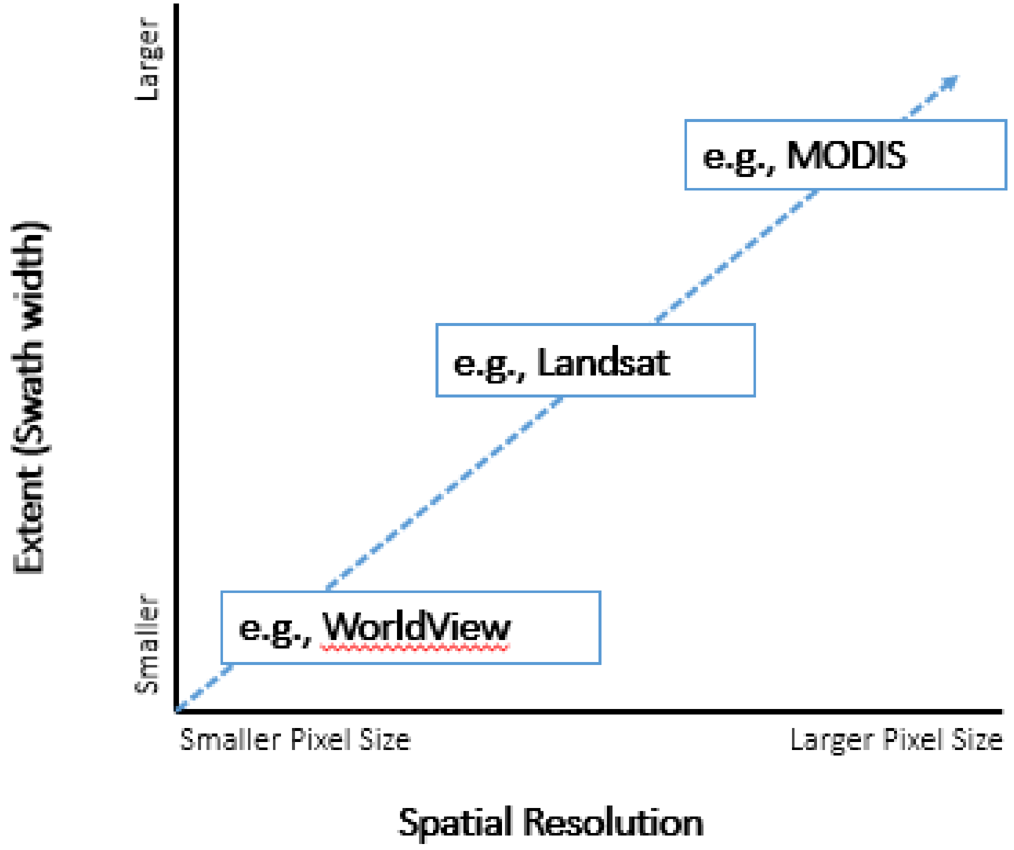
Though a finer temporal resolution is more desirable, there is often a tradeoff between a fine temporal resolution and a fine spatial resolution.



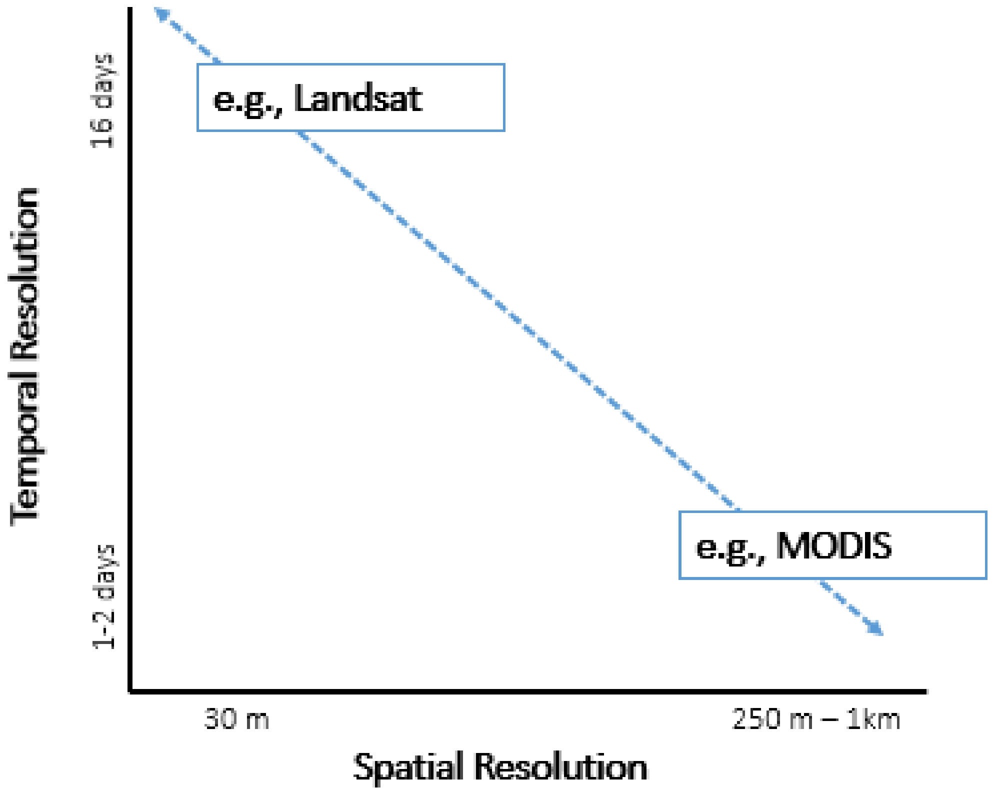
Source:
https://kb.descarteslabs.com/knowledge/introduction-to-remote-sensing

Resolution Tradeoffs

Spatial Resolution & Extent (Area) Tradeoff

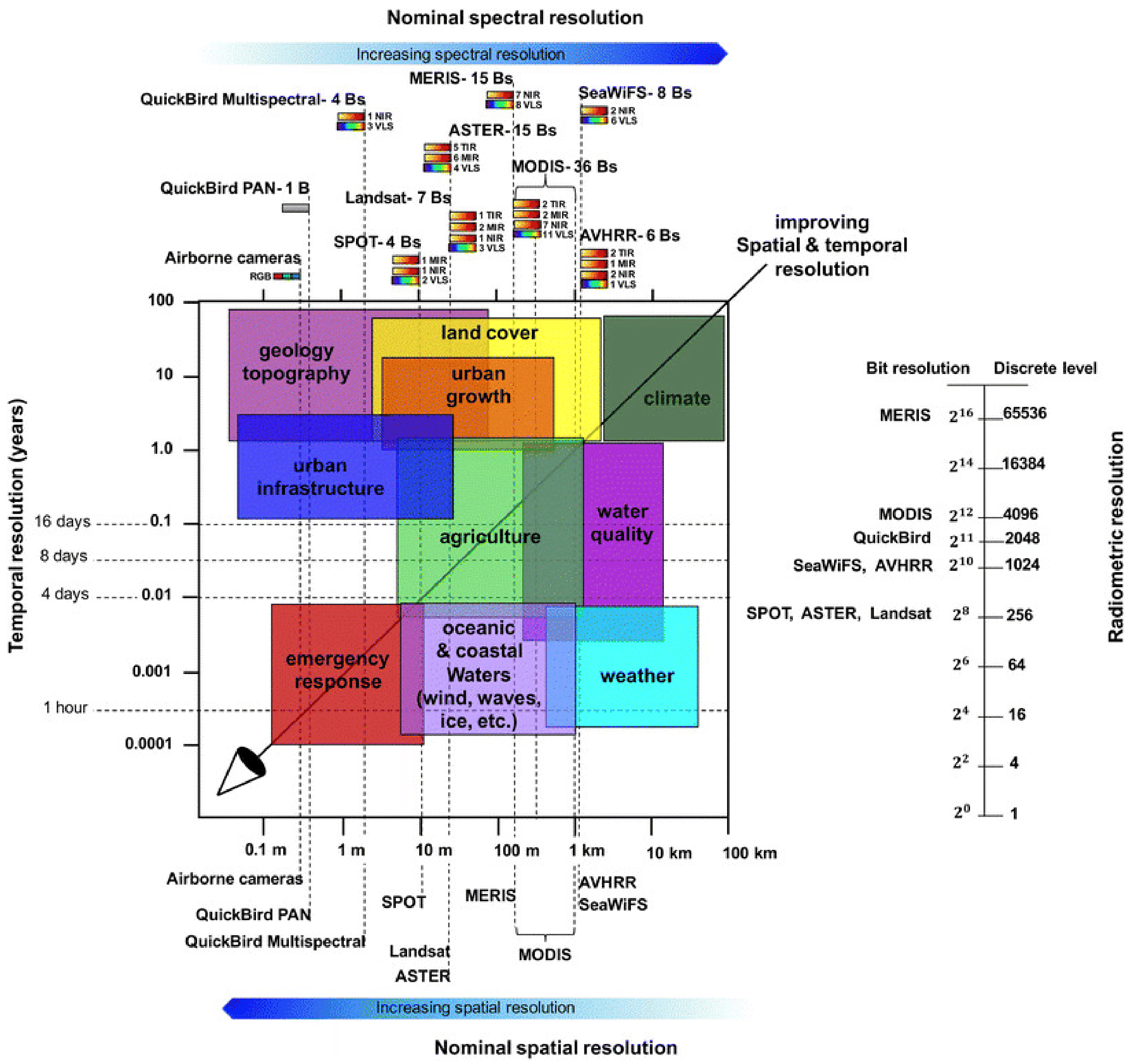


Temporal & Spatial Resolution Tradeoff



Source: https://reformingretail.com/index.php/2020/01/07/payfac-vs-iso-when-does-one-make-sense-over-the-other/

Resolution Tradeoffs



Comparison of temporal, spectral and spatial resolution of satellites

Source: https://www.researchgate.net/publication/308514016_Advances_in_remote_sensing_applications_for_urban_sustainability/figures?lo=1&utm_source=google&utm_medium=organic

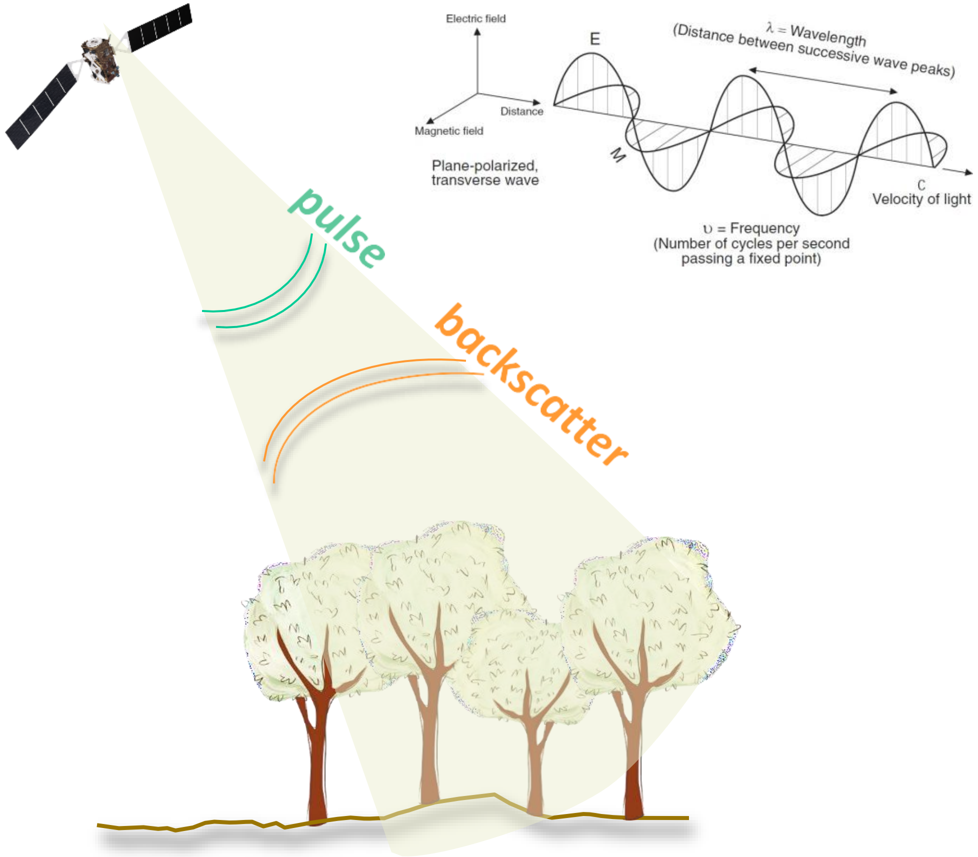
For more information, see the tutorial: 4. Optical remote sensing using ESA Copernicus´ data: image metadata, image resolution (spect ral, spatial, temporal and radiomet ric resolution), color compositions and spect ral indices, using SNAP software

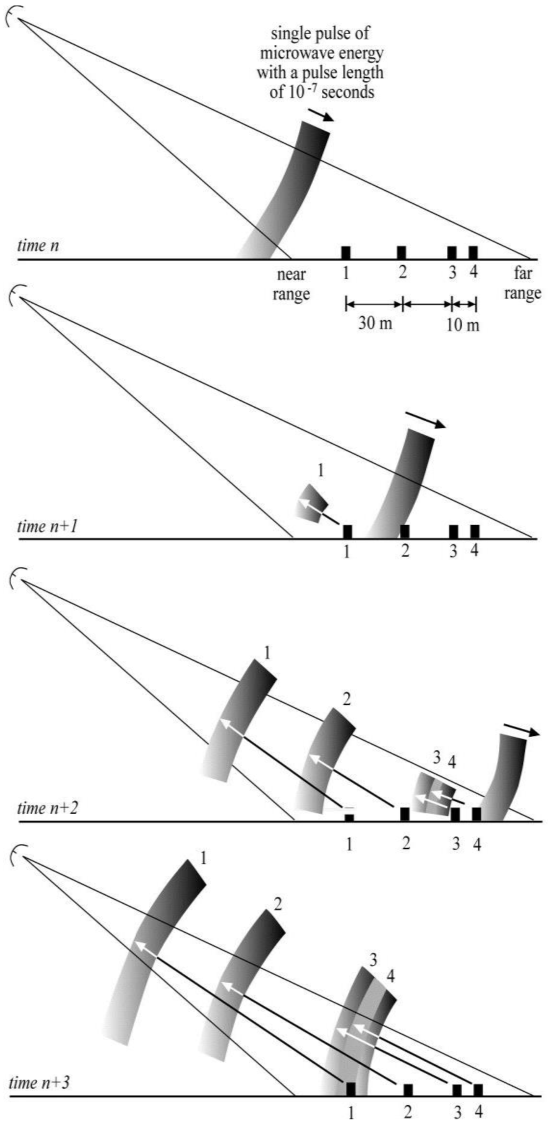
5. Basics of Radar Remote Sensing - principles and applications

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)

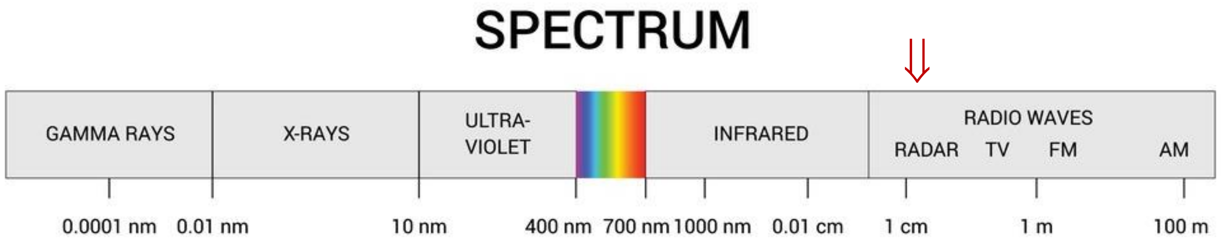
The energy of a single pulse is reflected from objects on the surface in order of distance from source/ transmitter on board

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

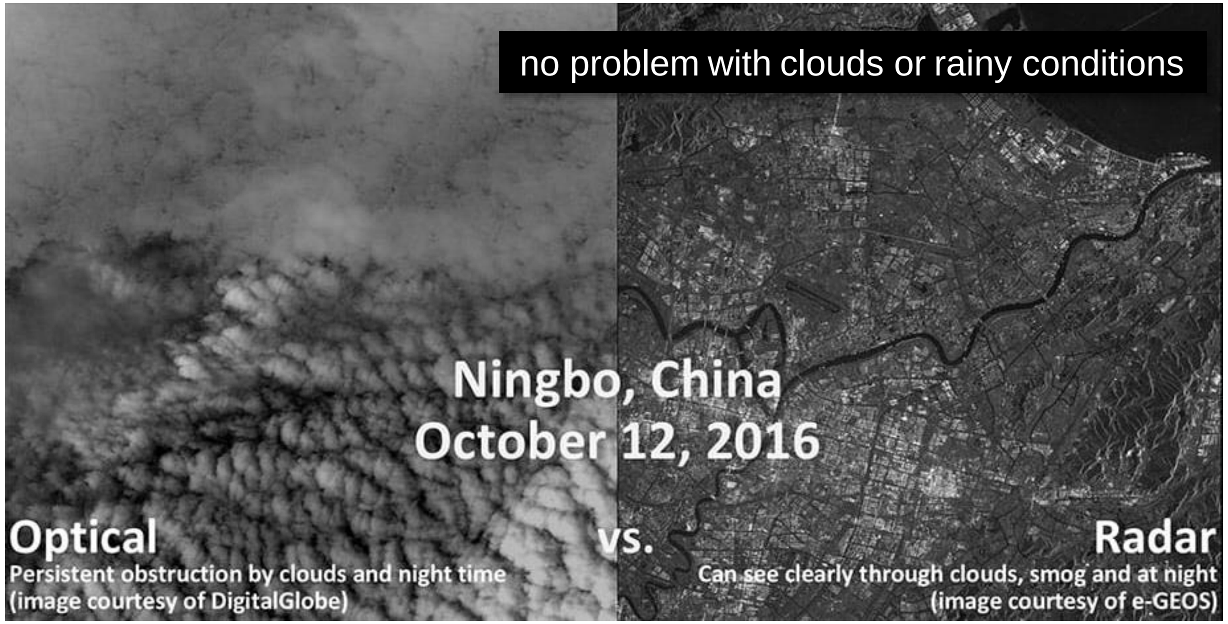
Source: https://www.researchgate.net/publication/349395724_Spaceborne_SAR_Remote_Sensing_for_Monitoring_of_Vegetation_Dynamics_in_Arid_and_Semi-arid_Environment/figures?lo=1&utm_source=google&utm_medium=organic/
Jensen (2008)

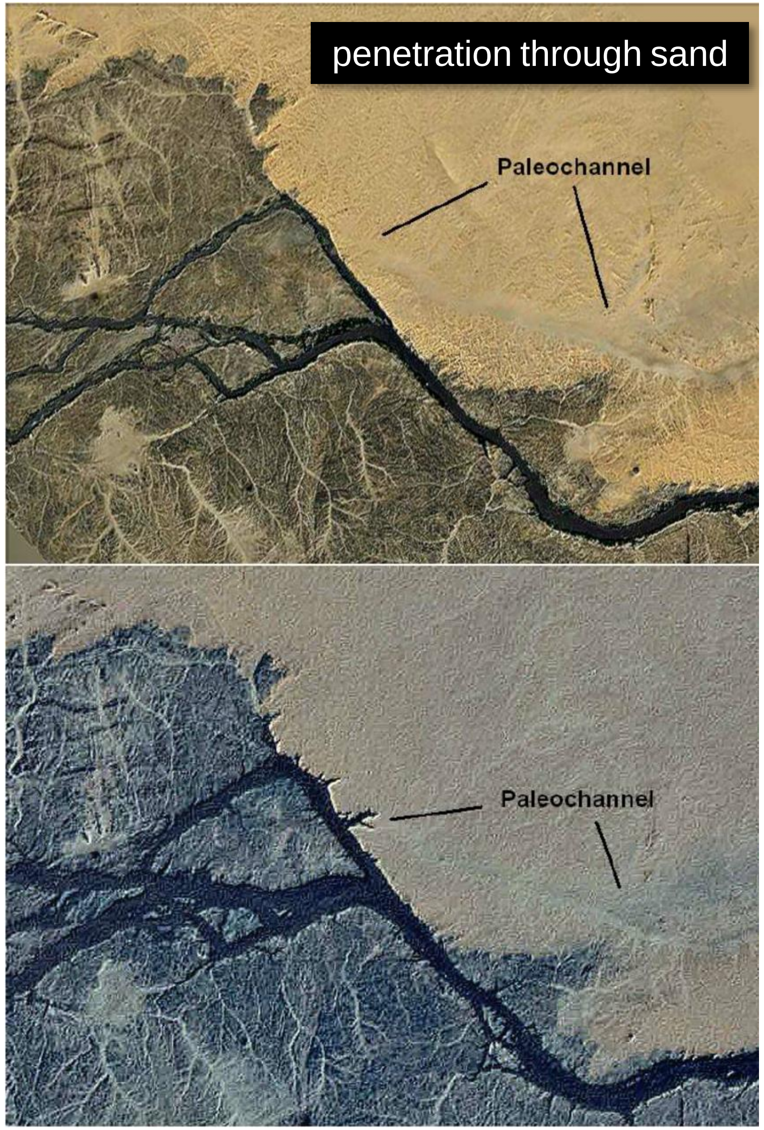
Active Radar Remote Sensing

Basic characteristics of radar systems/SAR sensors



Microwave ⇒ penetrates into/through objects



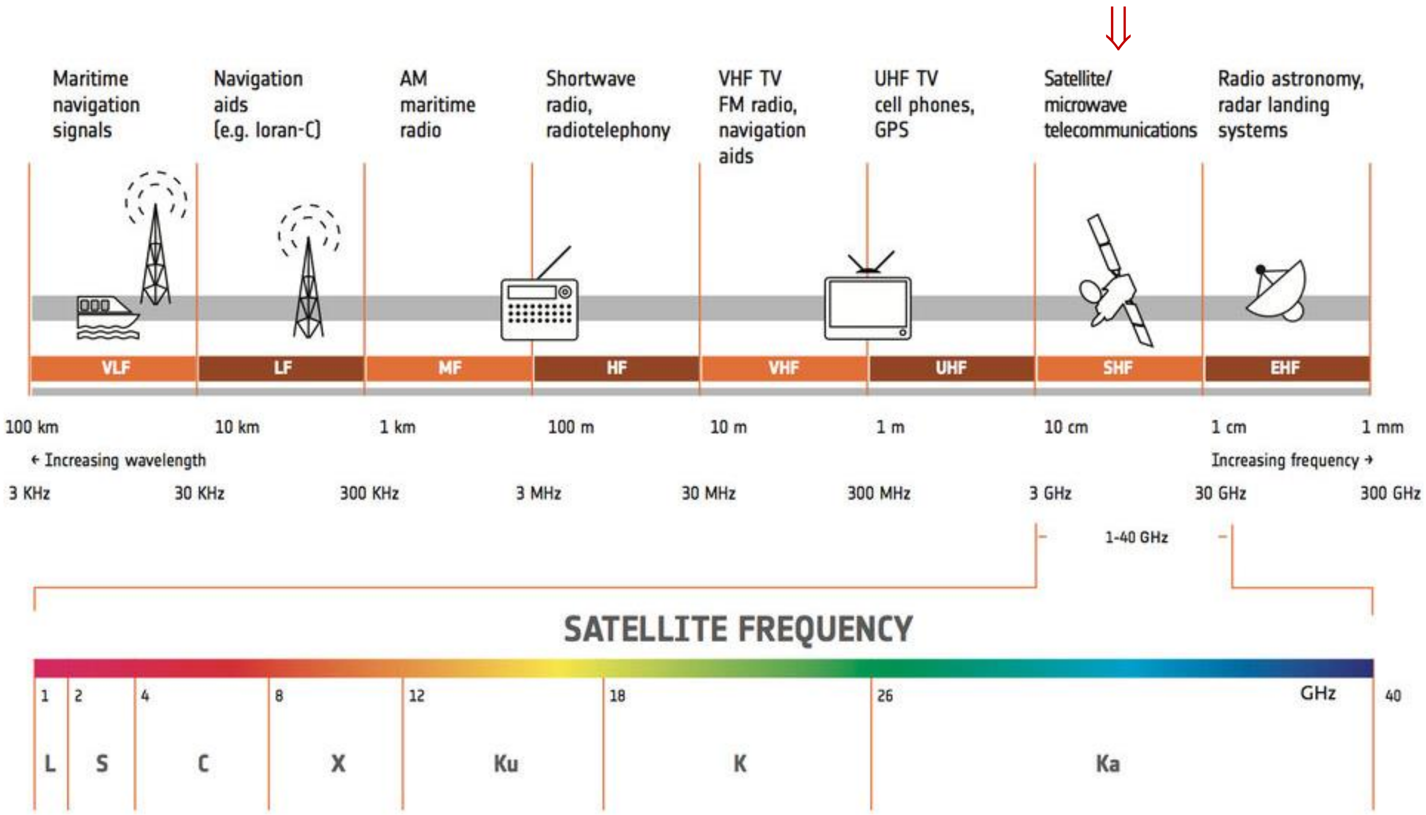


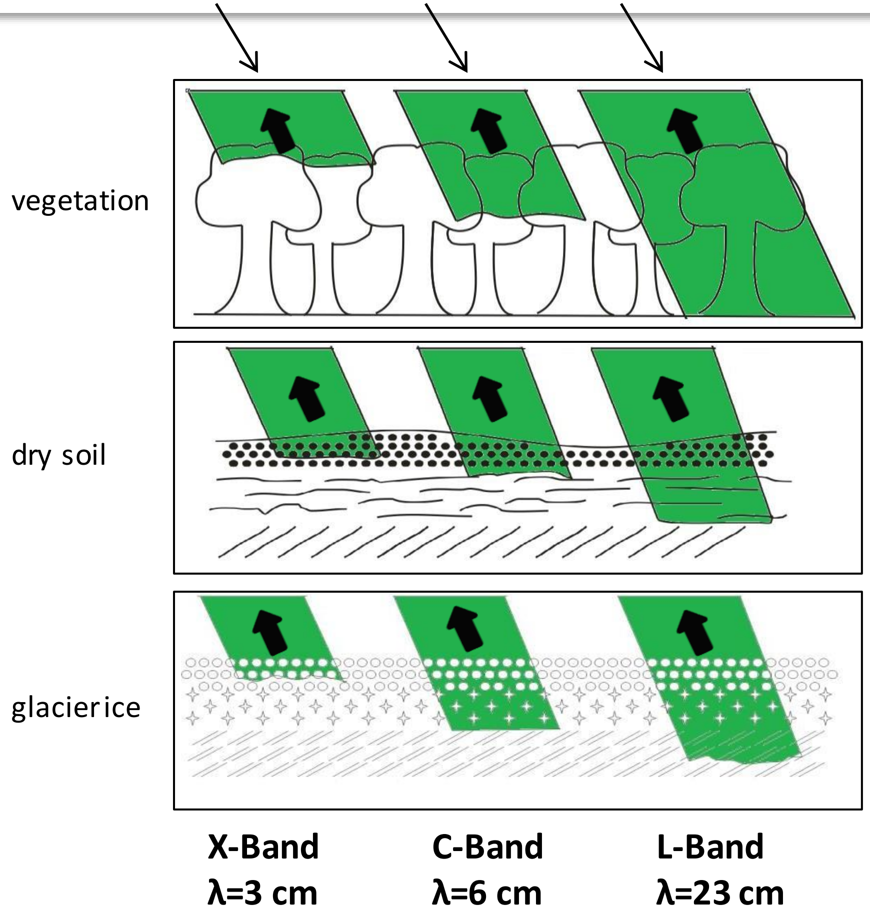
Source: https://resources.pcb.cadence.com/blog/2023-using-the-x-band-and-ka-band-frequencies-for-radar-applications, https://apogeospatial.com/a-killer-app-for-sats/, https://arxiv.org/abs/1011.4911,

Active Radar Remote Sensing

RADAR band designations, wavelenghts and frequencies

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





Source: https://www.esa.int/ESA_Multimedia/Images/2013/11/Satellite_frequency_bands, https://dges.carleton.ca/courses/IntroSAR/Winter2019/SECTION%202%20-%20Carleton%20SAR%20Training%20-%20Radar%20Basics%20-%20FINAL.pdf

Active Radar Remote Sensing

RADAR band designations, wavelenghts and frequencies

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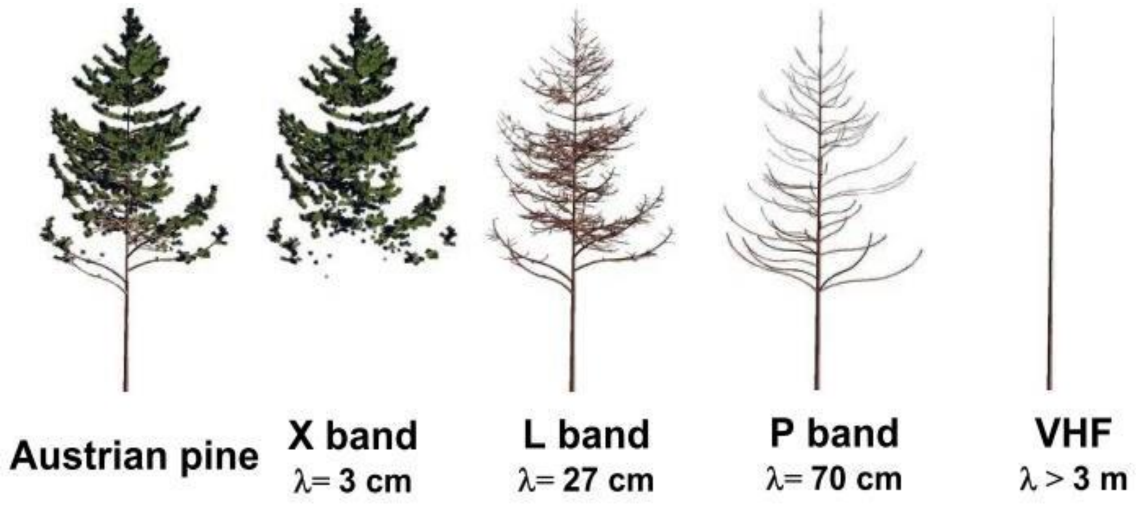
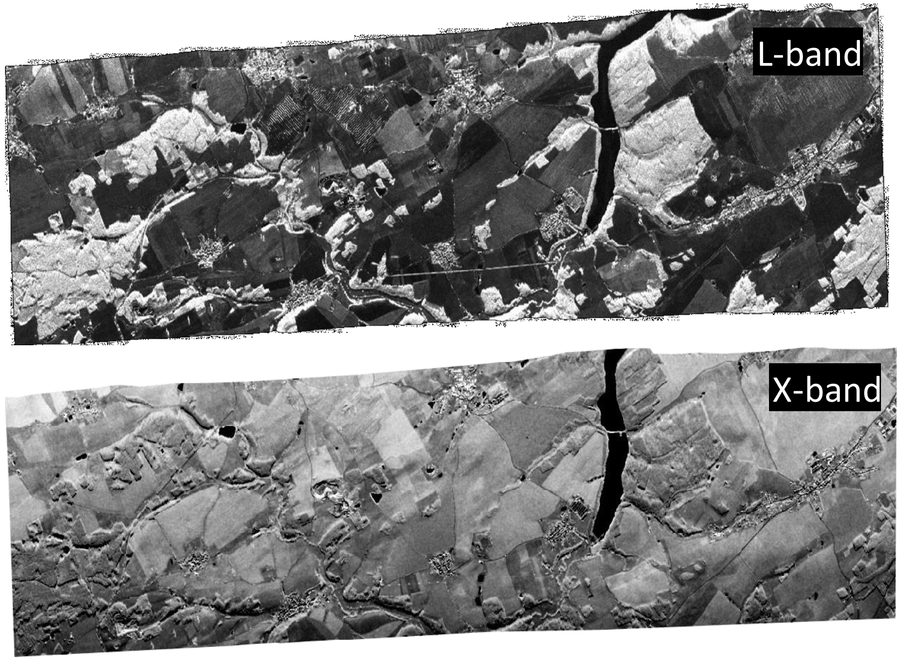




Source: https://eo-college.org/topic/forest/

Active Radar Remote Sensing

SAR IMAGING, POLARIMETRY

- SAR (Synthetic Aperture Radar) polarimetry is a technique that uses the polarization properties of radio waves for Earth observation. In the context of forestry, polarimetry has several significant applications. Here are some ways SAR polarimetry is employed in forestry:

- **Vegetation Characterization**:
  - Different types of vegetation have distinct backscatter characteristics depending on the signal's polarization.

- **Forest Structure**:
  - Polarimetric data can reveal information about tree heights, tree trunk thickness, or forest age. For instance, vertical polarization is often more strongly reflected by taller trees compared to shorter ones.

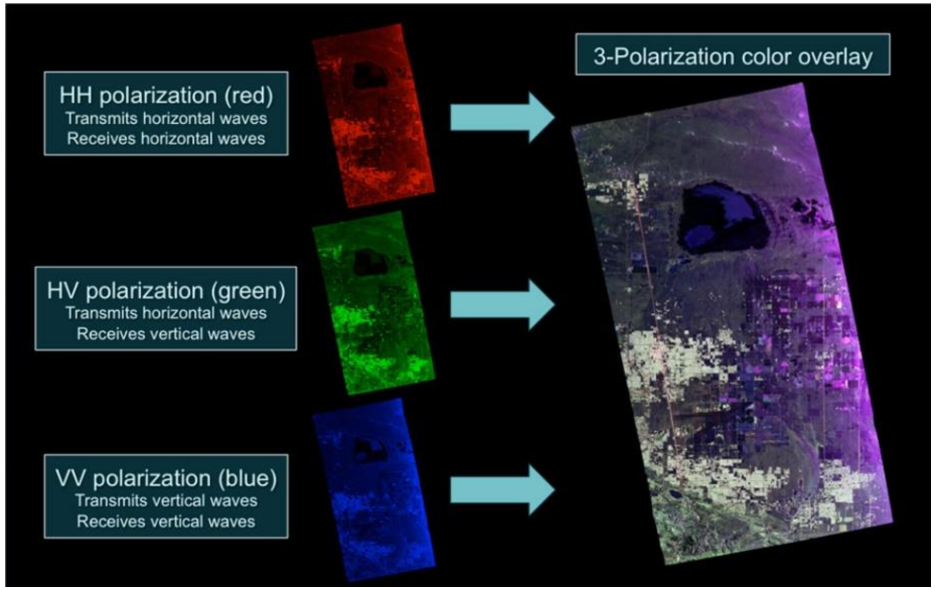
- **Biomass Estimation**:
  - Biomass is a key indicator of forest health and its carbon storage capability. Through polarimetry, the amount of biomass in a forest can be estimated.

- **Change Detection**:
  - By comparing polarimetric images from different time periods, areas of deforestation, forest damage, or regeneration can be identified.

- **Soil Moisture Determination**:
  - Beneath vegetation, there might be backscatter related to soil moisture. Polarimetry can help isolate these signals from the vegetation backscatter, allowing for a more accurate estimate of soil moisture.

- **Forest Damage Identification**:
  - Whether due to pests, diseases, natural disasters, or human activities, polarimetry can help pinpoint areas where the forest is damaged or stressed.

- Thus, SAR polarimetry offers a comprehensive view of forest ecosystems and their dynamics. With this technology, scientists, foresters, and natural resource managers can better understand the state of forests, monitor changes over time, and make informed decisions about the management and protection of these vital ecosystems.



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

Active Radar Remote Sensing

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

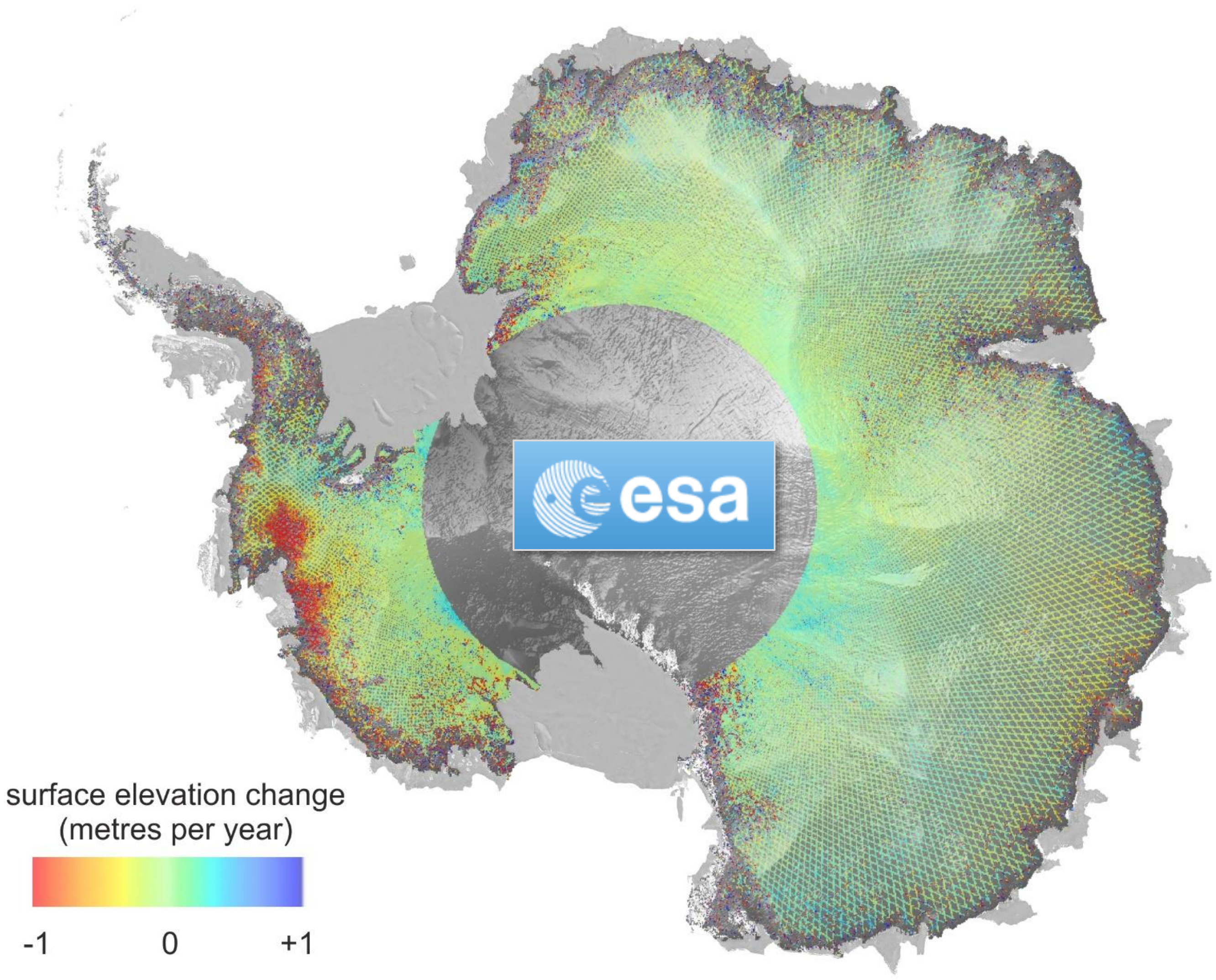
Radar Altimetry = measuring altitude / vertical height

ESA article

video

video 2

Radar Altimetry = measuring altitude / vertical height



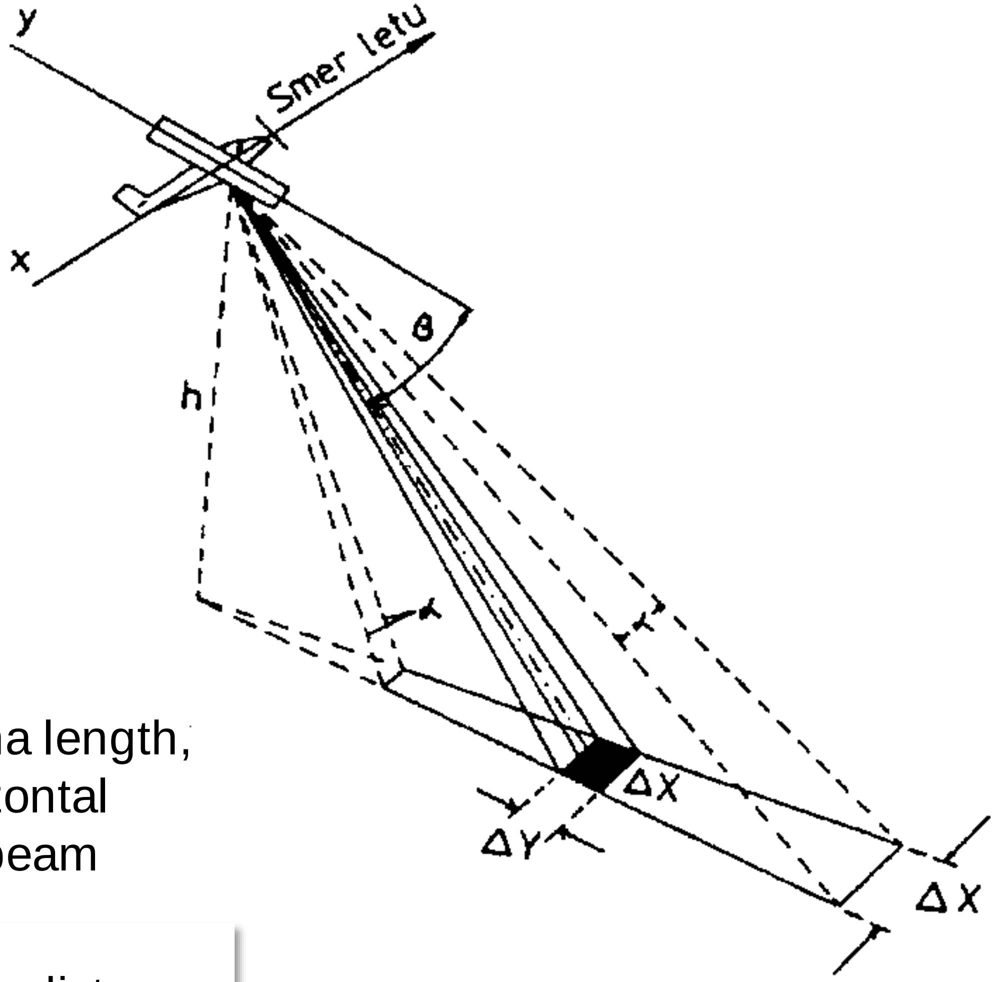
[Copernicus Sentinel-3 provides new measurements of Antarctic Ice Sheet
08 March 2019]

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 - antenna length,
β - angle between the horizontal plane and the transmitted beam



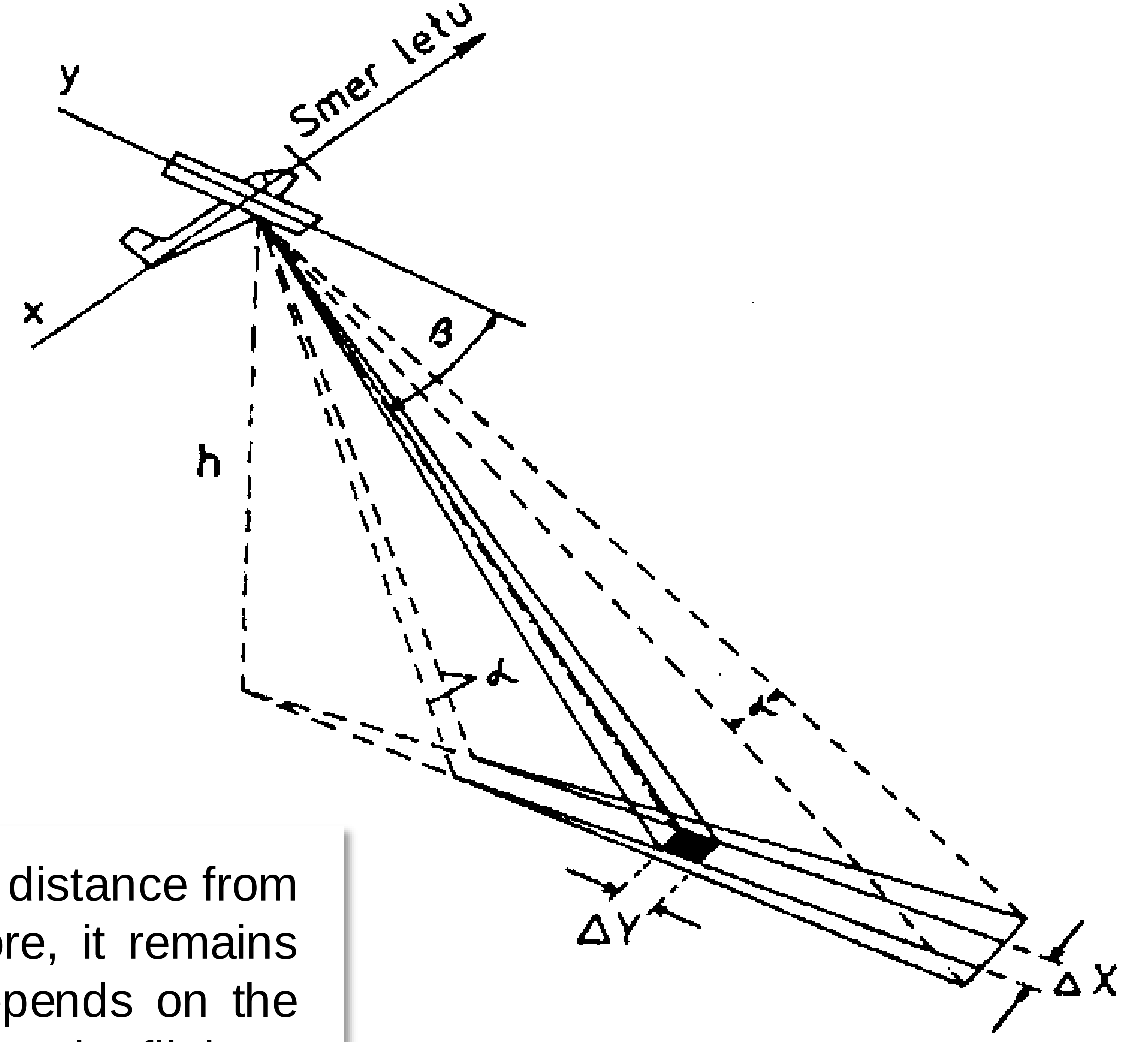
Spatial resolution deteriorates as the distance between the object and the antenna increases.

Synthetic aperture radar (SAR)

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

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

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



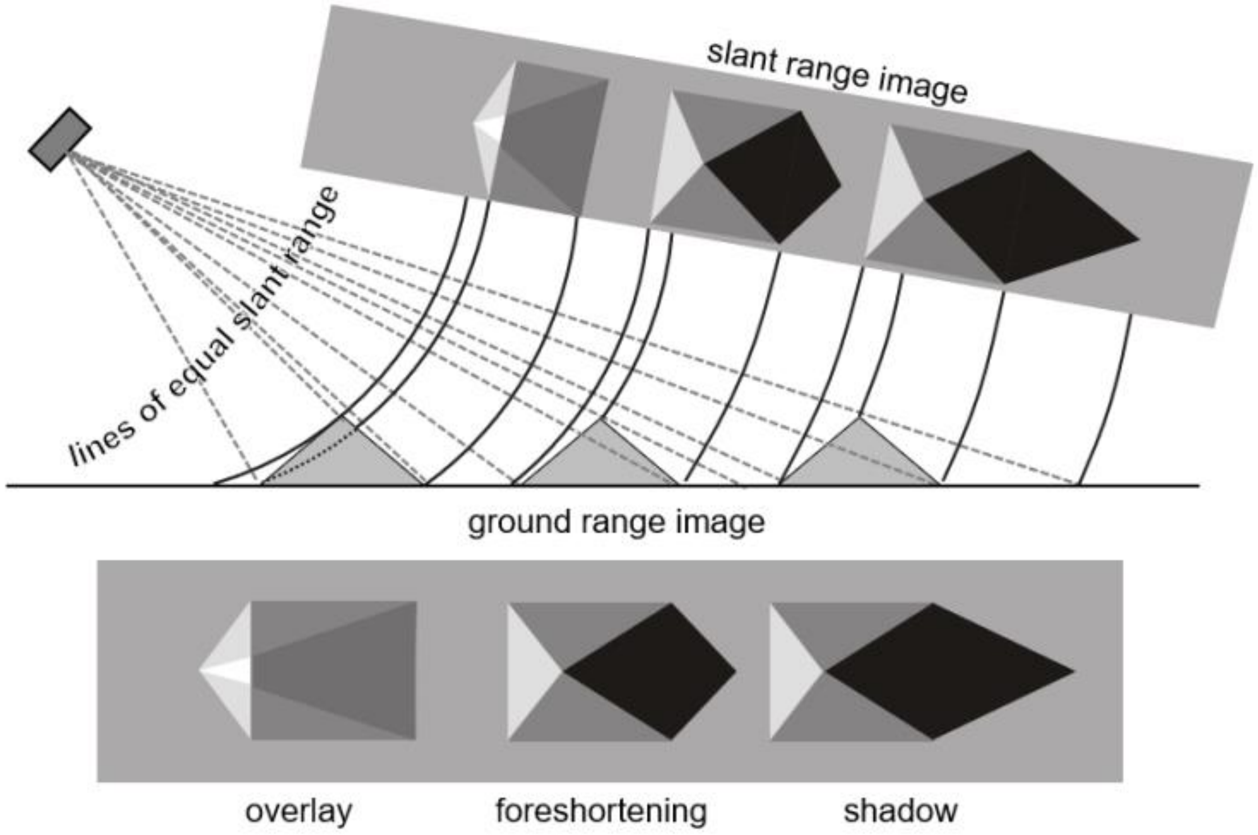
The spatial resolution is independent of the distance from the antenna in the flight direction. Therefore, it remains constant in the flight direction, while it depends on the viewing angle in the direction perpendicular to the flight.

Geometric Effects in SAR images

Effects of side-looking geometry

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

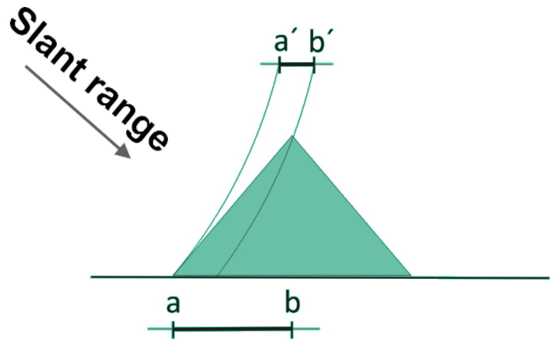
- The effects are:
  - ❖ Foreshortening
  - ❖ Layover
  - ❖ Radar shadow
- Controlled by:
  - ❖ Incidence angle
  - ❖ Topography



Geometric distortions in radar images (Braun 2019)

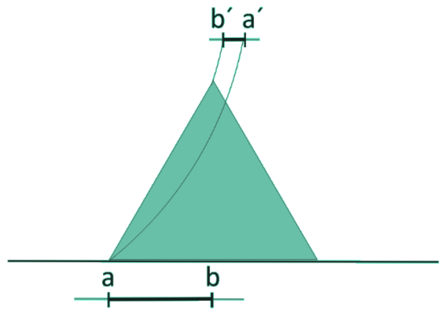
Geometric Effects in SAR images

Foreshortening



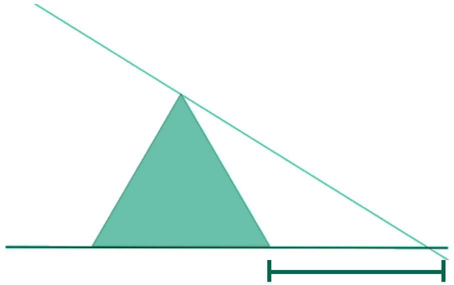
- Slopes oriented to the SAR appear compressed (Distance between a and b is shortened)
- Appears as very bright area
- More pronounced in near range (small incidence angle) than in far range (high incidence angles)

Layover

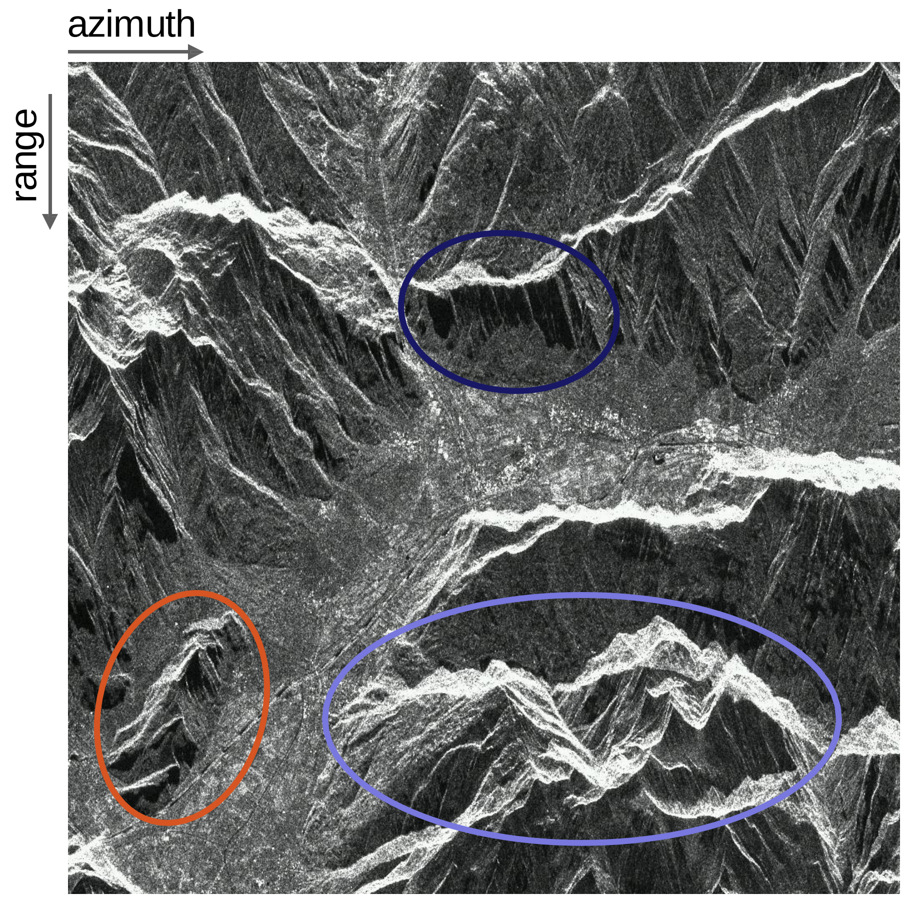


- Steep slopes oriented to the SAR lead to ghost images
- When radar beam reaches the top of a high feature (b) before it reaches the base (a)

Radar shadow



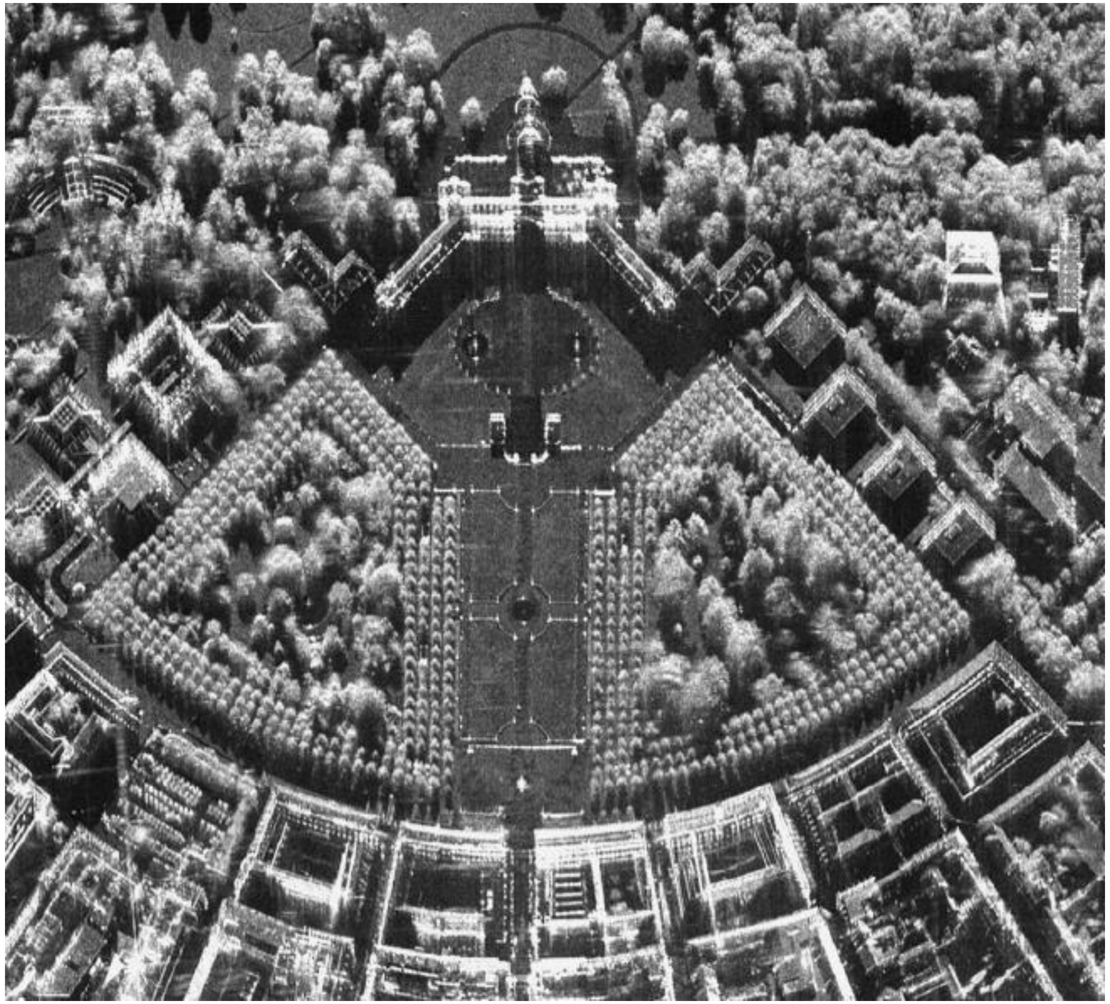
- Steep slopes oriented away from the SAR return no signal
- No signals can be transmitted to this area (as it is blocked by the slope), thus no signals can be scattered back from these areas
- Appears as black area in the image



Geometric Effects in SAR images

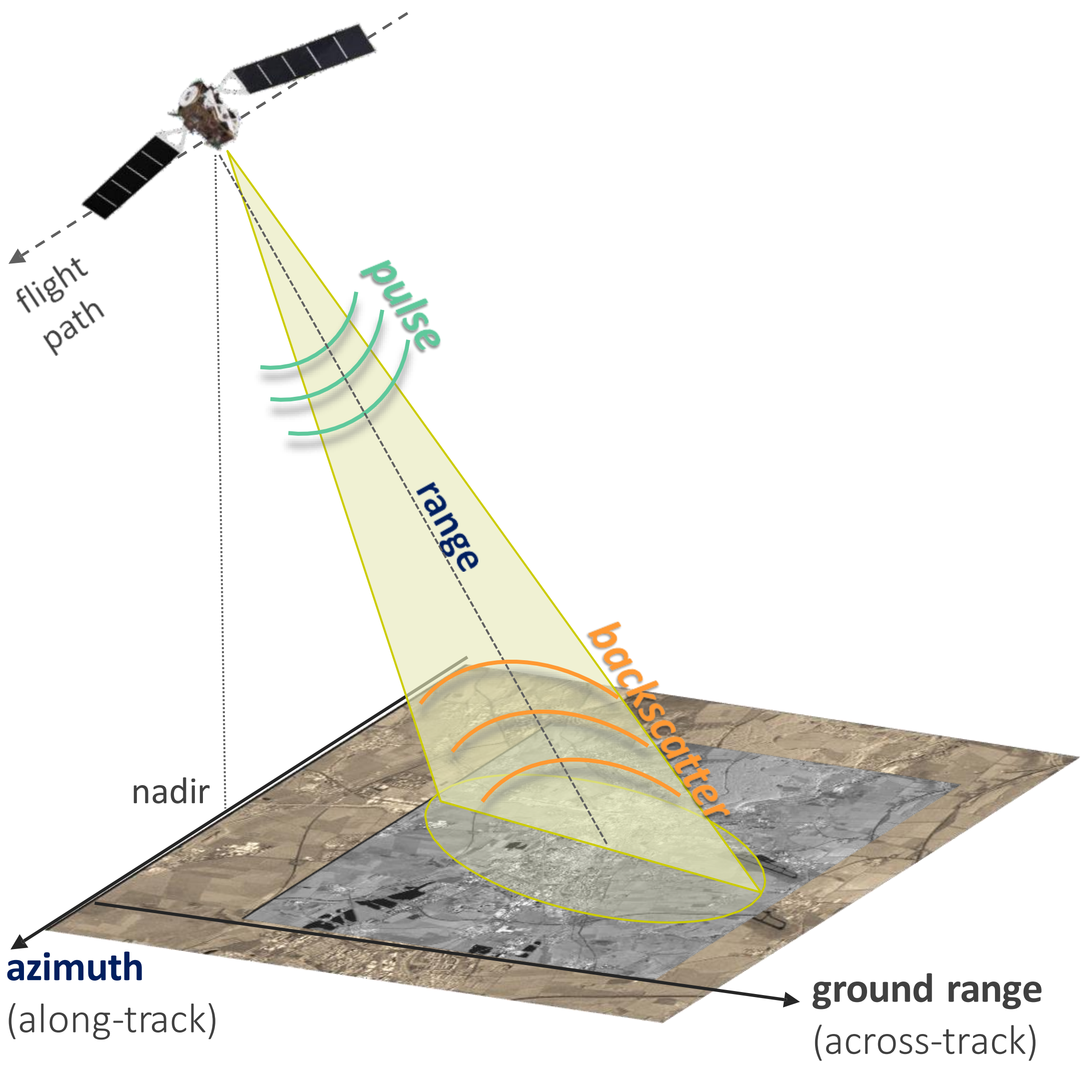
Effects of side-looking geometry

Google maps

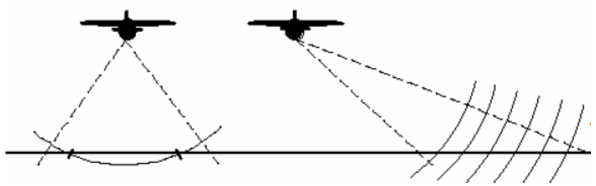


Andreas R. Brenner and Ludwig Roessing, Radar Imaging of Urban Areas by Means of Very High-Resolution SAR and Interferometric SAR, IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 46, NO. 10, OCTOBER 2008 (X-band)

Radar side looking imaging geometry



Is side looking really necessary?



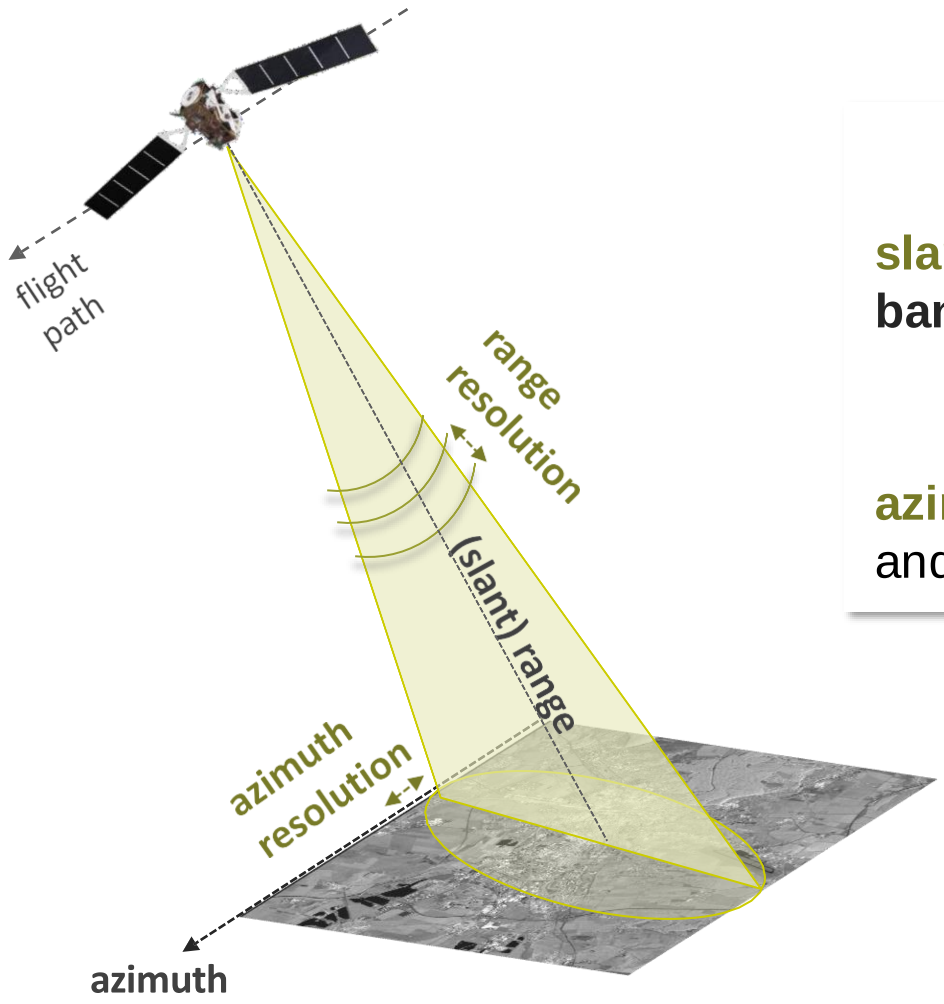
Nadir looking,
e.g. aerial photography

Side looking,
e.g. SLAR, SAR

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



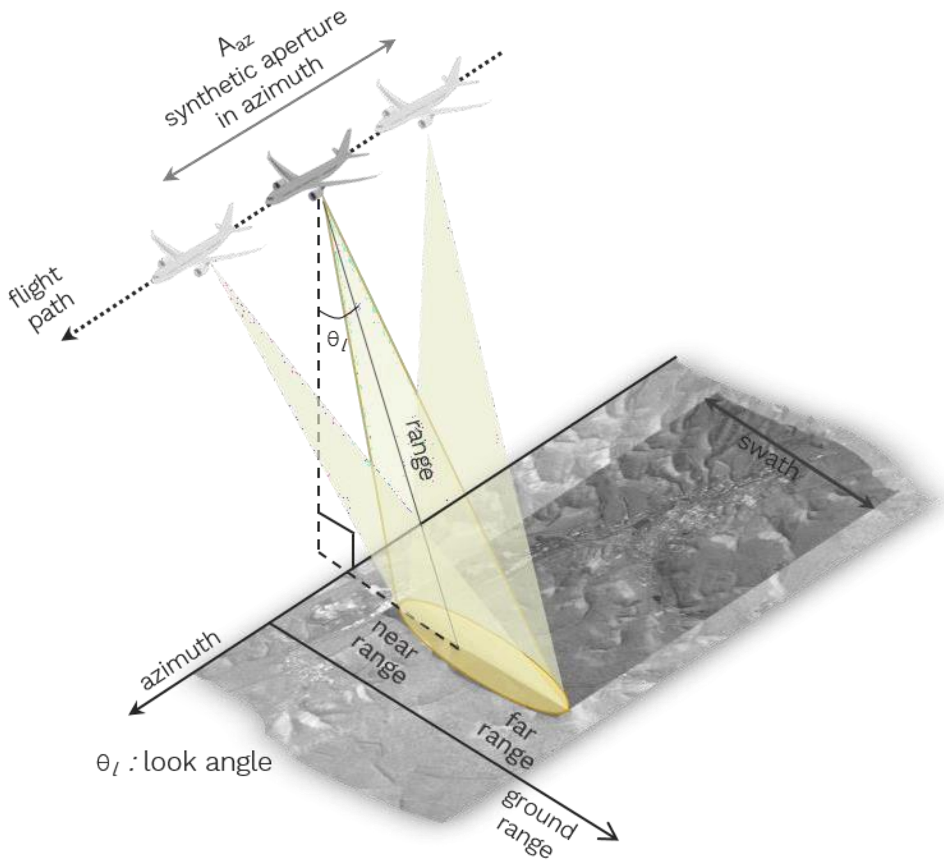
slant-range resolution depends on the **bandwidth of the system**

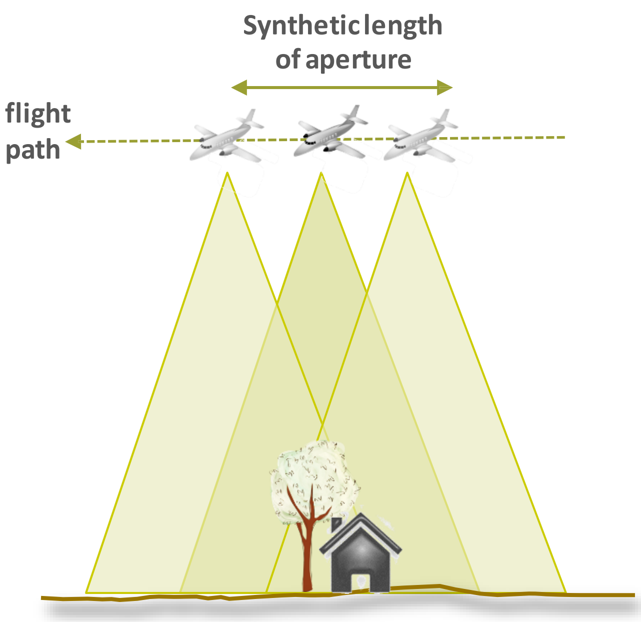
azimuth resolution is a function of the **antenna length** and **sensor height** over the Earth's surface

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.



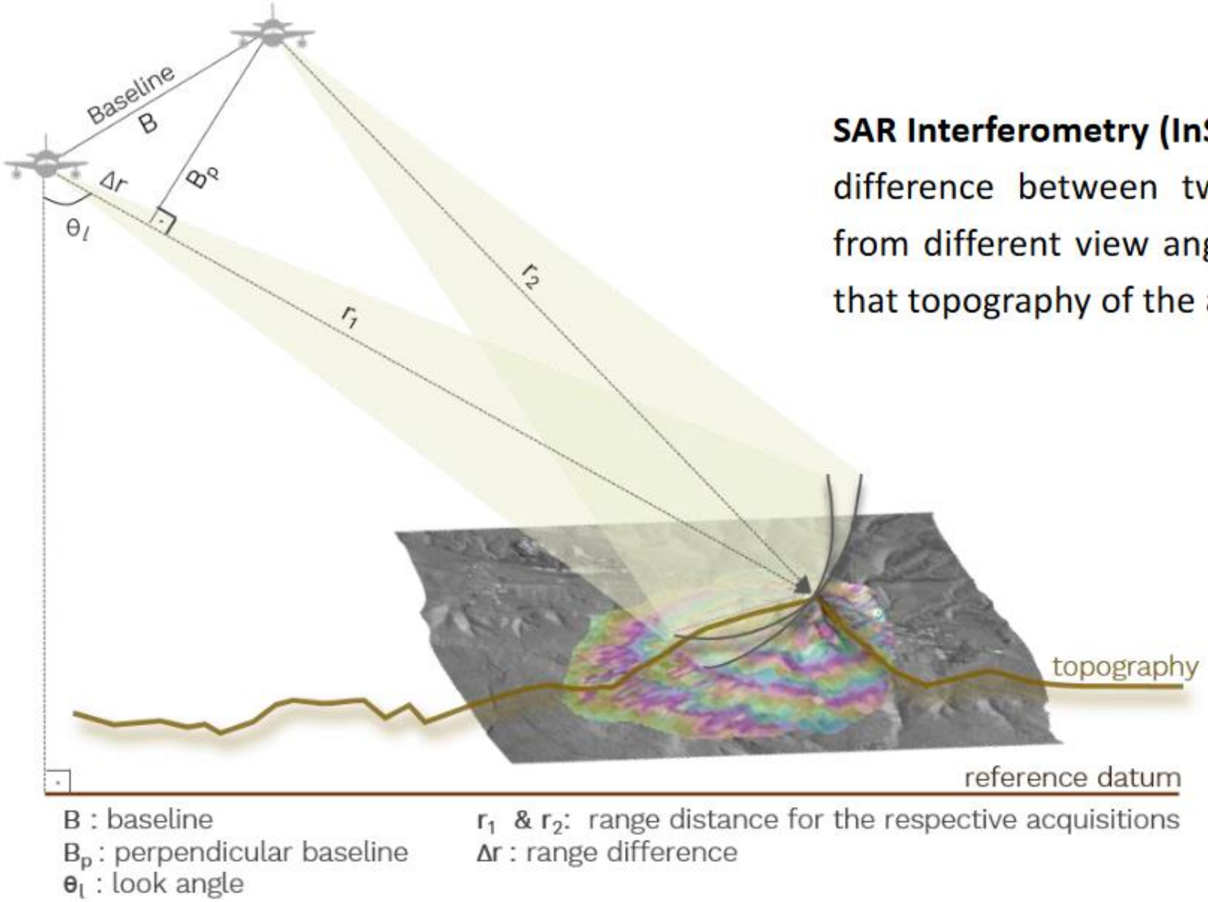


Side view

Synthetic Aperture Radar (SAR)

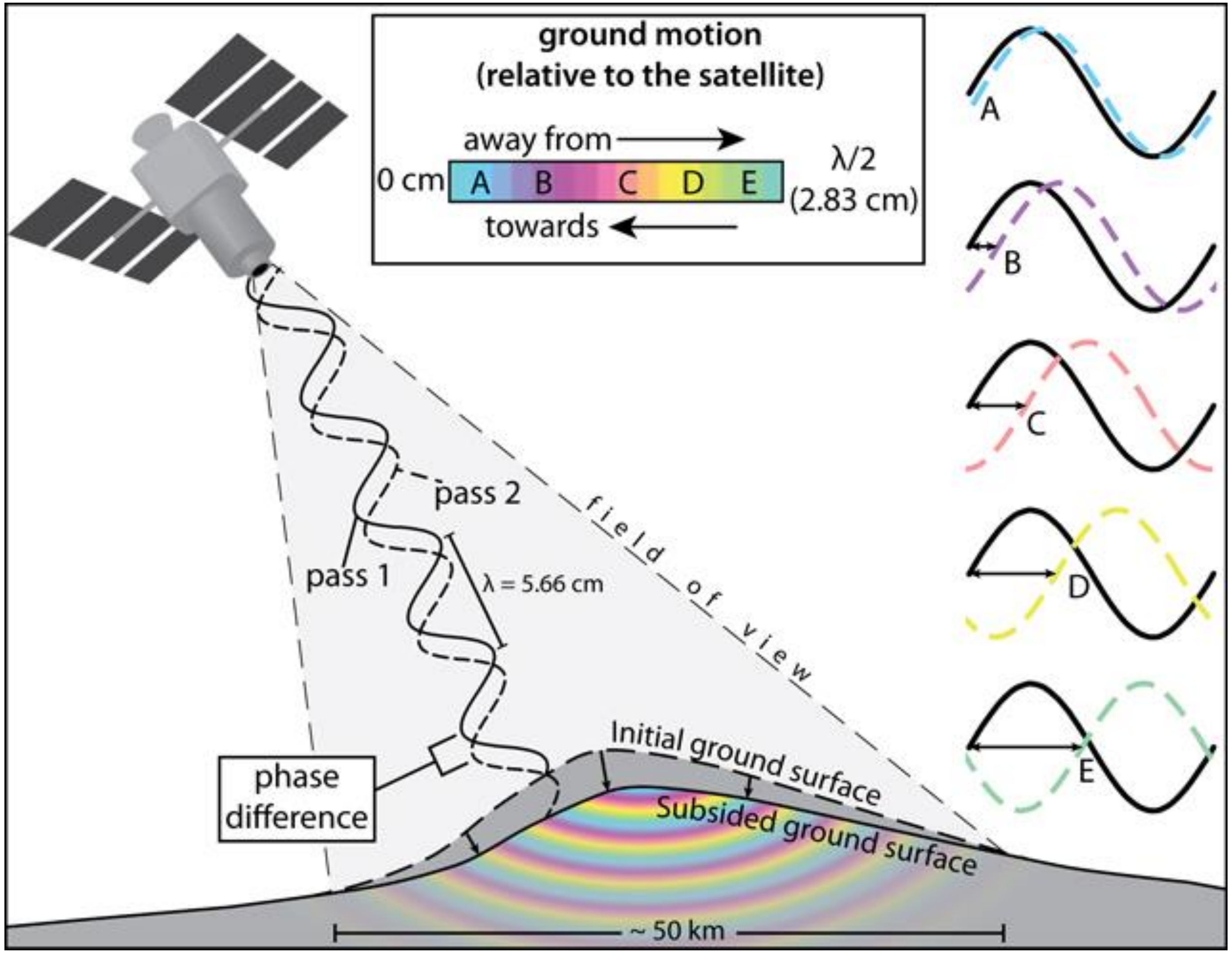
Determining elevation

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.



Synthetic Aperture Radar (SAR)

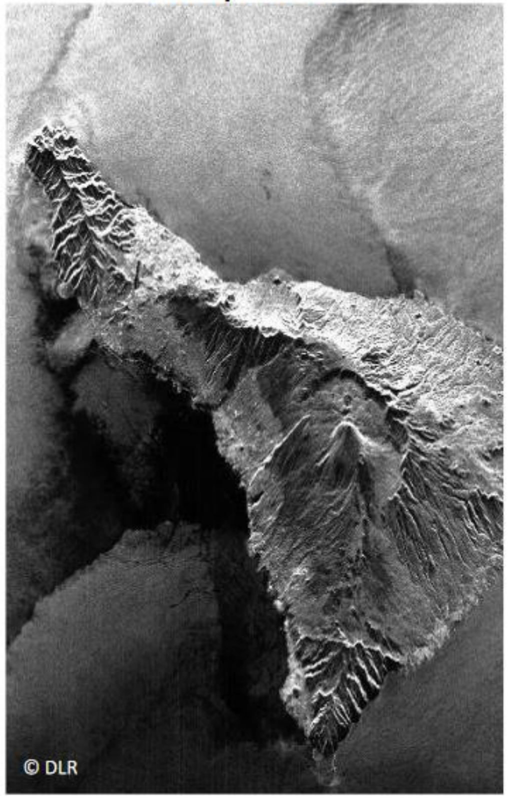
Determining elevation

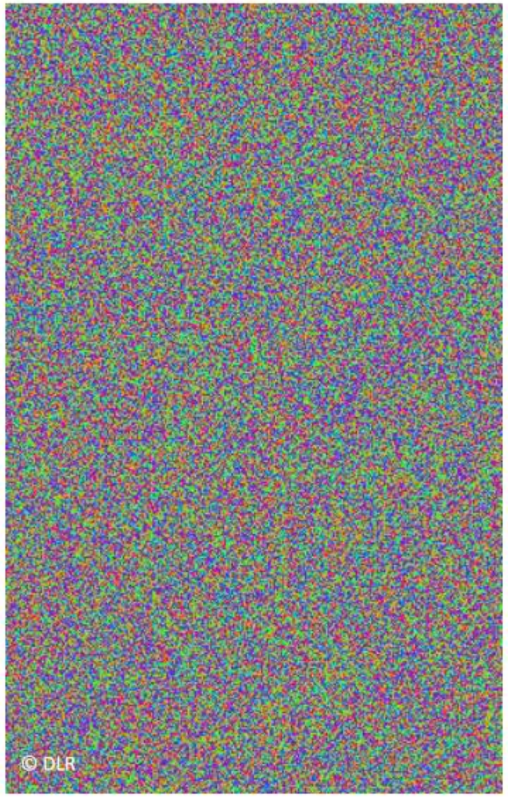


Synthetic Aperture Radar (SAR)

A complex SAR image can be decomposed into …

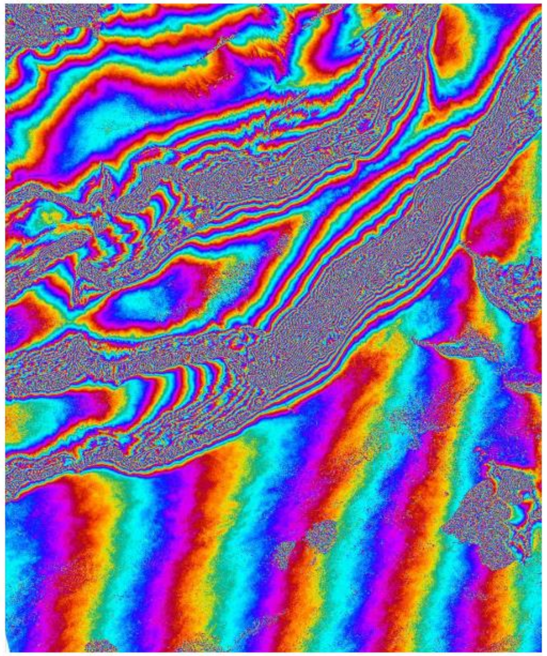
Amplitude & Phase

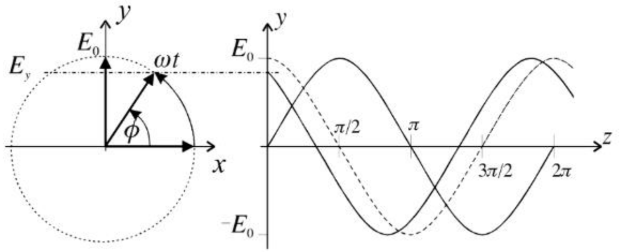




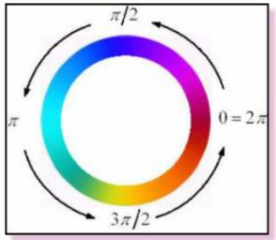
Synthetic Aperture Radar (SAR)

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



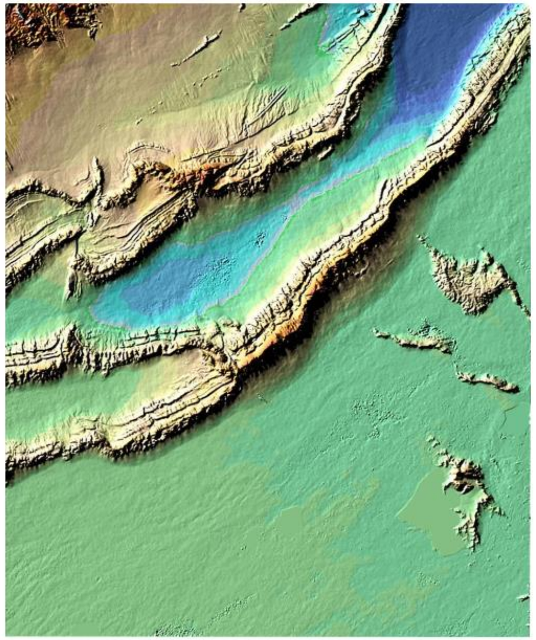


color wheel



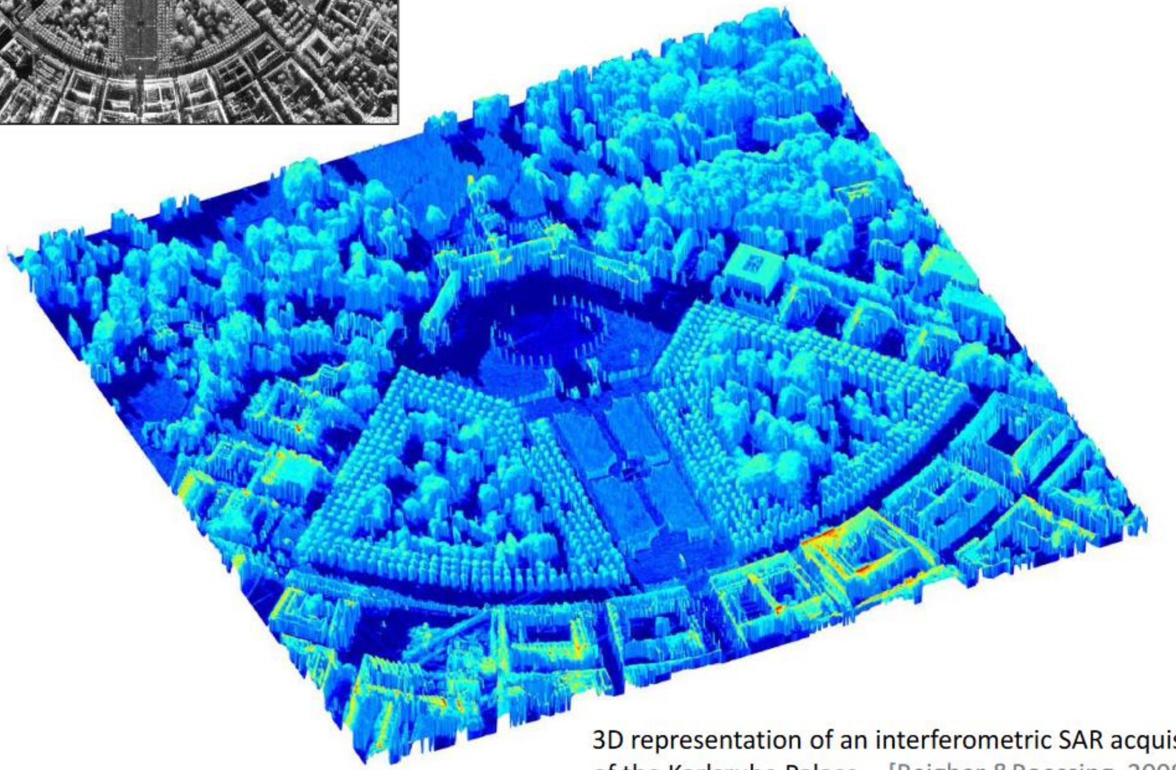
Phase is always ambiguous w.r.t. integer multiples of 2π
→ phase unwrapping required!

Final DEM



Synthetic Aperture Radar (SAR)

Trees acquired at superhigh resolution (X-band)



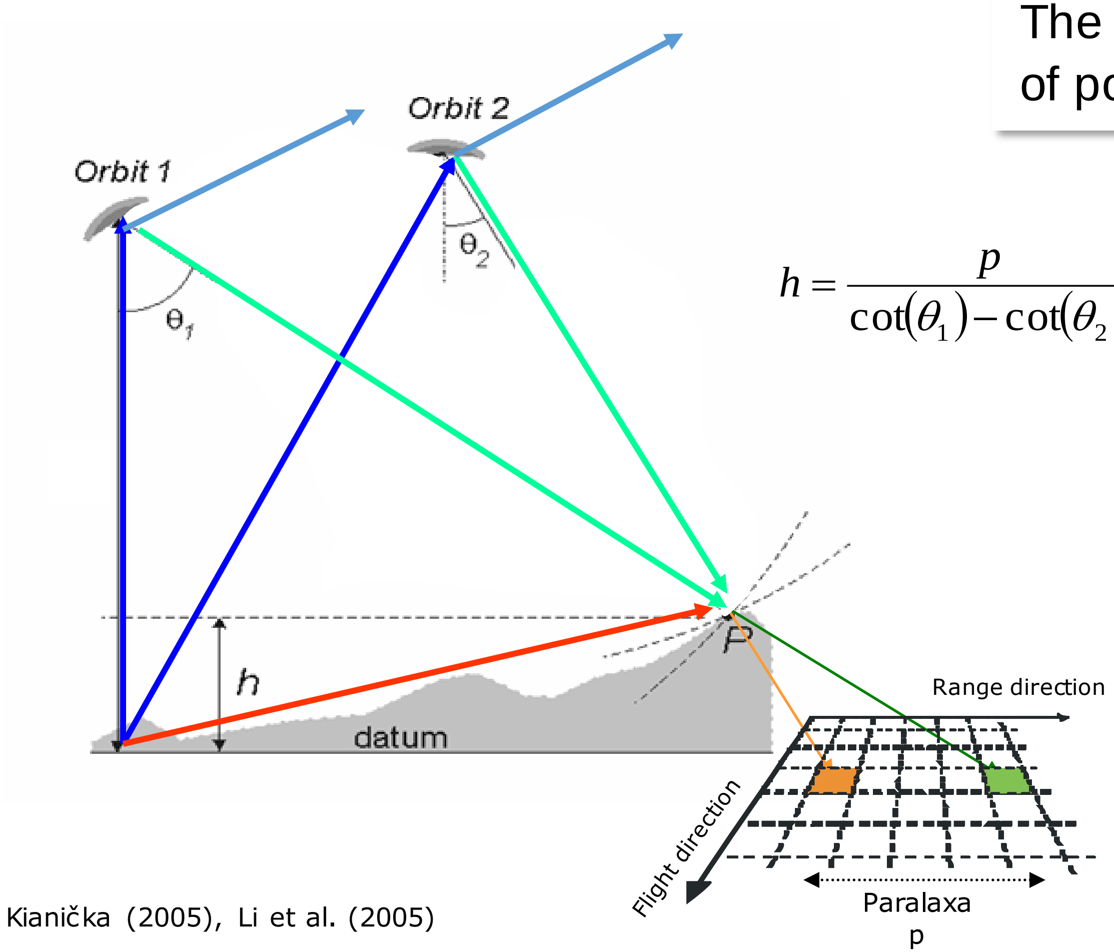
3D representation of an interferometric SAR acquisition
of the Karlsruhe Palace [Reigber &Roessing, 2008]

Synthetic Aperture Radar (SAR)

Image analysis methods

Radargrametry

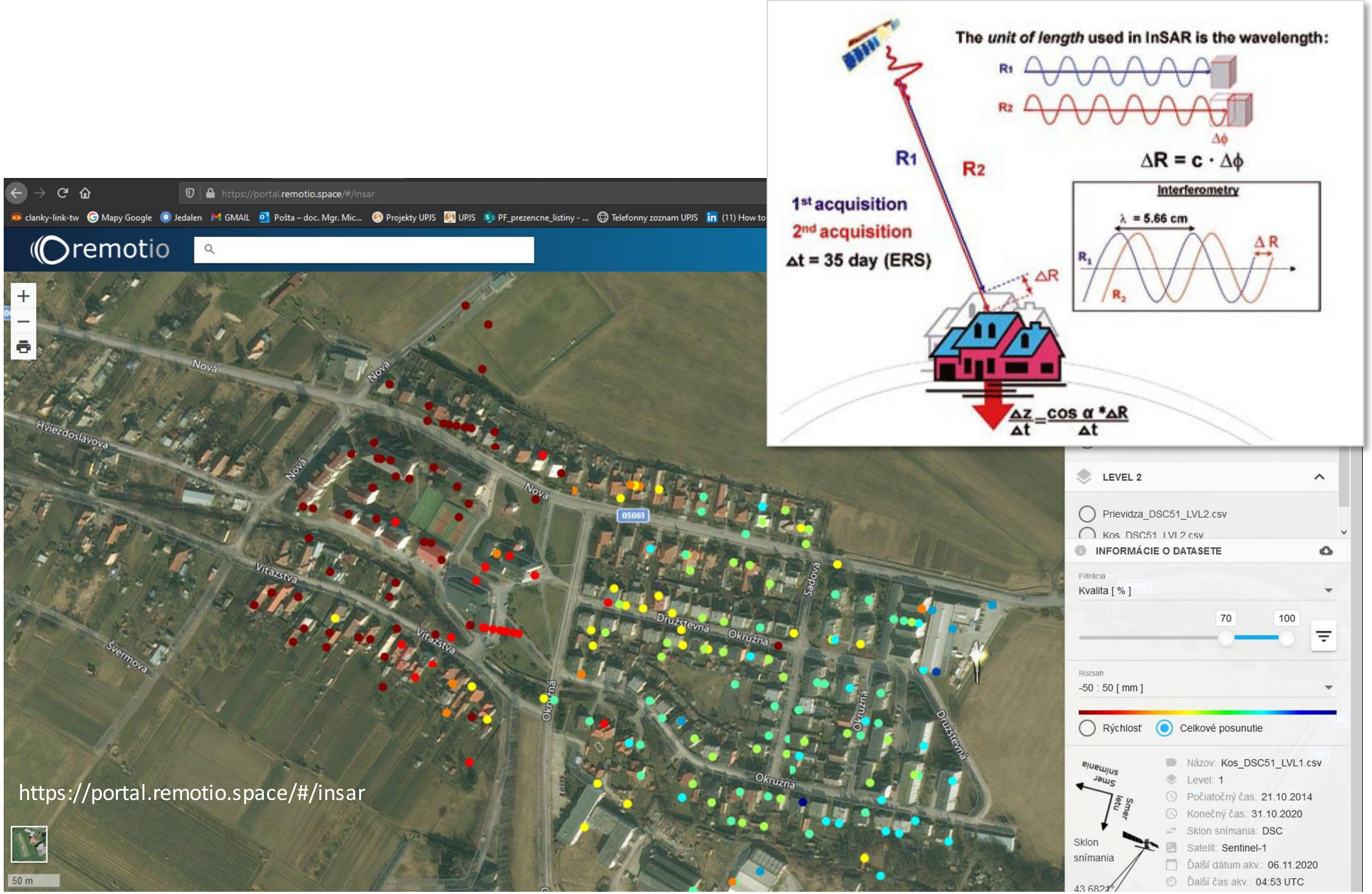
The principle of measuring the parallax of point P using SAR stereo images.



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

Kianička (2005), Li et al. (2005)

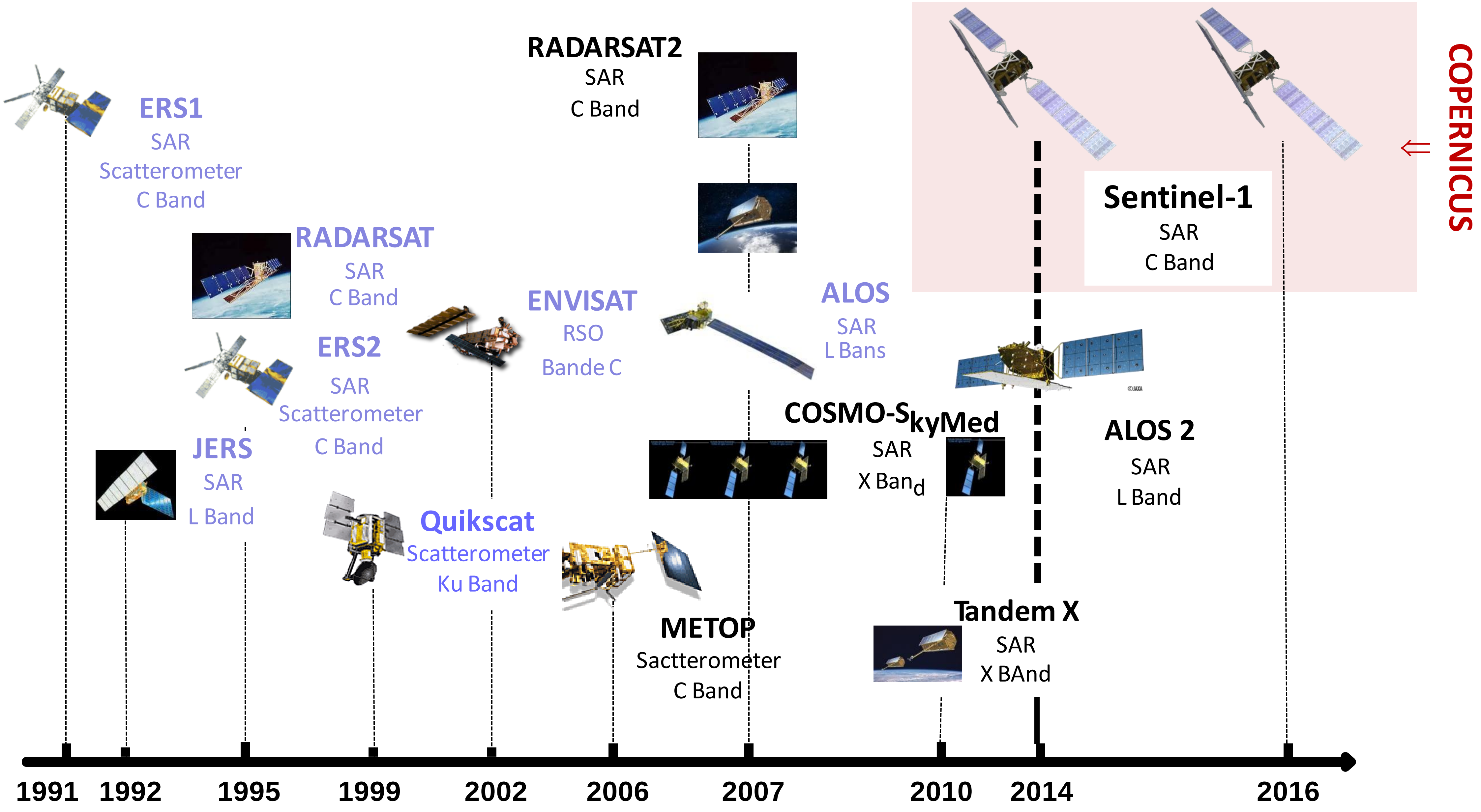
Persistent scatter SAR interferometry - PSInSAR



Persistent scatter SAR interferometry - PSInSAR

- Measurement of movement in points intensely reflecting radar signal, thus not using all pixels of the radar record as in D-InSAR, many of which have unstable coherence of reflected radiation over time (reflectivity over time changes) due to changes in moisture, vegetation growth.
- Such objects, well and stably reflecting microwaves, occur naturally - rock outcrops, cliffs, or artificially - roofs, buildings, building corners, antennas, pipelines.
- The method determines the change in wave phase due to slight movement of the signal reflector.
- This way, surface deformation/movement of objects on it can be determined with millimeter precision.
- Compared to GNSS measurements, the advantage of PSInSAR is the ability to monitor a large number of points over a larger area and lower cost.

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-

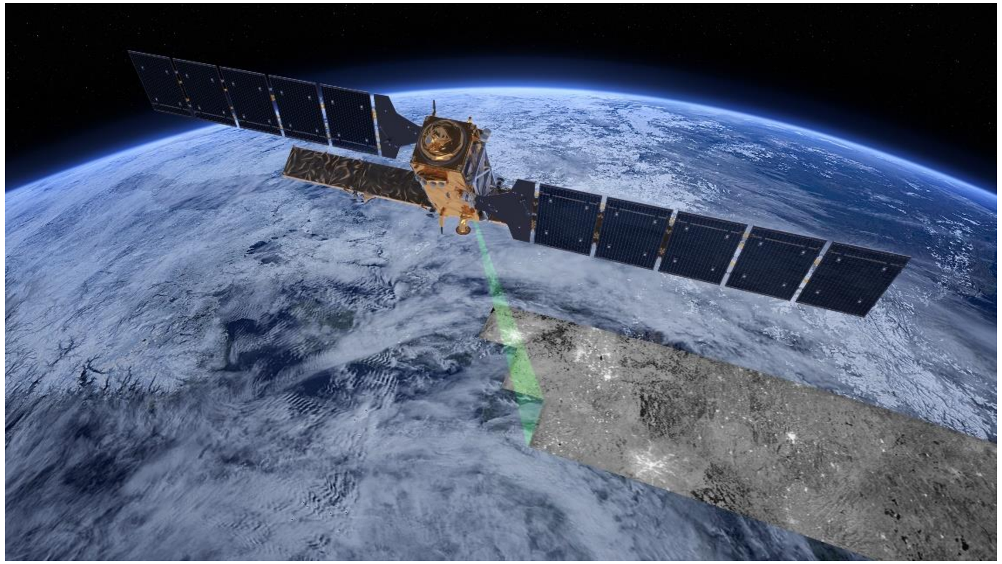
Sentinel-1 – Radar vision

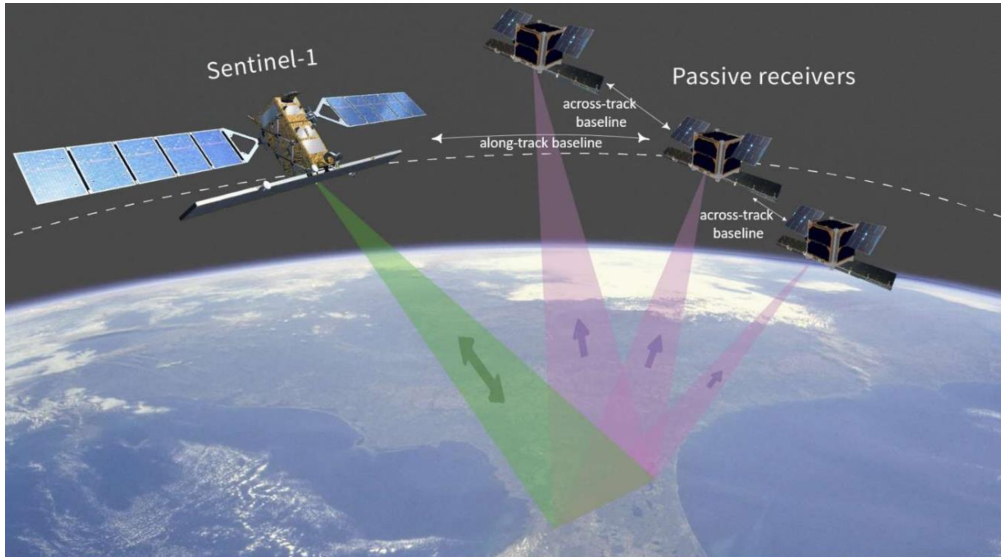
Mission profile:

- 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

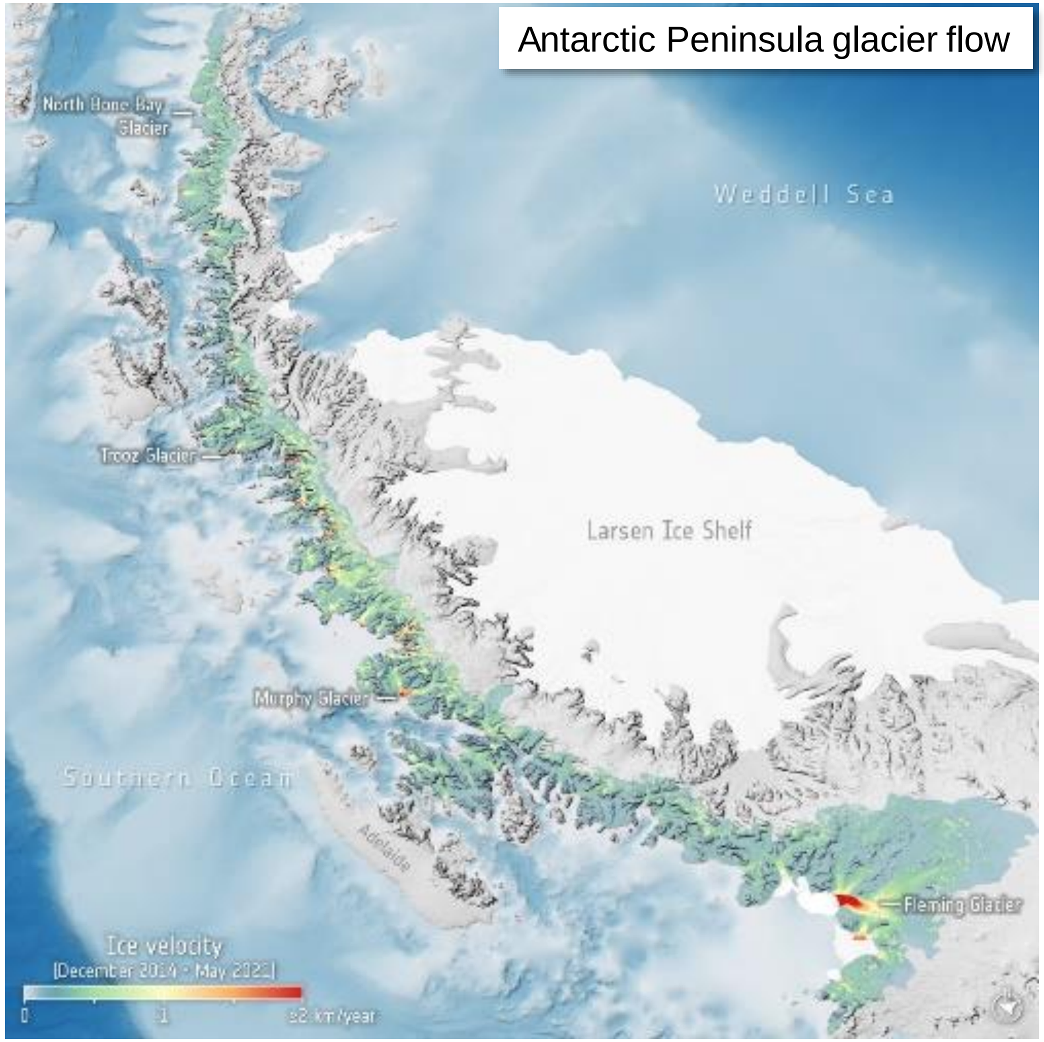
Mission objectives:

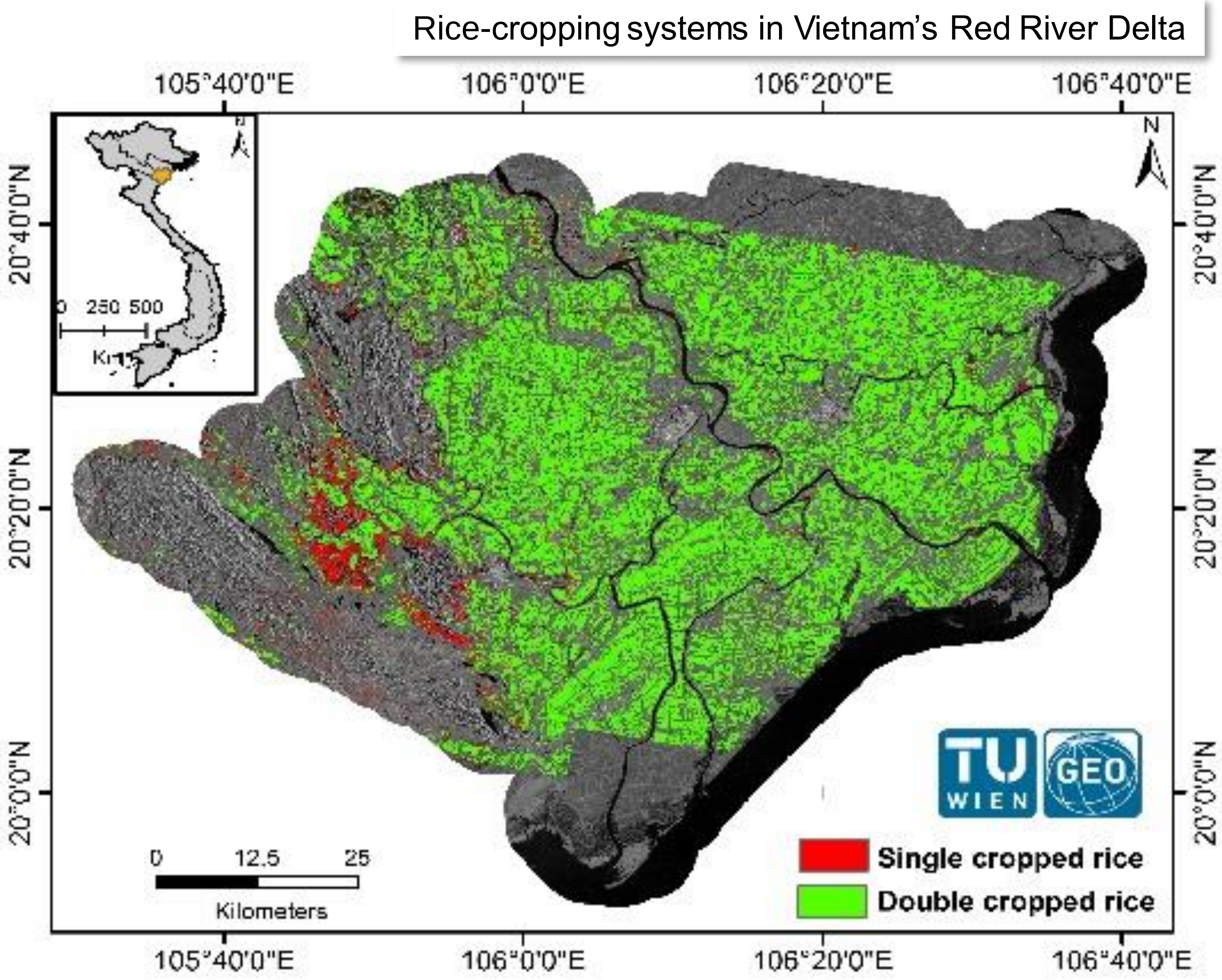
- Marime and land monitoring
- Emergency management



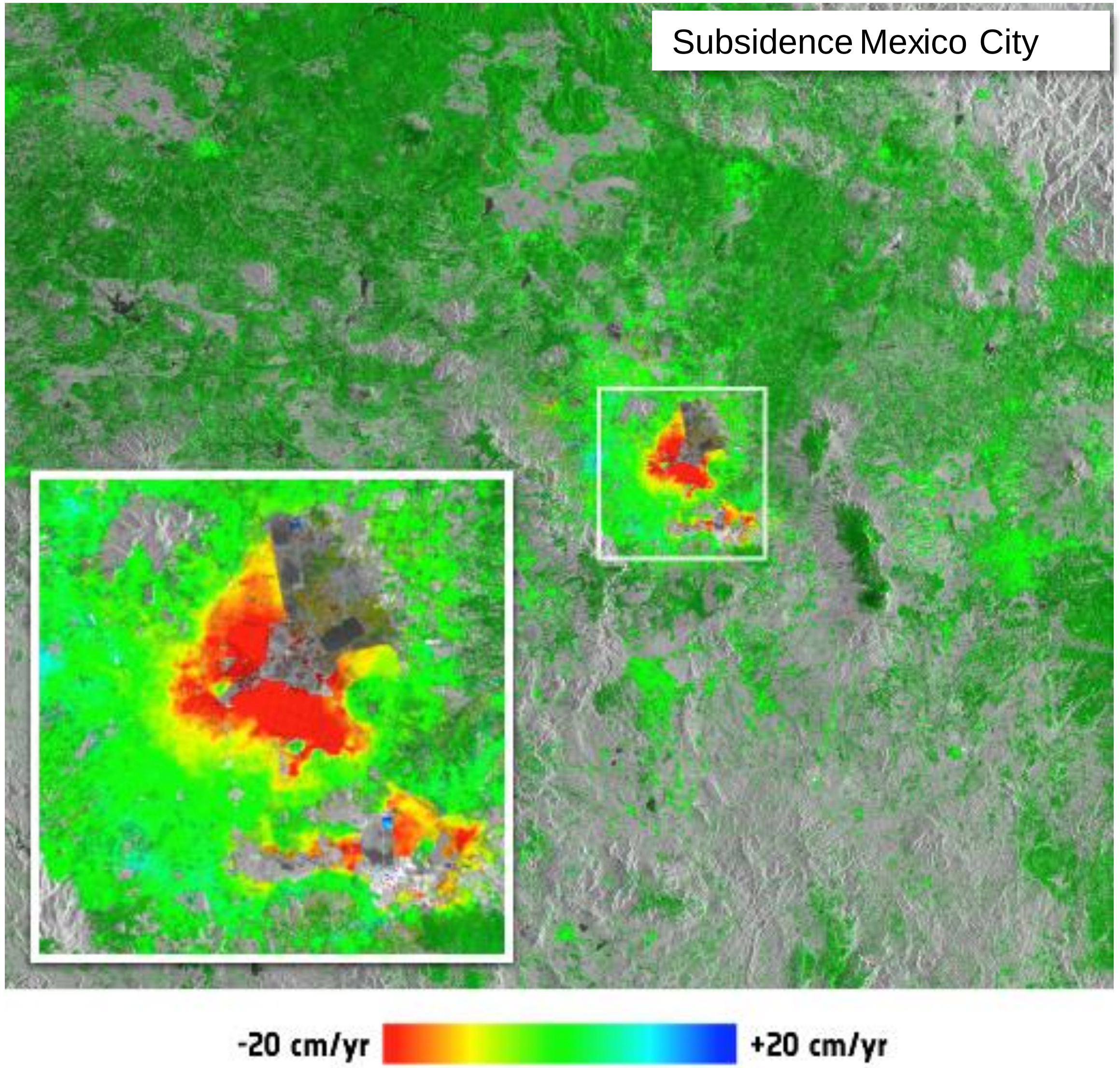


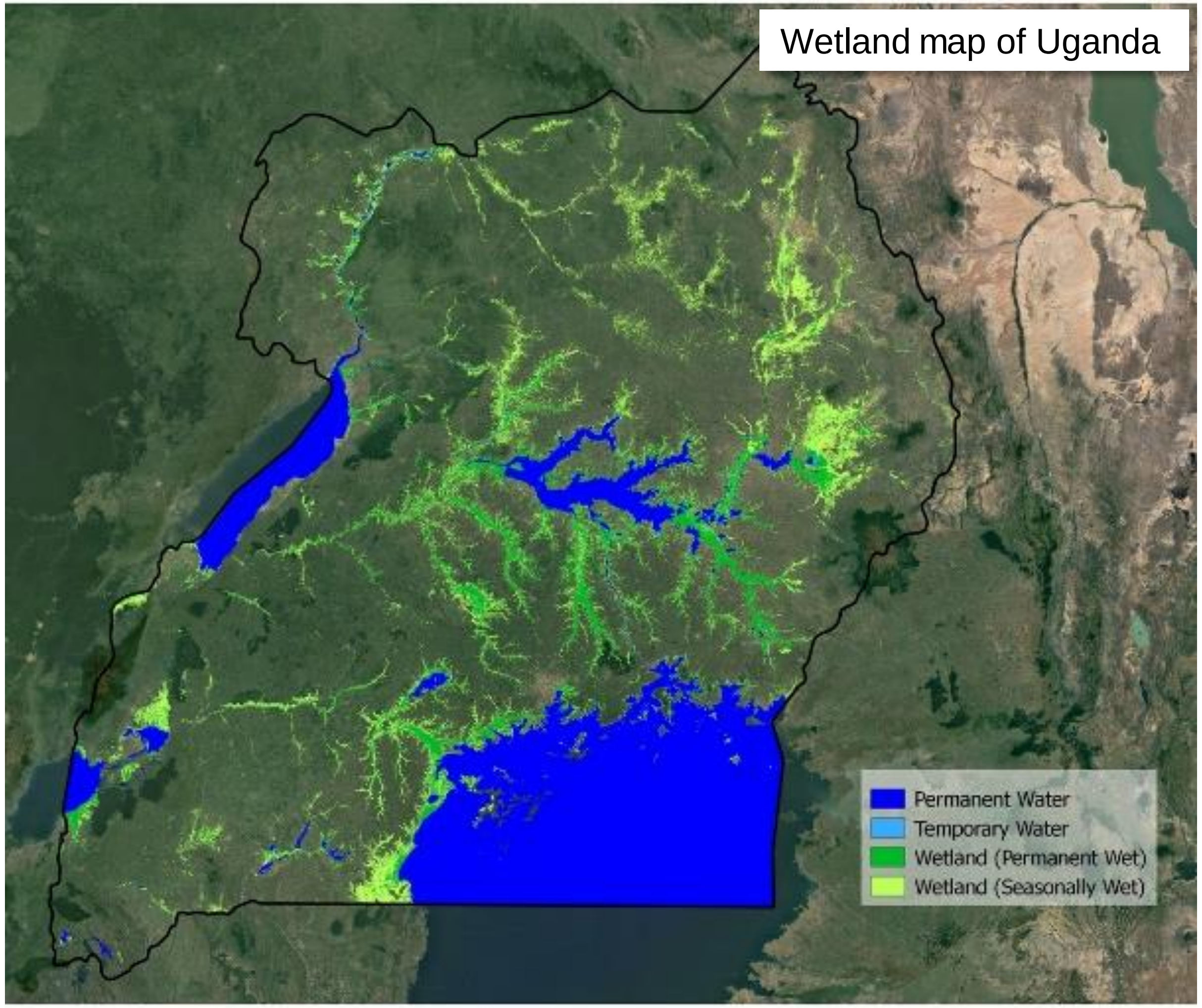
Sentinel-1 – Applications



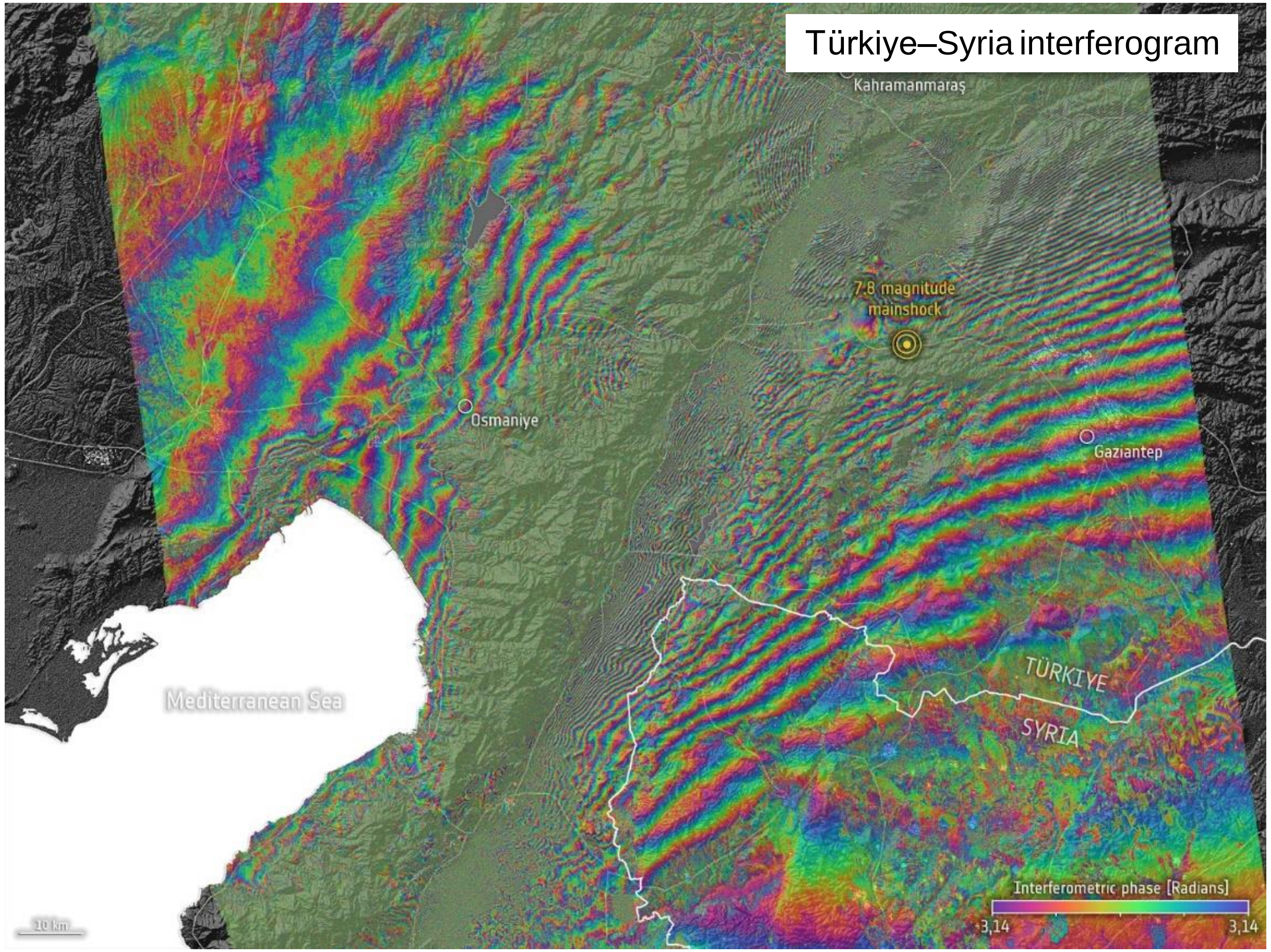


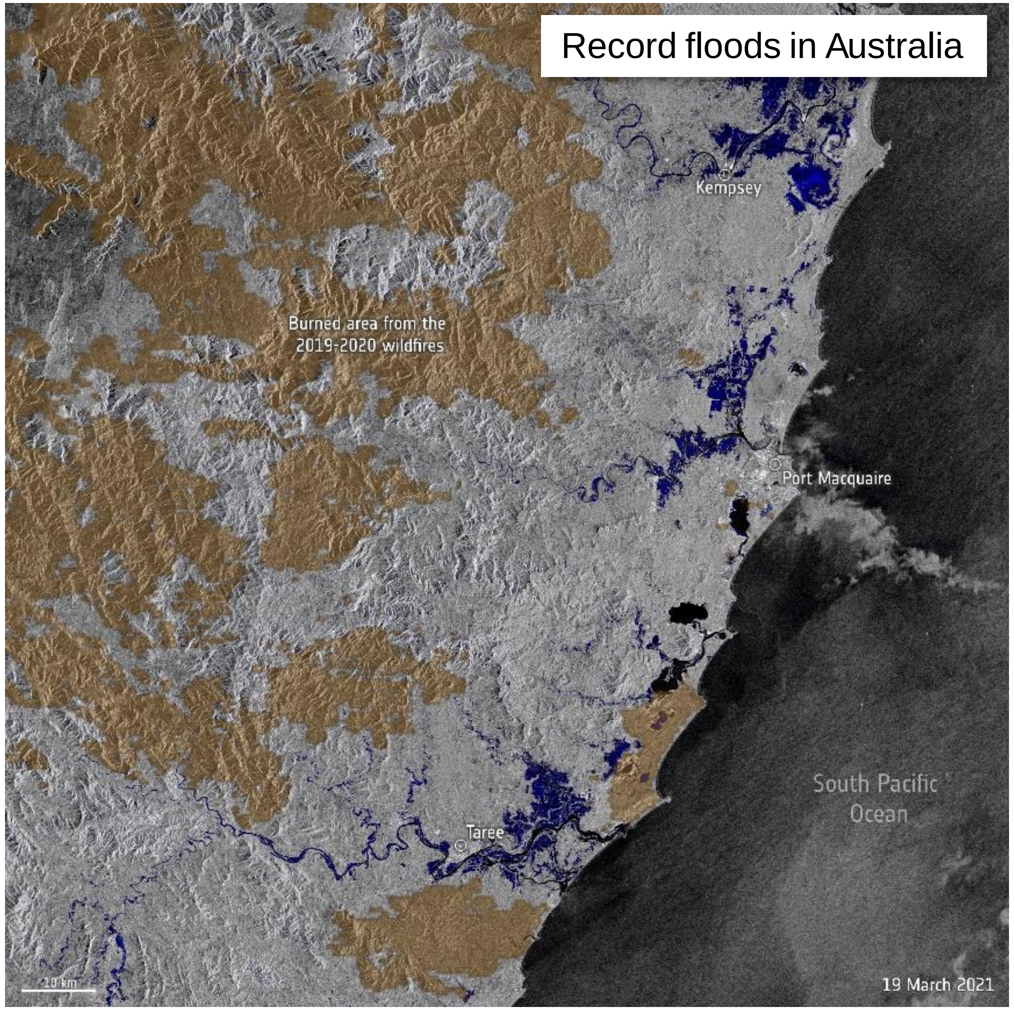
Sentinel-1 – Applications





Sentinel-1 – Applications





For more information, see the tutorial:

[5. Basics of Radar Remote Sensing - data processing using SNAP software]

6. Precision agriculture mapping using multispectral data

From EO signal to agriculture information content

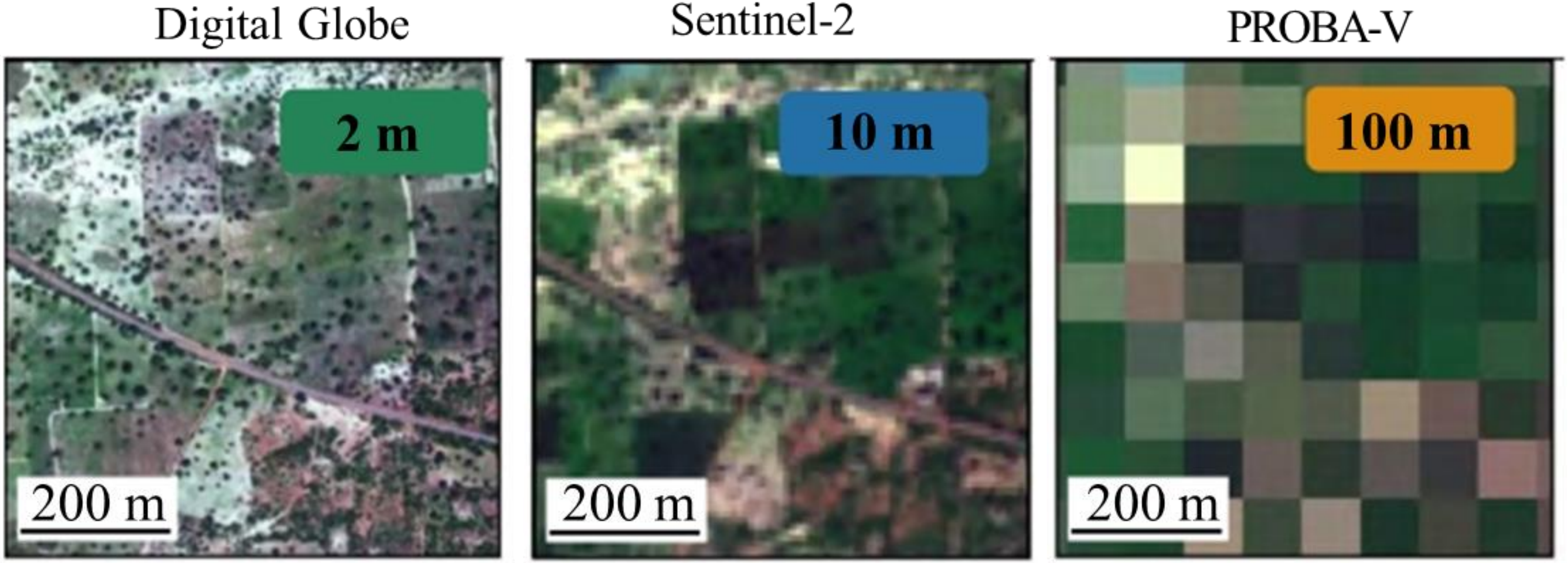
Spatial + spectral + temporal information content + Machine learning for classification

Resolutions offered by popular satellite imagery providers

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

From EO signal to agriculture information content

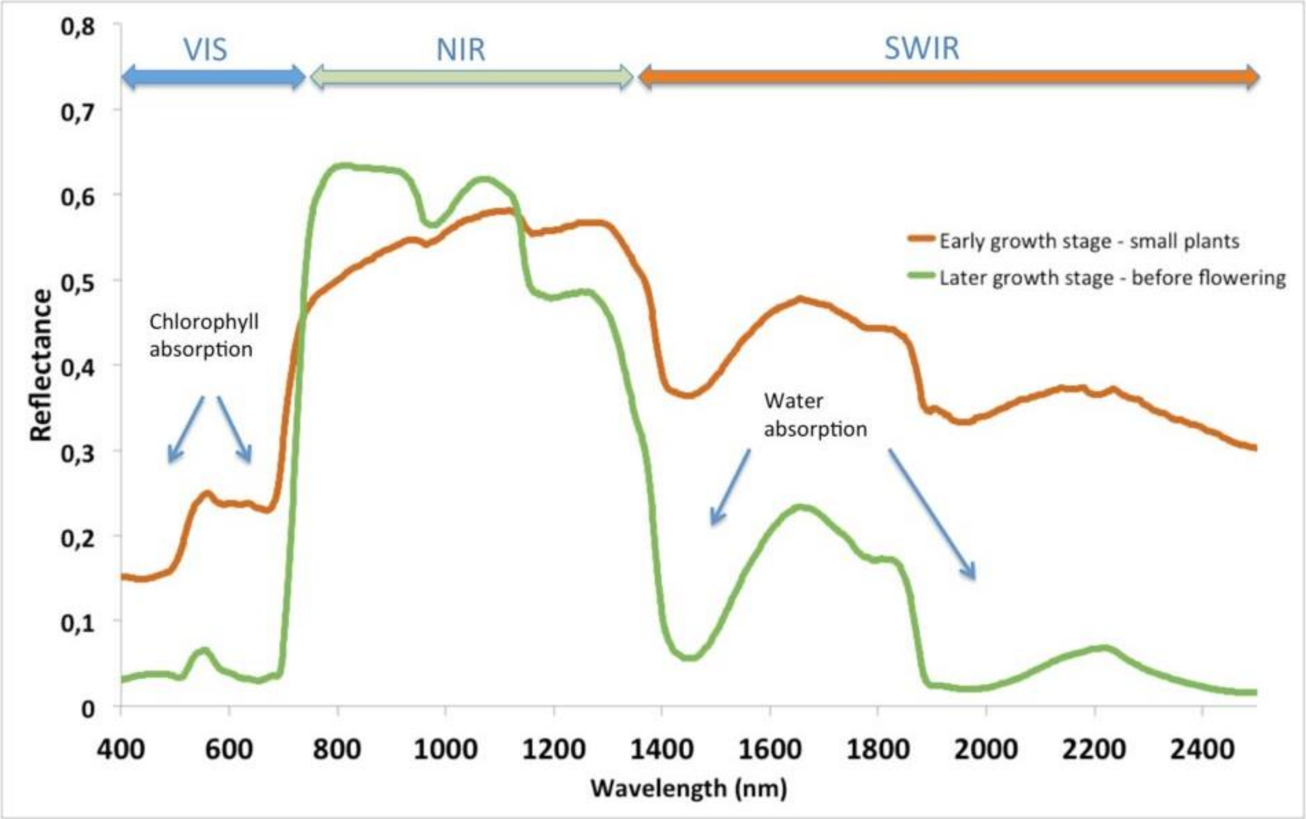
Spatial resolution



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



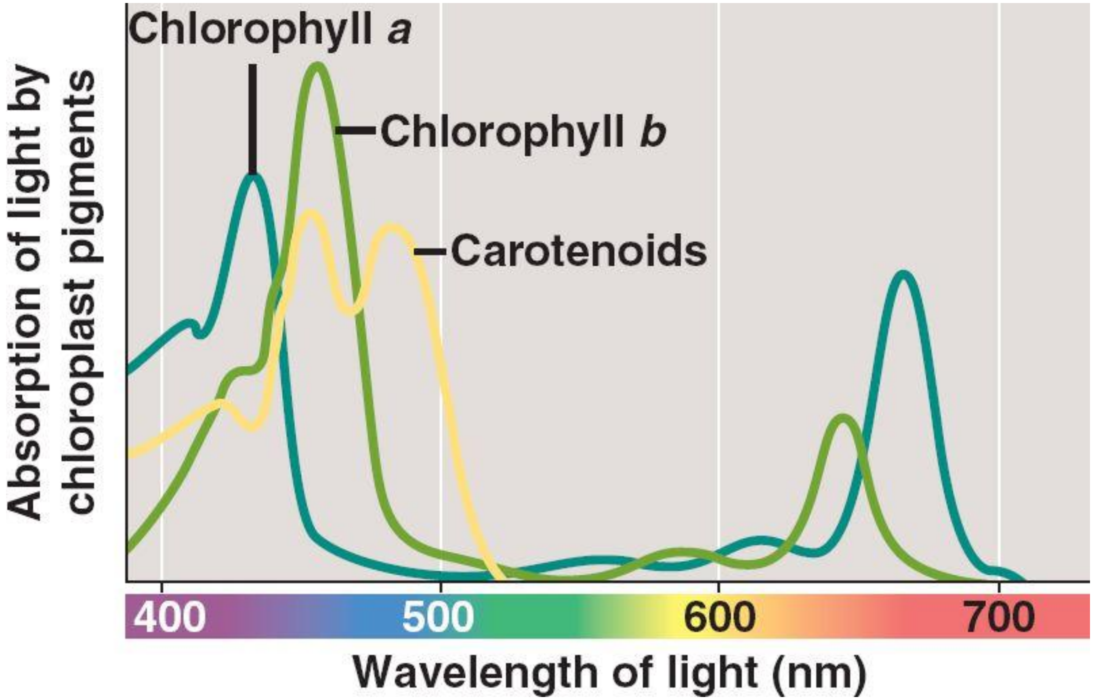
Vegetation indices:

- 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

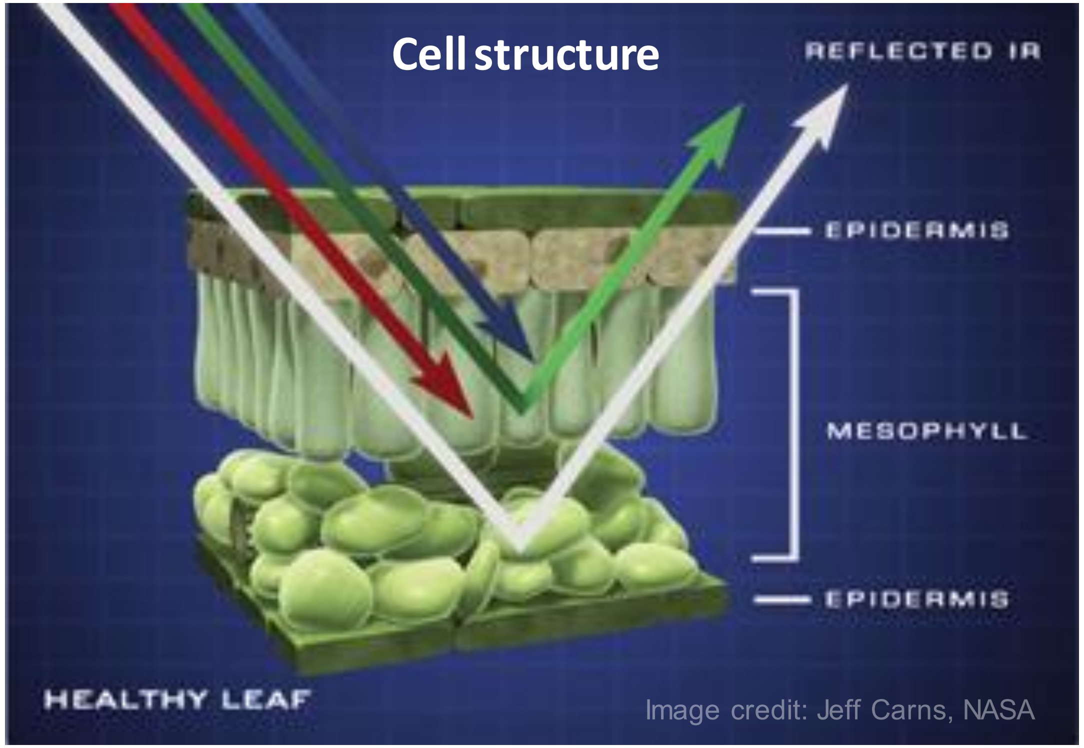
Spectral signature of the plants

Plant pigments

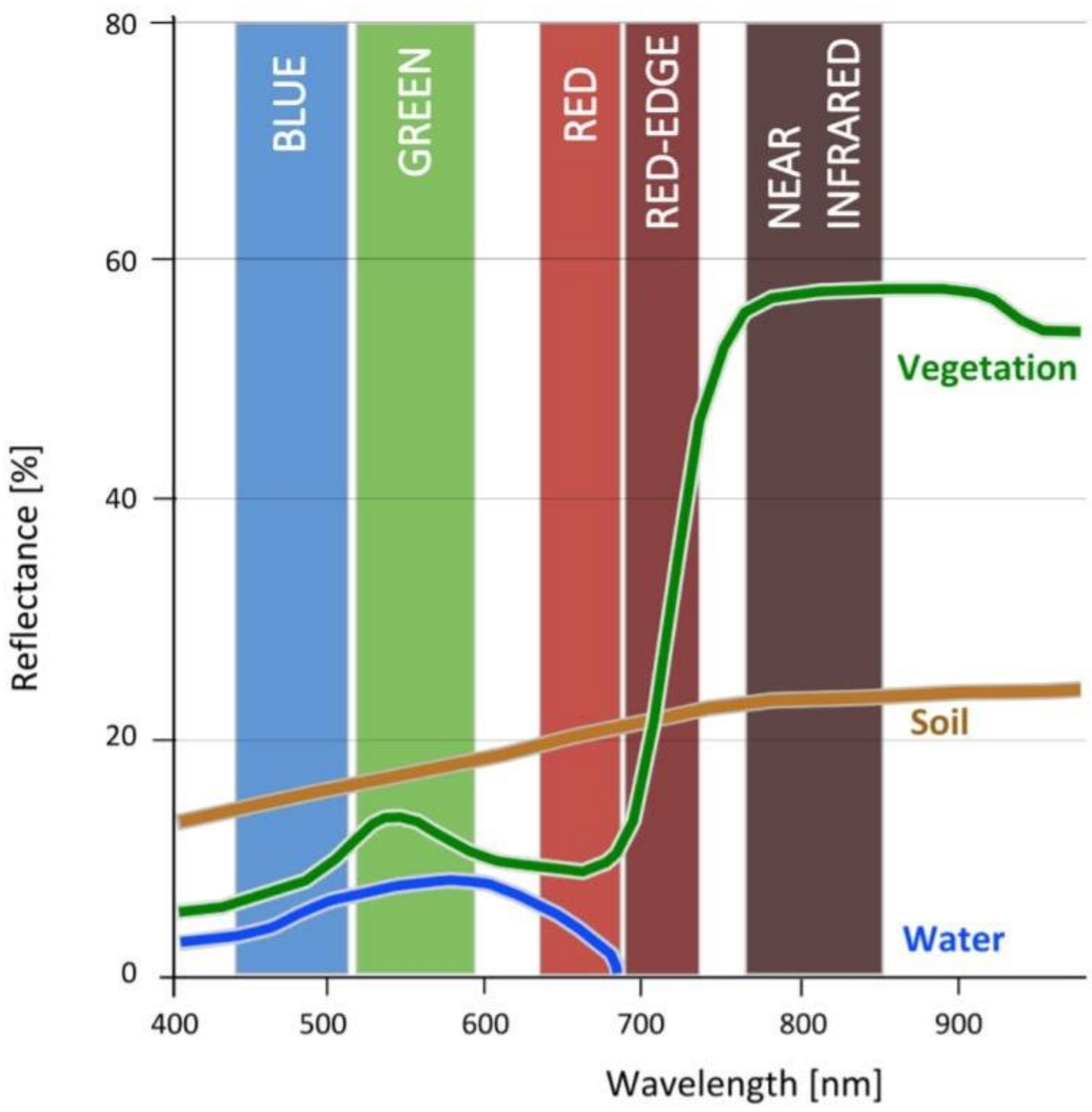


Chlorophyll predominately absorbs blue wavelengths (400-500 nm) and red (600-700 nm). Note that carotenoids absorb blue light as well as some green.

- 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)

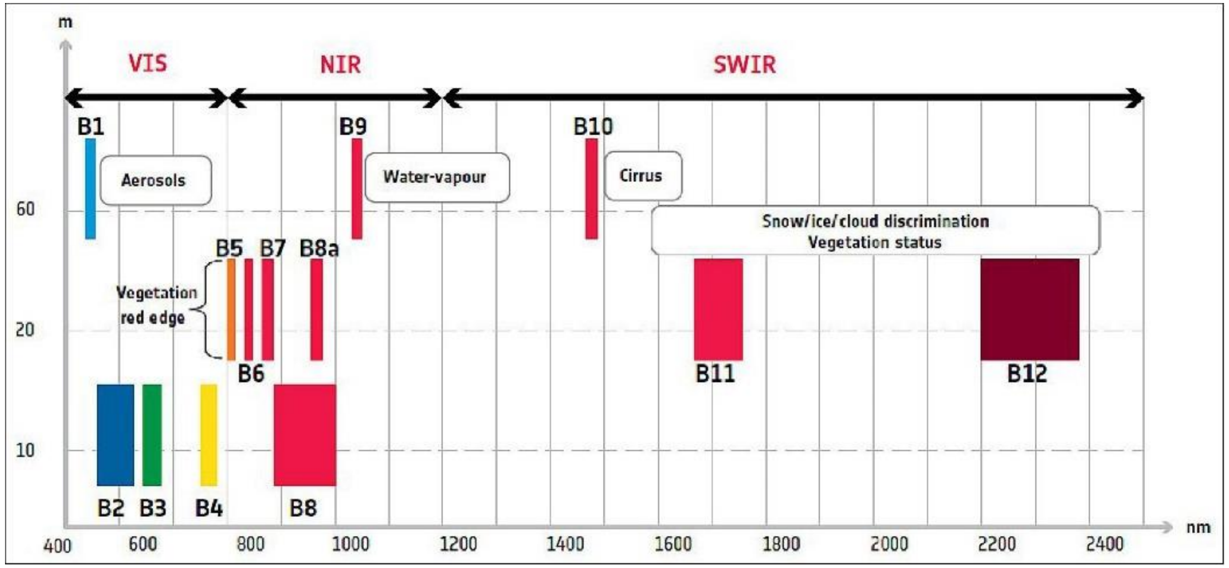


From EO signal to agriculture information content



RED EDGE

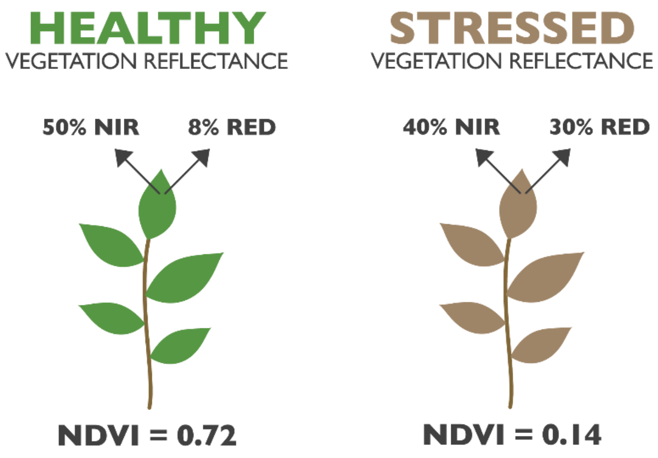
- The three 20m 'red edge' bands of Sentinel-2 provide key information on the state of vegetation
- Very narrow band (700 – 730 nm) corresponding to the red NIR transition zone
- Very sensitive to plant stress – provides information on the canopy chlorophyll and nitrogen content



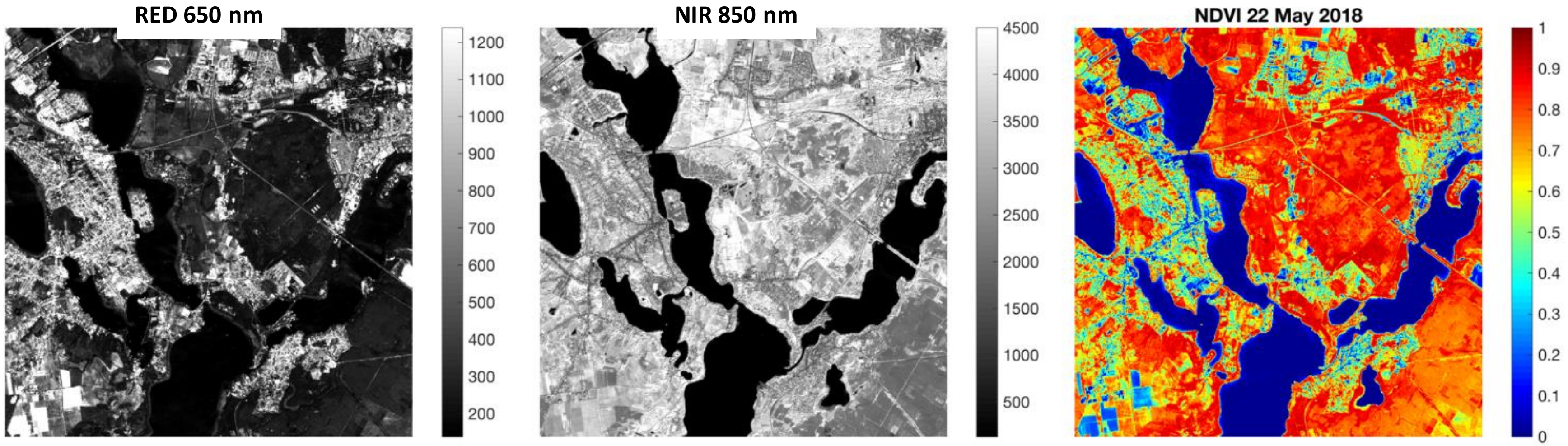
From EO signal to agriculture information content

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



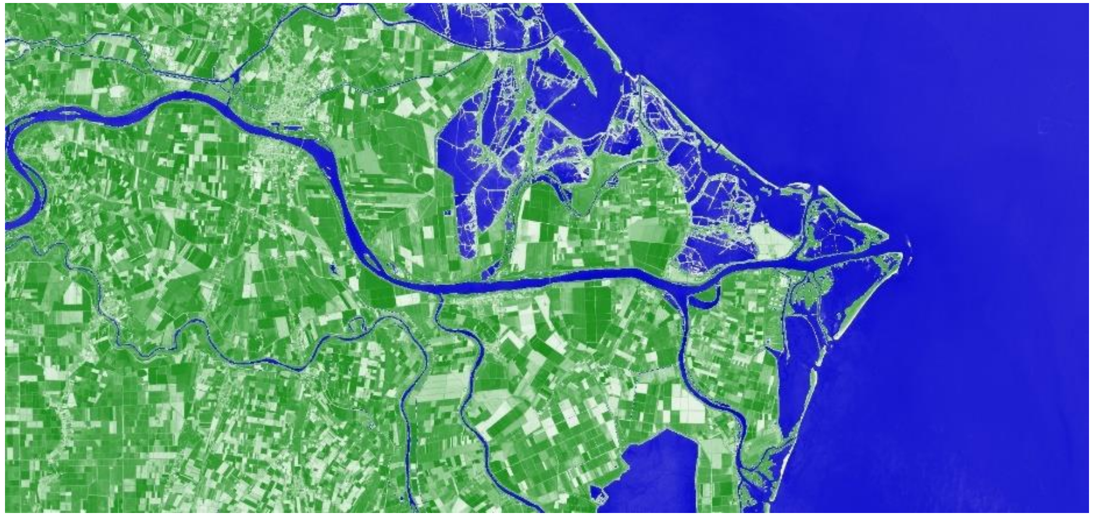
$$NDVI = \frac{NIR - RED}{NIR + RED}$$



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

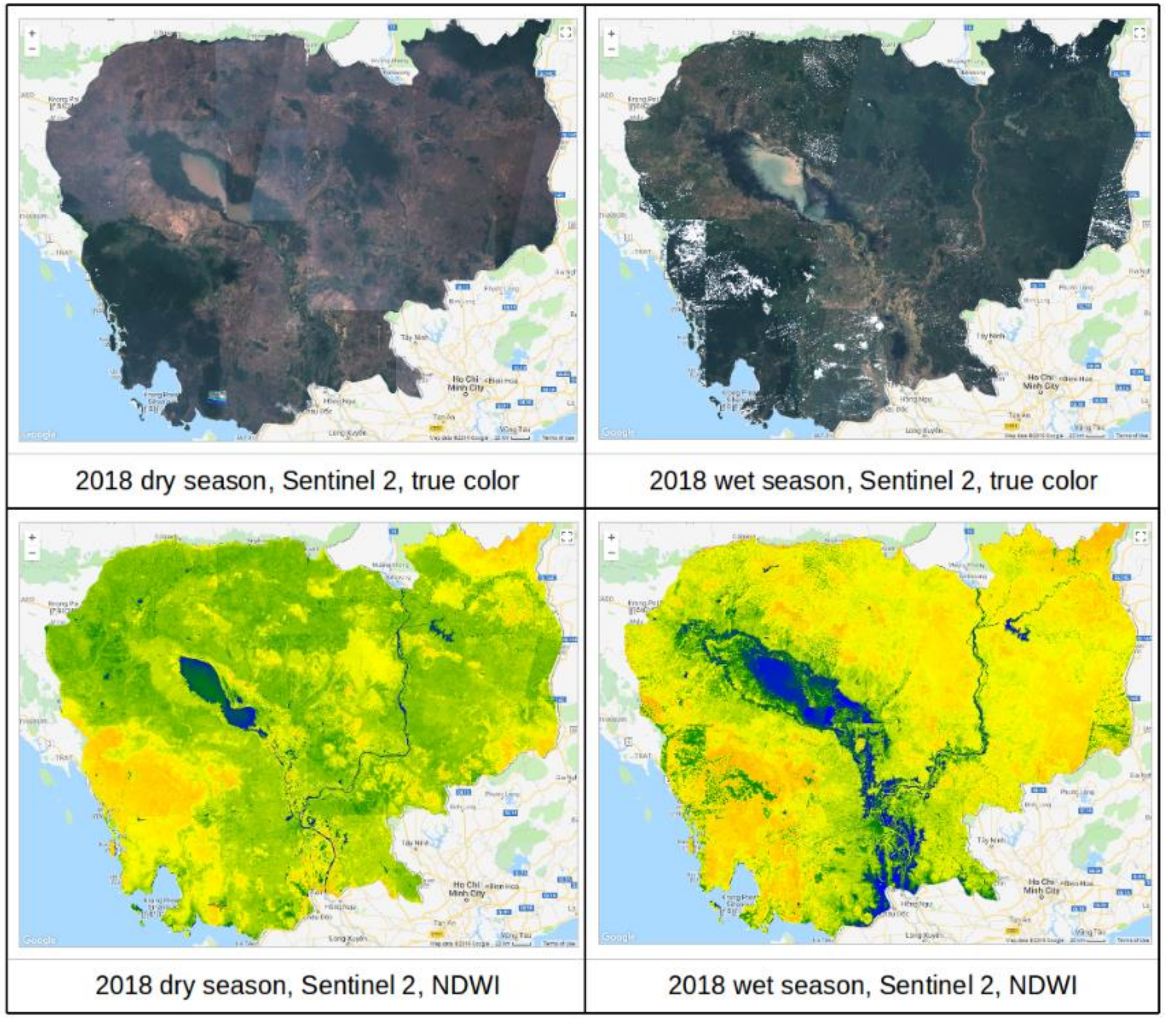


NDWI of Italy. Acquired on 2020-08-01.

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

From EO signal to agriculture information content

NORMALIZED DIFFERENCE WATER INDEX (NDWI)



2018 dry season, Sentinel 2, true color

2018 wet season, Sentinel 2, true color

2018 dry season, Sentinel 2, NDWI

2018 wet season, Sentinel 2, NDWI

From EO signal to agriculture information content

Biophysical variables estimation for agriculture applications

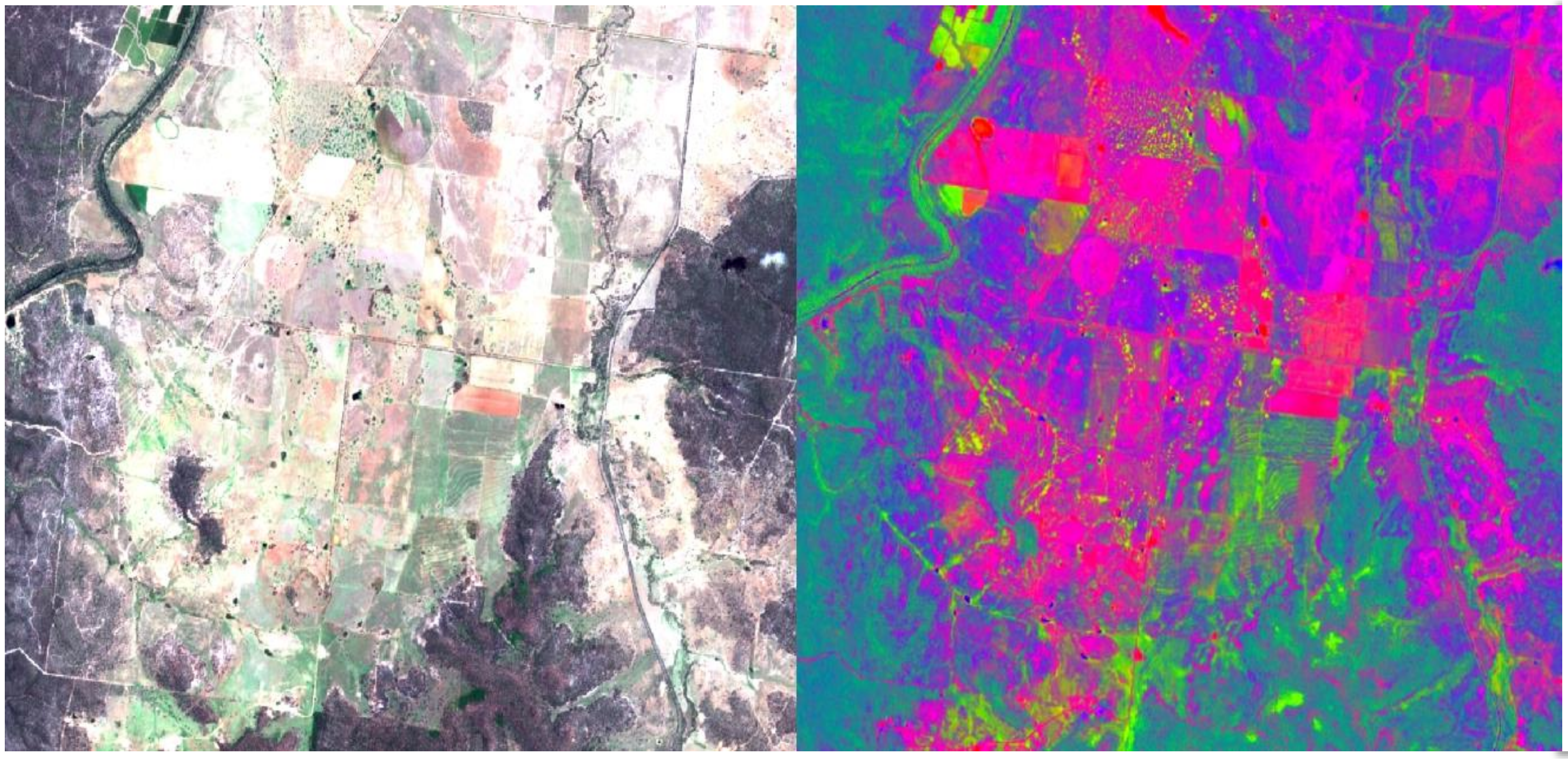
Biophysical variables are plant traits or characteristics of interest which can be measured on the ground and possibly estimate by remote sensing at various scales depending of the sensor spatial resolution

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

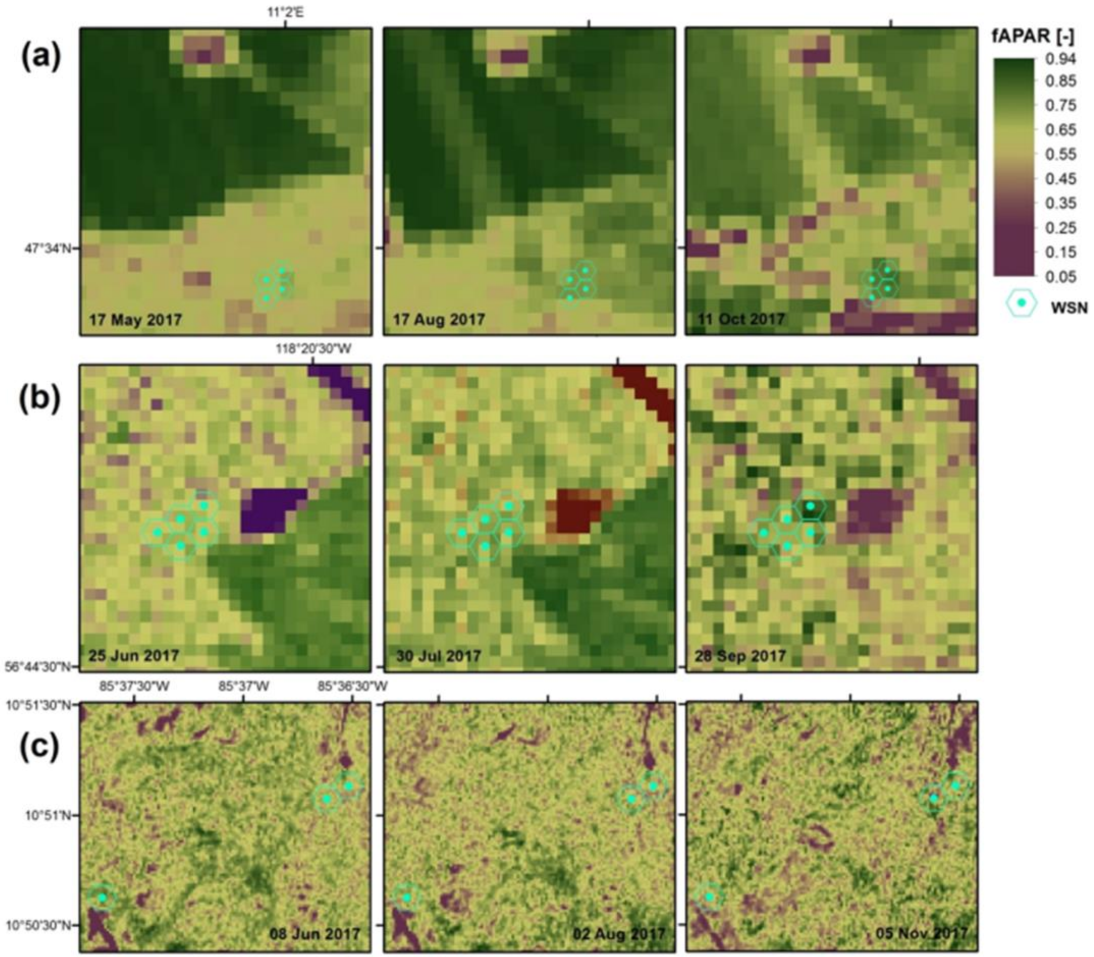


Fig. 7. The S2 fAPAR products at (a) Graswang, (b) Peace River and (c) Santa Rosa for several dates, representing early, peak and end of vegetation periods.

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

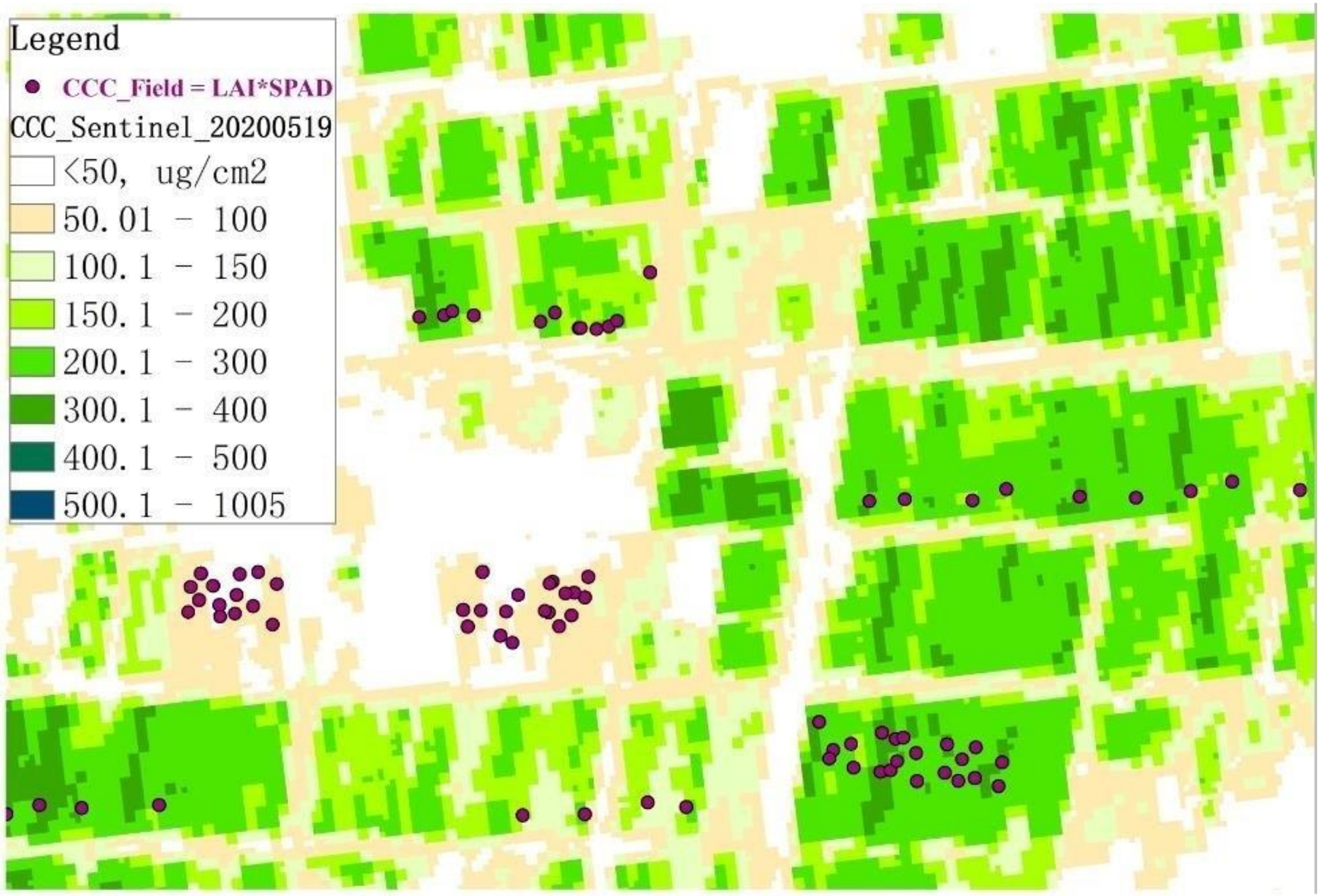
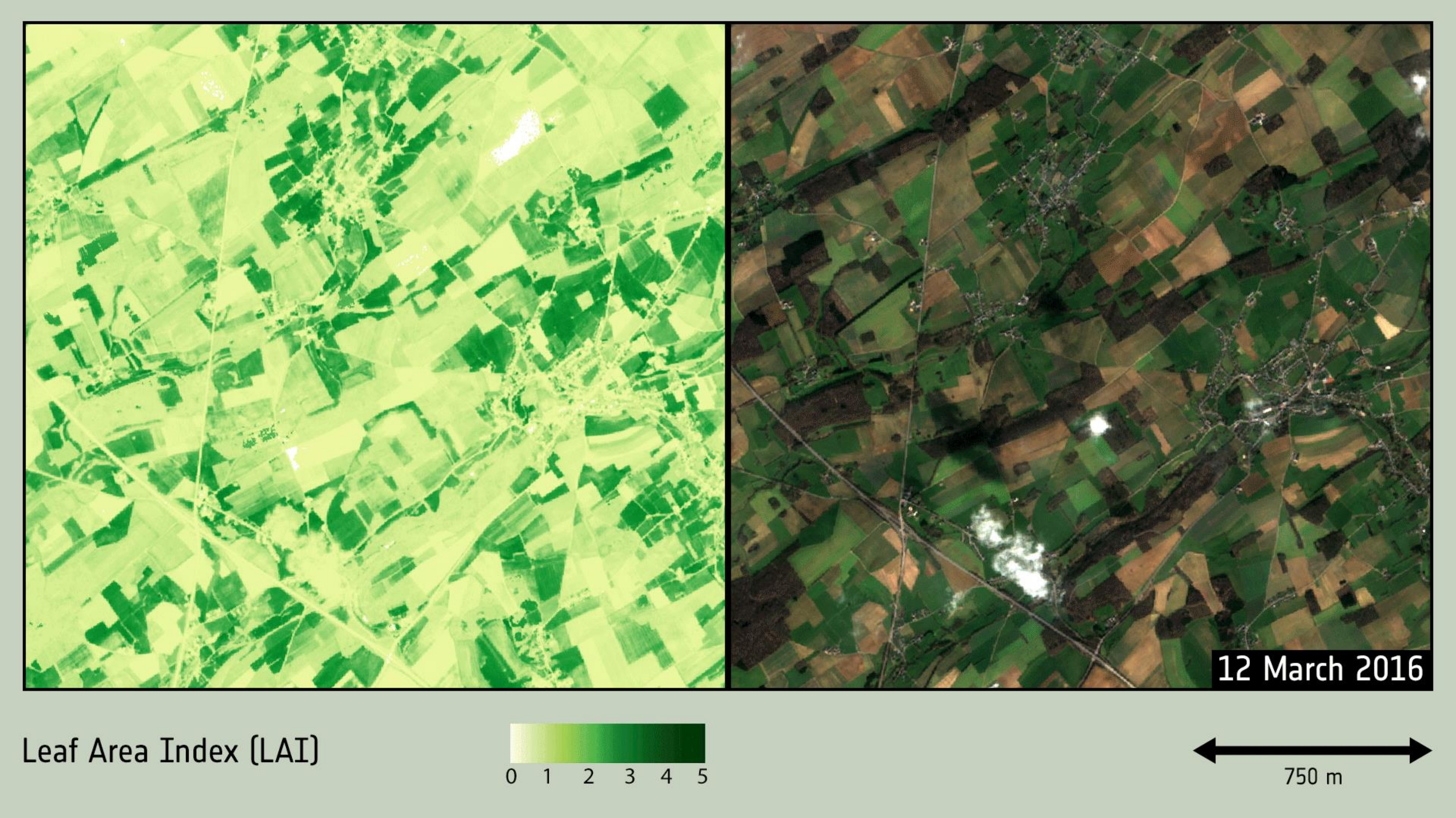


Figure 1 Winter wheat Crown Chlorophyll Content and sample sites in Yucheng, Shandong Province

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).

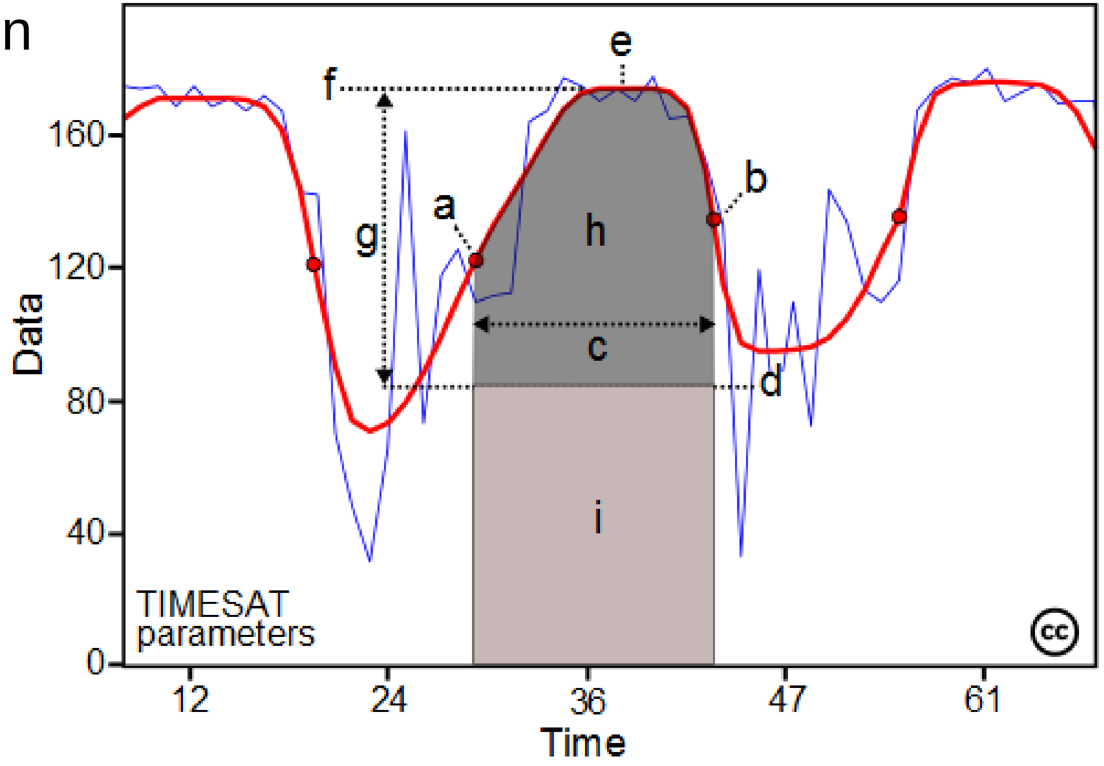


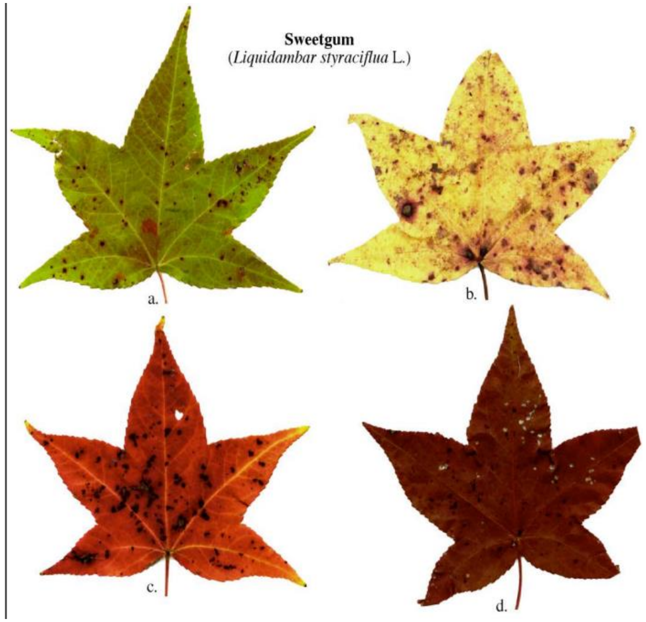
Data from the Copernicus Sentinel-2 mission can be used to measure the 'leaf area index' of vegetation (left). This information can, in turn, be used to monitor crop growth and agricultural practices like harvesting. The animation shows the development of crop fields in Belgium between March and October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

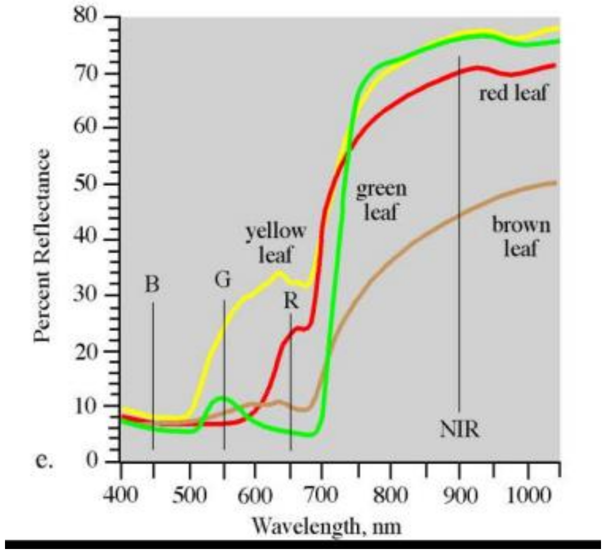
From EO signal to agriculture information content

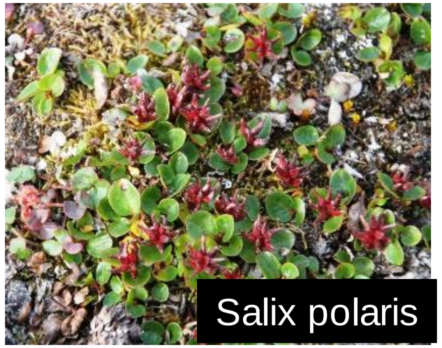
Temporal development of vegetation

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

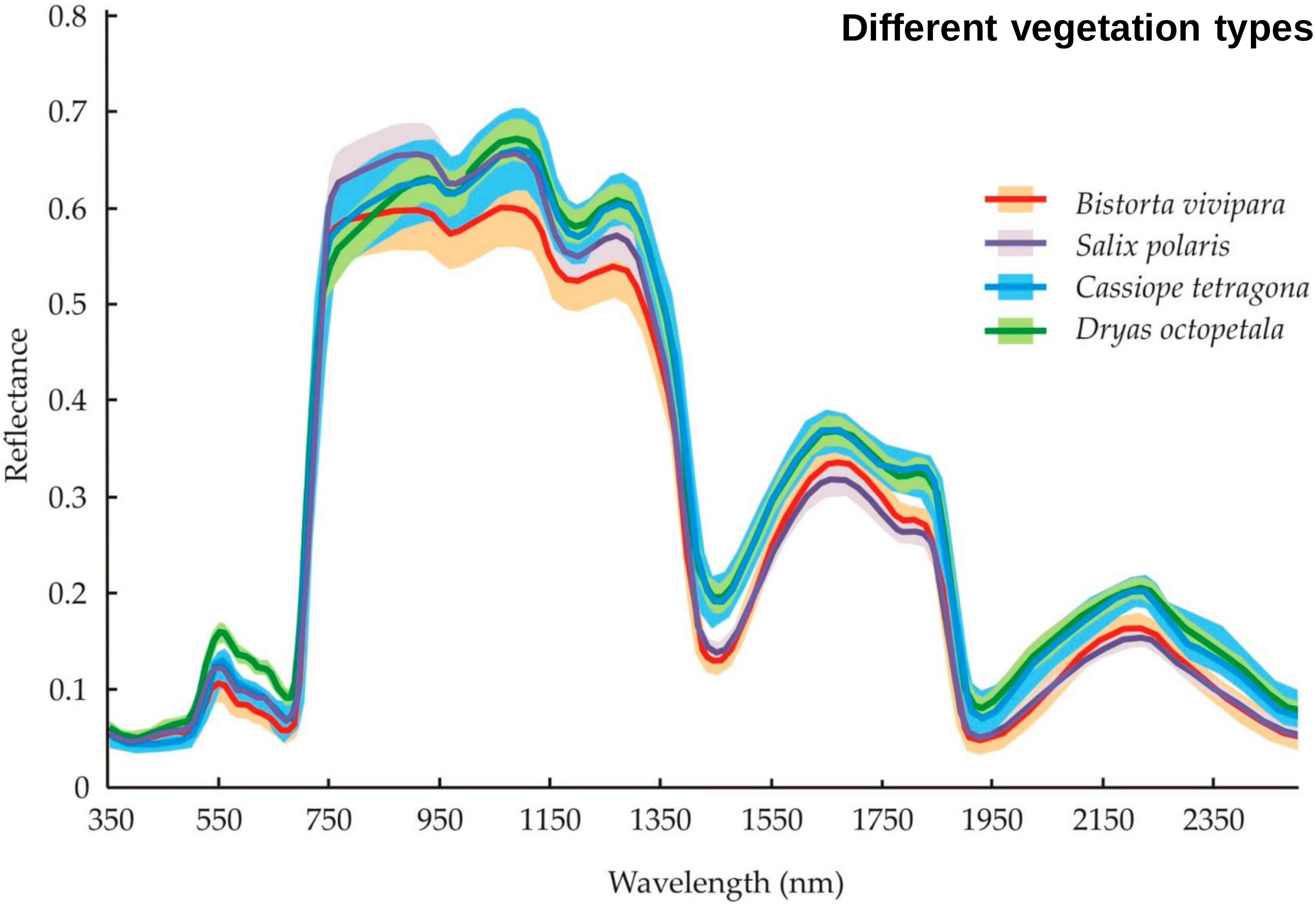




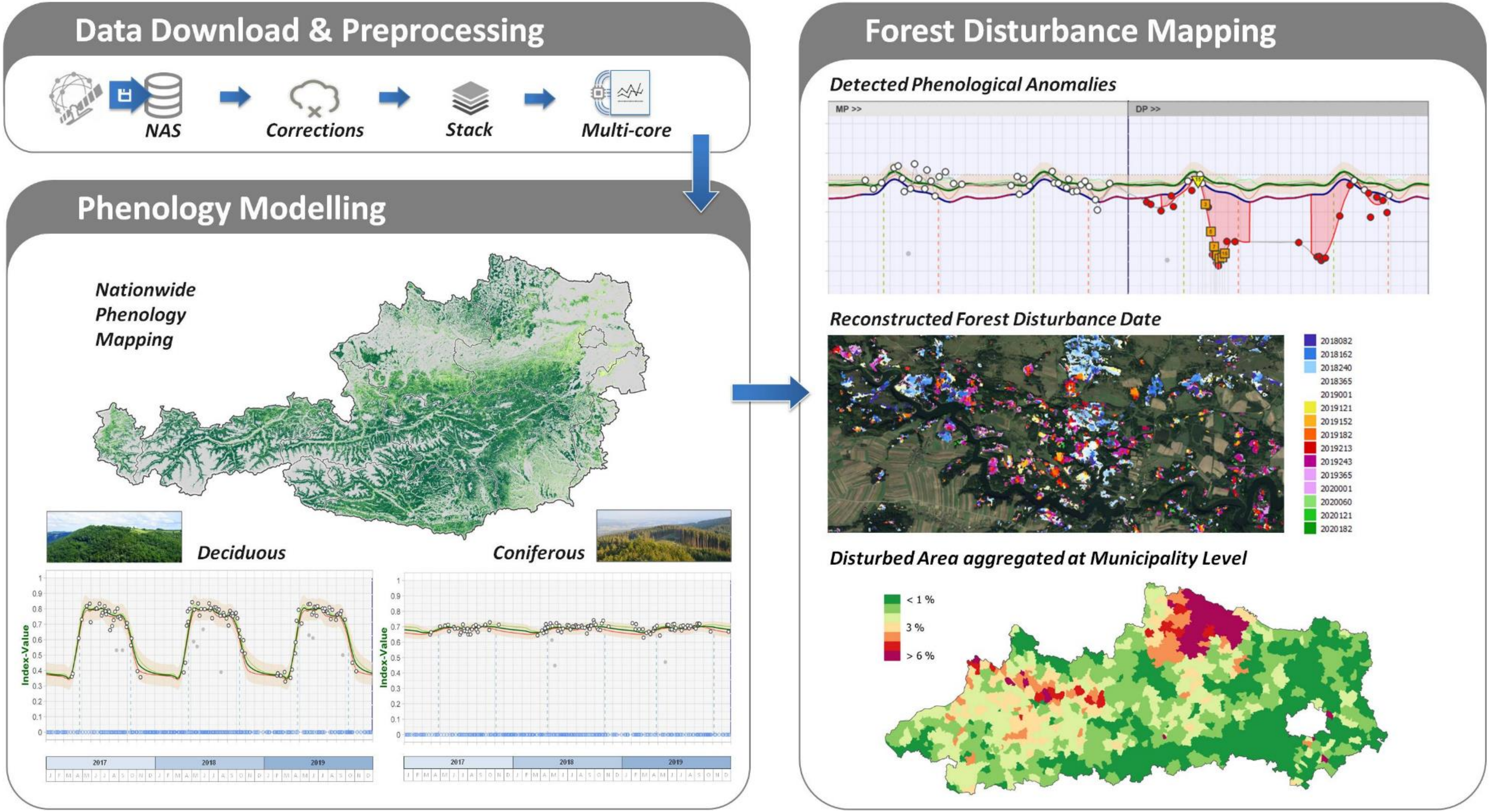




Different vegetation types



Phenology and disturbances

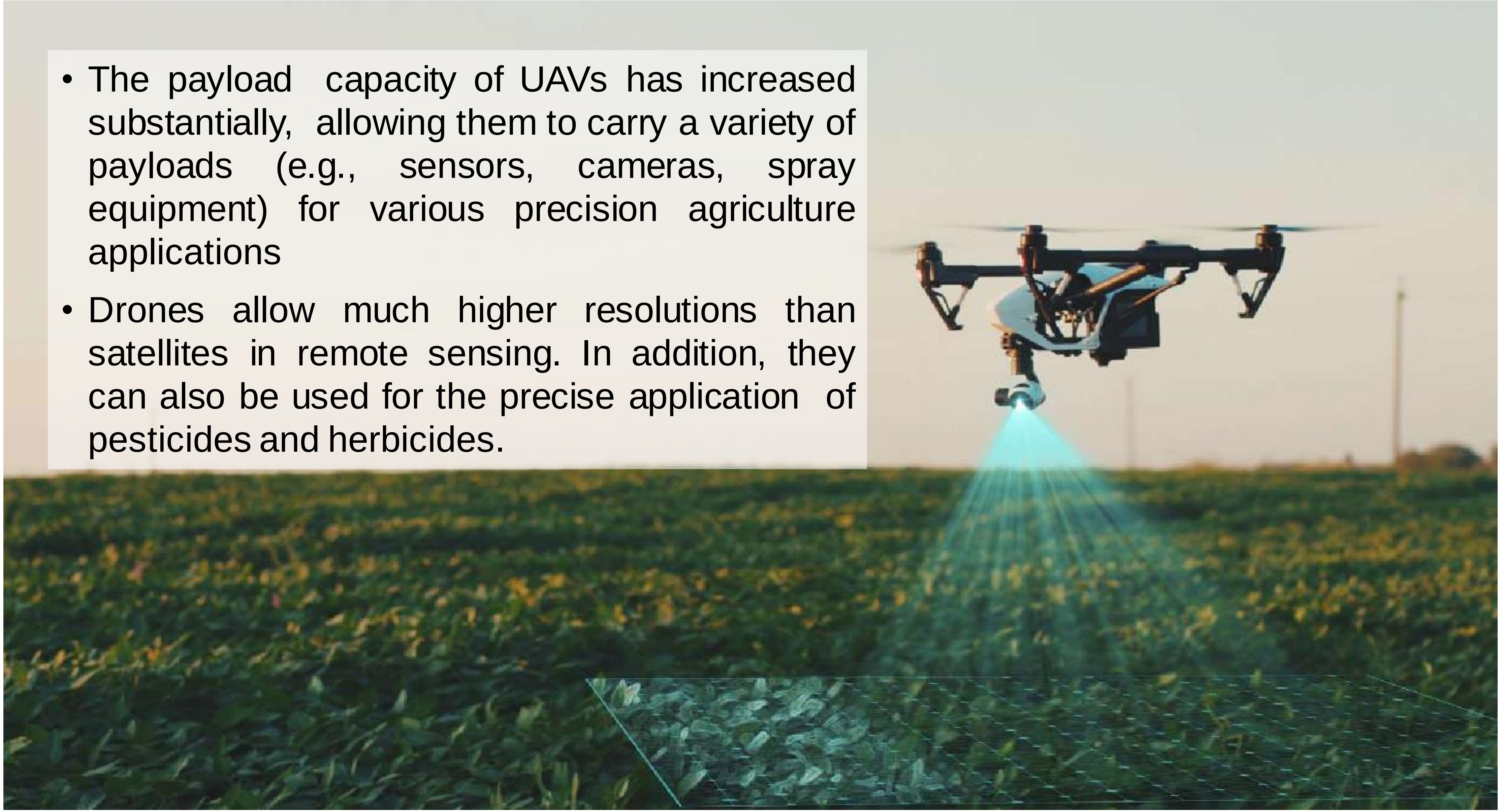


Sentinel-based markers for CAP Monitoring

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

Other 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]

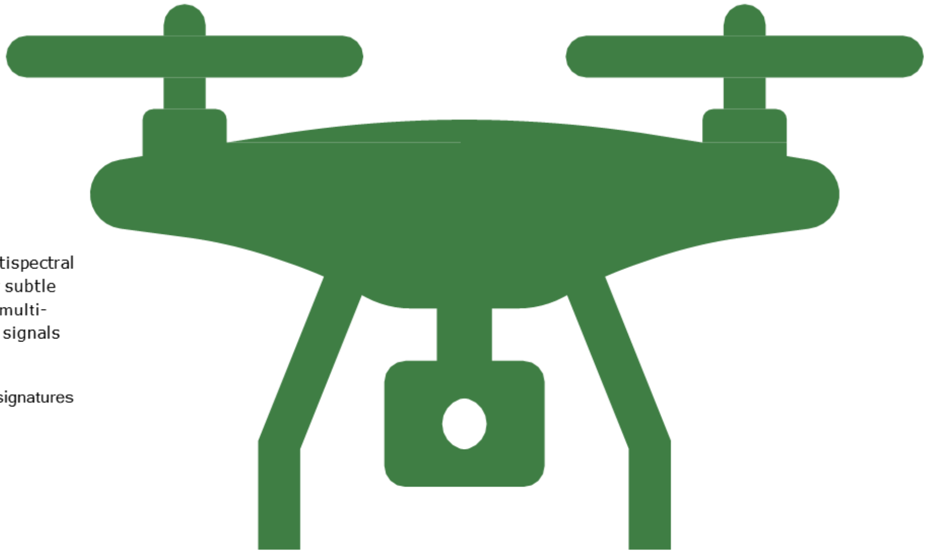
- Monitoring and mapping crop diseases and weeds
- Estimating the vegetation state
- Detecting nutrient deficiency
- Mapping vegetation height

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

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

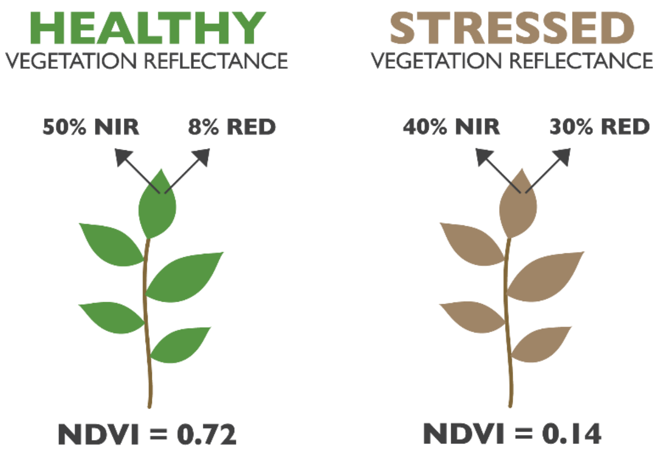
For more information, see the tutorial:
6. Precision agriculture mapping – digital image analyses using Sentinel-2 multispectral data, image classification, comparison with UAV multispectral data, using SNAP software

7. Spatio-temporal mapping of deforestation using multispectral data

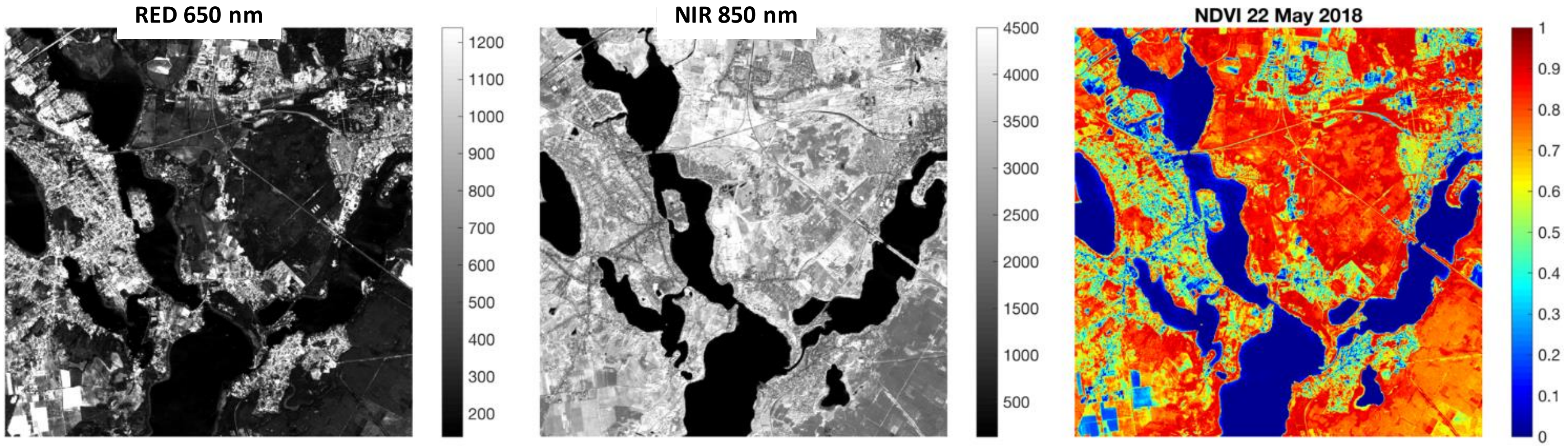
From EO signal to forest information content

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



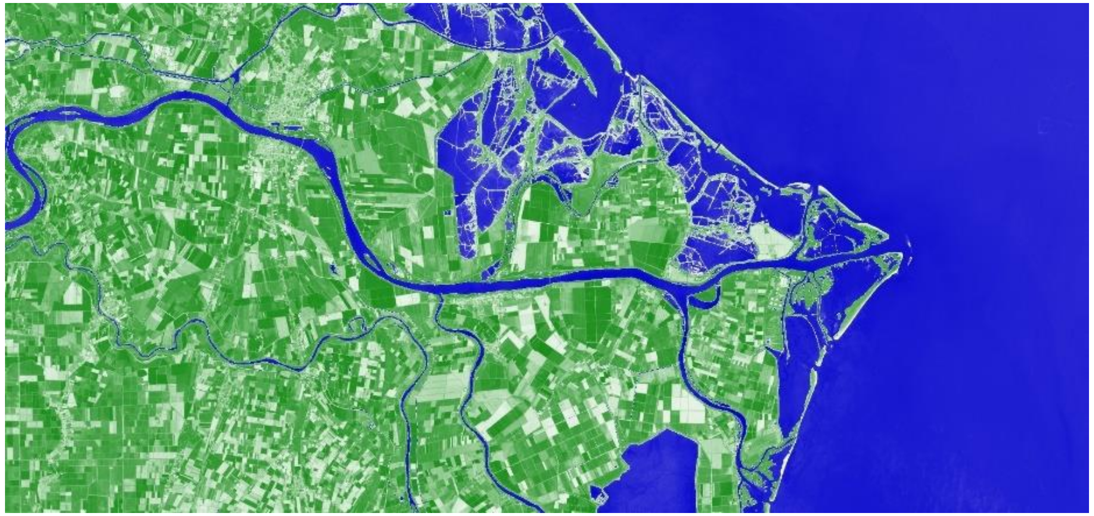
$$NDVI = \frac{NIR - RED}{NIR + RED}$$



From EO signal to forest 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

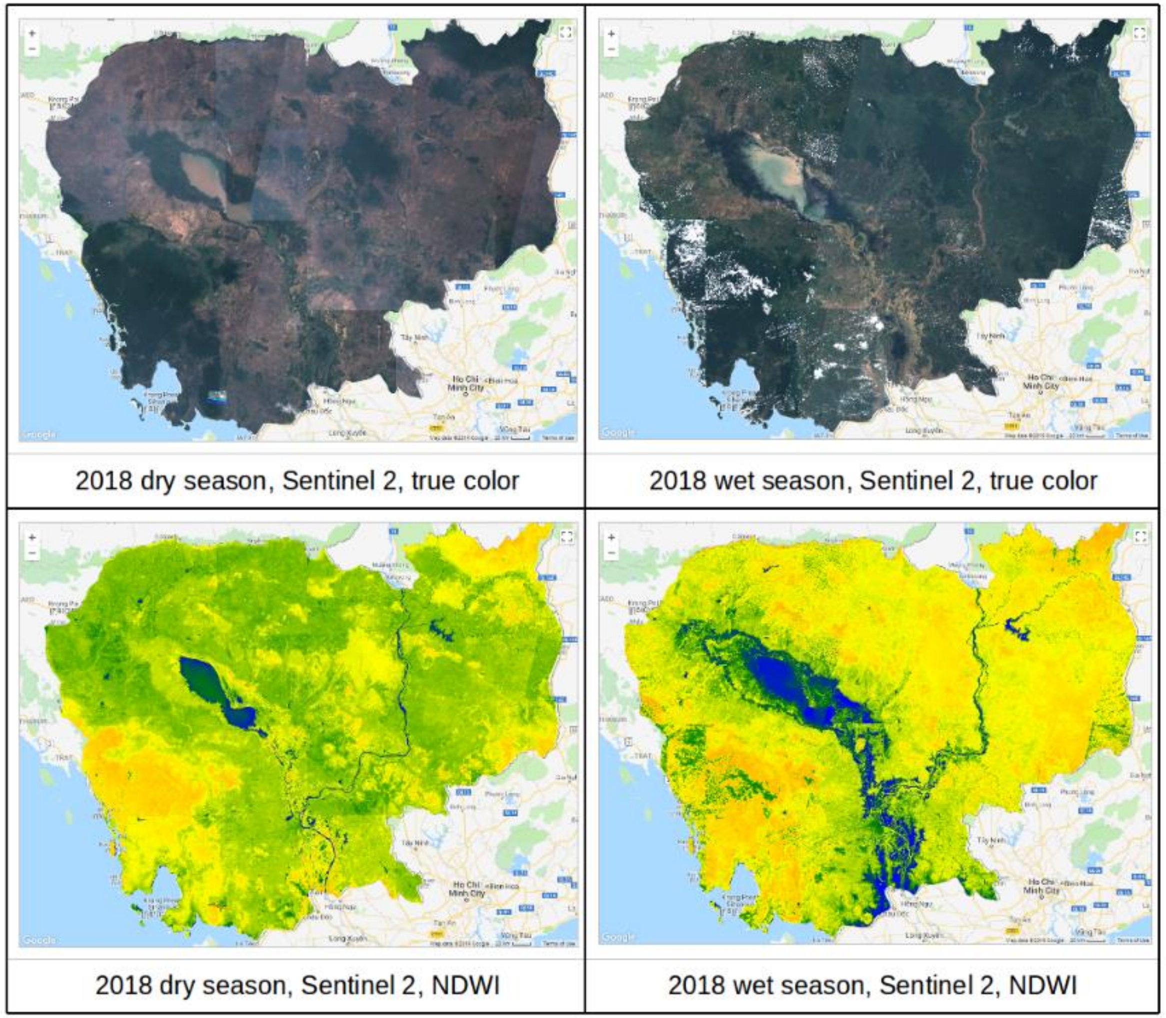


NDWI of Italy. Acquired on 2020-08-01.

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

From EO signal to forest information content

NORMALIZED DIFFERENCE WATER INDEX (NDWI)



2018 dry season, Sentinel 2, true color

2018 wet season, Sentinel 2, true color

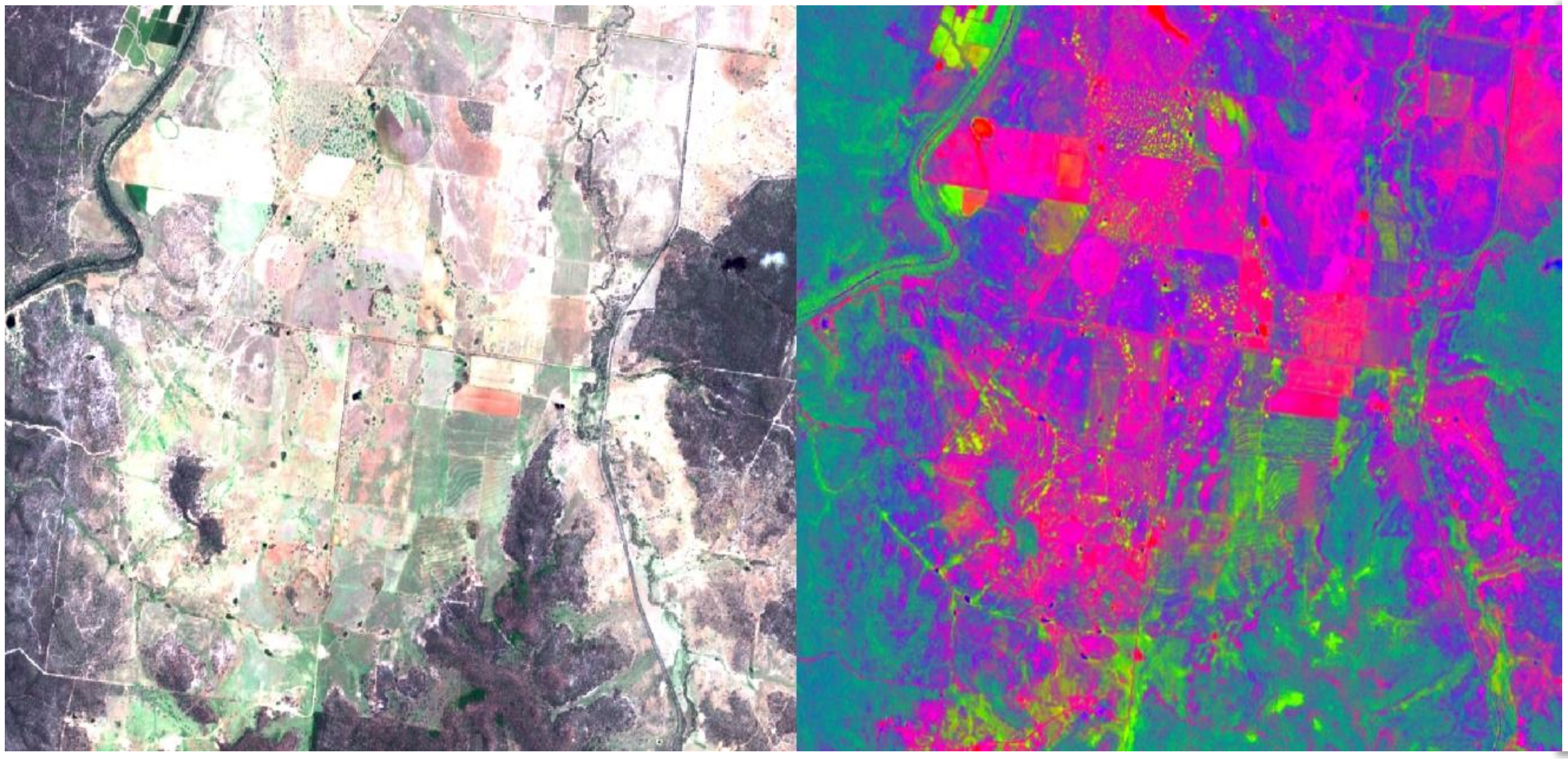
2018 dry season, Sentinel 2, NDWI

2018 wet season, Sentinel 2, NDWI

From EO signal to forest 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 forest 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

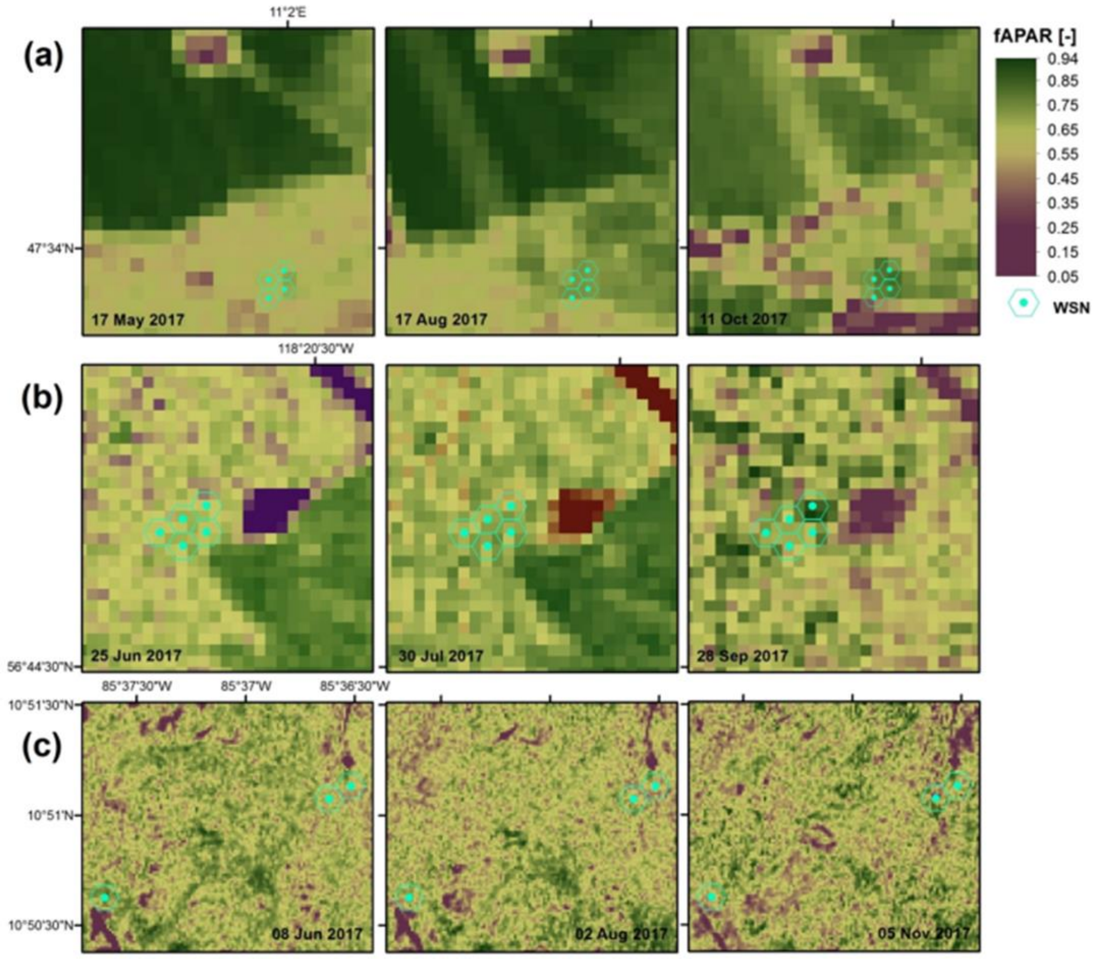


Fig. 7. The S2 fAPAR products at (a) Graswang, (b) Peace River and (c) Santa Rosa for several dates, representing early, peak and end of vegetation periods.

From EO signal to forest 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

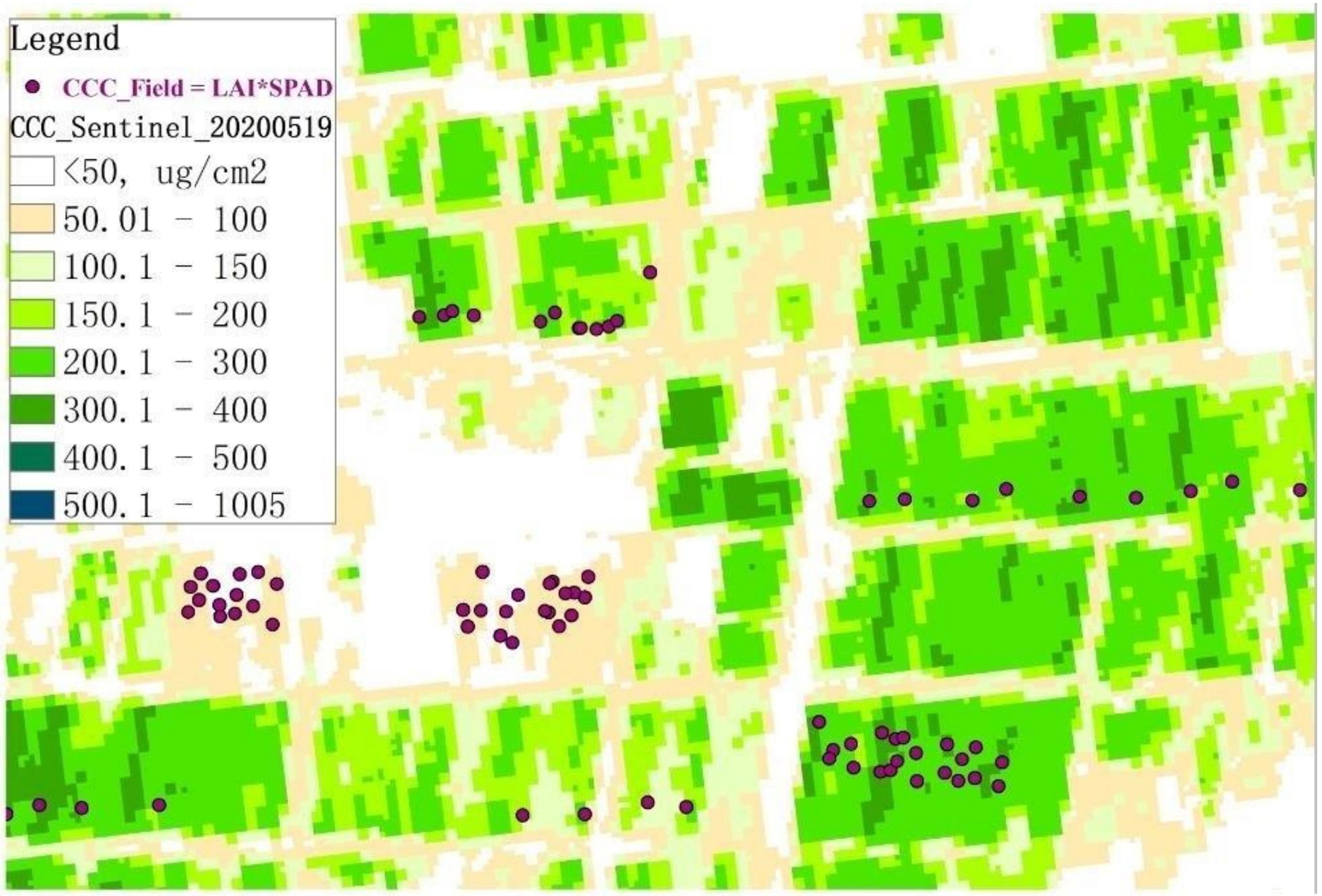
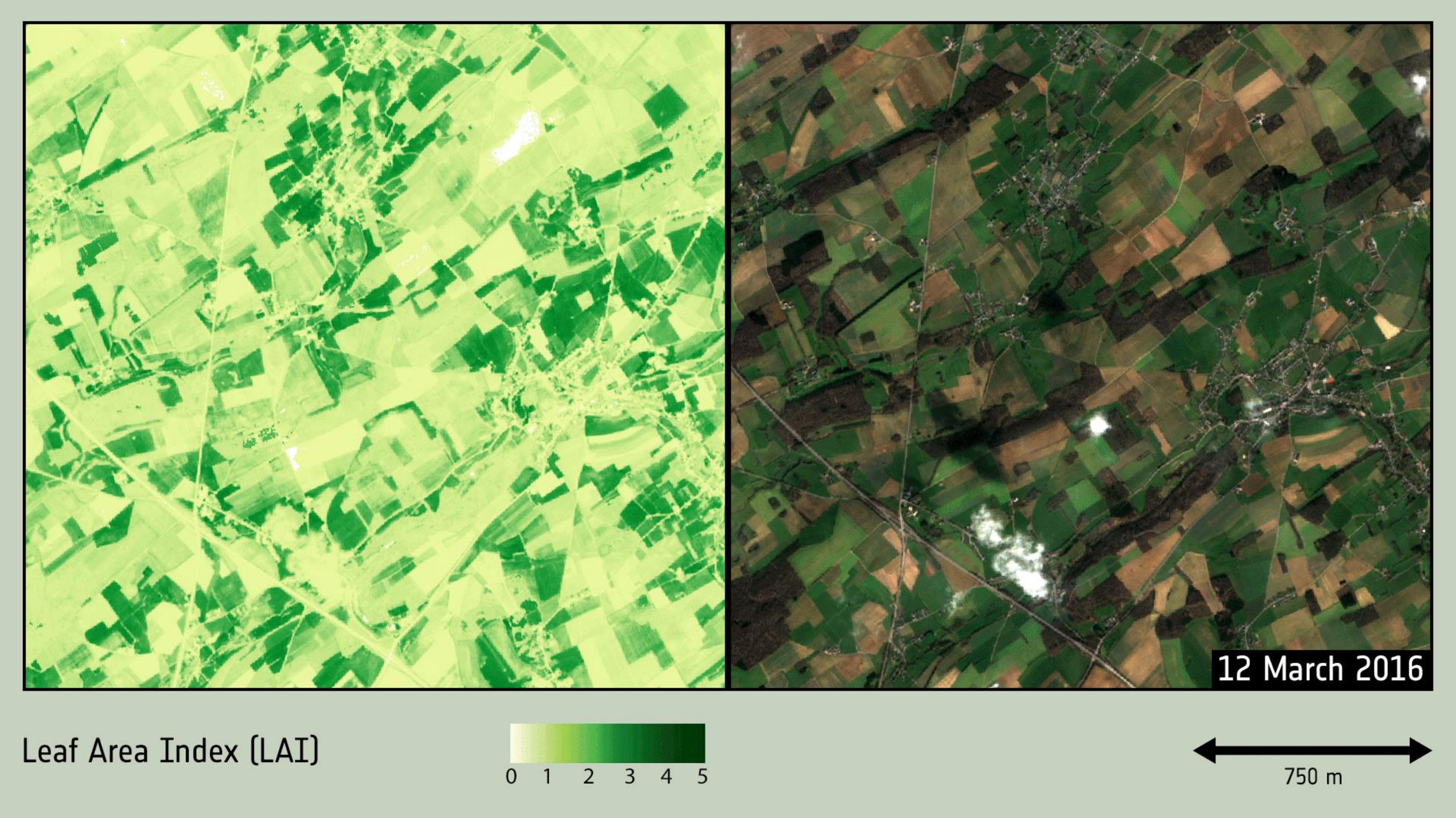


Figure 1 Winter wheat Crown Chlorophyll Content and sample sites in Yucheng, Shandong Province

From EO signal to forest information content

LEAF AREA INDEX (LAI)

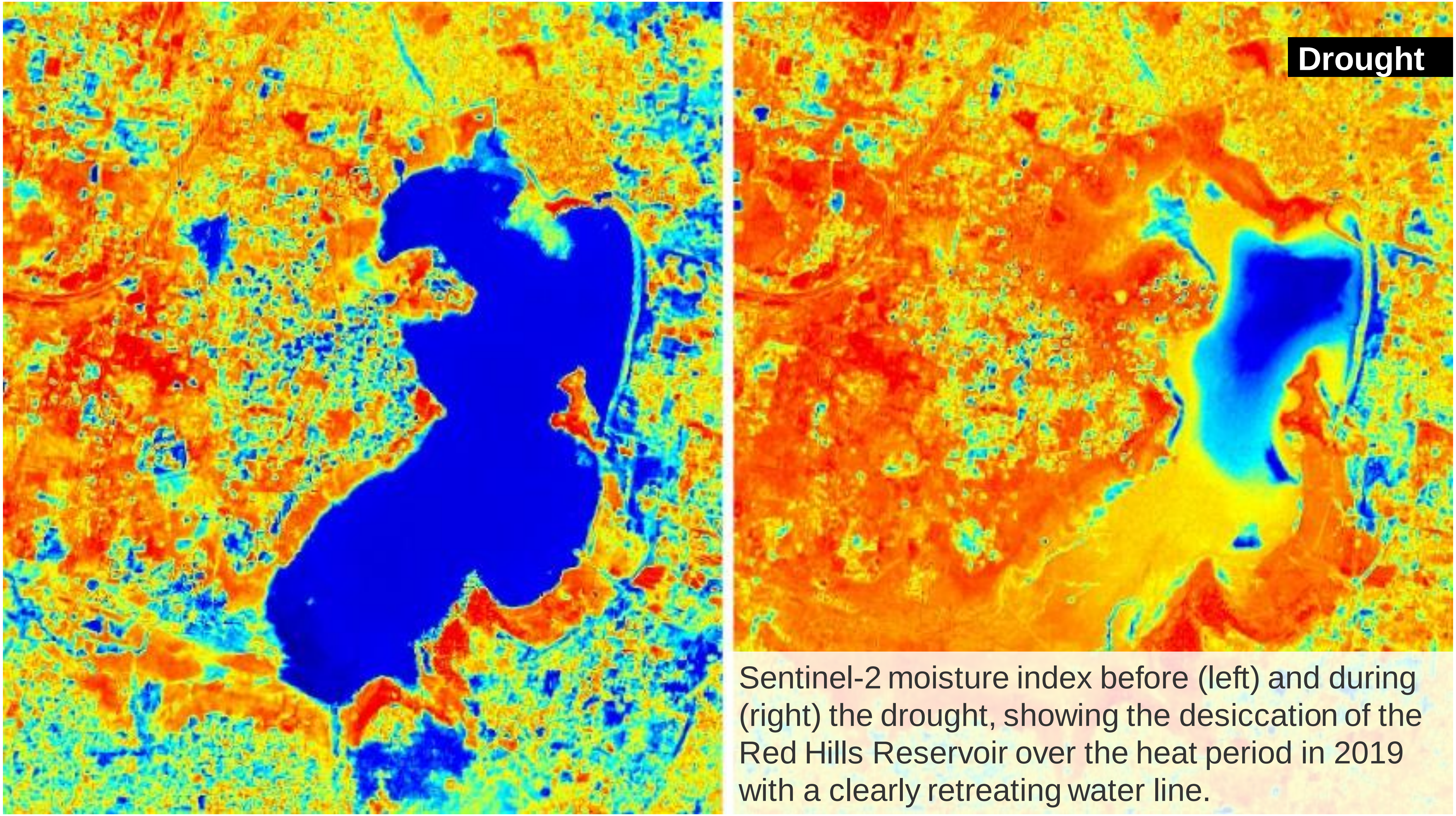
LAI is a dimensionless index measuring the one-sided green leaf area over a unit of land (m^2 / m^2).



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.

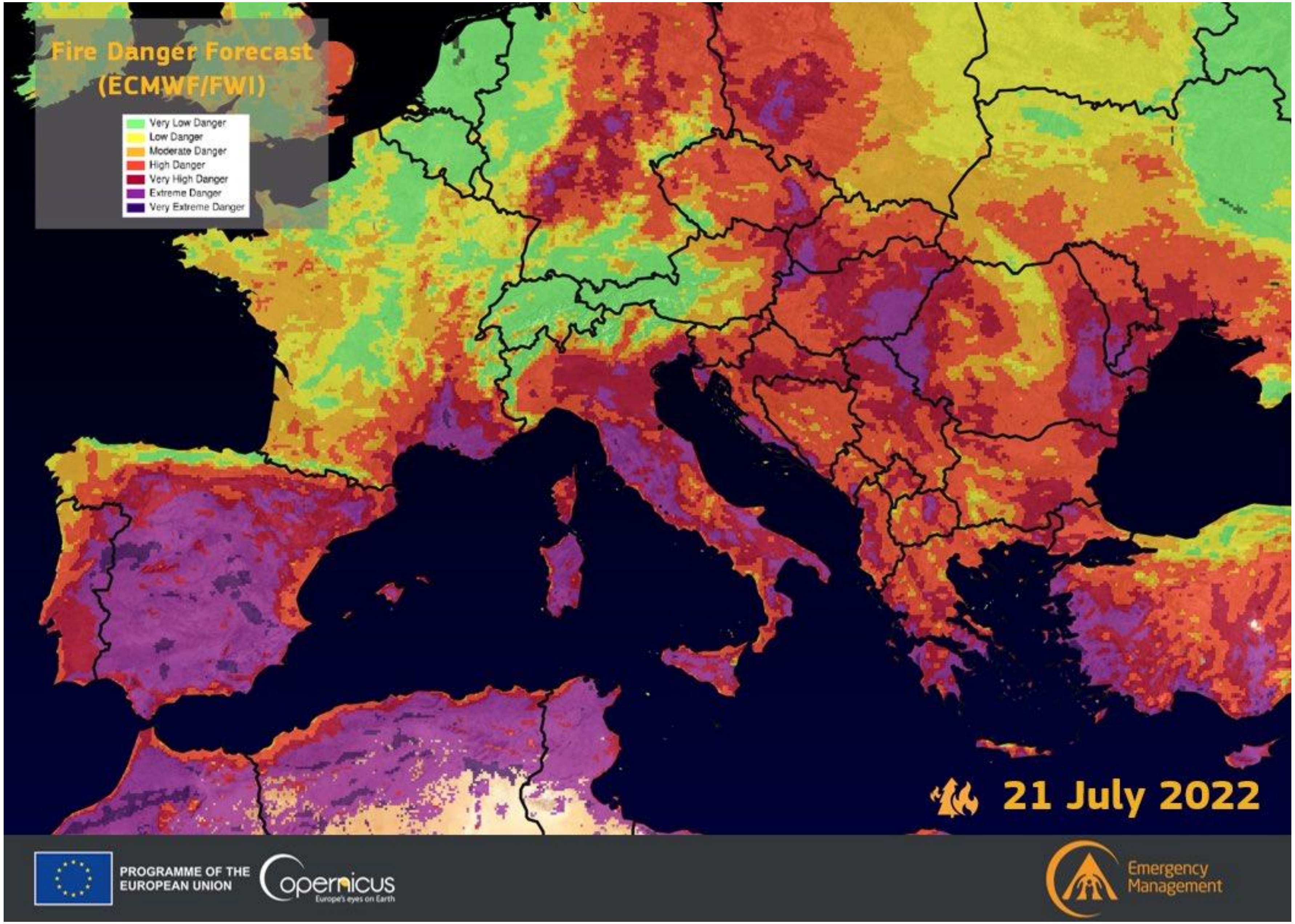
Deforestation

Deforestation

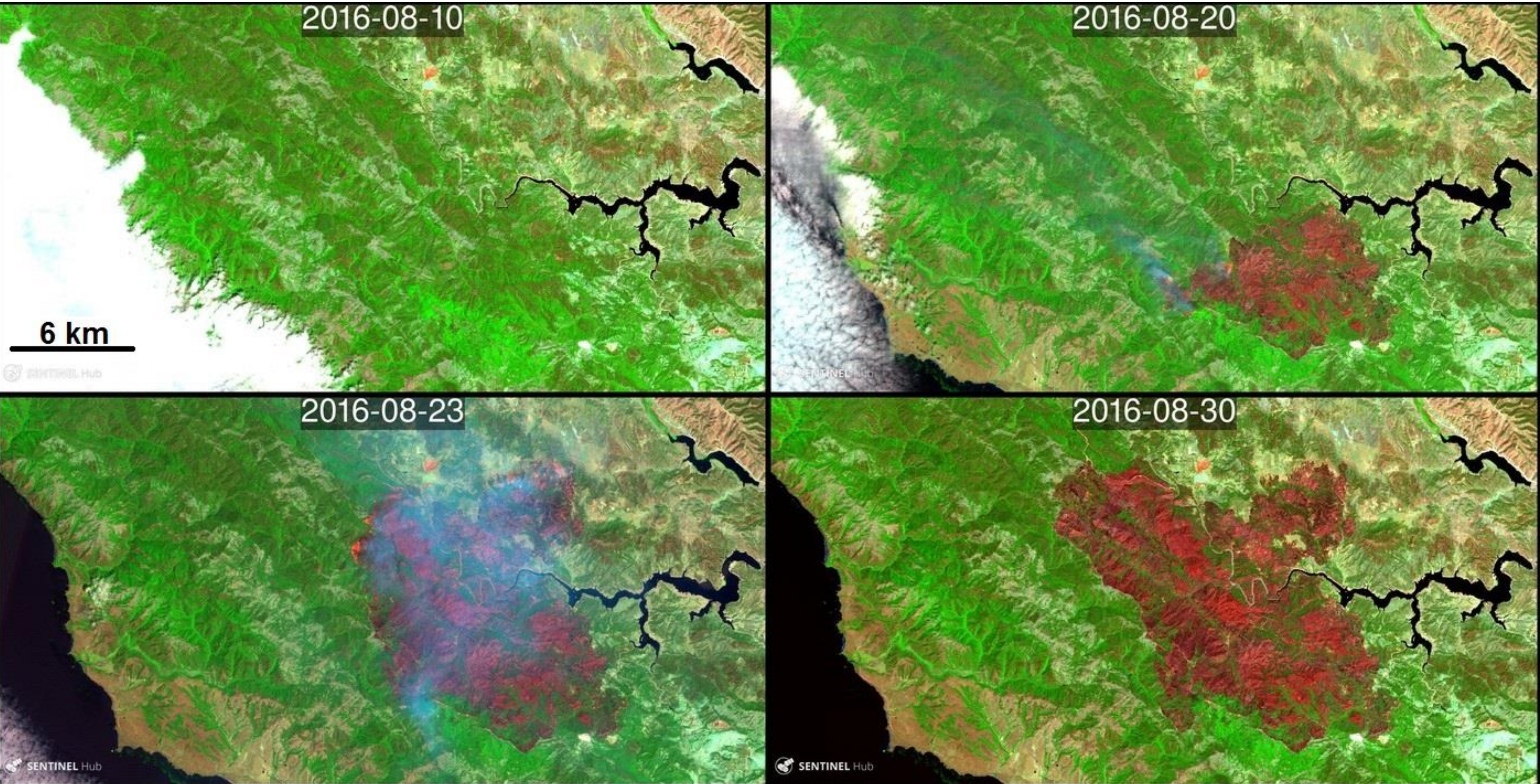


Sentinel-2 moisture index before (left) and during (right) the drought, showing the desiccation of the Red Hills Reservoir over the heat period in 2019 with a clearly retreating water line.

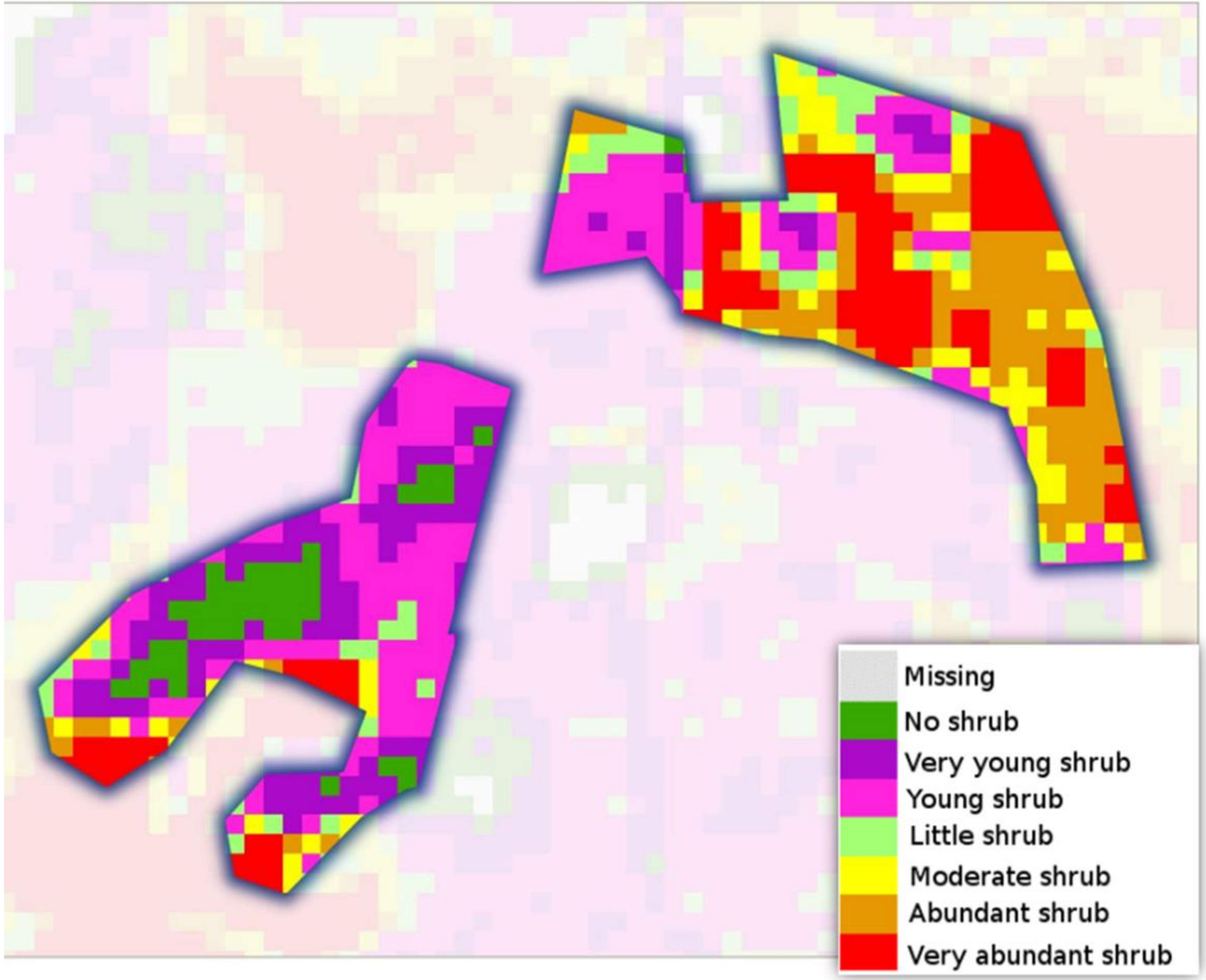
Emergency Management Service: Wildfires



Emergency Management Service: Wildfires



Information for Forest Management



Mapping of harmful broadleaved shrubs in forest regeneration areas based on Sentinel-2 data

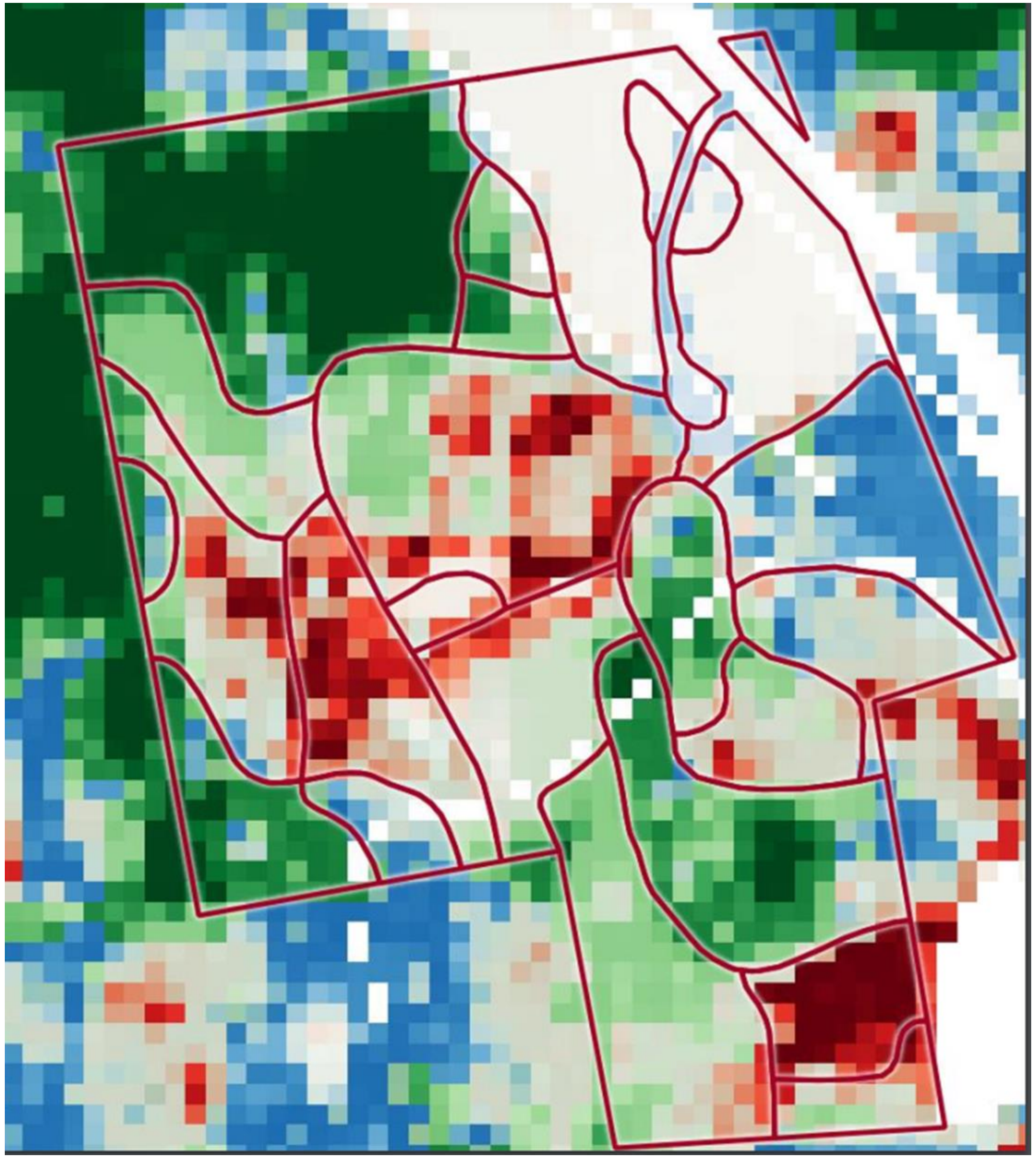
Information for Forest Management

- Stem volume per species

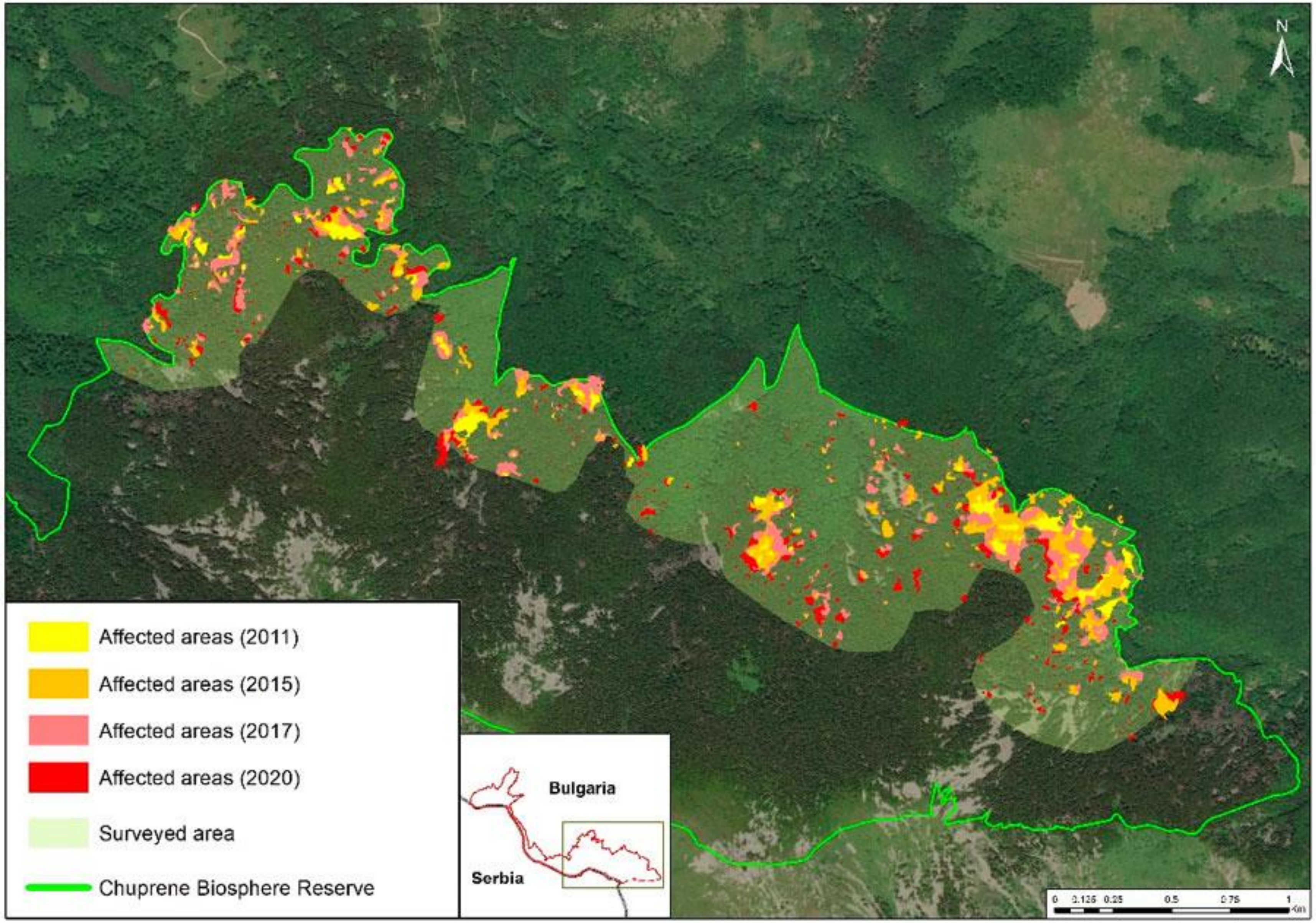
Red = Broadleaved

Blue = Pine

Green = Spruce



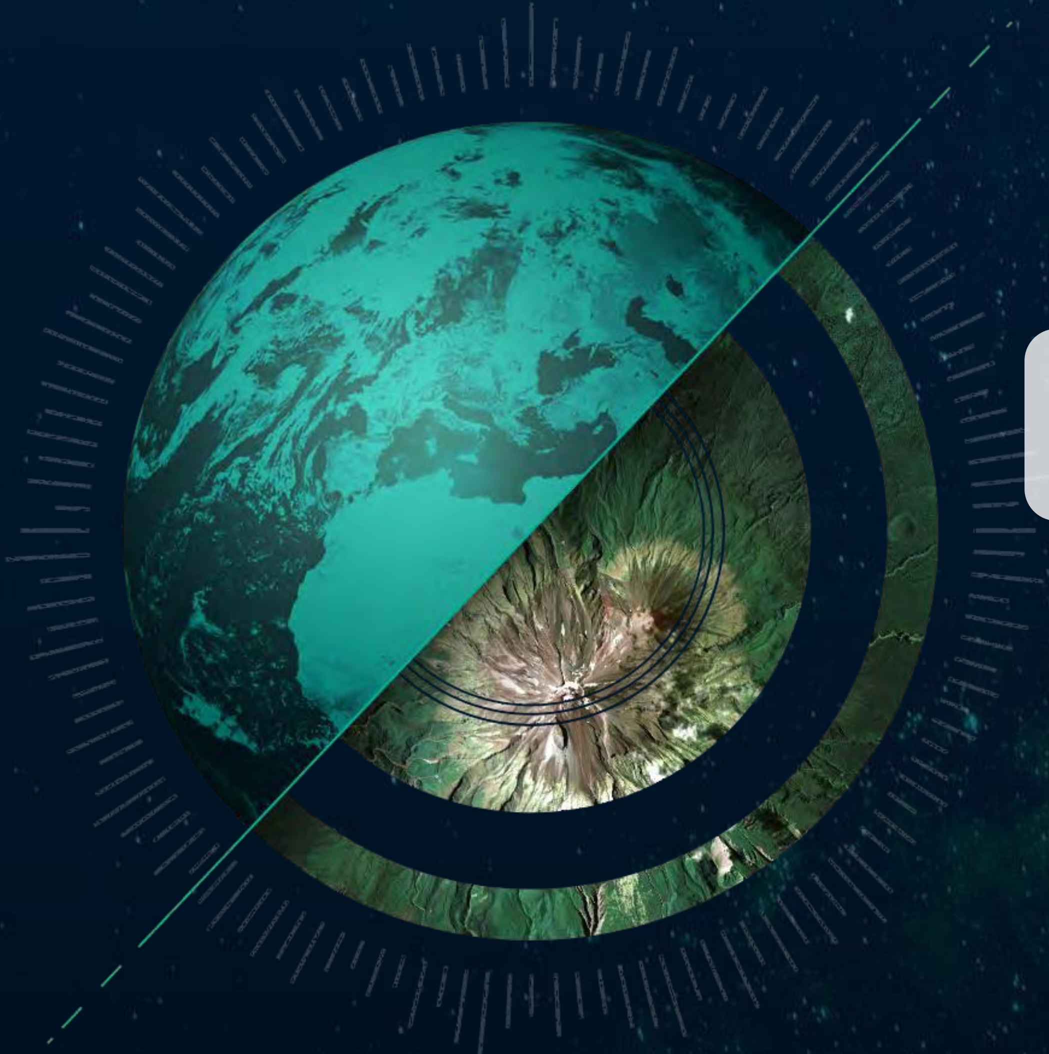
Detecting bark beetle damage



Bark beetle spots identified in the north-eastern area of the Chuprene Reserve.

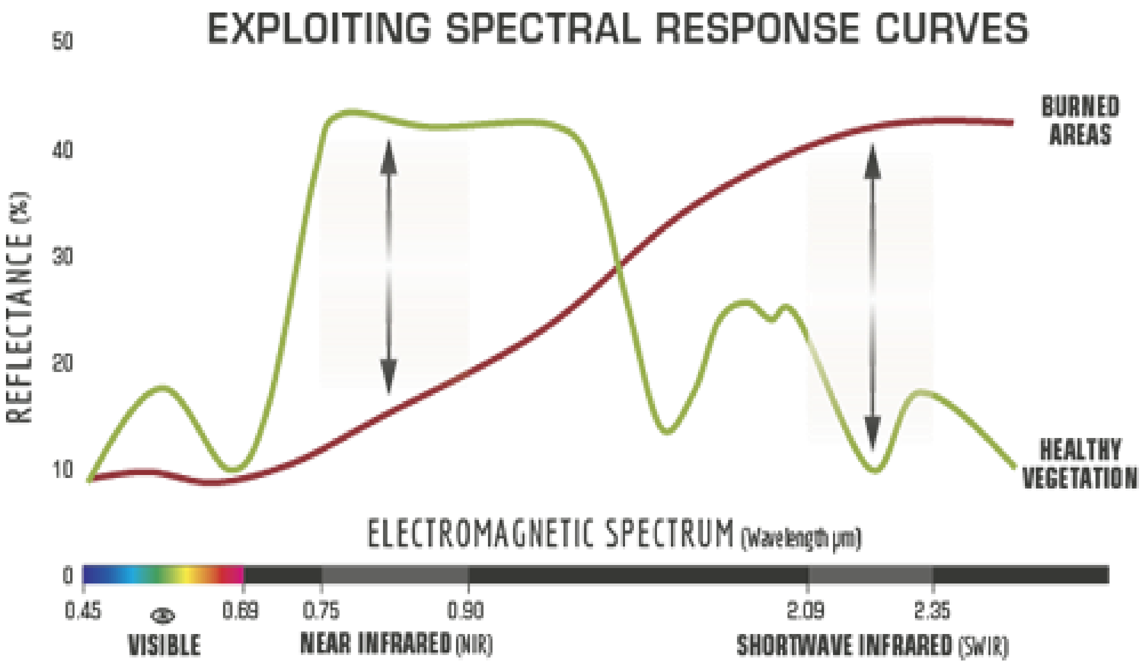
Analysis determined from 2011 and 2015 airborne images; 2017 UAV images and 2020 satellite images

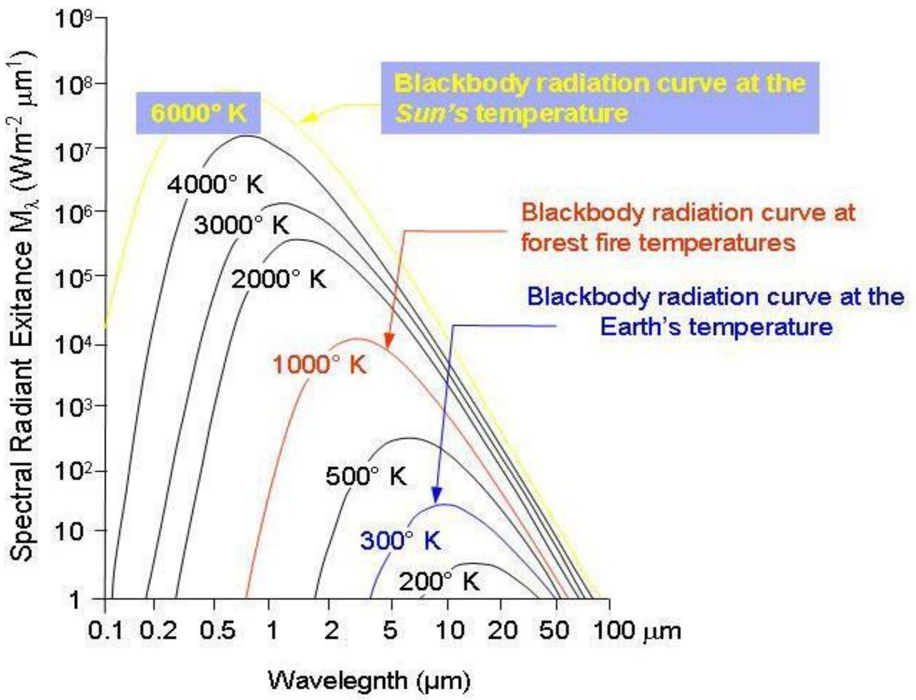
For more information, see the tutorial:
7. Spatio-temporal mapping of deforestation using Sentinel-2 data, comparison with high-resolution orthophoto imagery, using SNAP software



8. Mapping wildfires and burn severity using multispectral data

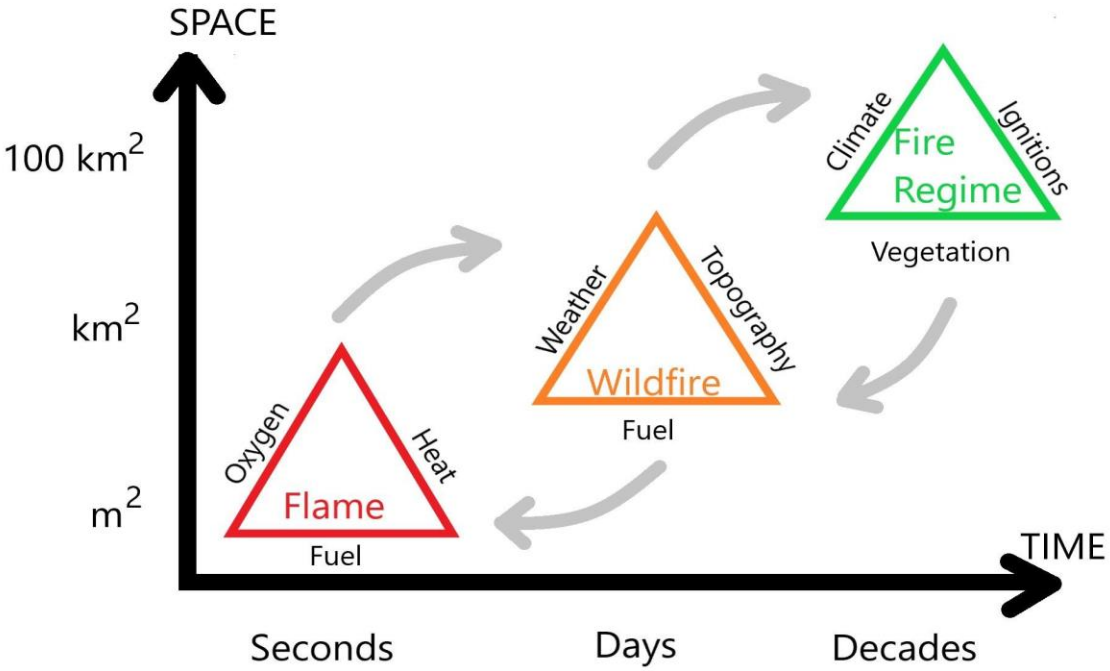
Introduction on the radiometry of forest fires





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.

Remote sensing observations and forest fires



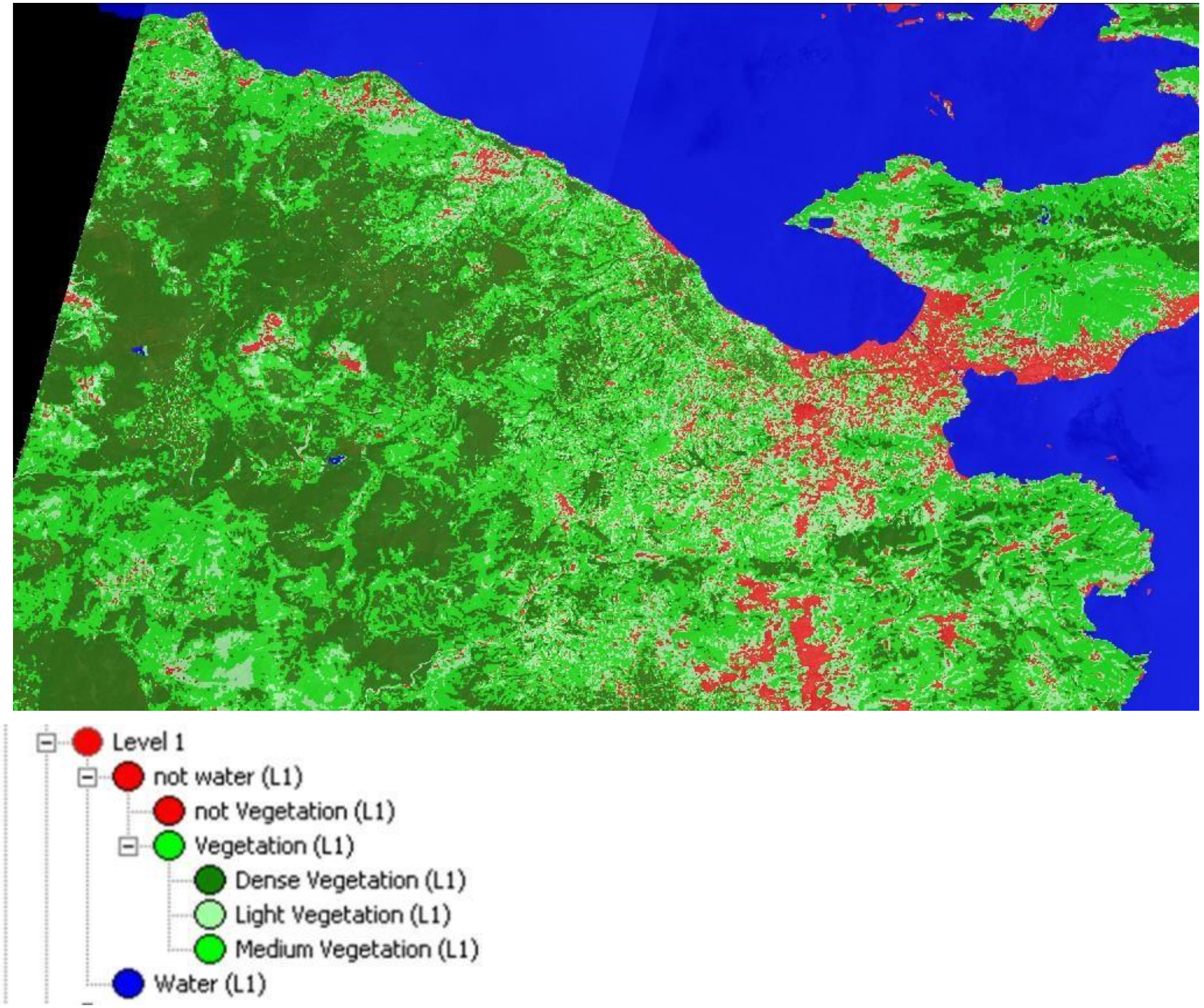
Pre-Fire Risk Assessment	Vegetation density and extent Soil moisture/drought severity Topography Fire risk mapping
Active Fire Detection	Hot Spot Detection Total area burning Fire Radiative Power and Thermal Infrared Pyro cloud formation
Post Fire Assessment	Total area burned Burn severity Post fire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

Remote sensing observations and forest fires stages

The pre-fire stage

Vegetation density

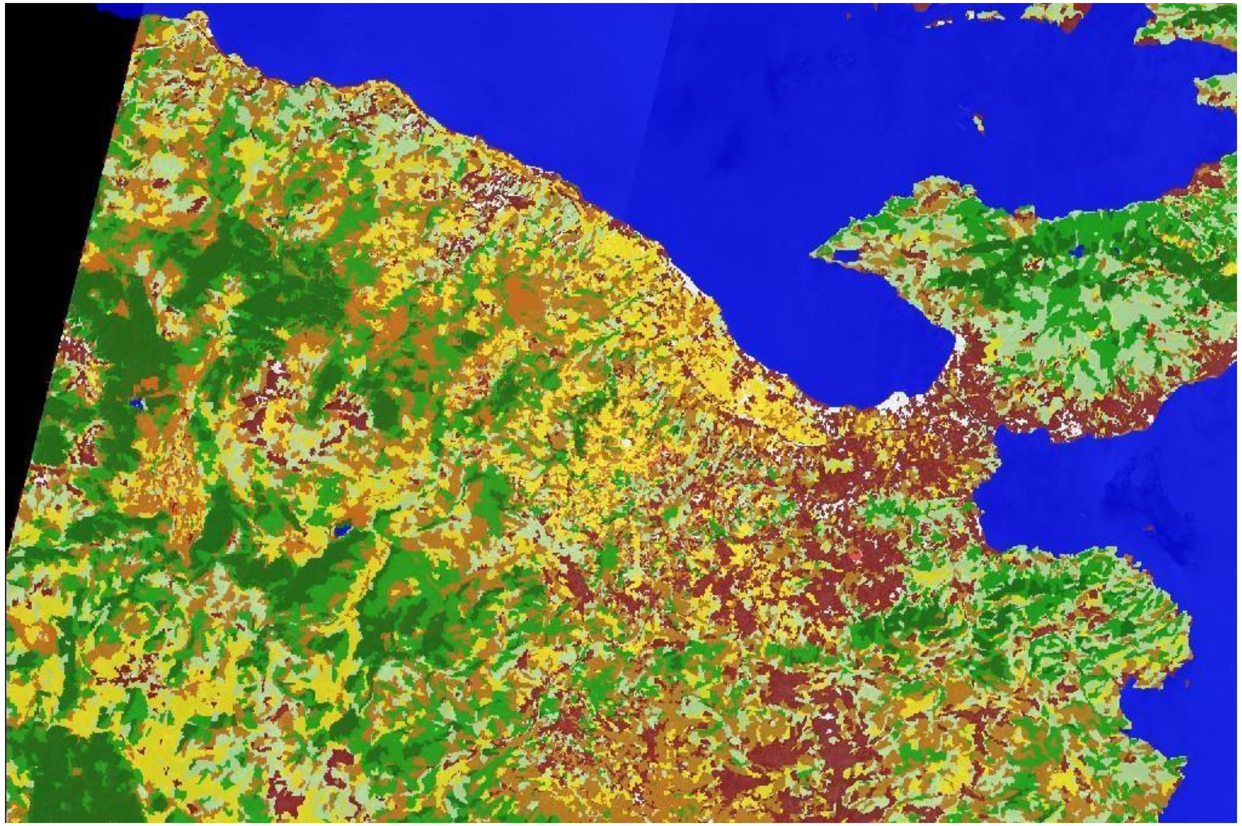
- Fire risk as varies with vegetation density VD. VD also influences fire dispersion.
- Classification of a forest in terms of VD depends strongly on spatial resolution



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

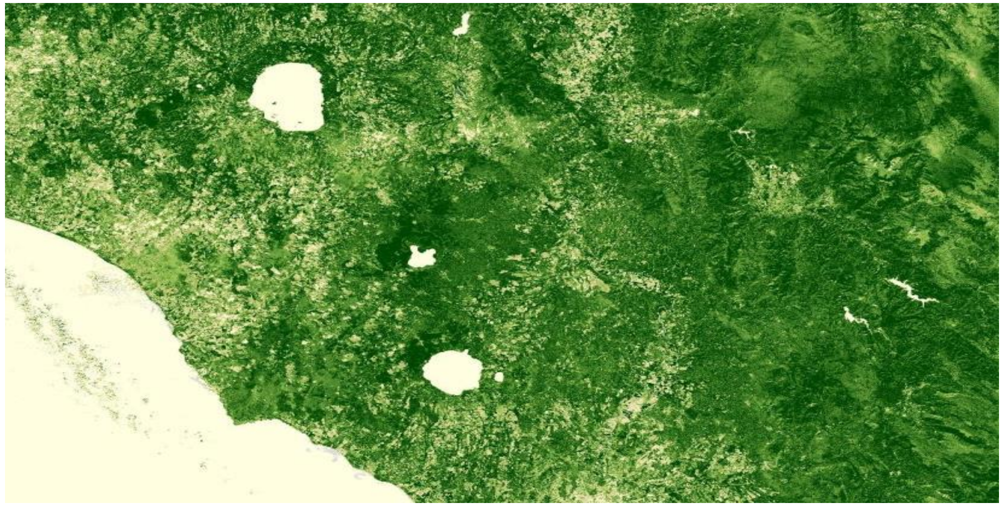
The pre-fire stage

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

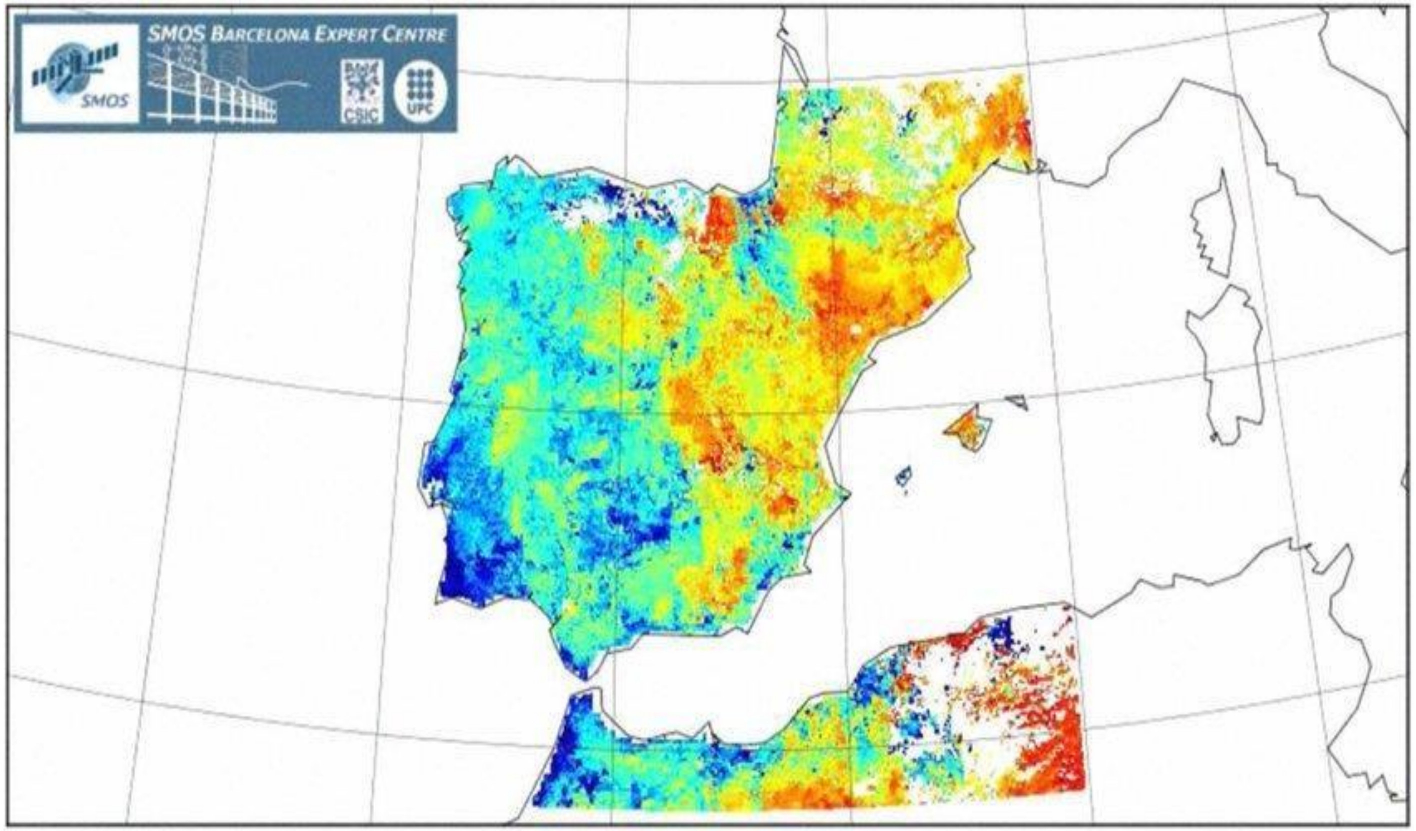
The pre-fire stage

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 such as ERS1&2/AMI and MetOp/ASCAT as well as by passive microwave radiometers such as Sentinel 1, Aqua/AMSR-E, Coriolis/WindSat...



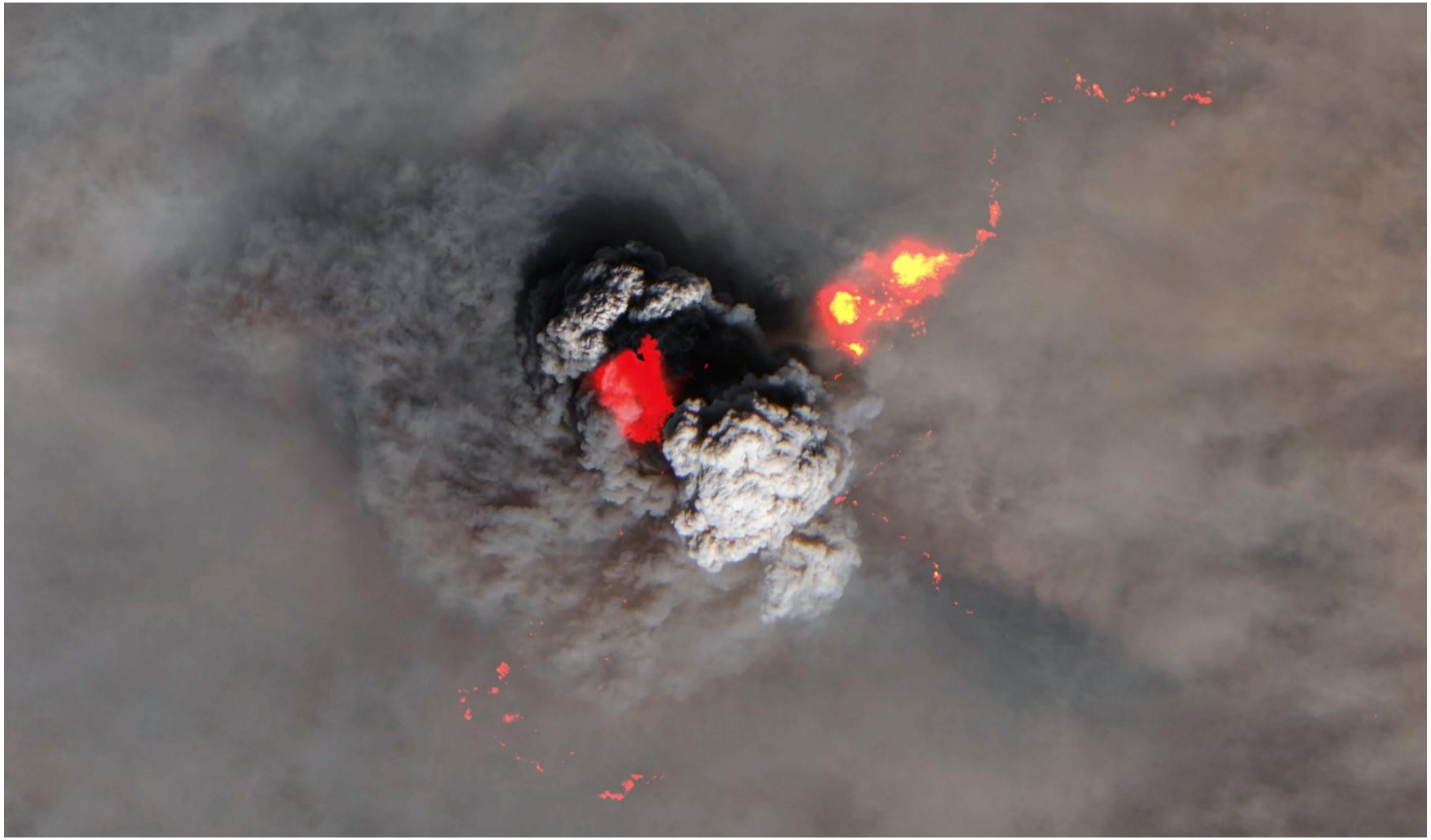
Example of high resolution (1 km) soil moisture maps of the Iberian peninsula generated from SMOS data (10 days average)

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

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

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.

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 Vegetation-Based Fire Applications (-day revisit, Resolution: 10 meters)

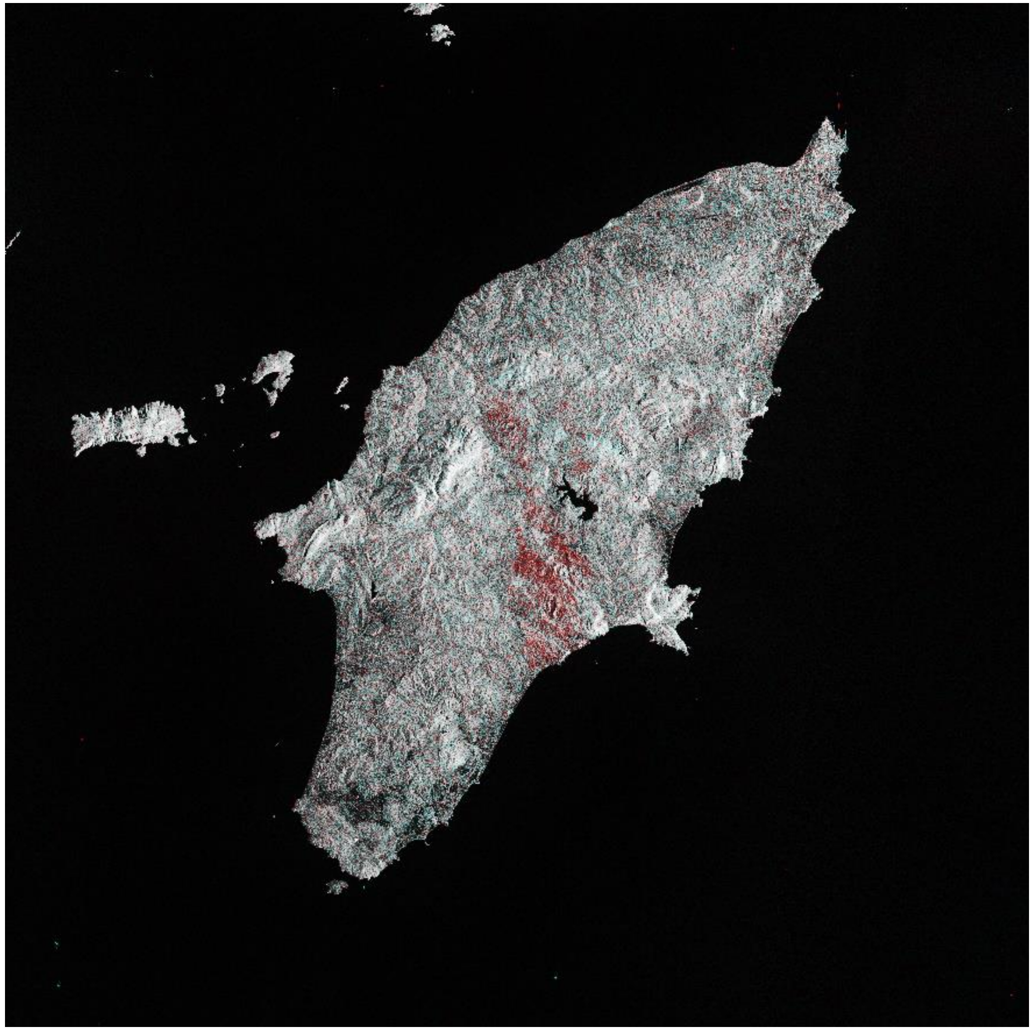
– Vegetation Extent and Type: Land cover classification

– 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

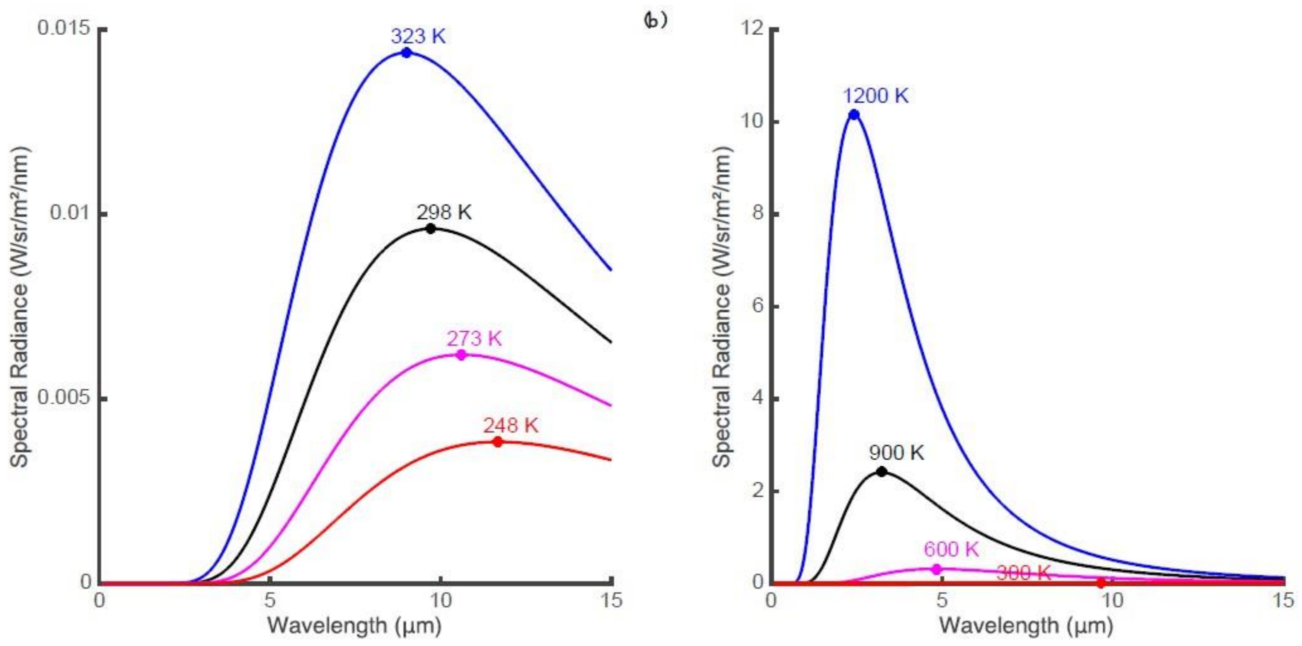
To provide reliable Fire Risk Mapping, spatial resolution needs to be high

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.

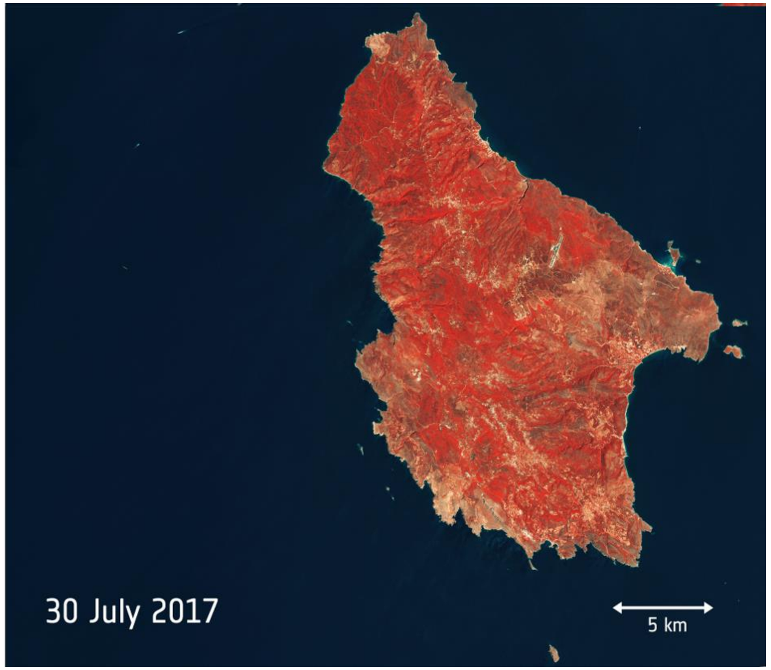


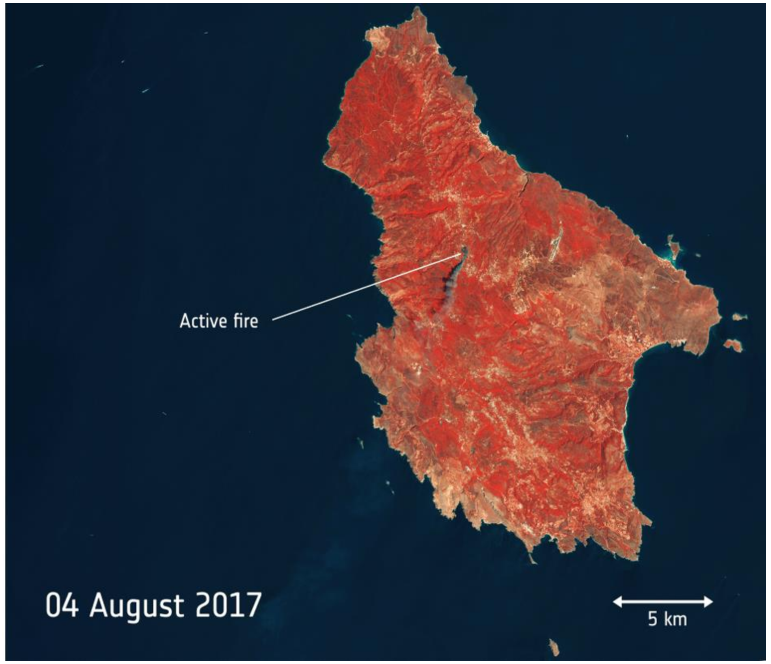
At normal ambient temperature, the peak is in the range 8–12 µm and most of the radiant energy lies at wavelengths greater than 5 µm (left image).

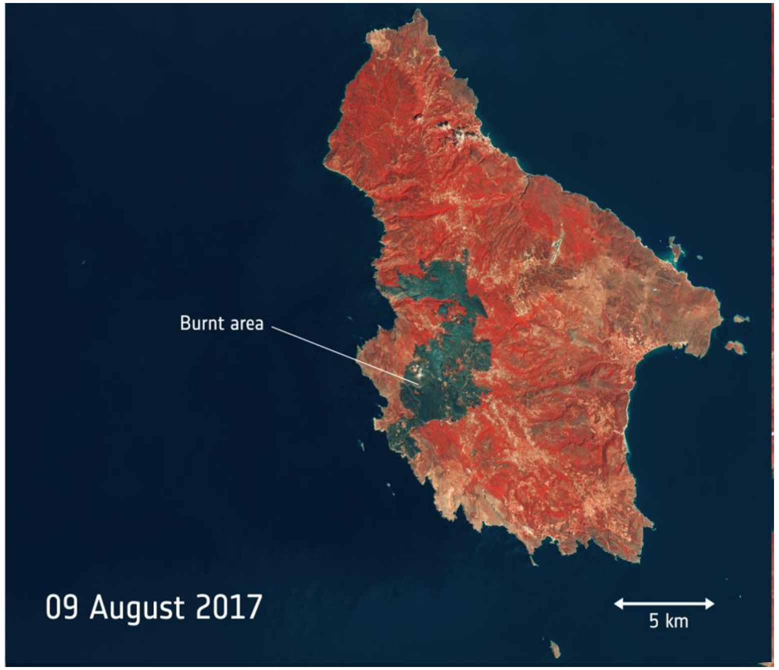
At higher temperatures typical of forest fires, the peak of the response shifts to mid-wave infrared (MWIR, 3–5 µm) or shorter wavelengths (right image).

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.**

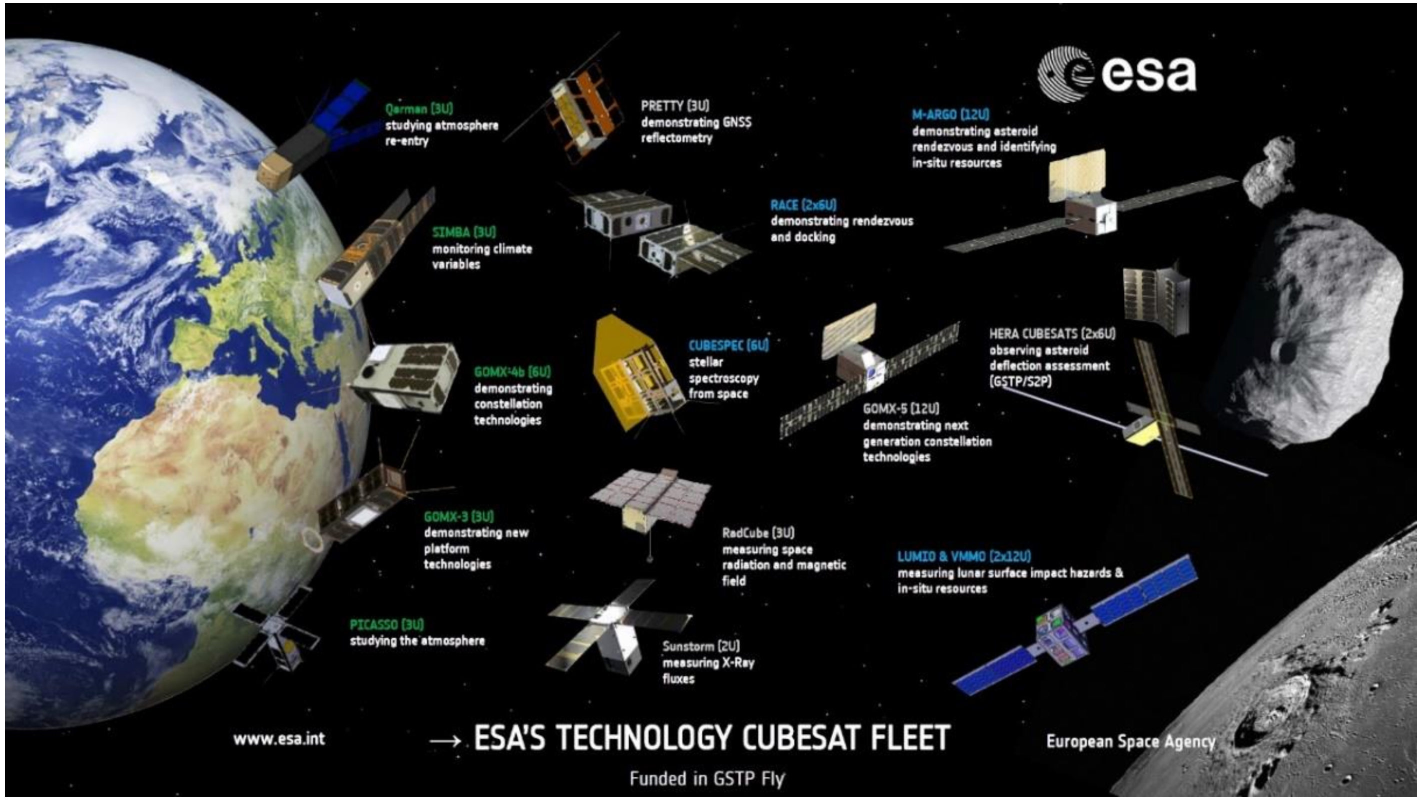
Sensor/Satellite	Channels	Product	Spatial/Temporal
SEVIRI/Meteosat	3.9µm, 10.8µm	FIR (Active Fire Monitoring)	3 km/5 min
MODIS/Aqua and Terra	4µm, 11µm	Active Fire	1km/ 1-2 days per satellite
SLSTR/SENTINEL 3	3.7µm, 10.8µm	Active Fire	1km/approx. 1 day
SENTINEL 1	Radar	Burned area	5m/2 days at mid-latitudes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

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

- 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.

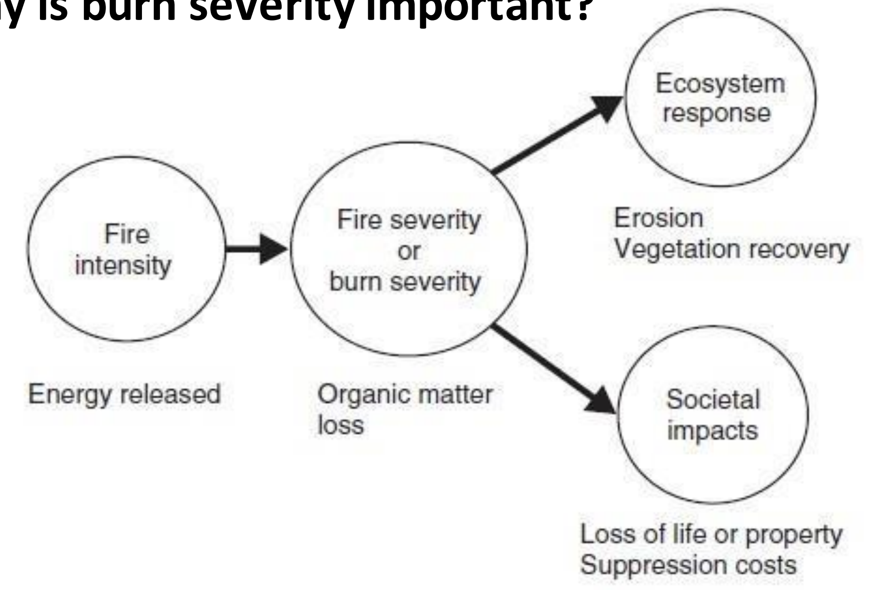
- Healthy vegetation has very high NIR reflectance and low reflectance in the SWIR portion of the spectrum
- Burned areas on the other hand have relatively low reflectance in the NIR and high reflectance in the SWIR band

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. **It is estimated as the difference between pre-fire and post-fire NBR derived from satellite images.**
- **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.

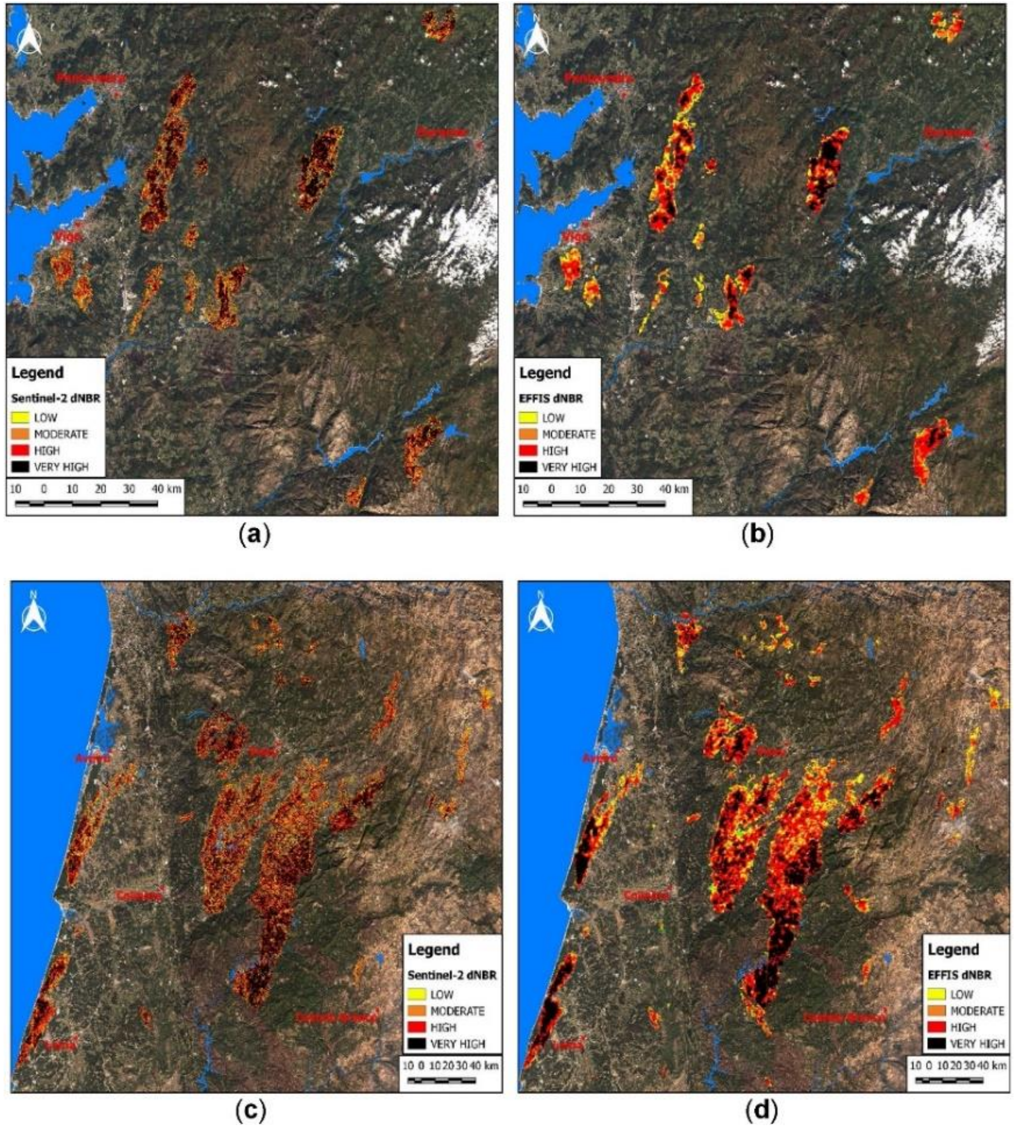
Why is burn severity important?



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).

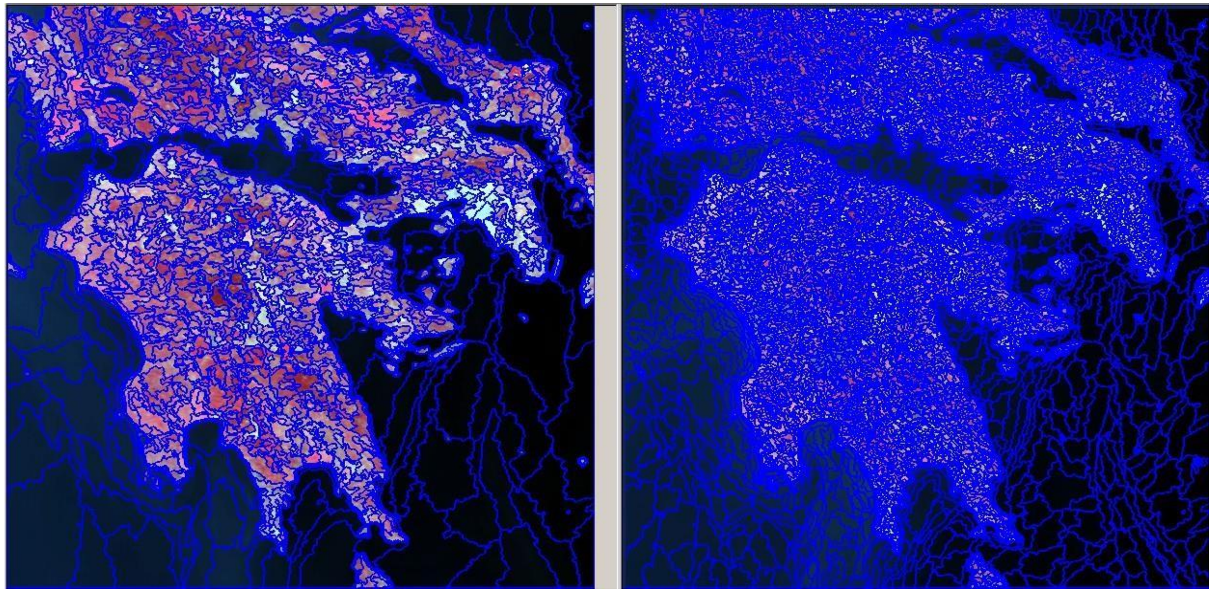
Source:
Rafael Llorensa, José Antonio Sobrino, Cristina Fernández, José M.Fernández- Alonso, José Antonio Vega, A methodology to estimate forest fires burned areas and burn severity degrees using Sentinel-2 data. Application to the October 2017 fires in the Iberian Peninsula, International Journal of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

Methodology and steps for estimating burned areas from forest fires

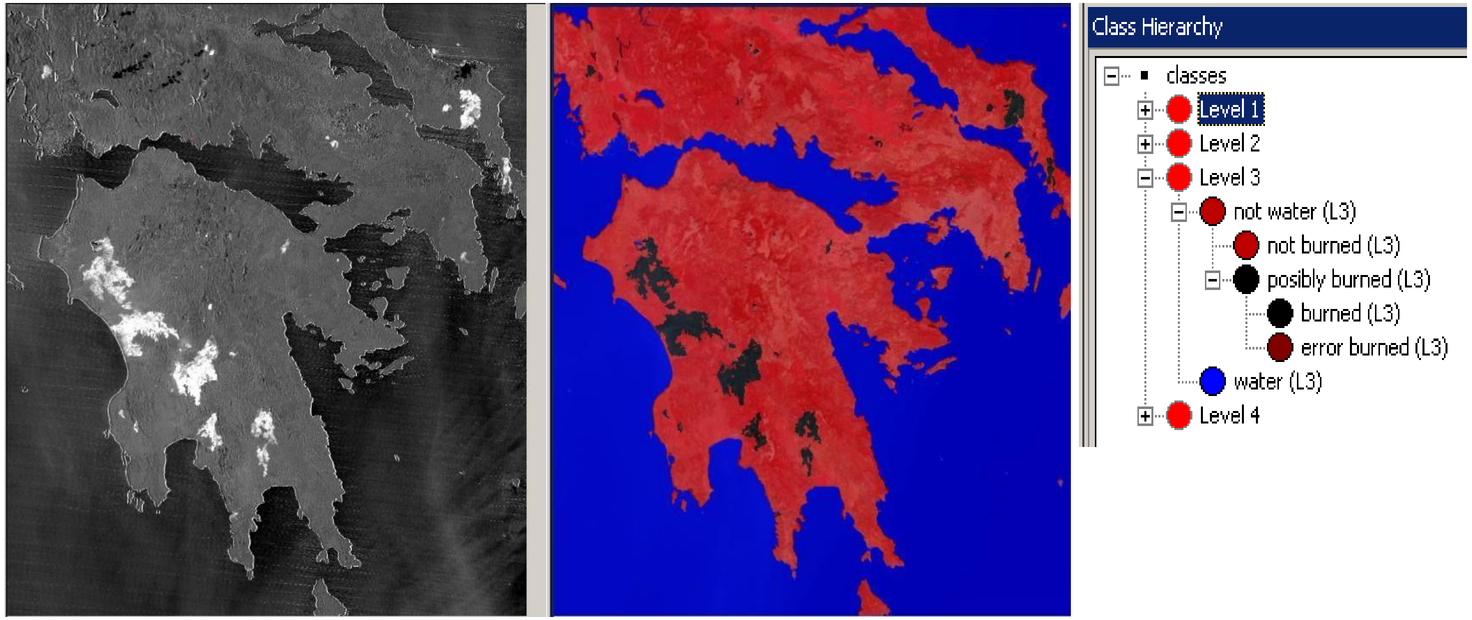
Step 1: Mapping the area before and after the forest fire

MODIS images prior and post a forest fire (RGB-124)

Step 2. Image segmentation



Step 3. Change detection



Step 4. Potential errors in the delineation of burned areas

Final map of burned areas

Two days later … 26,000 m²
of the forest were burned

Sources of information

The European Forest Fire Information System (EFFIS)

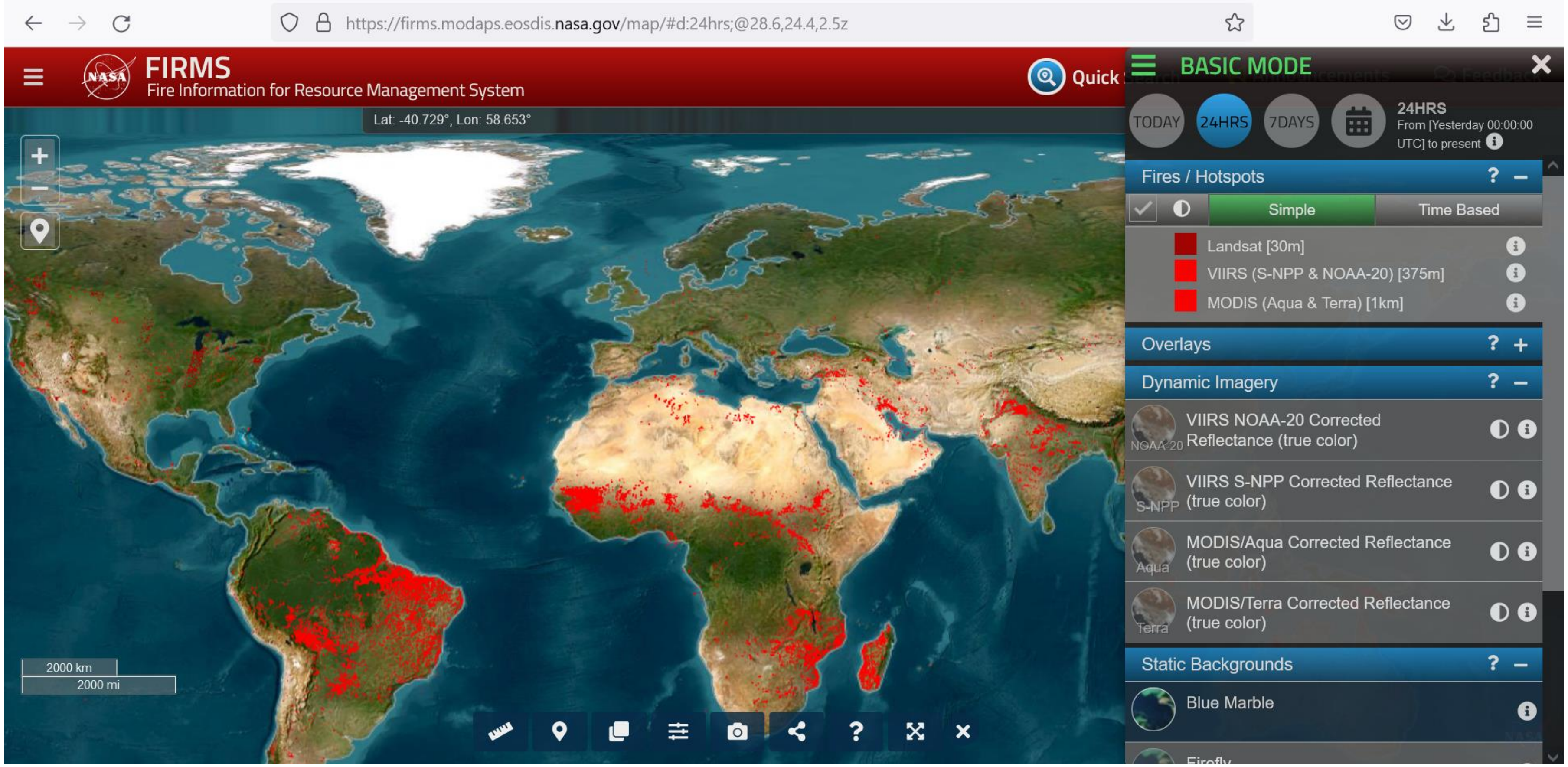
- The European Commission has developed the European Forest Fire Information System (EFFIS) (http://effis.jrc.ec.europa.eu/) to provide a fire risk forecast and a fire danger assessment in EU countries.

- 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.

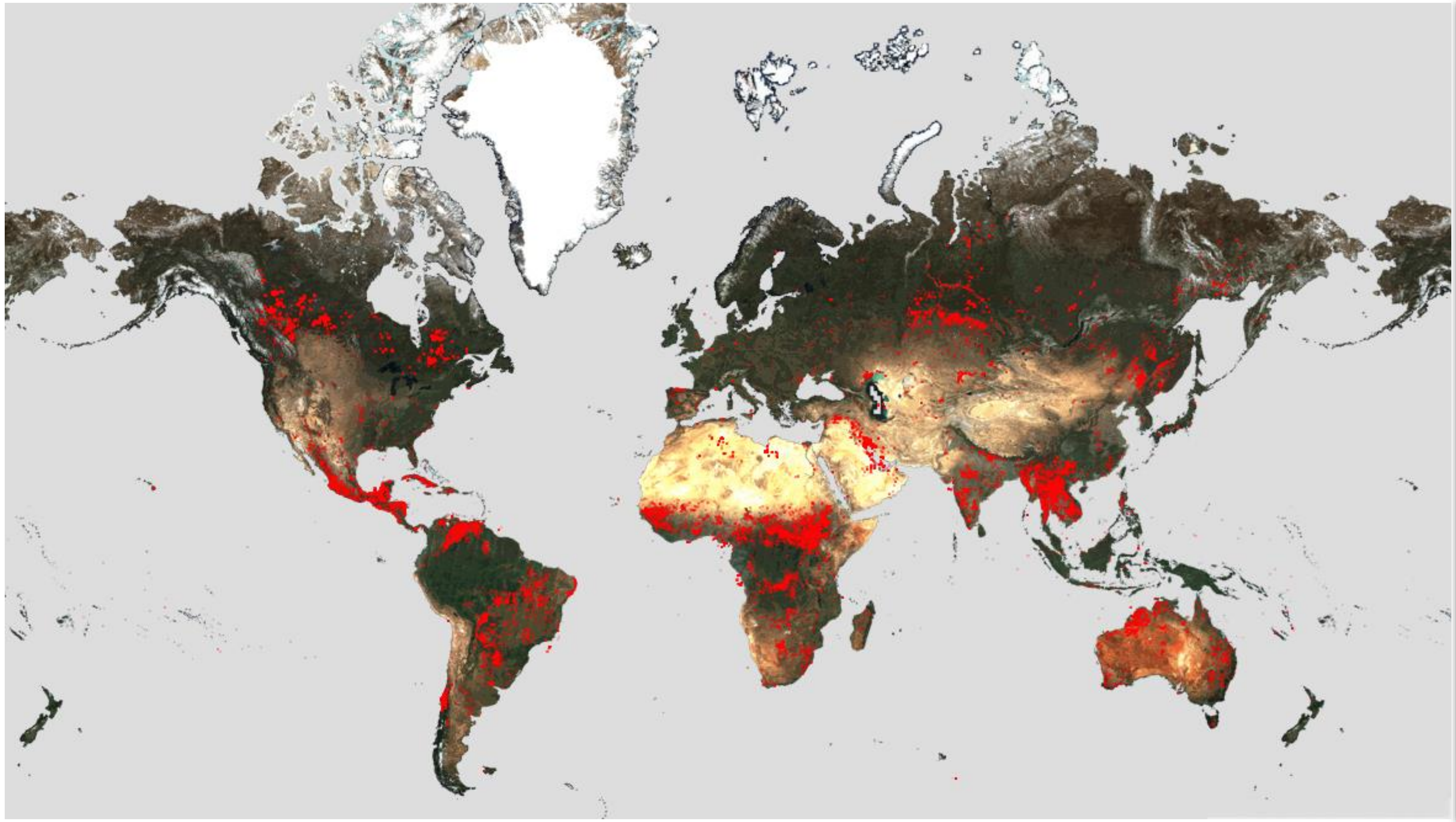
Fire Information for Resource Management System (FIRMS)



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).

Source: https://firms.modaps.eosdis.nasa.gov/

Worldwide fires from ESA's World Fire Atlas



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

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:
8. Mapping wildfires and burn sever ity using Sentinel-2 data, using SNAP software

9. Air quality monitoring using Sentinel-5 data

Copernicus Services

Services monitoring Earth systems

Land Monitoring

Marine Monitoring

Atmosphere Monitoring

Horizontal services

Emergency Management

Security

Climate Change

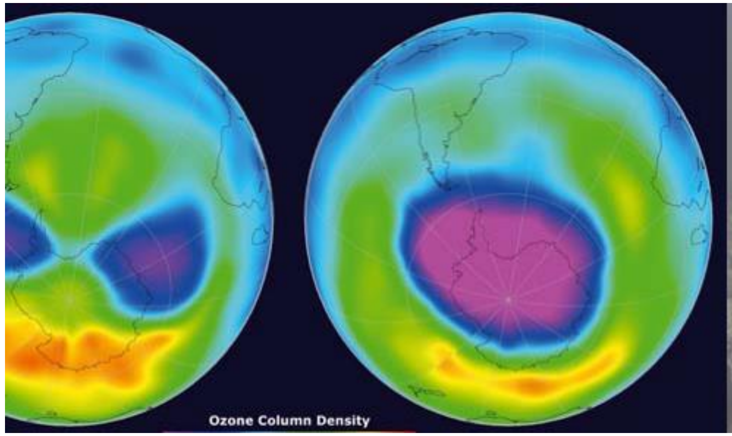
opernicus
The European Earth Observation Programme

→ AIR QUALITY MONITORING

Copernicus Requirements

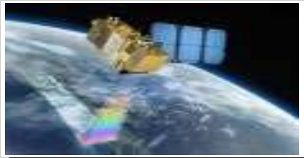
Drivers for operational space-borne atmospheric composition observations:

- Facilitation and improvement of operational applications and services related to atmospheric composition
- Provision of information on treaty verification and protocol monitoring
- Contribution to scientific understanding for environmental assessments to support policies
- Support the Copernicus Atmospheric Core and Downstream services




The Sentinel Family

Sentinel-1 (A/B/C/D) – SAR imaging
All weather, day/night applications, interferometry

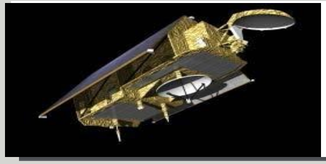


Sentinel-2 (A/B/C/D) – Multi-spectral imaging Land applications: urban, forest, agriculture,… Continuity of Landsat, SPOT

Sentinel-3 (A/B/C/D) – Ocean and global land monitoring
Wide-swath ocean color, vegetation, sea/land surface temperature, altimetry

Sentinel-4 (A/B) – Geostationary atmospheric (on MTG)
Atmospheric composition monitoring, trans-boundary pollution

Sentinel-5 Precursor/ Sentinel-5 (A/B/C) – Low-orbit atmospheric (on MetOp-SG Series A)
Atmospheric composition monitoring



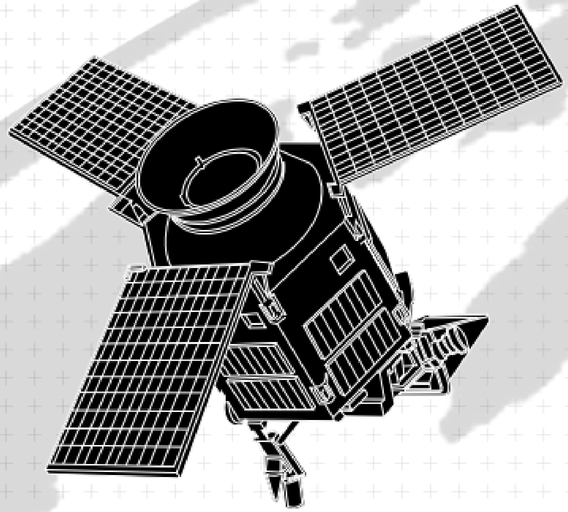
Sentinel-6 [Jason-CS] (A/B) – Low inclination altimetry
Sea-level, wave height and marine wind speed

Sentinel-5P and Sentinel-5

SENTINEL-5P

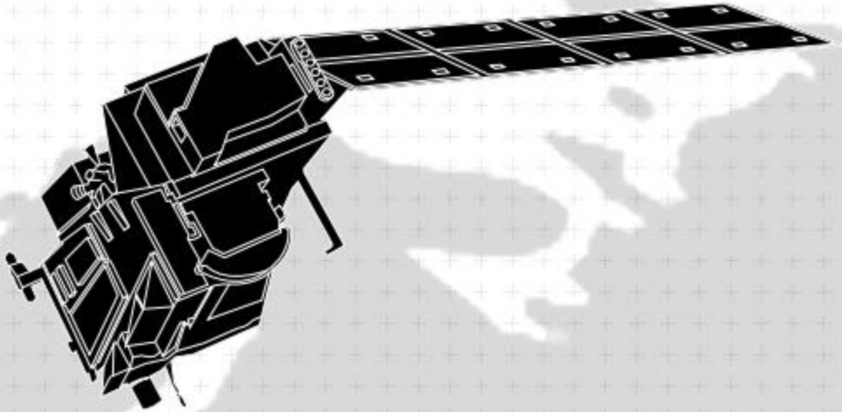
THE FORERUNNER TO THE SENTINEL-5

- **Global observation of key atmospheric constituents, including ozone, nitrogen dioxide, sulphur dioxide and other environmental pollutants**
- Improves climate models and weather forecasts
- Provides data continuously during five-year gap between the retirement of Envisat and the launch of Sentinel-5
- Airbus Defence and Space prime contractor for satellite and TROPOMI instrument



SENTINEL-5

- **Measures air quality and solar radiation, monitors stratospheric ozone and the climate**
- Global coverage of Earth's atmosphere with an unprecedented spatial resolution
- Airbus Defence and Space prime contractor for instrument
- Carried aboard EUMETSAT's MetOp Second Generation satellites



Sentinel-5 Precursor (S-5P)

- The ESA S-5P is a pre-operational mission focussing on global observations of the atmospheric composition for air quality and climate
- The TROPOspheric Monitoring Instrument (**TROPOMI**) is the payload of the S-5P mission and is jointly developed by The Netherlands and ESA
- The launch date: 2016 with a 7 year design lifetime

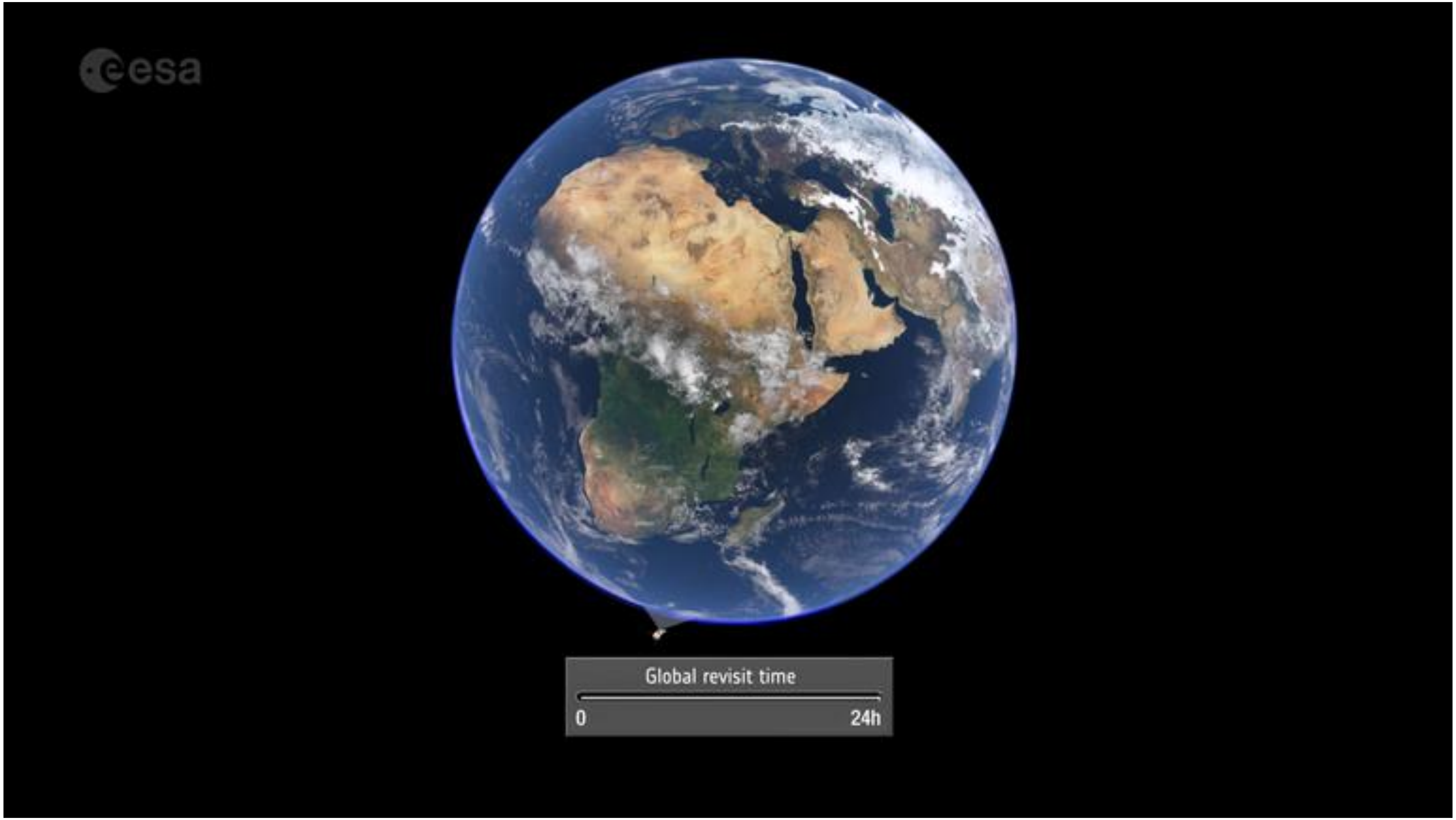
TROPOMI

- UV-VIS-NIR-SWIR nadir view grating spectrometer.
- Spectral range: 270-500, 675-775, 2305-2385 nm
- Spectral Resolution: 0.25-1.1 nm
- Spatial Resolution: 7x7km2
- Global daily coverage at 13:30 local solar time.

Contribution to Copernicus

- Total column O_3, NO_2, CO, SO_2, CH_4, CH_2O, H_2O, BrO
- Tropospheric column O_3, NO_2
- O_3 profile
- Aerosol absorbing index & layer height

Sentinel-5P Tropomi instrument to map trace gases



Sentinel-5P Tropomi instrument to map trace gases

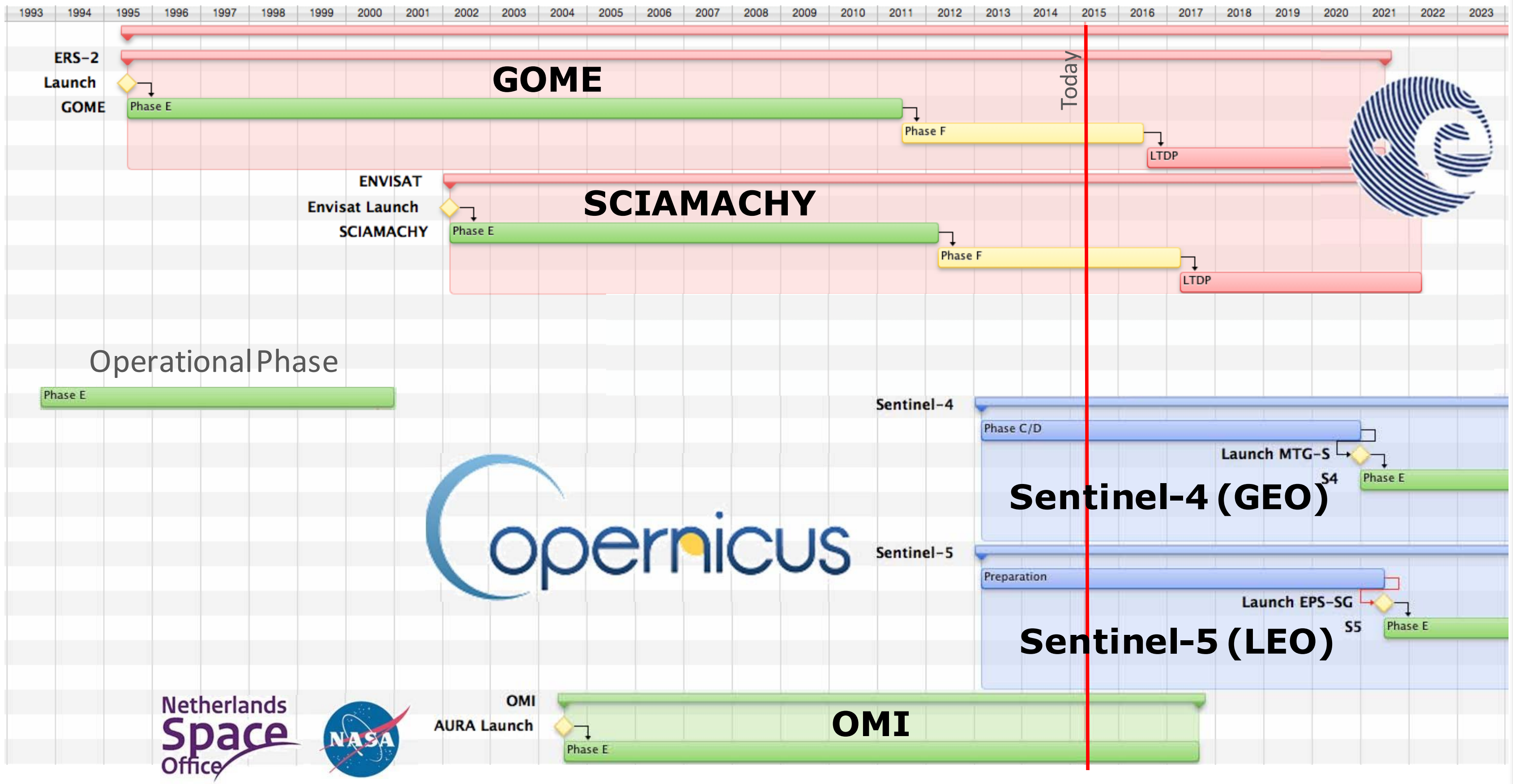
Level 2 Products and the L2 WG

Parameter	Data Product	Vertical Resolution	Accuracy	Precision
Ozone	Ozone Profile	6 km	10-30%	10%
	Total Ozone	total column	3.5-5%	1.6-2.5%
	Tropospheric Ozone	trop column		
NO_2	Stratospheric NO_2	strat column	<10%	0.5e15
	Tropospheric NO_2	trop column	25-50%	0.7e15
SO_2	SO_2 enhanced	total column	30%	0.15-0.3 (0.06-0.12) DU
	Total SO_2	total column	30-50%	1-3 (0.4-1.2) DU
Formaldehyde	Total HCHO	total column	40-80%	1.2e16 (4e15)
CO	Total CO	total column	15%	<10%
Methane	Total CH_4	total column	1.5%	1%
Cloud	Cloud Fraction	total column	<20%	0.05
	Albedo (Optical Thickness)	total column	<20%	0.05 (10)
	Cloud Height (Pressure)	total column	<20%	<0.5 km (<30hPa)
	SNPP VIIRS Cloud data			
Aerosol	Aerosol Layer Height	total column	<100hPa	<50hPa
	Aerosol Type	total column	~1 AAI	<0.1 AAI

All ATBDs (L1 and L2) will be made available to the science community

Source: S5P Level 2 Working Group

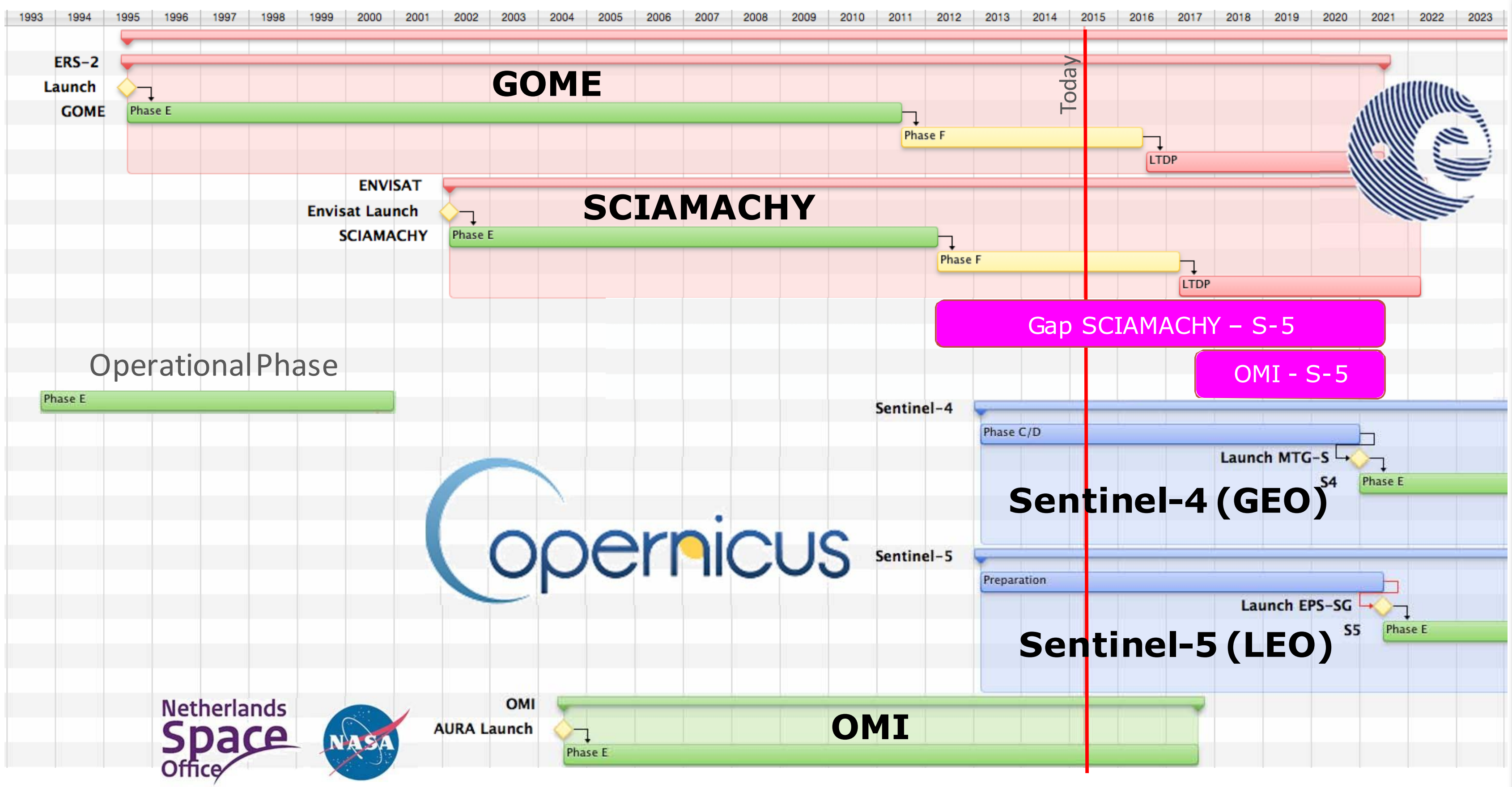
Sentinel-5 „Precursor"?



The Sentinel-5 (5-P) mission continues a series of spectrometers measuring atmospheric properties since 1995:

- The Global Ozone Monitoring Experiment (GOME) on ESA's ERS-2 - operated between 1995 and 2011
- GOME-2 on EUMETSAT's Met-OP-A satellite, launched in 2006, still in service; operating since 2012 on MetOp-B satellite
- SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) on ESA's ENVISAT mission which operated between 2002 and 2012
- Ozone Monitoring Instrument (OMI) since 2004 on NASA's AURA spacecraft, still in service

Sentinel-5 „Precursor“?



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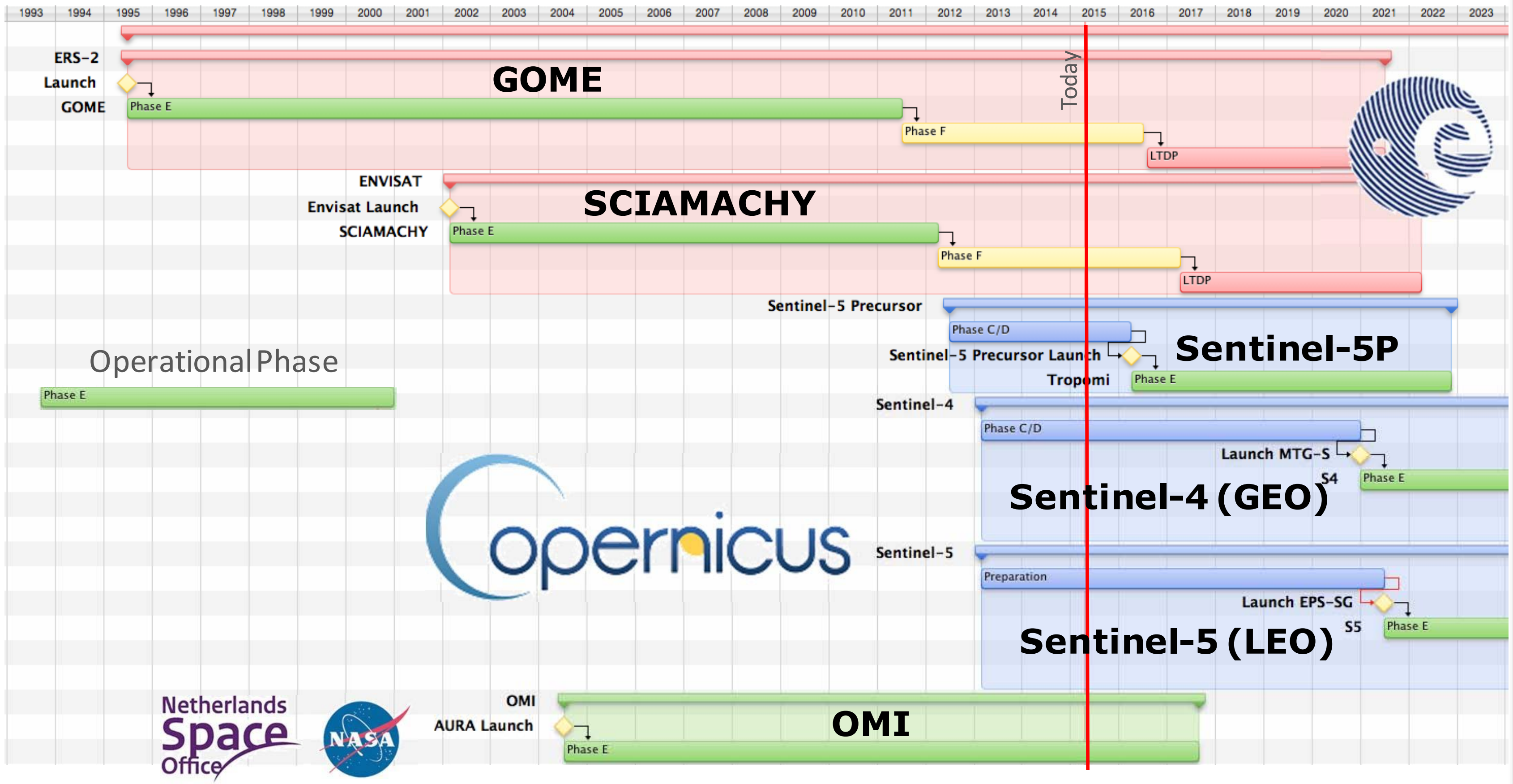

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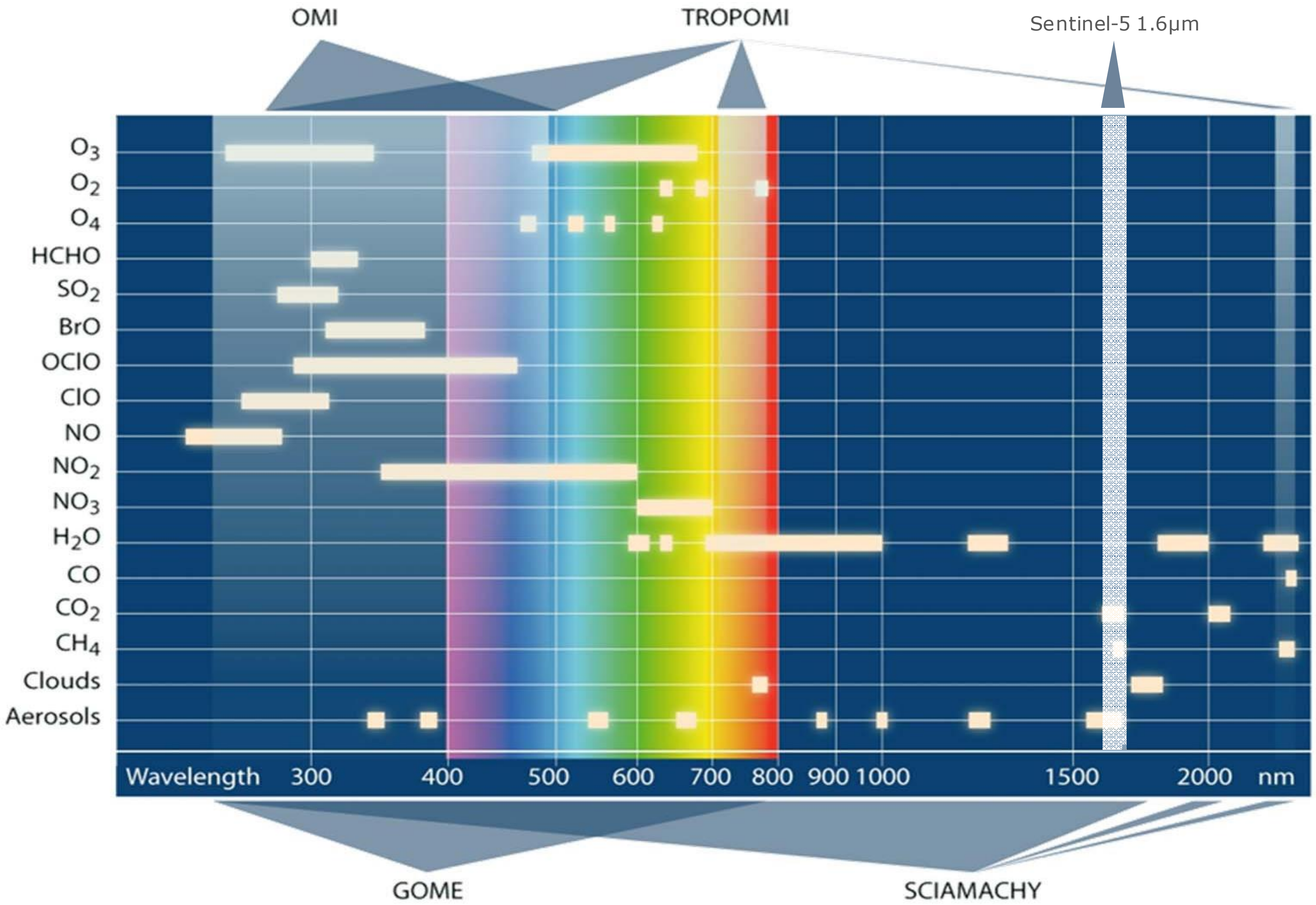
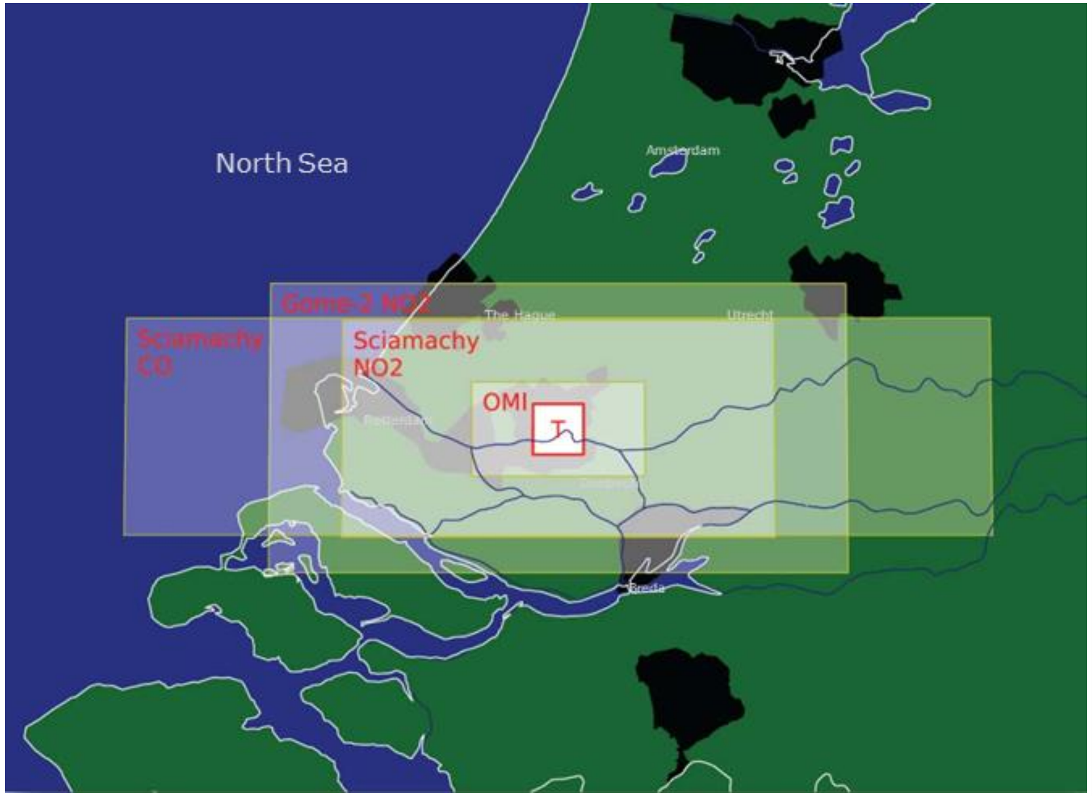
Spectral Range Comparison



SCIAMACHY measurements cover almost the entire solar irradiance spectrum from UV to SWIR (240 to 2 400 nm) whereas GOME(-2) and OMI are scaled down in terms of wavelength range covering the UV-VIS-NIR range (270-790 nm) and the UV-VIS range (270-500 nm) respectively.

Source: http://www.tropomi.eu

Spatial Resolution Comparison

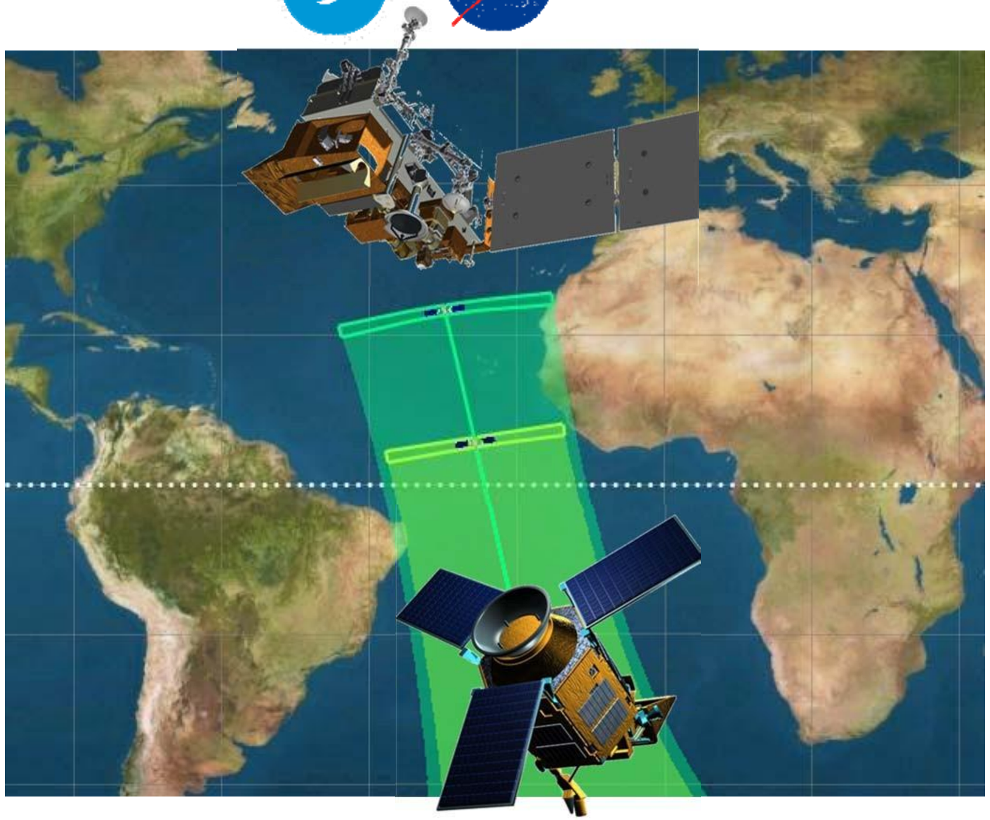


Source: KNMI

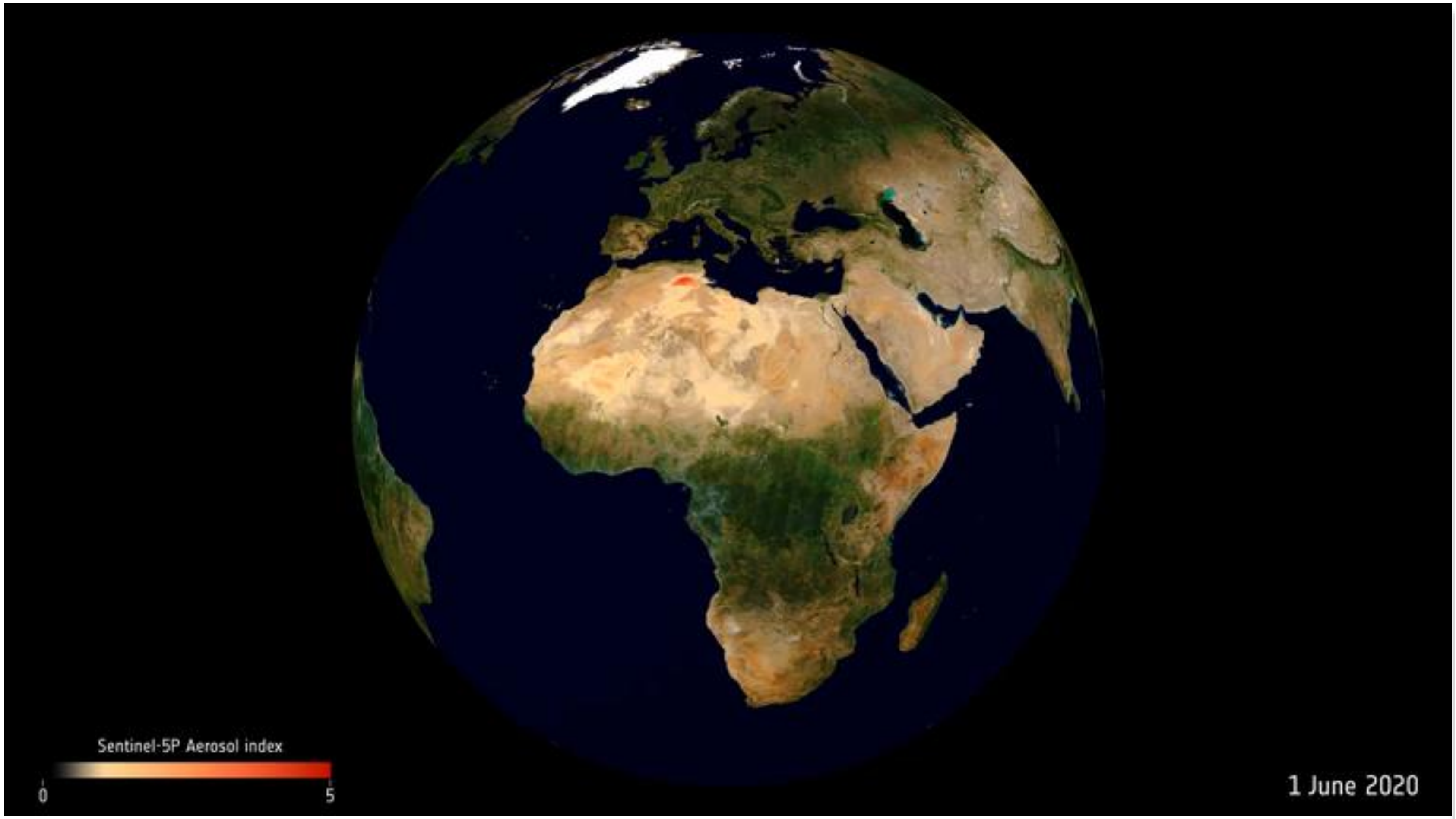
Instrument	Spectral Range	Spatial resolution (km x km)	Swath (km)	Overpass time	Operational
GOME	UV-VIS-NIR (240-790 nm)	320 × 40	960	10:30 local time	1995-2011
GOME-2	UV-VIS-NIR (240-790 nm)	80 × 40	1920	9:30 local time	2006-present
SCIAMACHY	UV to SWIR (240-2400 nm)	30 × 215	1000	10:00 local time	2002-2012
OMI	UV-VIS (270-500 nm)	13 ×24	2600	13:30 local time	2004-present
TROPOMI	UV-VIS-NIR-SWIR (270 – 2385 nm)	7 × 7	2600	13:30 local time	Launch scheduled for 2016
Sentinel-4	UV-VIS-NIR (305- 775 nm)	8 × 8	NA	Geostationary	Launch scheduled for 2021
Sentinel-5	UV-VIS-NIR-SWIR (270 – 2385 nm)	7 × 7	2670	9:30 local time	Launch scheduled for 2021

S-5p and S-NPP Loose Formation Flight

- In particular Methane requires a very reliable cloud clearing of optically thin layers (e.g. cirrus)
- “Loose formation” with separation 5 min +/- 5 min
- Close cooperation between ESA and NOAA/NASA on technical level
- Tailored VIIRS cloud products for S5P
- Synergistic use SNPP & S-5p products improve the S5P only cloud information

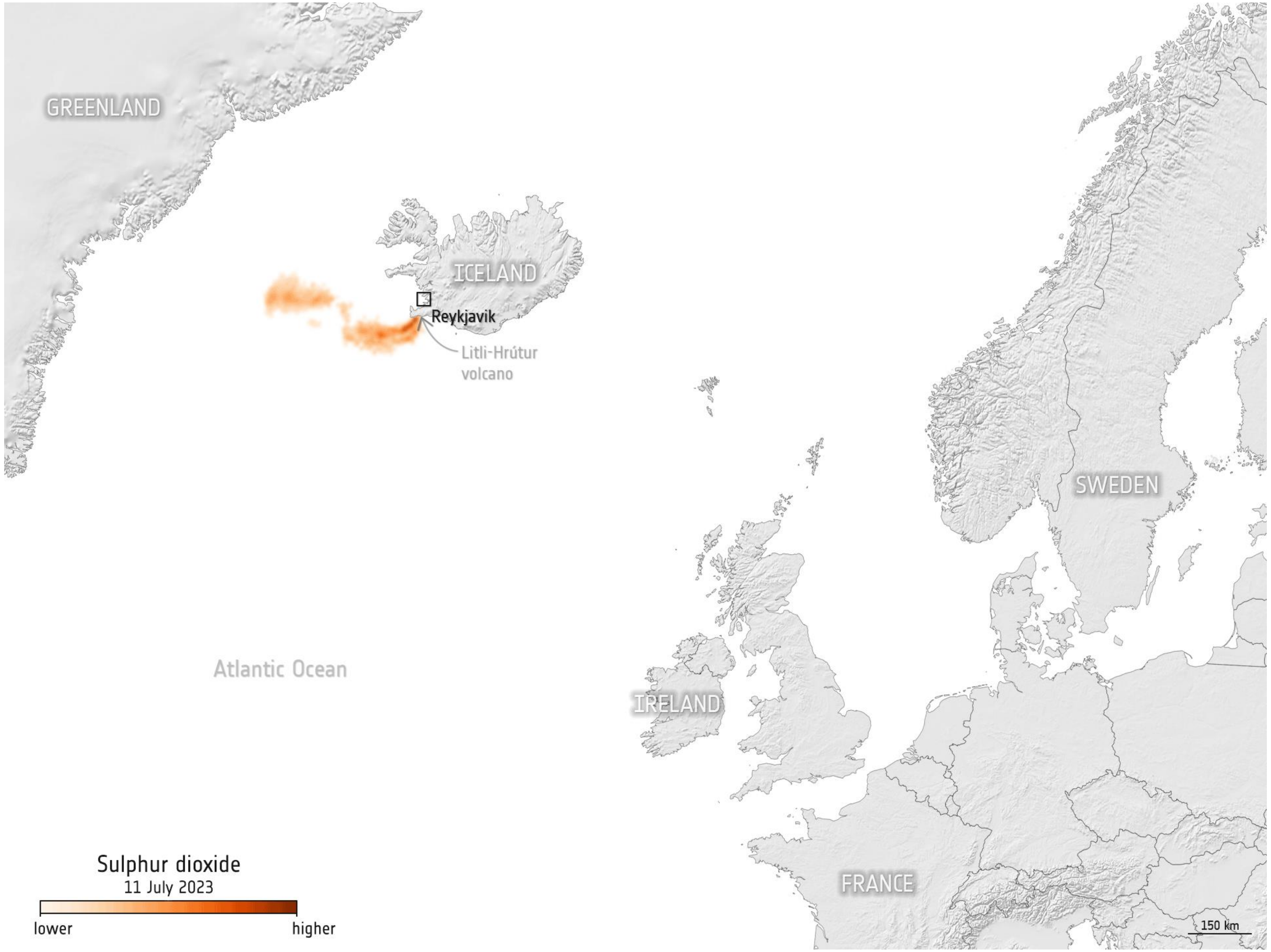


Tracking Saharan dust plume



This animation shows the spread of aerosols from the Saharan dust plume moving westward across the Atlantic Ocean from 1 June to 26 June 2020. This plume has reached the Caribbean, South America and the United States.

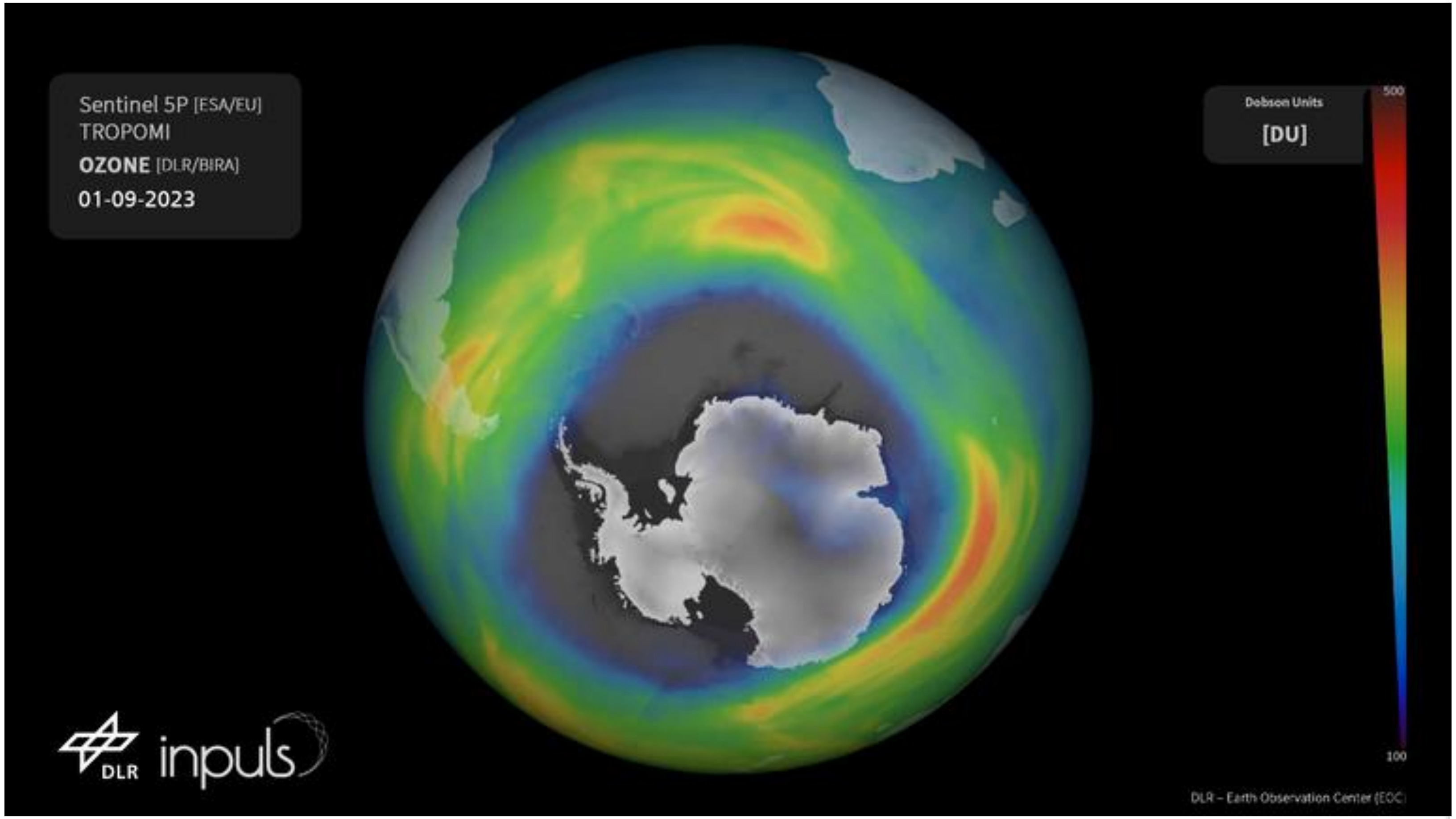
Volcano eruption seen from space



Litli-Hrútur eruption seen from space

Sentinel-5P – Ozone Hole Monitoring

https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Ozone_hole_goes_large_again



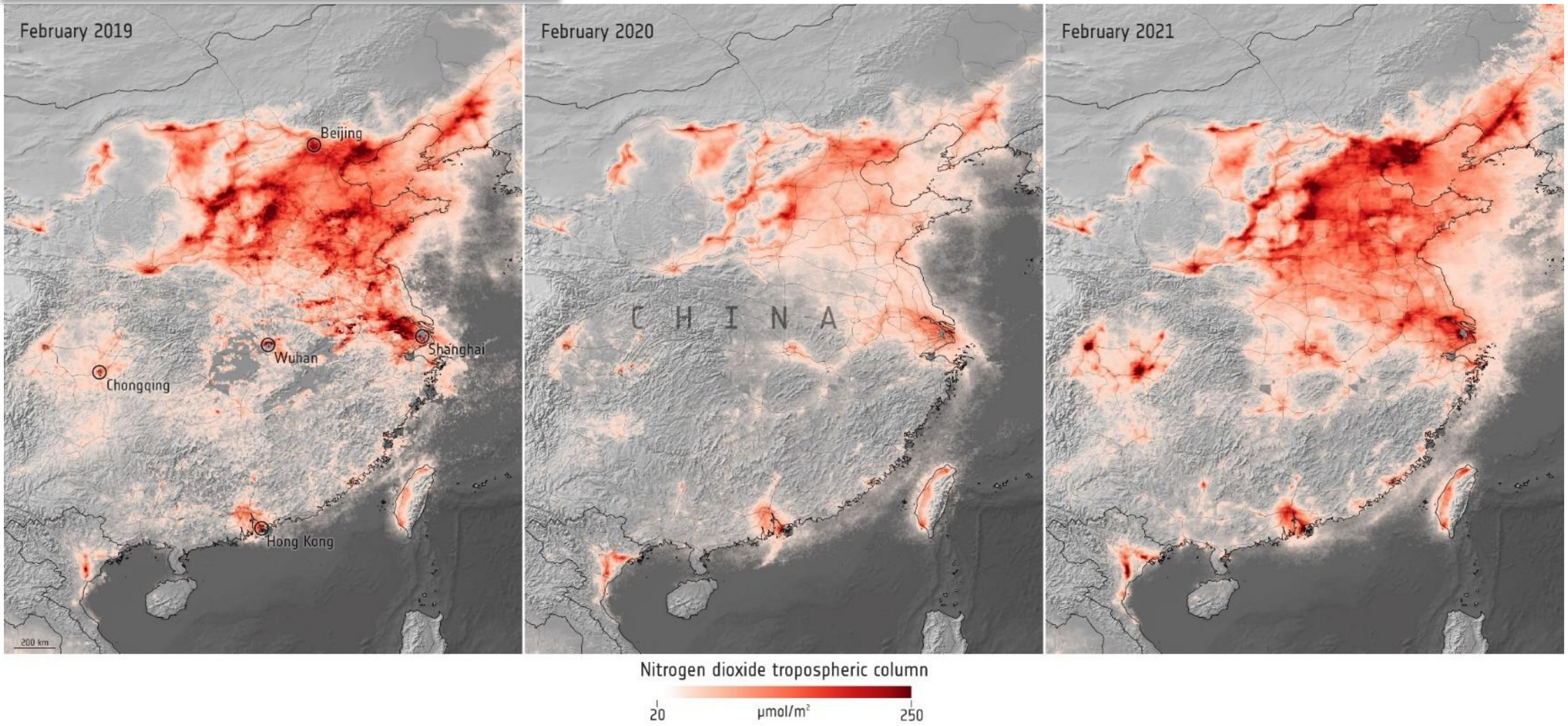
This animation uses Sentinel-5P total ozone measurements and shows the evolution of the ozone hole over the South Pole from 1 September to 29 September 2023.

Measurements from the Copernicus Sentinel-5P satellite show that this year's ozone hole over the Antarctica is one of the biggest on record. The hole, which is what scientists call an 'ozone depleting area,' reached a size of 26 million sq km on 16 September 2023. This is roughly three times the size of Brazil.

Source: contains modified Copernicus Sentinel data (2023)/processed DLR

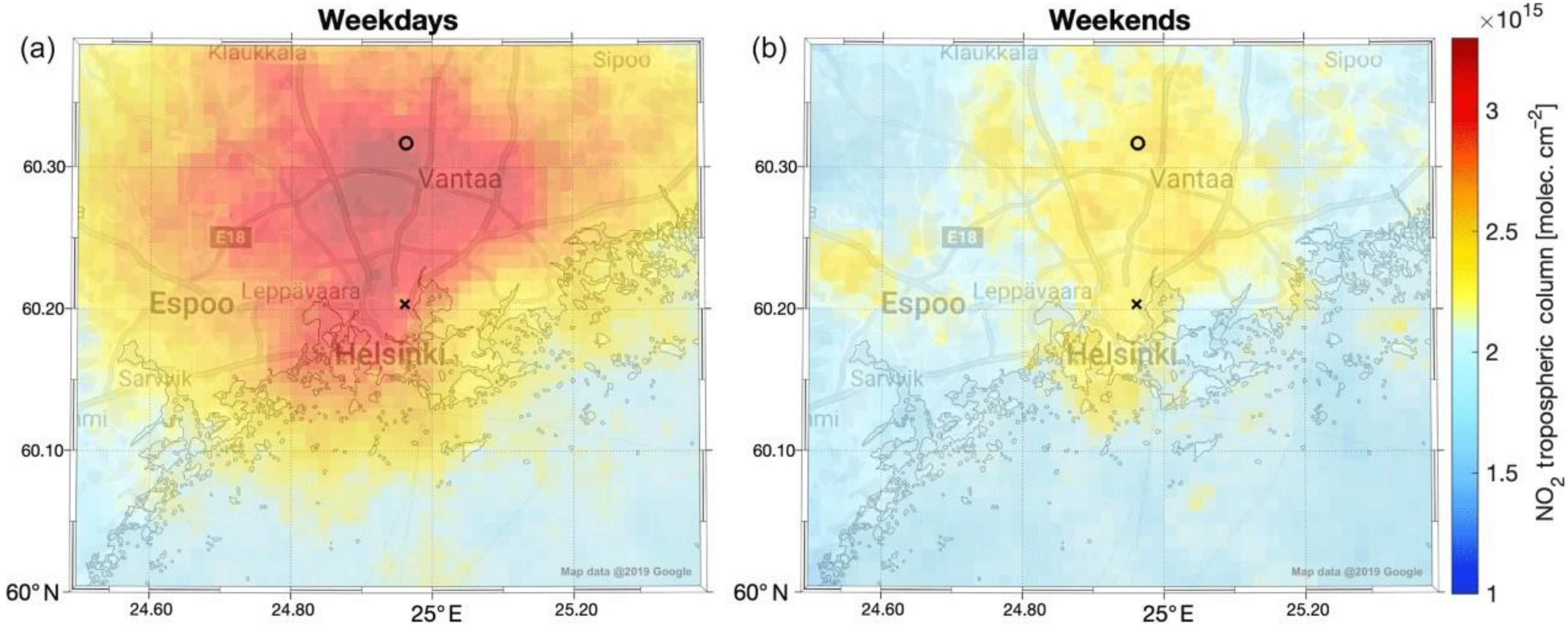
COVID-19 impact as ‘seen’ by Sentinel-5P

Nitrogen dioxide concentrations over China



These images, using data from the Copernicus Sentinel-5P satellite, show the monthly average nitrogen dioxide concentrations over China in February 2019, 2020 and 2021. In early 2020, data from satellites were used to show a decline in air pollution over China coinciding with nationwide lockdowns put in place to stop the spread of COVID-19. One year later, nitrogen dioxide levels in China have risen back to pre-COVID levels according to new data from the Sentinel-5P satellite.

Sentinel-5P data map nitrogen dioxide in Finland



Urban Helsinki shows a drop in pollutants during weekends. This research showed that overall, levels of nitrogen dioxide during weekends were 30% lower than those observed during weekdays, and that spatial distribution was partially affected by systematic wind patterns.

NO2 emissions from oil refineries in the Mississippi Delta

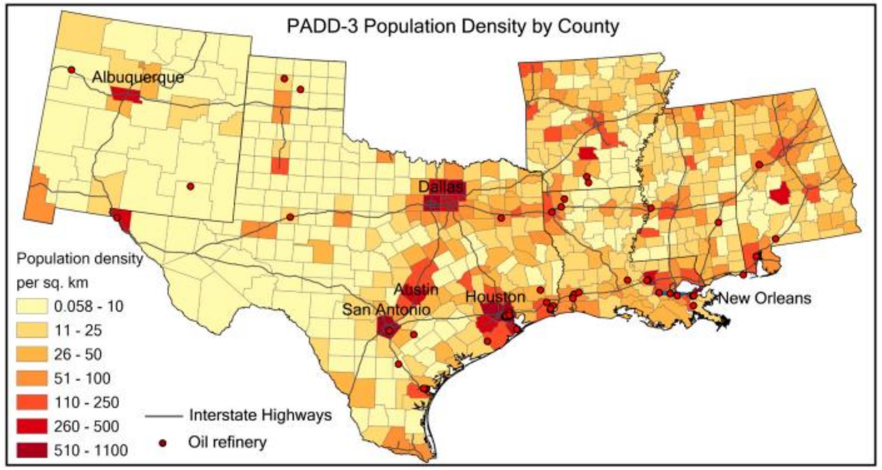


Fig. 3. Petroleum Administration for Defense Districts 3 (PADD-3) population density by county.

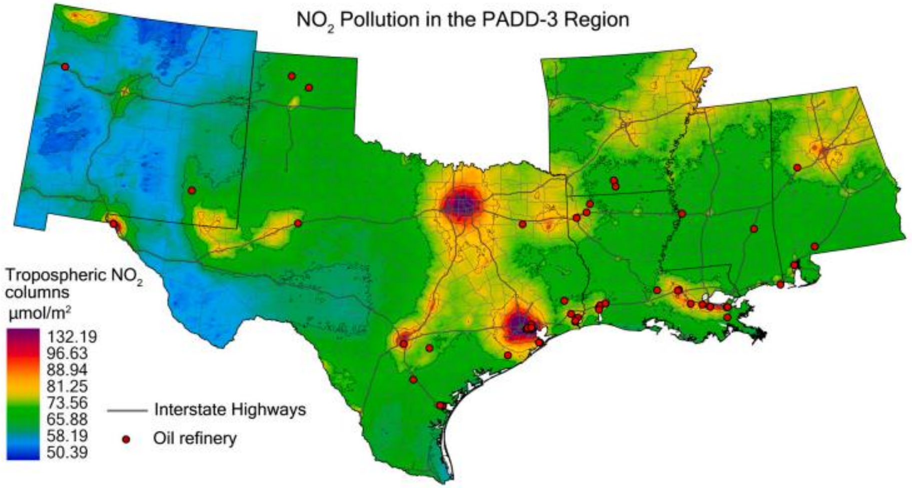


Fig. 4. Spatial distribution of TROPOMI NO_2 VCD (µmol/m²) during 2019–2022 over the US PADD-3 region. Red dots indicate the location of a refinery.

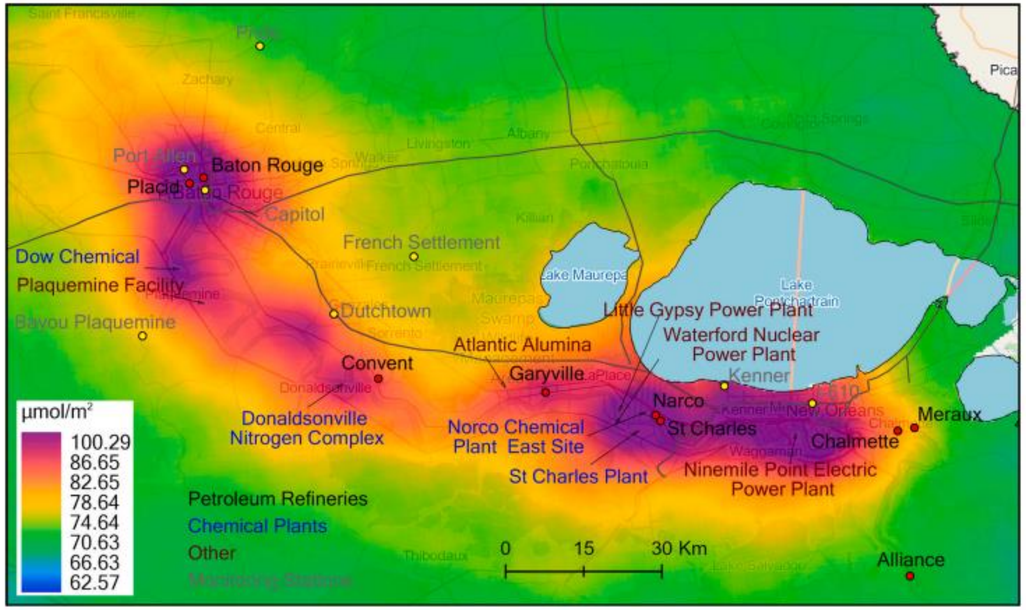


Fig. 5. Spatial distribution of TROPOMI NO_2 VCD during 2019–2022. Red dots indicate the location of a refinery, while yellow dots indicate the location of air quality monitoring stations. Background map from OpenStreetMap©.

This study uses TROPOMI data to observe the spatial patterns of NO2 pollution within the PADD-3 region of the lower Mississippi Delta, an area characterized by high industrial activity associated with oil refining and petrochemicals. The results show that TROPOMI captures small-scale spatial heterogeneities associated with industrial and other activities, such as emissions from oil refining and the chemical industry, as well as emissions from coal-fired power plants and vehicular traffic.

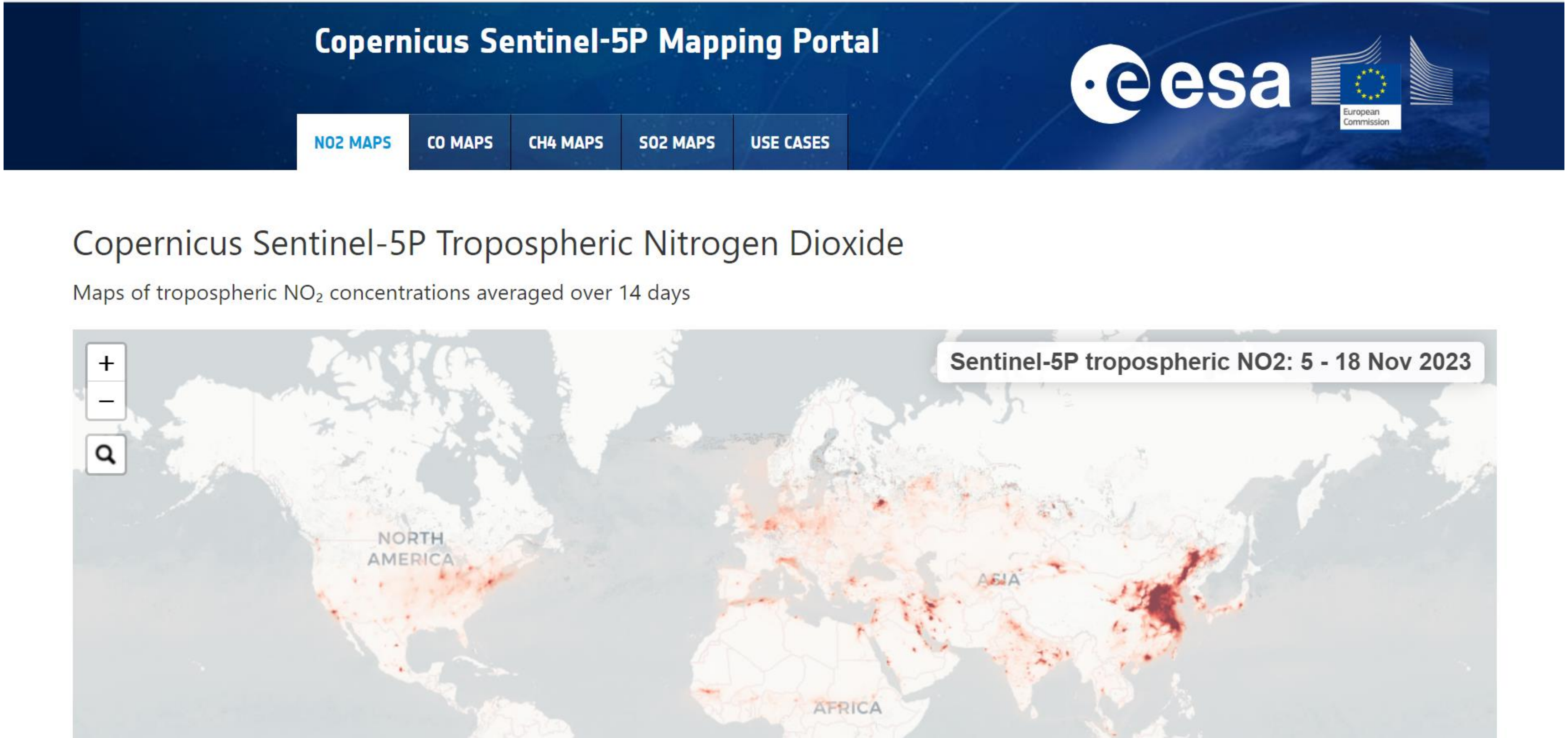
Methane Emission Source Detection by Sentinel-5P

Methane enhancement over Libya

Methane Emission Source Detection by Sentinel-5P

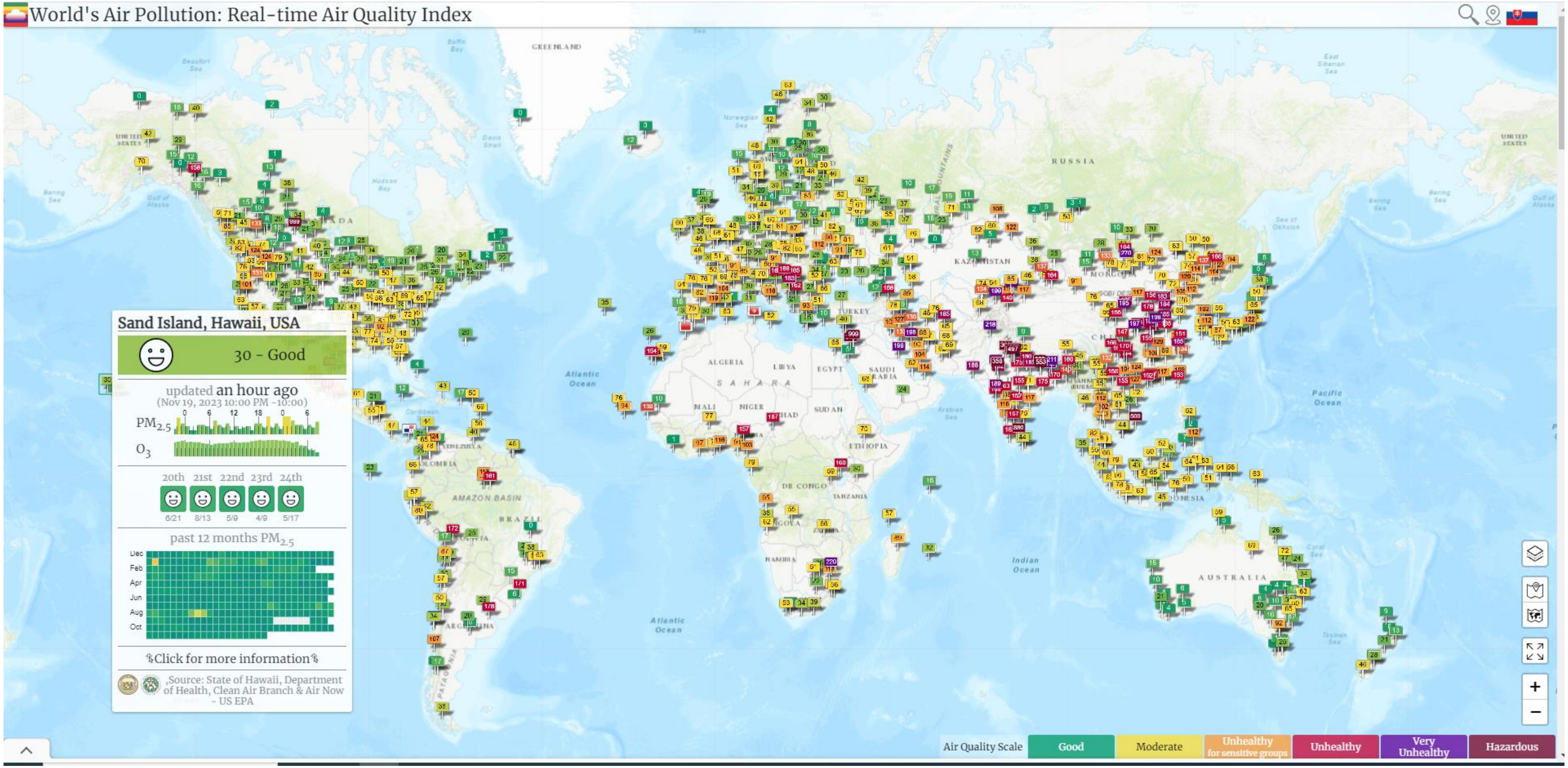
https://www.esa.int/ESA_Multimedia/Search?SearchText=methane+sentinel-5p&result_type=videos

Copernicus Sentinel-5P Mapping Portal



For more information, see the tutorial:
9. Air quality monitoring using Sentinel-5 data – practicals, using SNAP software

World's Air Pollution: Real-time Air Quality Index



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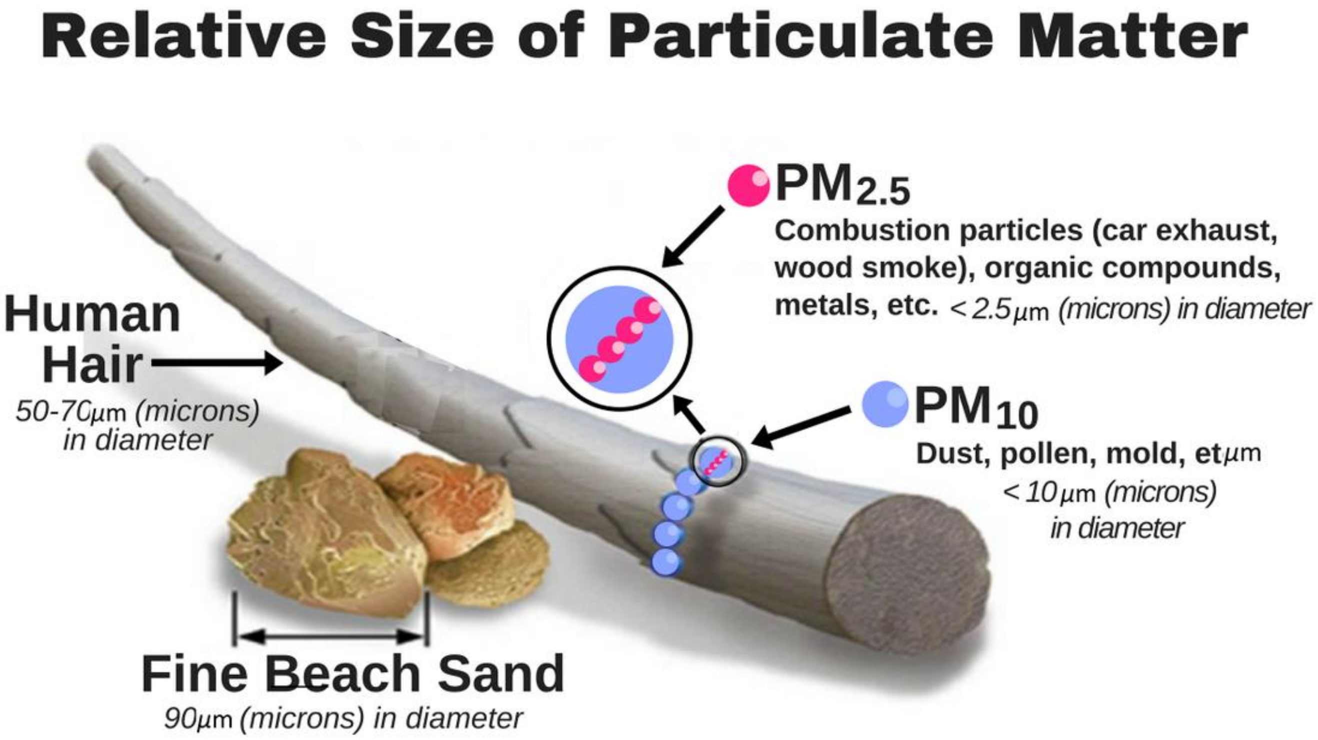
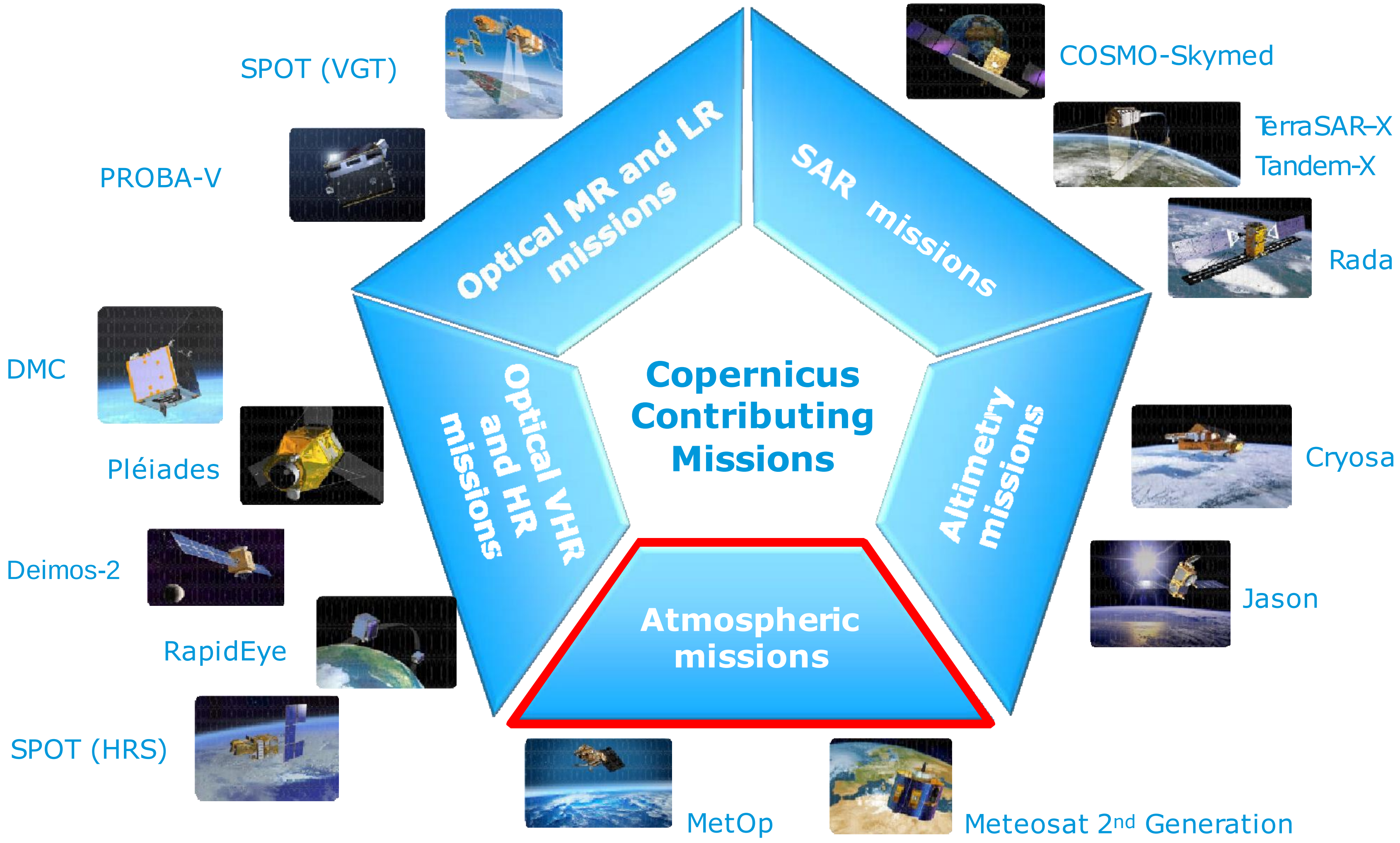


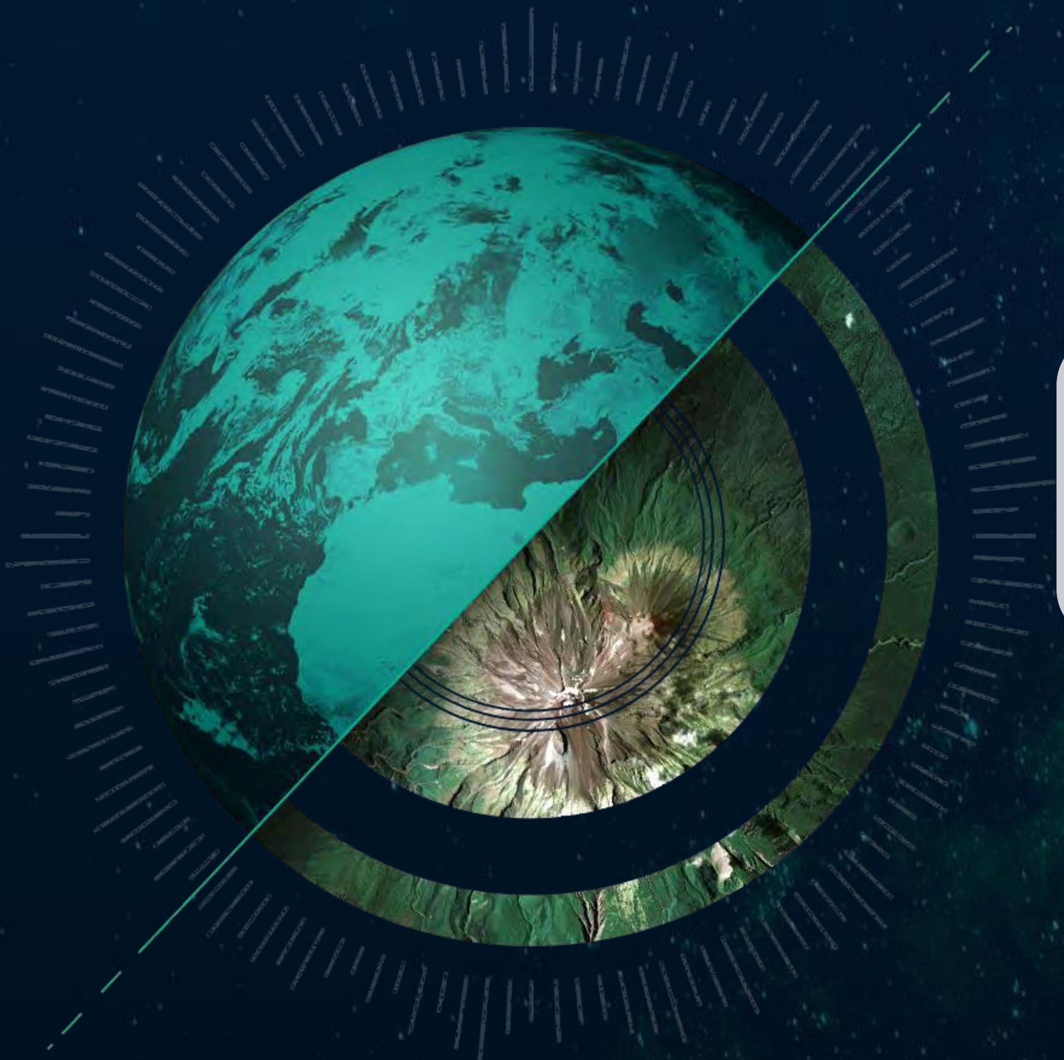
Why are PM particles harmful?

Airborne PM particles have an adverse effect on human health and the environment. Both PMPM2.5 and PM10 particles can be inhaled, while some settle in the respiratory system. PM2.5 gets deeper into the lungs (pulmonary alveoli), where it settles and enters the bloodstream. They can cause acute and chronic bronchitis or asthma.

… and Contributing Missions



Sentinel-5 Precursor, ACC-11, ESA/ESRIN, 29 April 2015

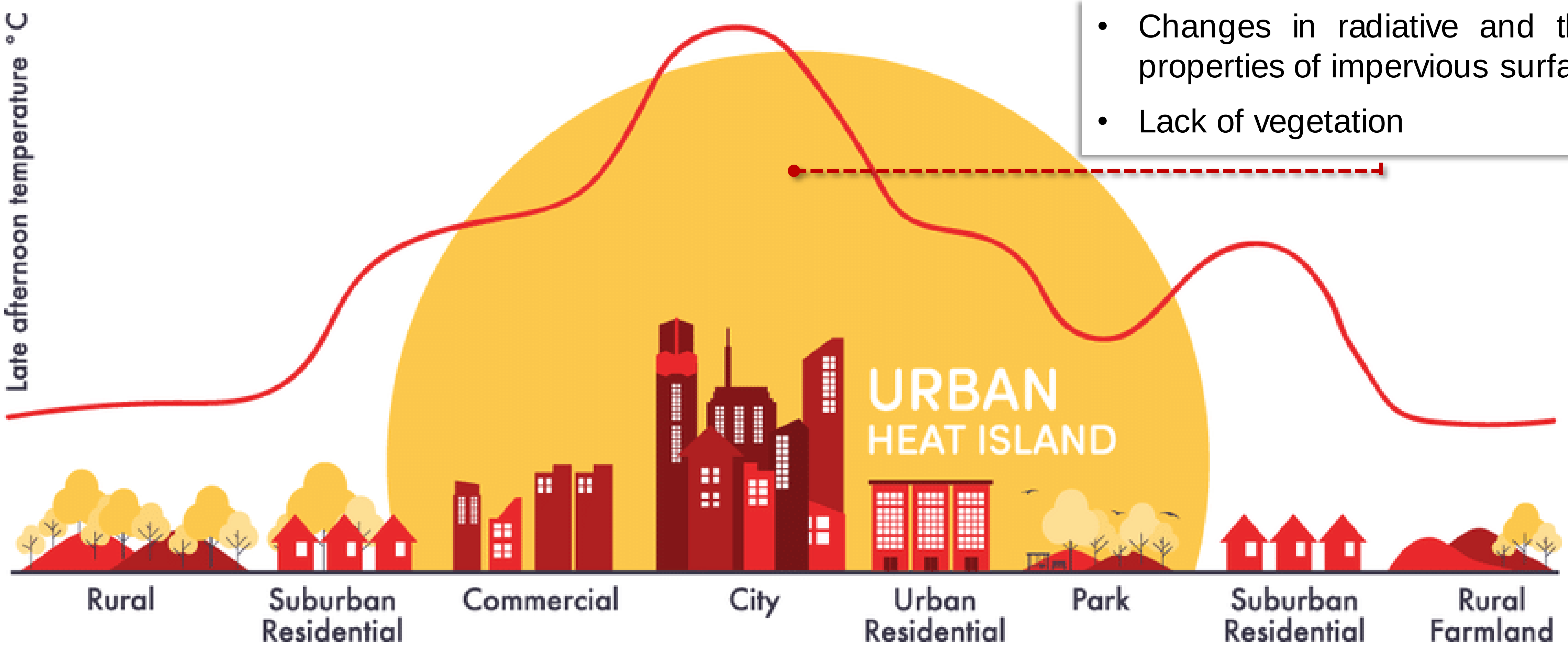


10. Land surface temperature mapping /urban heat island mapping using ESA EO data

Overview of Urban Heat Islands

Urban Heat Island (UHI) refers to the phenomenon where urban areas experience higher temperatures compared to their surrounding rural areas due to human activities and built infrastructure such as buildings, roads, and concrete surfaces absorbing and retaining heat.

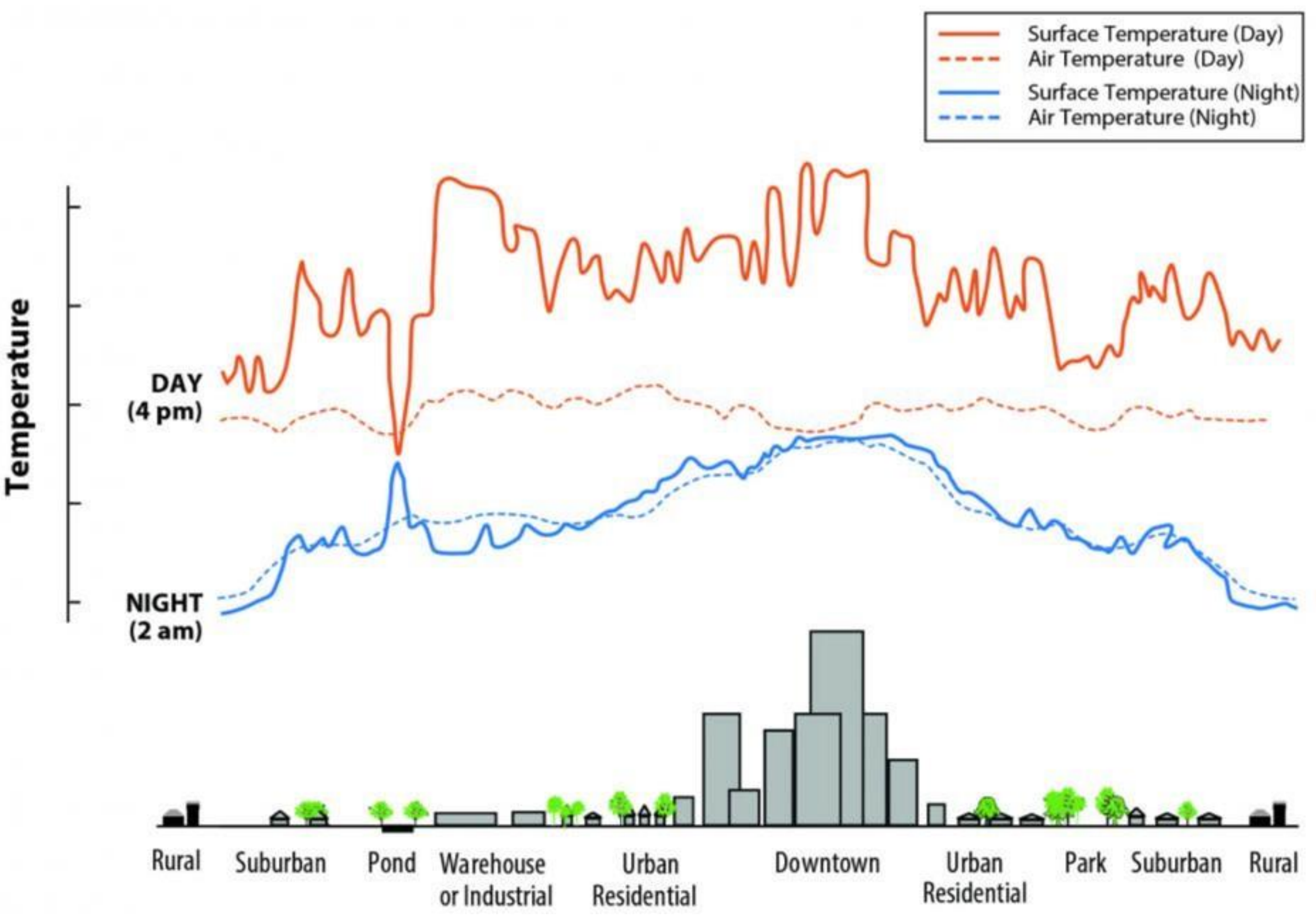
- Changes in radiative and thermal properties of impervious surfaces
- Lack of vegetation



Overview of Urban Heat Islands

- Urban heat islands can emerge during both daytime and nighttime, regardless of the city's size or the season.

- While surface temperatures exhibit greater fluctuations than air temperatures during the day, they become more conspicuous post-sunset owing to the gradual dissipation of heat from impermeable surfaces.

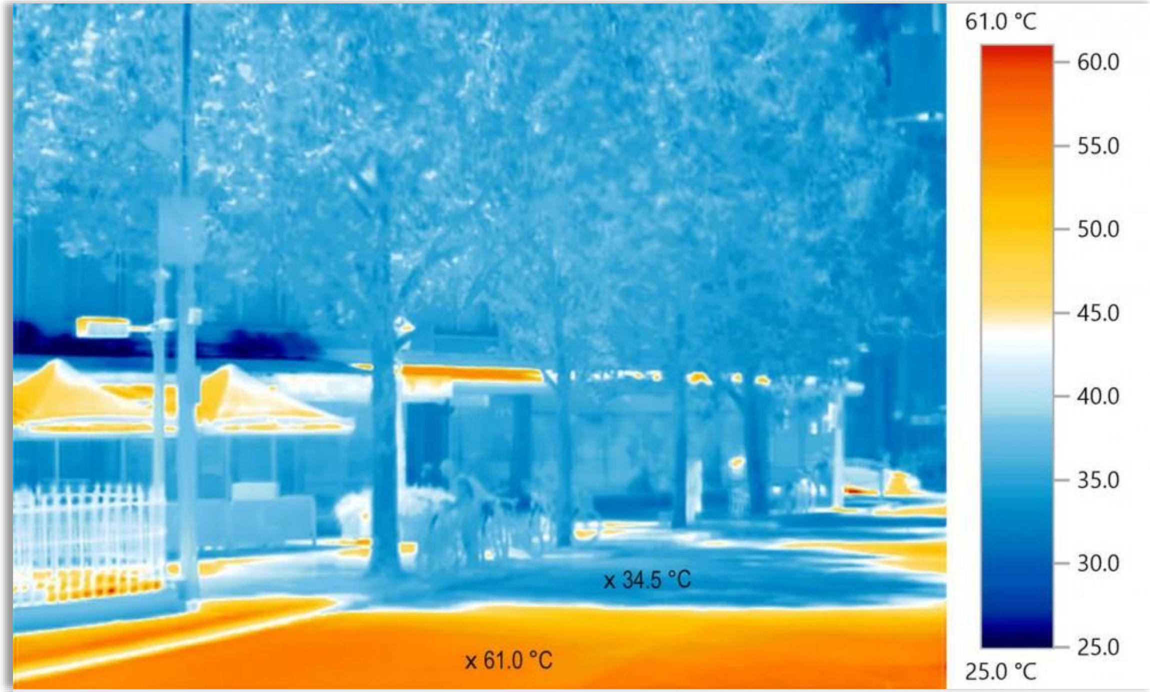


Source: EPA

Factors influencing the formation of the UHI

Main factors contributing to the formation of urban heat islands:

- anthropogenic heat emissions;
- reduction of urban vegetation;
- construction materials with low albedo;
- urban canyons trapping heat released from urban infrastructure;
- weather and geographic location



Source: City of Melbourne (2017)

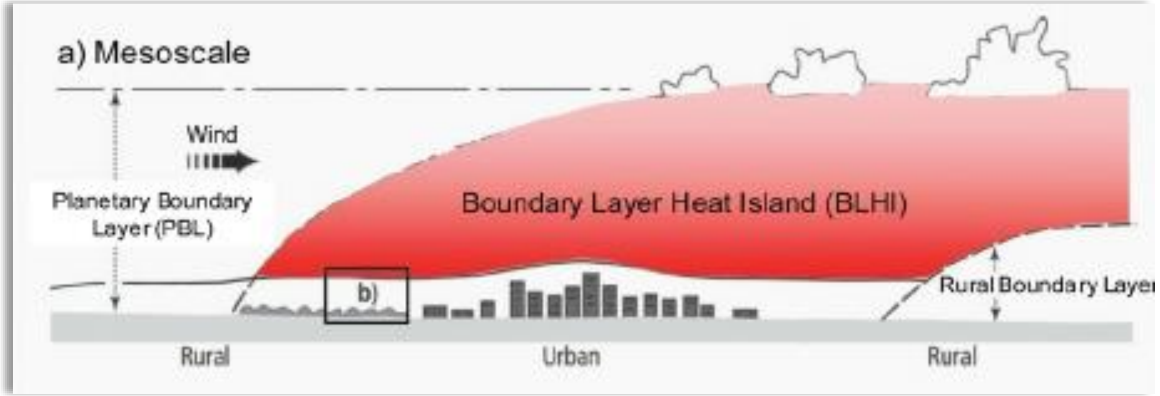
Types of urban heat islands

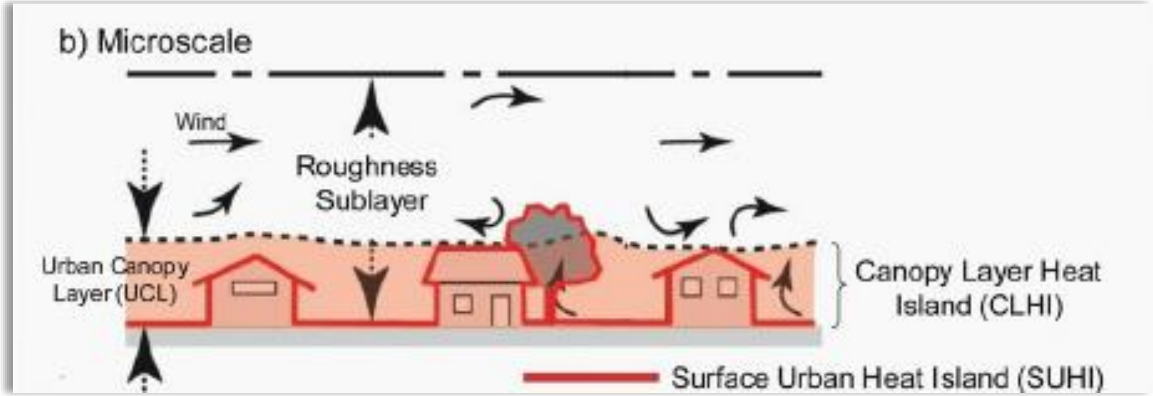
Analysis of urban heat islands in the urban environment typically occurs in one of three urban layers:

• **Surface Urban Heat Island (SUHI)**- measurement of infrared radiation reflected from surfaces.

• **Canopy Layer Heat Island (CLHI)** - the layer of the atmosphere between the Earth's surface and the tops of building roofs or urban greenery where most human activities occur.

• **Boundary Layer Heat Island (BLHI)** - the boundary layer above the urban canopy layer (up to 2 km above the Earth's surface).

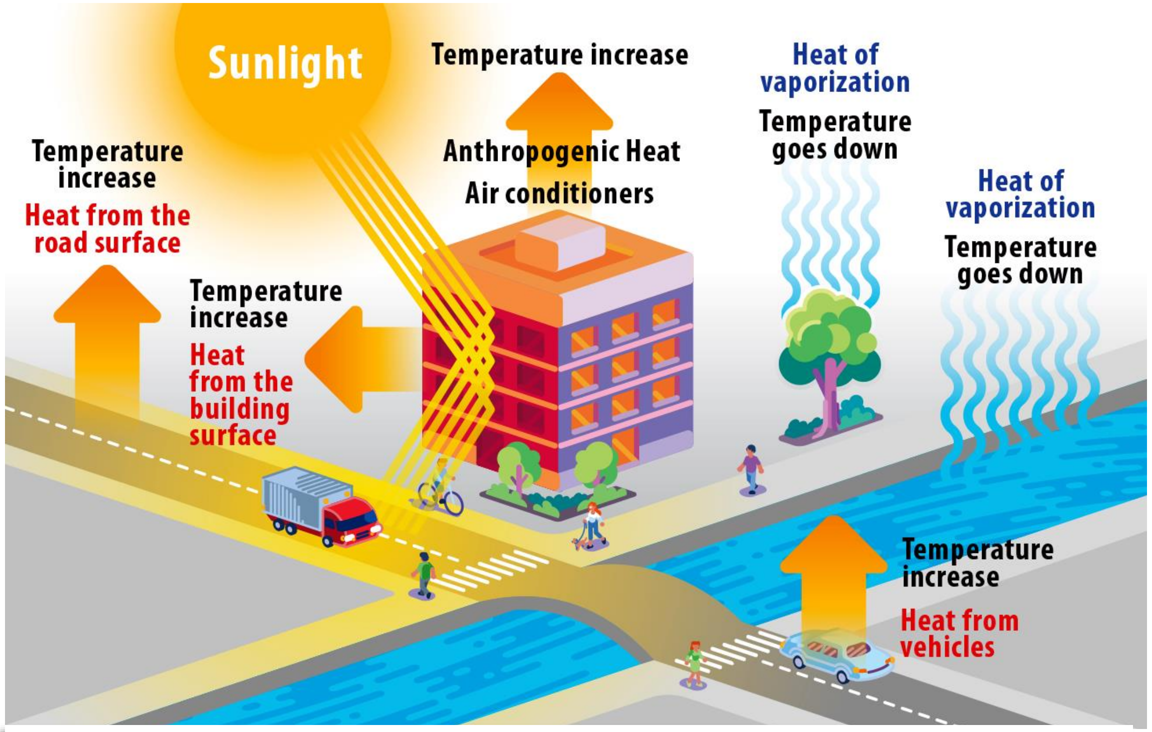




Source: Voogt (2002)

Surface UHI

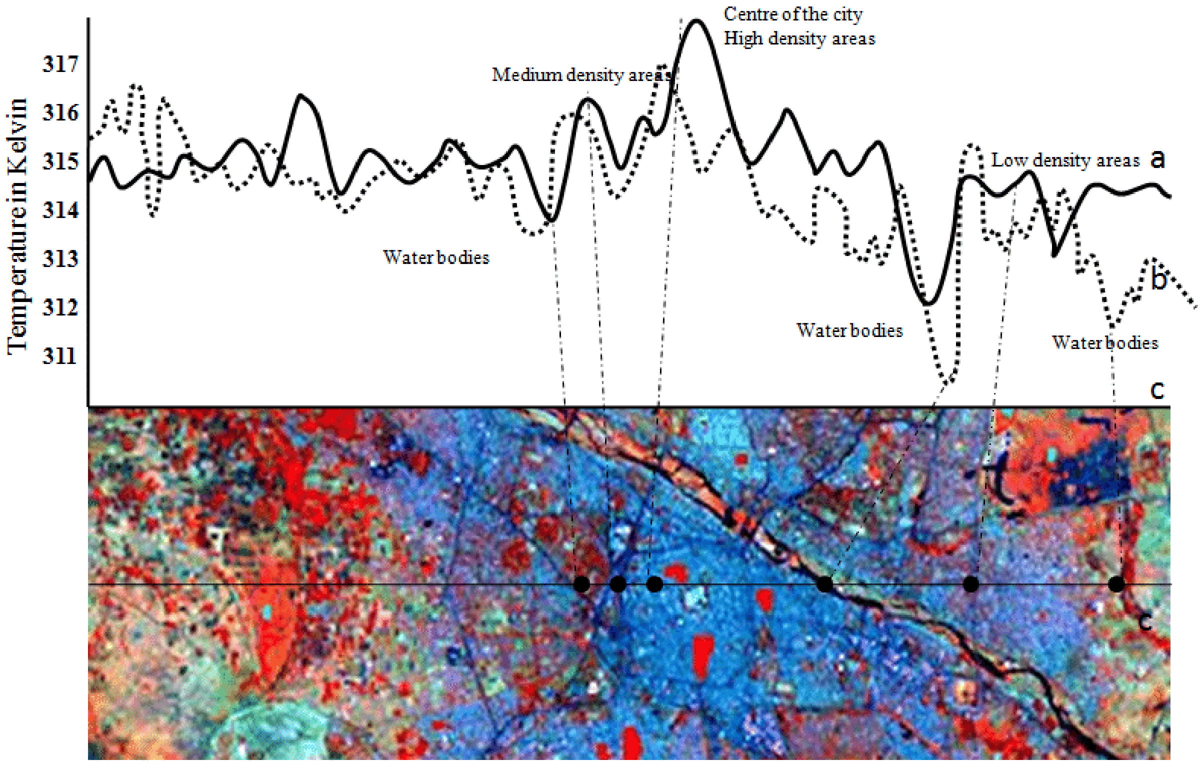
- Represents the temperature contrast in radiation between impervious and natural surfaces
- Usually most pronounced during daylight hours
- Their magnitude fluctuates with seasons, peaking typically in summer.
- Remote sensing in the thermal infrared (TIR) region of the electromagnetic spectrum is the primary method for measuring SUHIs.



https://www.pavetechinc.com/uhi-mitigation/

Atmospheric UHI

- Encompass phenomena occurring within the canopy layer or boundary layer.
- Canopy Layer Heat Island (CLHI) pertains to the atmospheric layer from the surface up to the tops of trees or buildings. CLHI is typically measured using in situ sensors installed on stationary meteorological stations or mobile traverses.
- Boundary Layer Heat Islands (BLHI) extend from the tops of trees or buildings to the point where urban landscapes cease to influence the atmosphere, roughly around 1.5 kilometers in height. BLHI is measured using tall towers, radiosondes, and aircraft.



Source: https://www.researchgate.net/publication/323181233_Study_and_analysis_of_efficient_green_cover_types_for_mitigating_the_air_temperature_and_urban_heat_island_effect/figures?lo=1

Types of urban heat islands

	Surface UHI	Atmospheric UHI
Time occurence	• Present throughout the entire day • Most intense during daytime in summer, especially during anticyclonic weather	• Insignificant/non-existent during the day • Most intense during the night, before dawn, in winter, during anticyclonic weather
Mean intensity	• Higher temperature, spatial, and temporal variability: • Day: 10 – 15 °C • Night: 5 – 10 °C	• Lower temperature, spatial, and temporal variability: • Day: -1 – 3 °C • Night: 7 – 12 °C
Identification method	• Indirect measurement: • Remote sensing of Earth • Manual thermal cameras	• Direct measurement: • Meteorological stations • Temperature data loggers (dataloggers)
Common representation	• Thermal image	• Isothermal maps, temperature tgraphs

Source: U.S. EPA (2017), Akbari (2009)

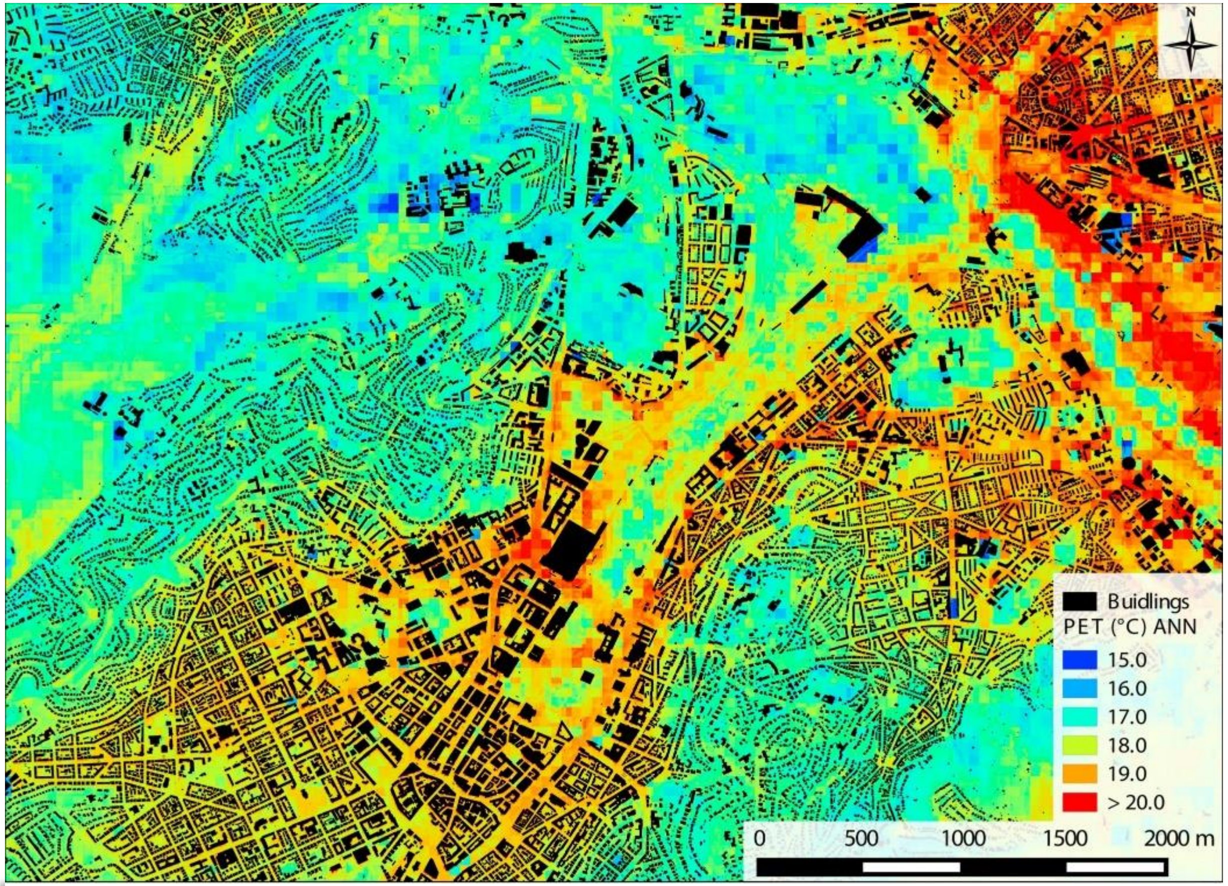
Consequences of the UHI

→ Climate change at both local and global scales:

- Depletion of groundwater
- Increased precipitation intensity leading to floods
- Soil erosion
- Formation of urban heat canyons
- Elevated concentration of carbon dioxide
- More frequent occurrence of fog
- Intensification of smog presence during the winter
- Increased risk of heat-related mortality and morbidity
- Disruption of ecosystems

→ Worsening of residents' thermal comfort

Methods of urban heat island detection



Meteorological data obtained through mobile transects using vehicles were used to derive a physiologically equivalent temperature map (PET) for the city of Stuttgart (Ketterer & Matzarakis, 2016).

Studies of the UHI are generally conducted using one of two approaches:

- Measurement of air temperature using networks of meteorological stations and mobile measurements along transects
- Measurement of surface temperature through aerial or satellite remote sensing.

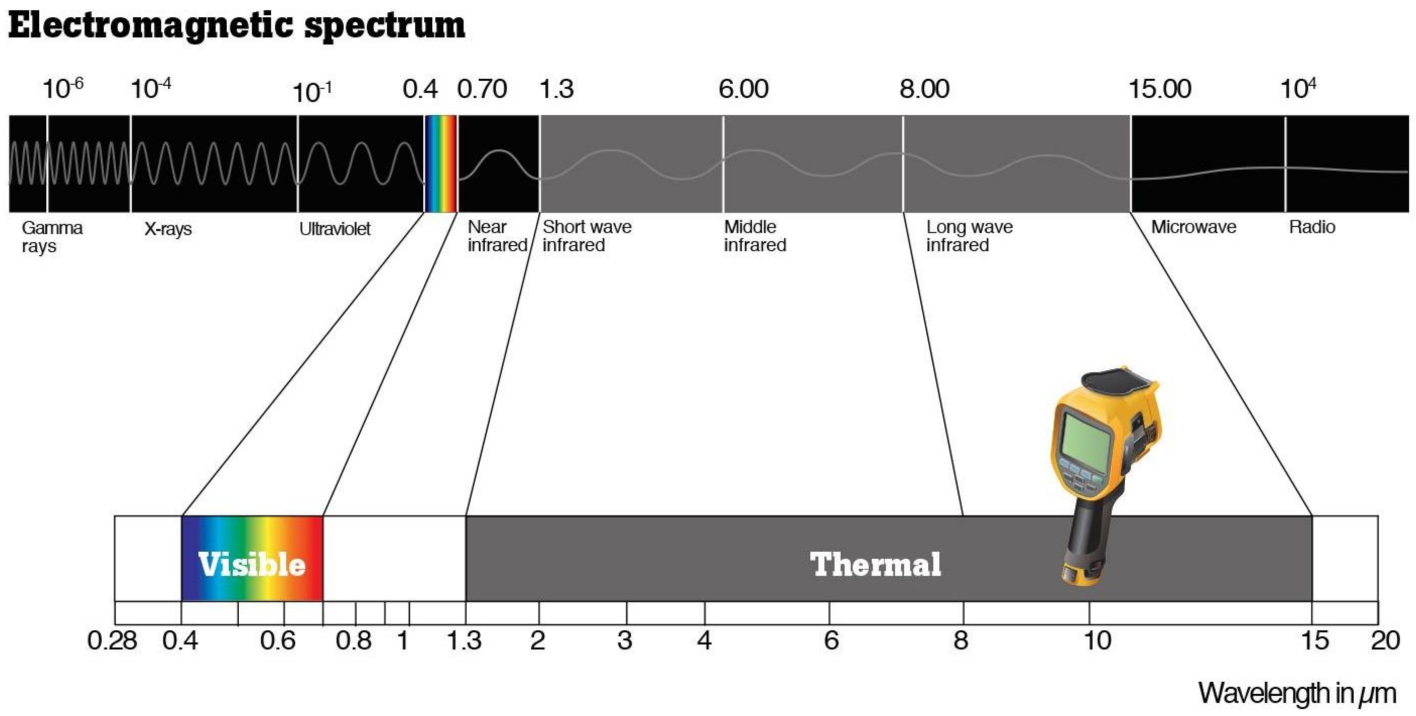
Distribution of surface temperature within the city of Sacramento in California. Image in the visible spectrum (left) and infrared spectrum (right). Source: NASA (2016).

Satellites and Sensors Used in Analyzing UHI

Remote Sensing of LST

- For Land Surface Temperature (LST) estimation, remote sensing typically utilizes wavelengths within the thermal infrared (TIR) spectrum

- Specifically, the wavelengths used for LST estimation usually fall within the range of approximately 8 to 14 µm that is particularly sensitive to thermal emissions from the Earth's surface and allows for accurate measurement of LST variations



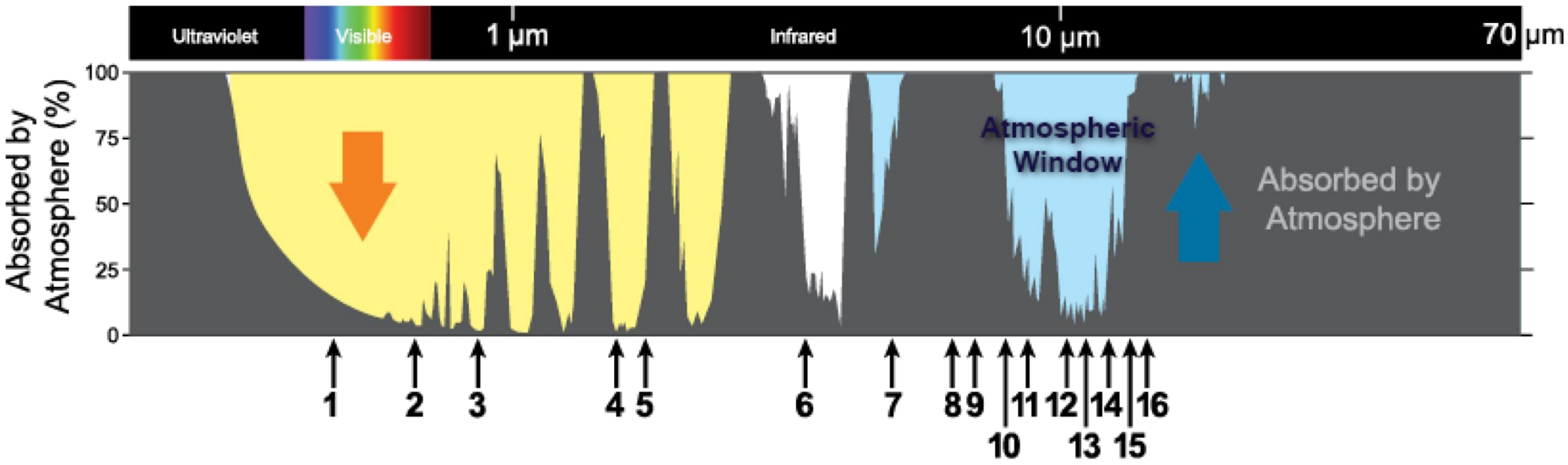
Source: https://reliabilityweb.com/articles/entry/a-practical-guide-to-emissivity-in-infrared-inspections

Satellites and Sensors Used in Analyzing UHI

Satellite TIR sensors measure the radiance emitted from the top of the atmosphere (TOA) by the Earth's surface and atmosphere. The TOA radiances are influenced by several factors:

- Surface emissivity: different surfaces have different emissivity values, which affect the amount of radiation emitted and detected by the satellite sensor
- Atmospheric attenuation: the presence of water vapor and aerosols in the atmosphere can absorb or scatter thermal infrared radiation, affecting the amount of radiation reaching the satellite sensor
- Sensor viewing angle: The angle at which a satellite sensor receives radiation from the Earth's surface also influences the observed radiance

Satellites and Sensors Used in Analyzing UHI



- **Atmospheric Window:** Between 10-12 micrometers, the atmosphere exhibits minimal absorption of infrared (IR) radiation emitted by the land surface. Consequently, this spectral range is utilized for Land Surface Temperature (LST) derivation.
- Multiple polar orbiting and geostationary satellites are equipped with sensors that observe in one or more bands within this infrared (IR) spectral range.

Satellites and Sensors Used in Analyzing UHI

Satellite	Sensor	Temporal Coverage
Landsat 4 Landsat 5 Landsat 7 Landsat 8	Thematic Mapper (TM) Enhanced Thematic Mapper (ETM+) Operational Land Imager (OLI) Thermal Infrared Sensor (TIRS)	07/1982 -12/1993 03/1984 - 01/2013 04/1999 - Present 02/2013 – Present
Terra Aqua	Advanced Spaceborne Thermal Emission and Reflection Radiometer(ASTER) & MODIS MODerate-resolution Imaging Spectroradiometer (MODIS)	12/1999 - Present 04/2002 - Present
ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)	Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR)	06/2018 - Present

Satellites and Sensors Used in Analyzing UHI

Satellite	Sensor	Temporal Coverage
Suomi National Polar Partnership (NSPP) Joint Polar Satellite System-1 (NOAA 20)	Visible Infrared Imaging Radiometer Suite (VIIRS)	10/2011 - Present 11/2018 – Present
NOAA Operational Series Current: NOAA 15,18,19 ESA- Metop-A & B	Advance Very High-Resolution Radiometer (AVHRR)	1979 - Present
NOAA Geostationary Operational Environmental Satellites (GOES) Current: GOES-16 & GOES-17	Imager & Sounder Advance Baseline Imager (ABI)	1975 - Present
ESA - Sentinel 3A & 3B	Sea and Land Surface Temperature Radiometer (SLSTR)	02/2016 - Present 04/2018 - Present
ESA - Sentinel 2A & 2B	MultiSpectral Instrument (MSI)	07/2015 - Present 03/2017 - Present

Spectral bands for LST mapping

Sensor	Spectral Bands (µm)	Spatial Resolution	Temporal Resolution	Sensor	Spectral Bands (µm)	Spatial Resolution	Temporal Resolution
TM ETM+ TIRS	10.40 - 12.50 10.40 - 12.50 10.60 - 11.19 11.50 - 12.51	120 m (30 m) 60 m (30 m) 100 m 100 m	16 days	VIIRS	10.26 - 11.26 11.54 - 12.49	750 m	12 hours
MODIS	10.78 - 11.28 11.77 - 12.27	1 km	12 hours	AVHRR	10.30 - 11.30 11.5 - 12.50	1 km & 4 km	
ASTER	10.25 - 10.95 10.95 - 11.65	90 m	12 hours	VISSR ABI	10.10 - 10.60 **10.80 - 11.60** **11.80 -12.80** 13.0 - 13.6	2 km CONUS and Full Disk	minutes, hours, day/night
PHyTIR	8.28, 8.79, 9.06, 10.5, 12.05	60 m CONUS only	varies/ every few days	SLSTR	10.45 - 11.24 11.57 - 12.48	1 km	12 hours

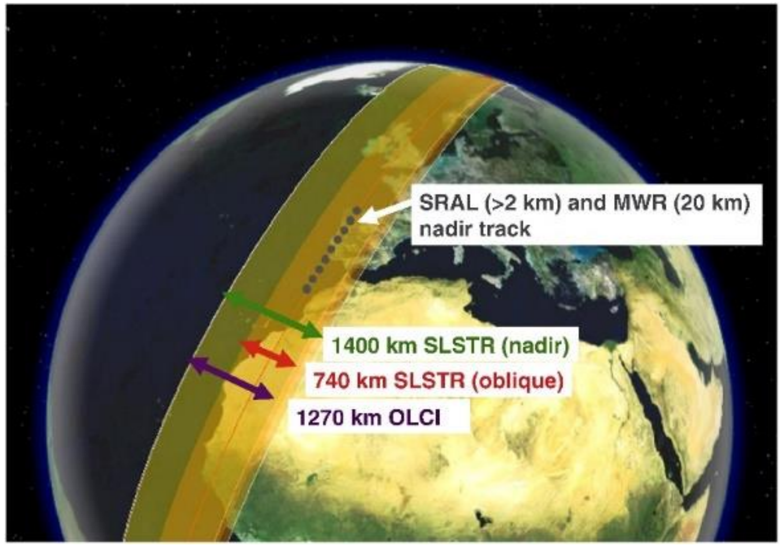
Sentinel-3 – A bigger picture

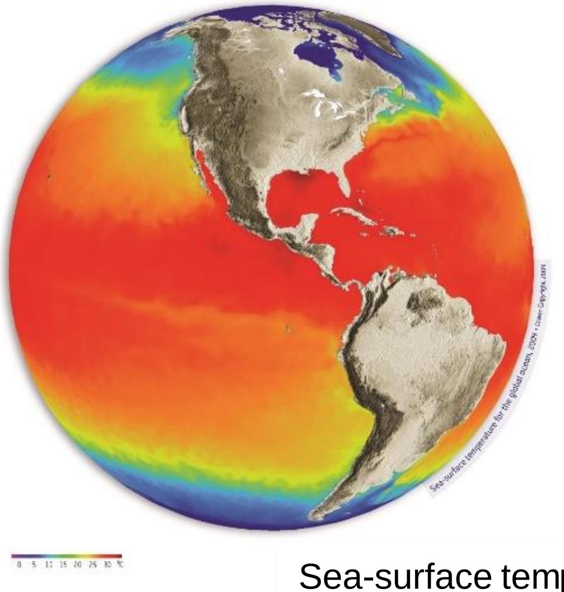
Mission objectives:

- Ocean, inland sea, coastal zone colour measurements
- Sea surface temperature measurements
- Sea surface topography measurements

Mission profile:

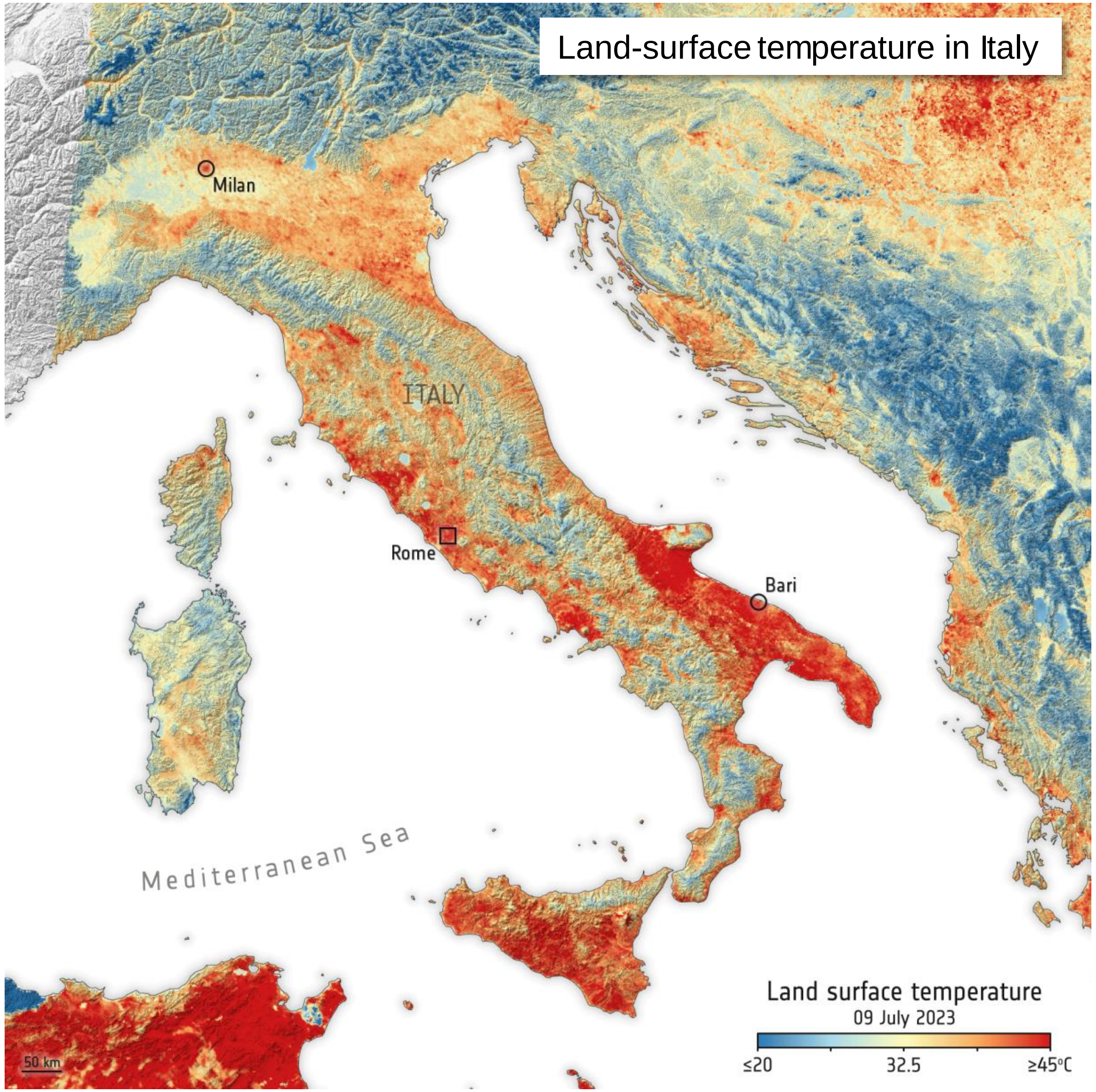
- Operational mission in high-inclination, low Earth orbit
- Orbital cycle is 27 days
- Ocean and Land Colour Instrument (OLCI),
  Sea and Land Surface Temperature Radiometer (SLSTR),
  SAR Radar Altimeter (SRAL),
  MicroWave Radiometer (MWR)
  and Precise Orbit Determination (POD) instruments
- Full performance achieved with 2 satellites in orbit

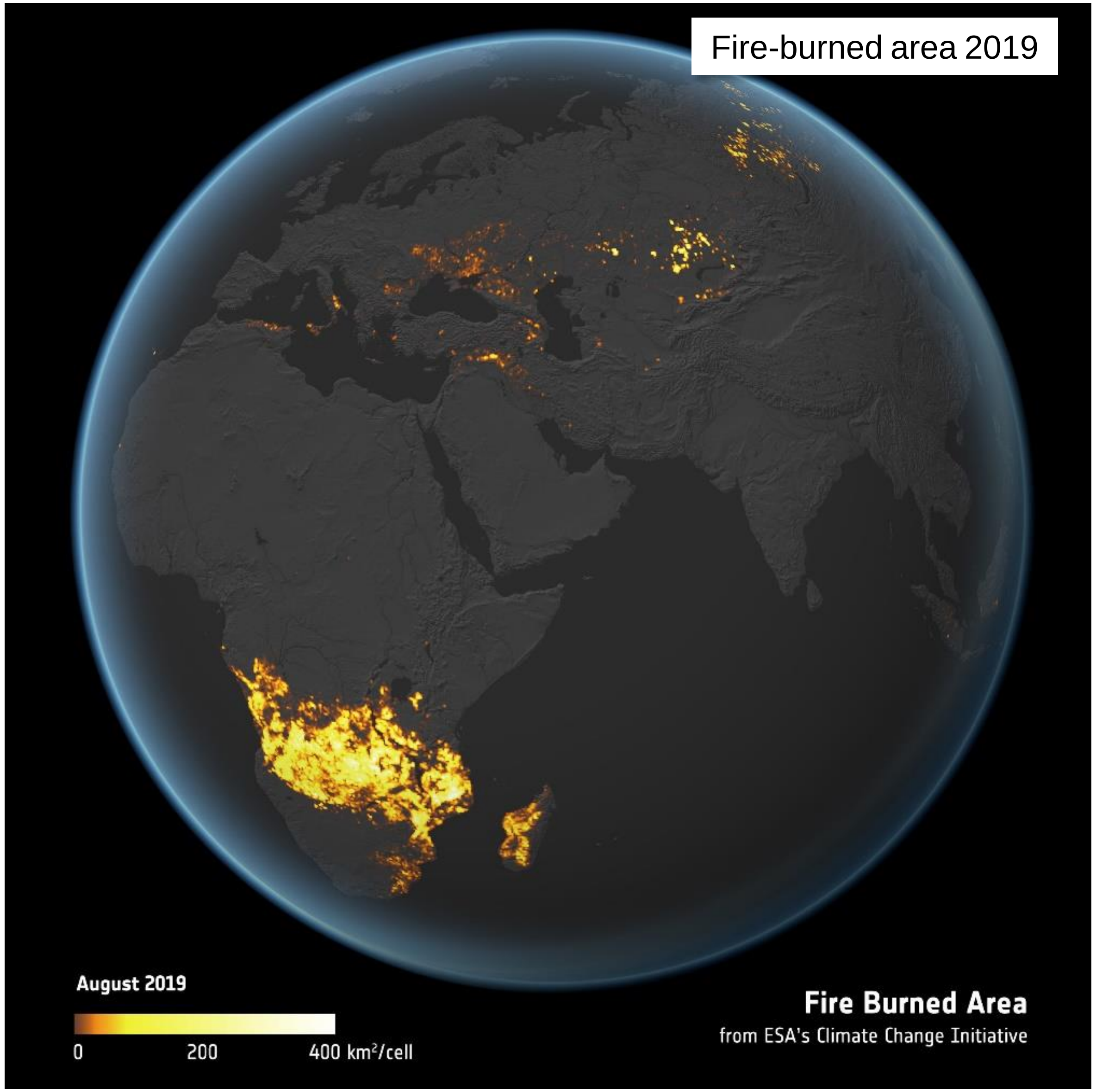




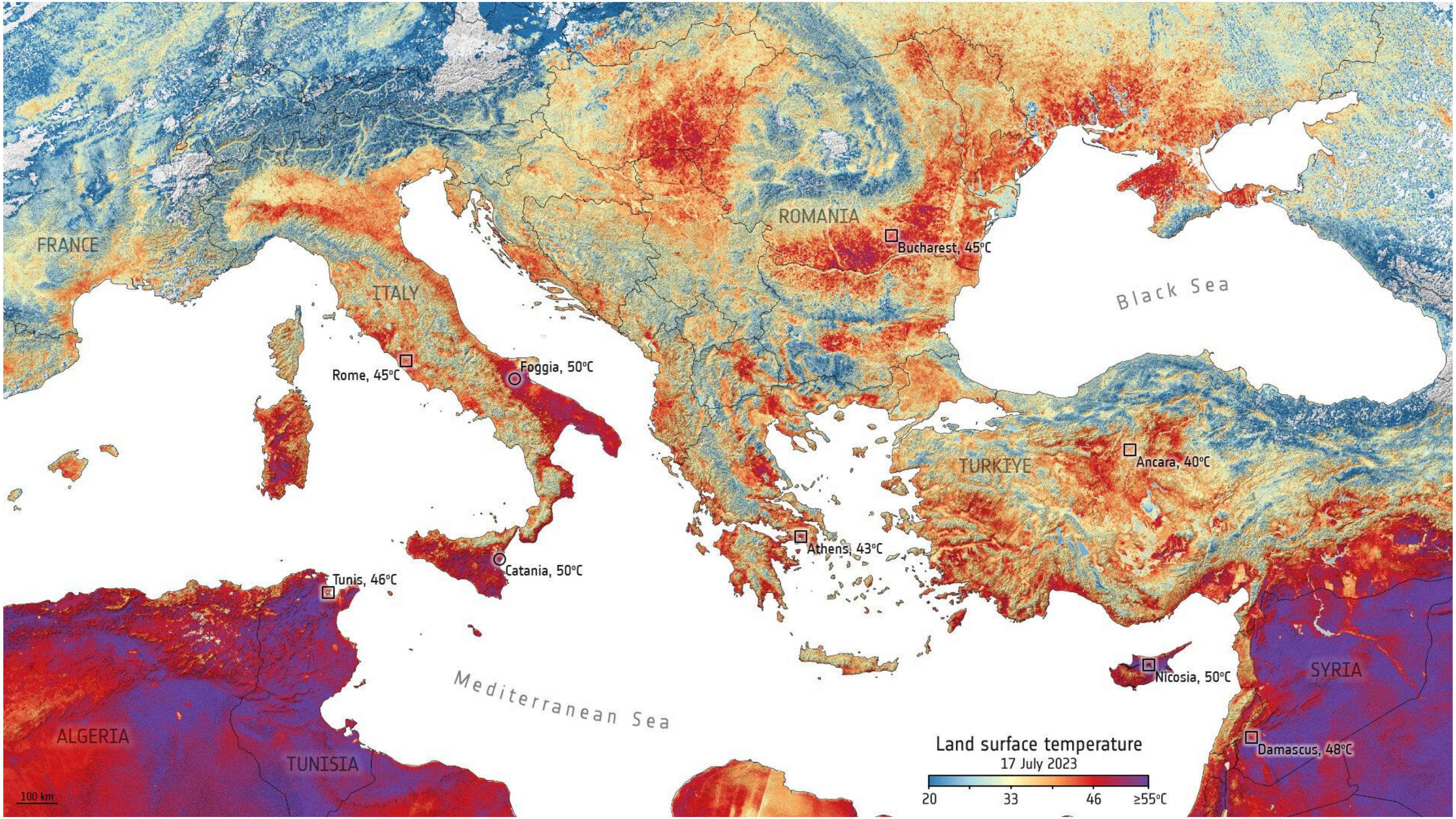
Sea-surface temperature

Sentinel-3 – Applications

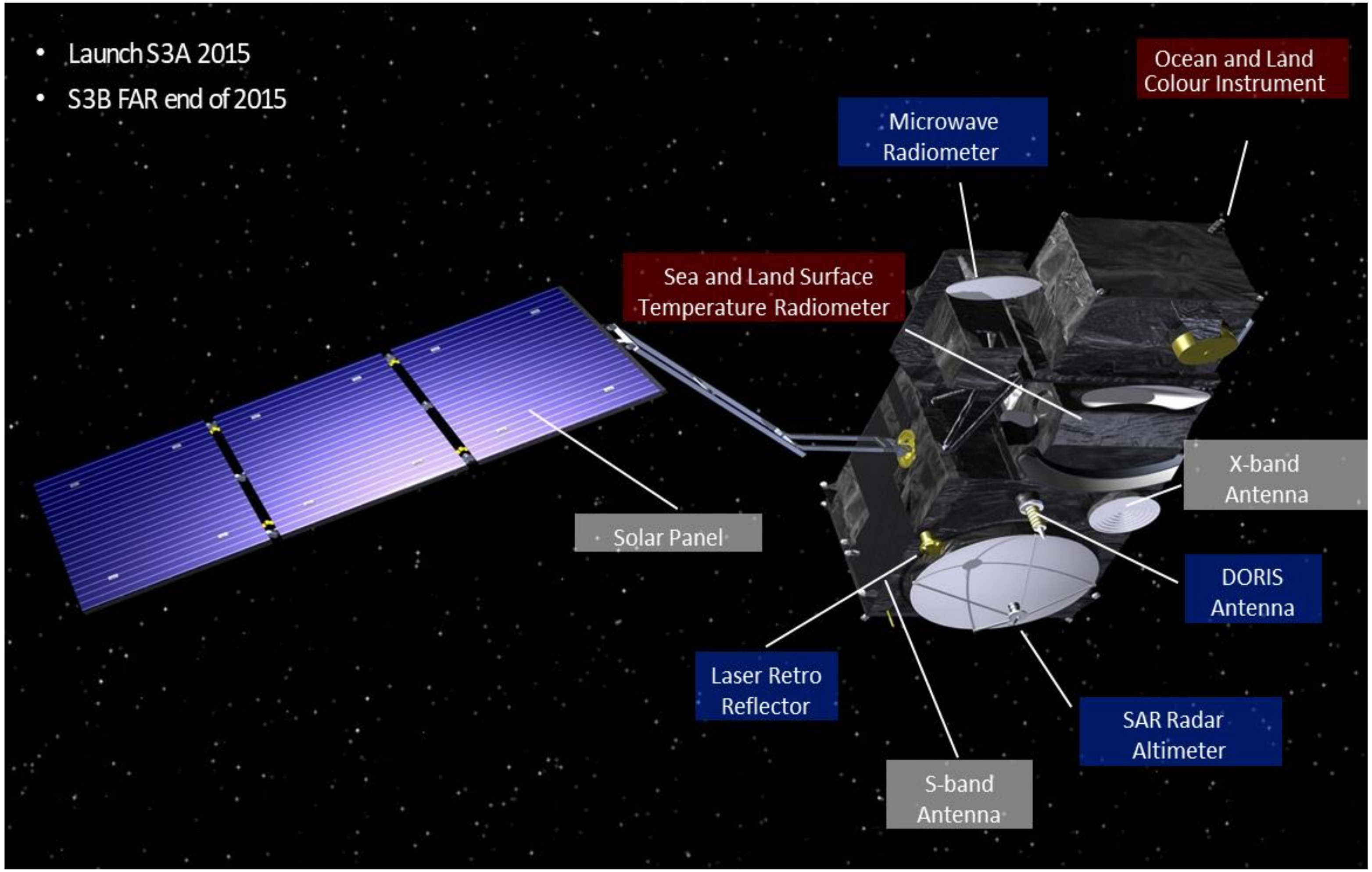




Sentinel-3 – Applications



Sentinel-3 Mission



•**Ocean and Land Colour Instrument (OLCI)** - 5 cameras, 8 bands (VIS) for open ocean (low res), 15 bands (only VIS) for coastal zones (high res). Spatial sampling: 300m → *MERIS follow-on*

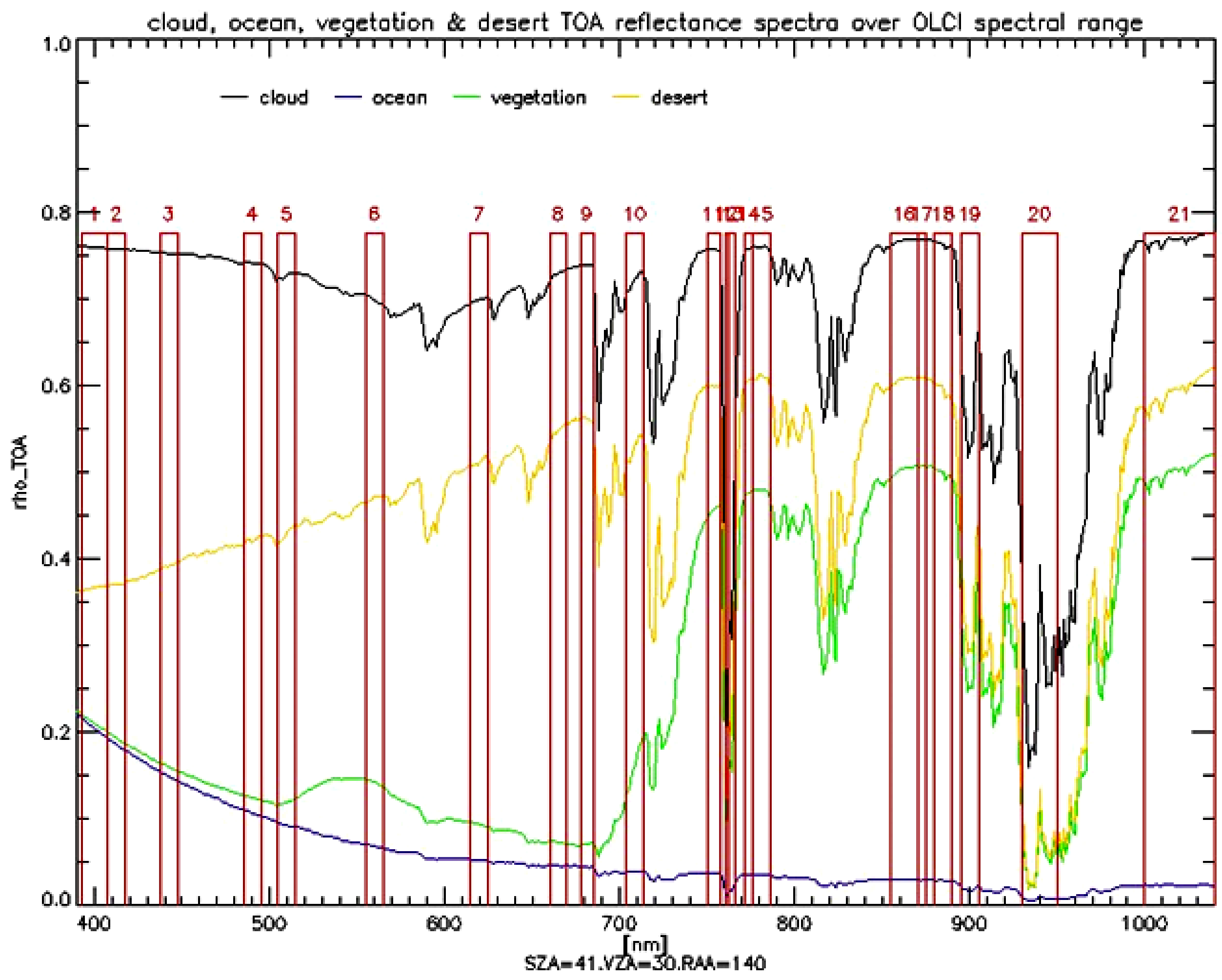
•**Sea and Land Surface Temperature (SLST)** with 9 spectral bands, 0.5 (VIS, SWIR) to 1 km res (MWIR, TIR). Swath: 180rpm dual view scan, nadir & backwards → *ATSR follow-on*

•**Radar Altimeter package** - SRAL Ku-C altimeter (LRM and SAR measurement modes), MWR, POD (with Laser Retro Reflector and DORIS)

•

OLCI instrument

Channel	Central wavelength (nm)	Width (nm)
1	400	15
2	412.5	10
3	442.5	10
4	490	10
5	510	10
6	560	10
7	620	10
8	665	10
9	681.25	7.5
10	708.75	10
11	753.75	7.5
12	761.25	2.5
13	764.375	3.75
14	773.75	5
15	781.25	10
16	862.5	15
17	872.5	5
18	885	10
19	900	10
20	940	20
21	1020	40



SLST instrument

Sea & Land Surface Temperature Radiometer

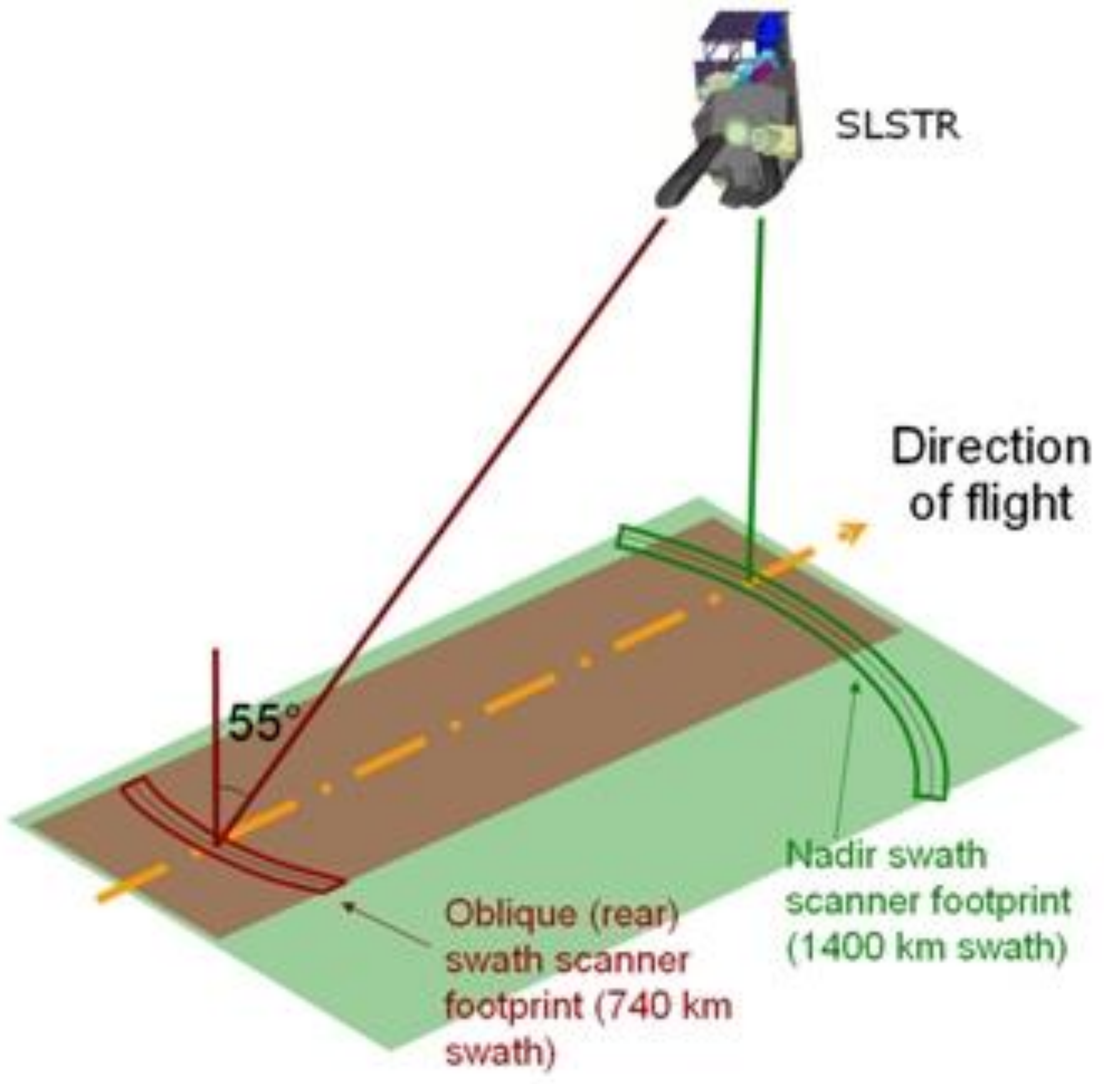
Dual-view (nadir & backward) required for aerosol corrections:

Nadir swath >74° (up to 1800 km)
Dual view swath 49° ~ 750 km
Nadir swath covering OLCI

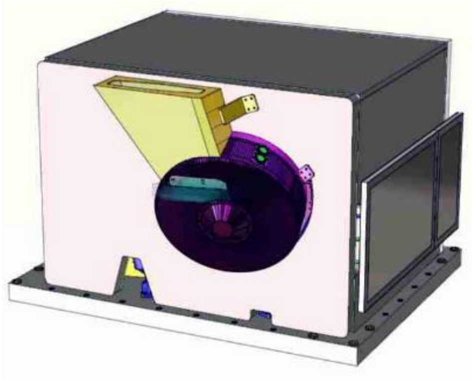
9 spectral bands:

3 Visible : 555 – 659 – 865 nm
3 SWIR : 1.38 – 1.61 – 2.25 µm
3 TIR : 3.74 – 10.85 – 12 µm

One Vis/IR channel used for co-registration with OLCI

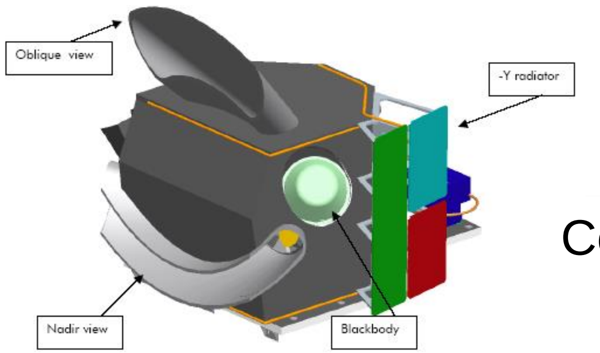


OLCI and SLST spatial resolution



Pushbroom type imager spectrometer
21 Spectral Channels
Full Resolution: Coastal/Land
Reduced Resolution: Open Ocean

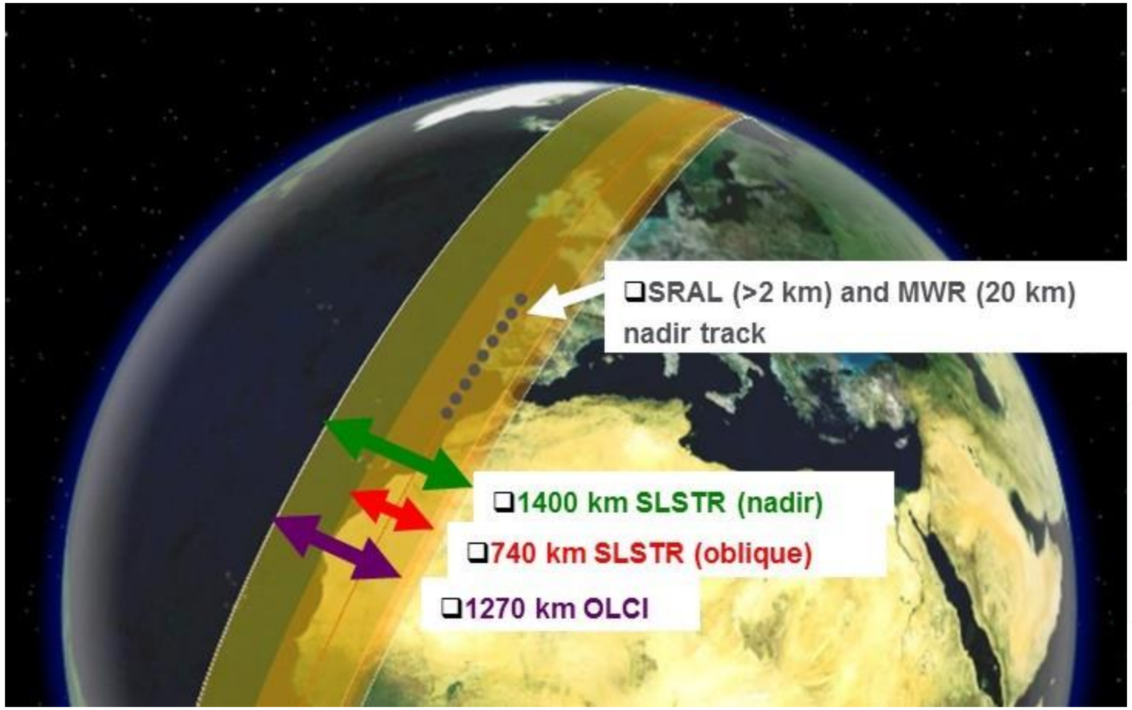
OLCI – Open ocean	**1.2 km**
OLCI – Coastal ocean	**300 m**
OLCI - Land	**300 m**
SLST – Solar channels	**500 m**
SLST – Thermal channels	**1 km**



Conical scanning imaging radiometer with dual view capability:
- Near-nadir view
- Inclined view with an OZA of 55º ± 0.1º

9 Spectral Channels + 2 (option) for Active FIRE

Sentinel-3 – revisit capability



Orbit type	❑ Repeating frozen SSO
Repeat cycle	❑ 27 days (14 + 7/27 orbits/day)
LTDN	❑ 10:00 hr
Average altitude	❑ 815 km
Inclination	❑ 98.65 deg

Optical missions:

Short Revisit times for optical payload, even with 1 single satellite

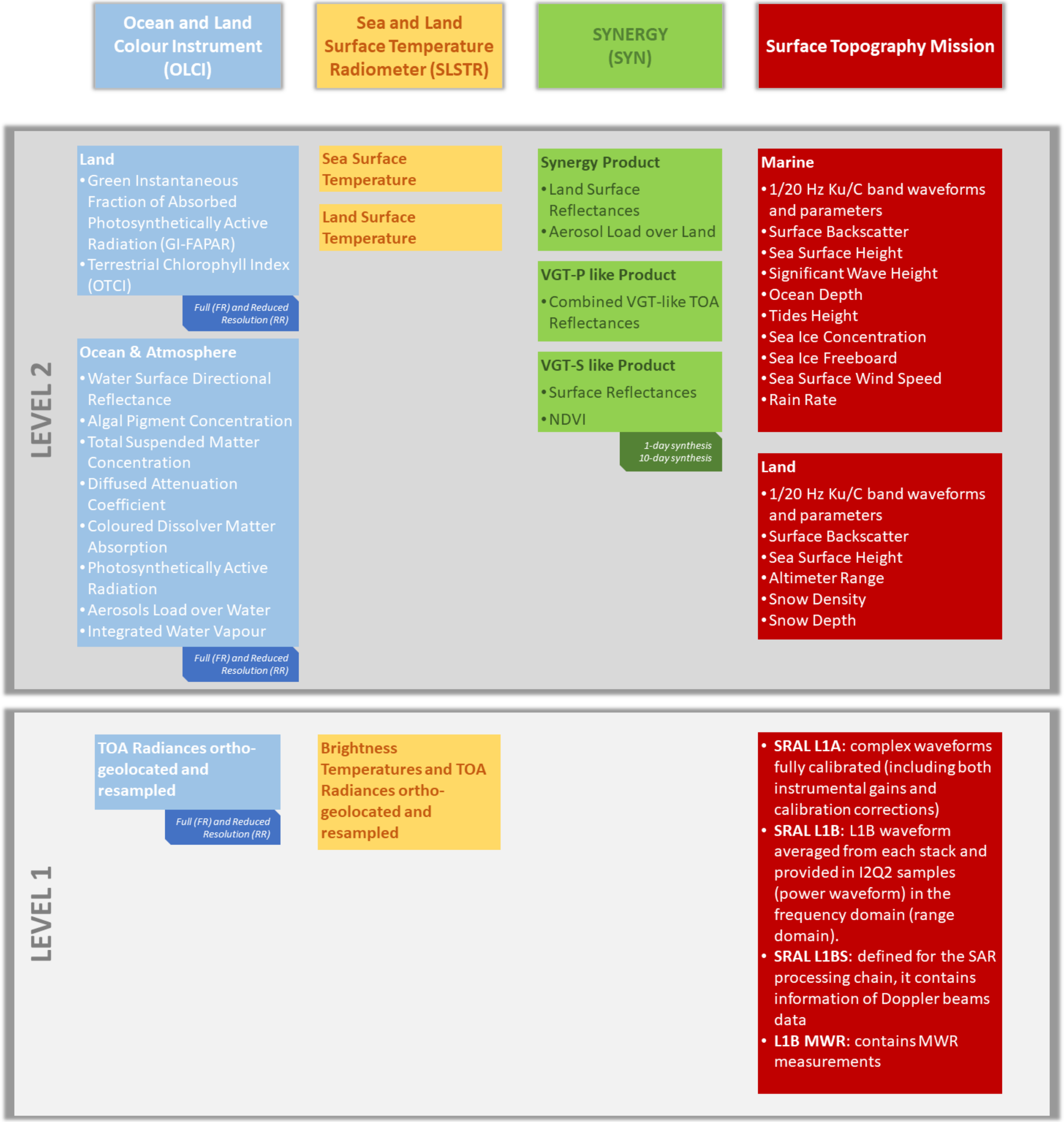
		Revisit at Equator	Revisit for latitude >30°	Specification
Ocean Colour (Sun-glint free)	1 Satellite	< 3.8 days	< 2.8 days	< 2 days
	2 Satellite	< 1.9 days	< 1.4 days	
Land Colour	1 Satellite	< 2.2 days	< 1.8 days	< 2 days
	2 Satellite	< 1.1 day	< 0.9 day	
SLST dual view	1 Satellite	< 1.8 days	< 1.5 days	< 4 days
	2 Satellite	< 0.9 day	< 0.8 day	

Sentinel-3 Product Structure

Sentinel-3 Core Land Products :

Sentinel-3 core products play a crucial role in monitoring and understanding Earth's oceans, land surfaces, and atmosphere, contributing to efforts to address global environmental challenges and ensure the sustainable management of natural resources.

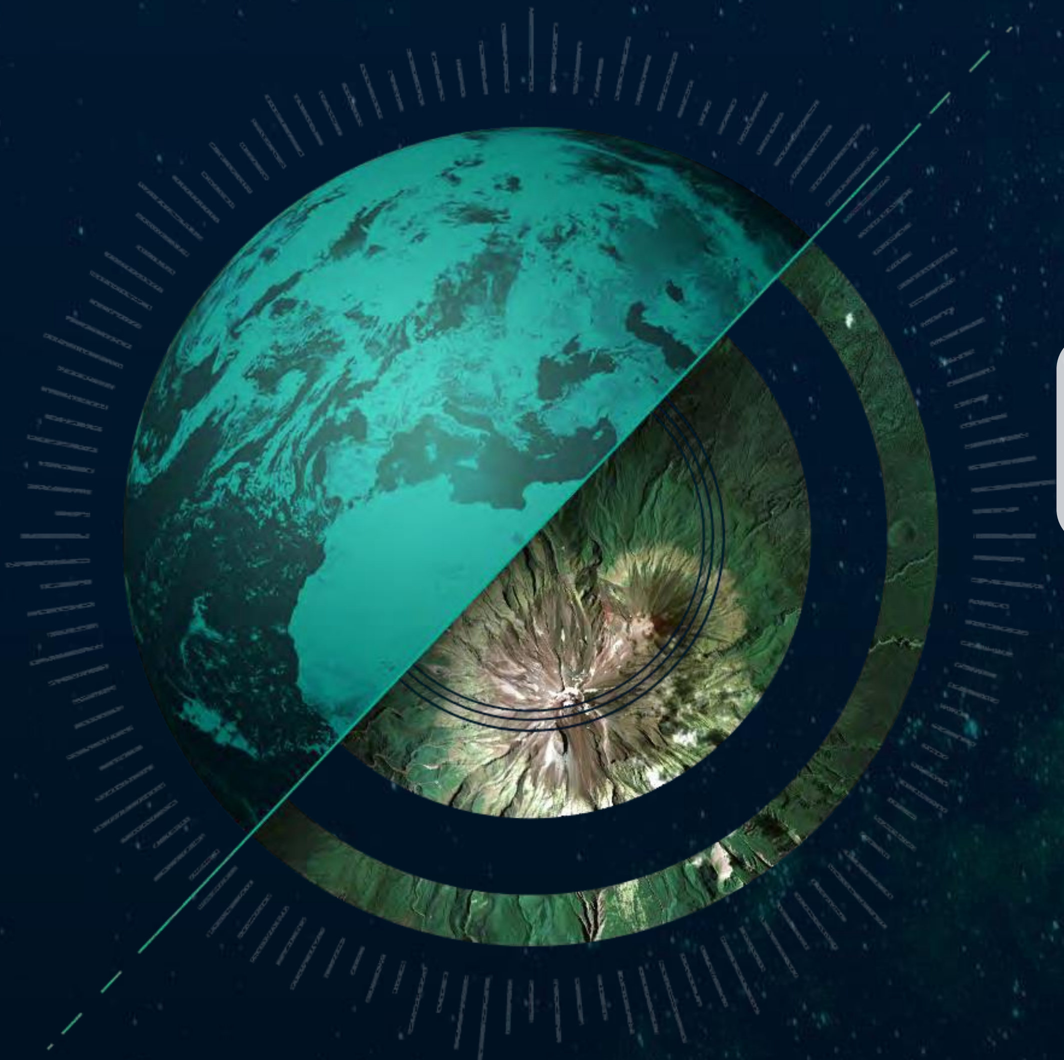
For more information, see the tutorial:
[10. Land surface temperature mapping using Sentinel-3 data using SNAP software]



esa space solutions

Copernicus Academy

ÚSTAV GEOGRAFIE
Prírodovedecká fakulta UPJŠ v Košiciach

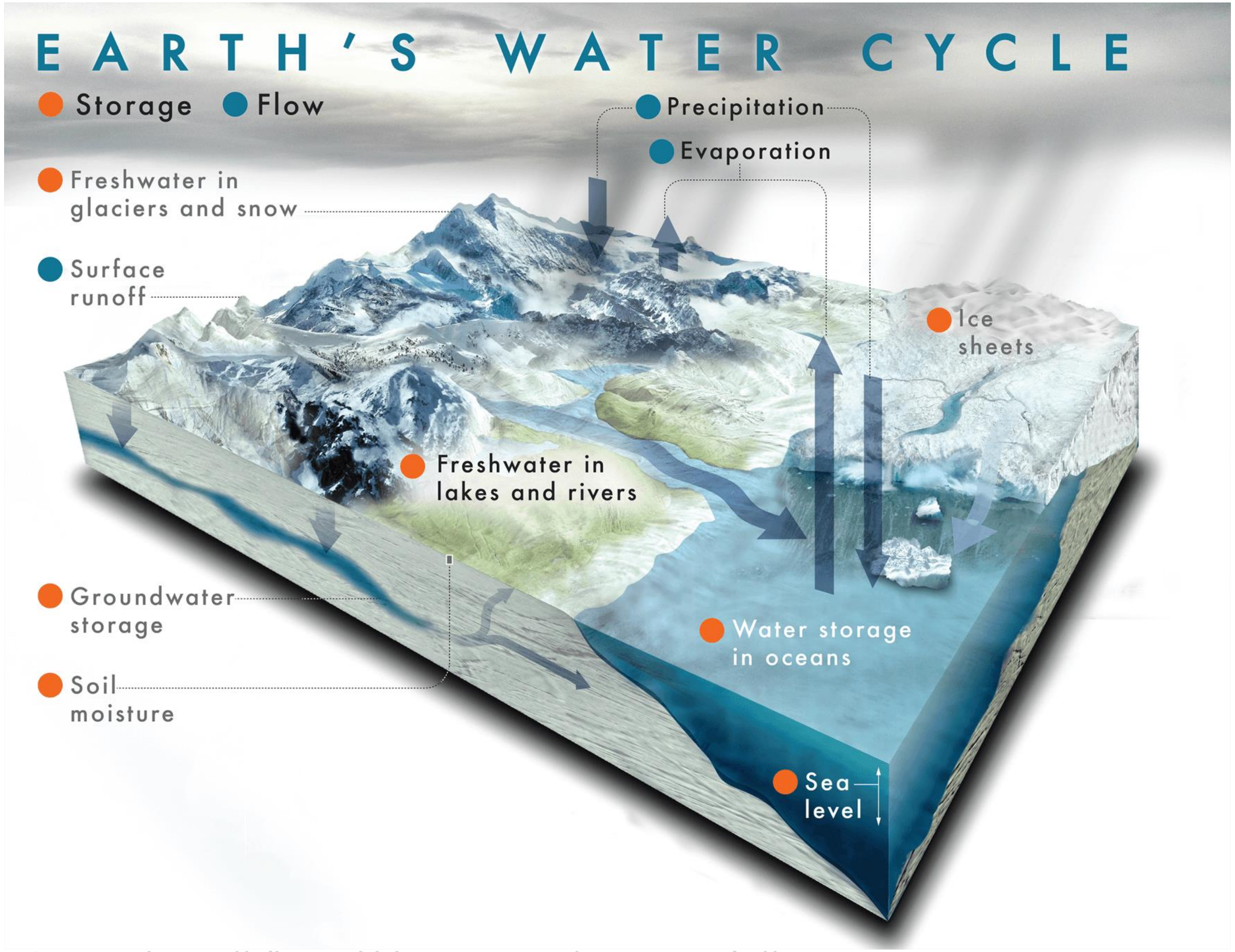


11. Snow and ice cover mapping using ESA Sentinel-1 and Sentinel-2 data

Why do we need information about snow and 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 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/

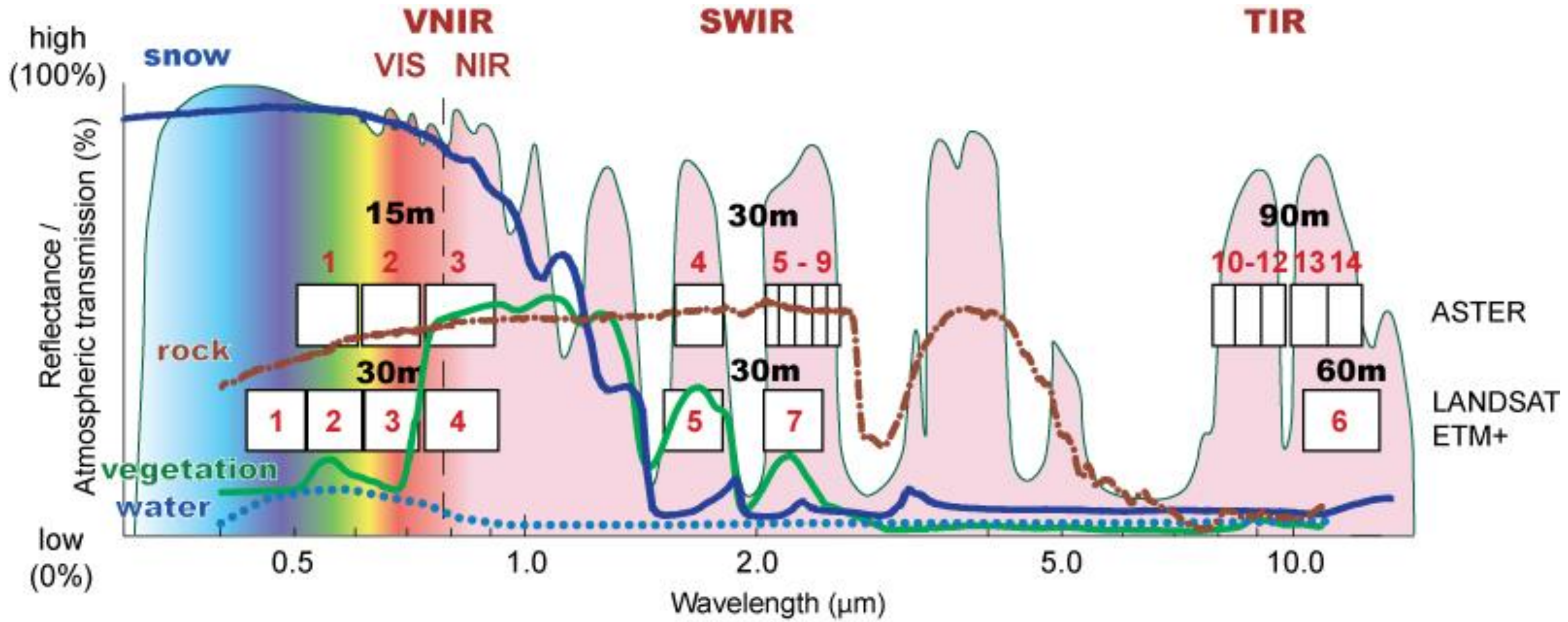
Typical densities of snow and ice

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 and 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

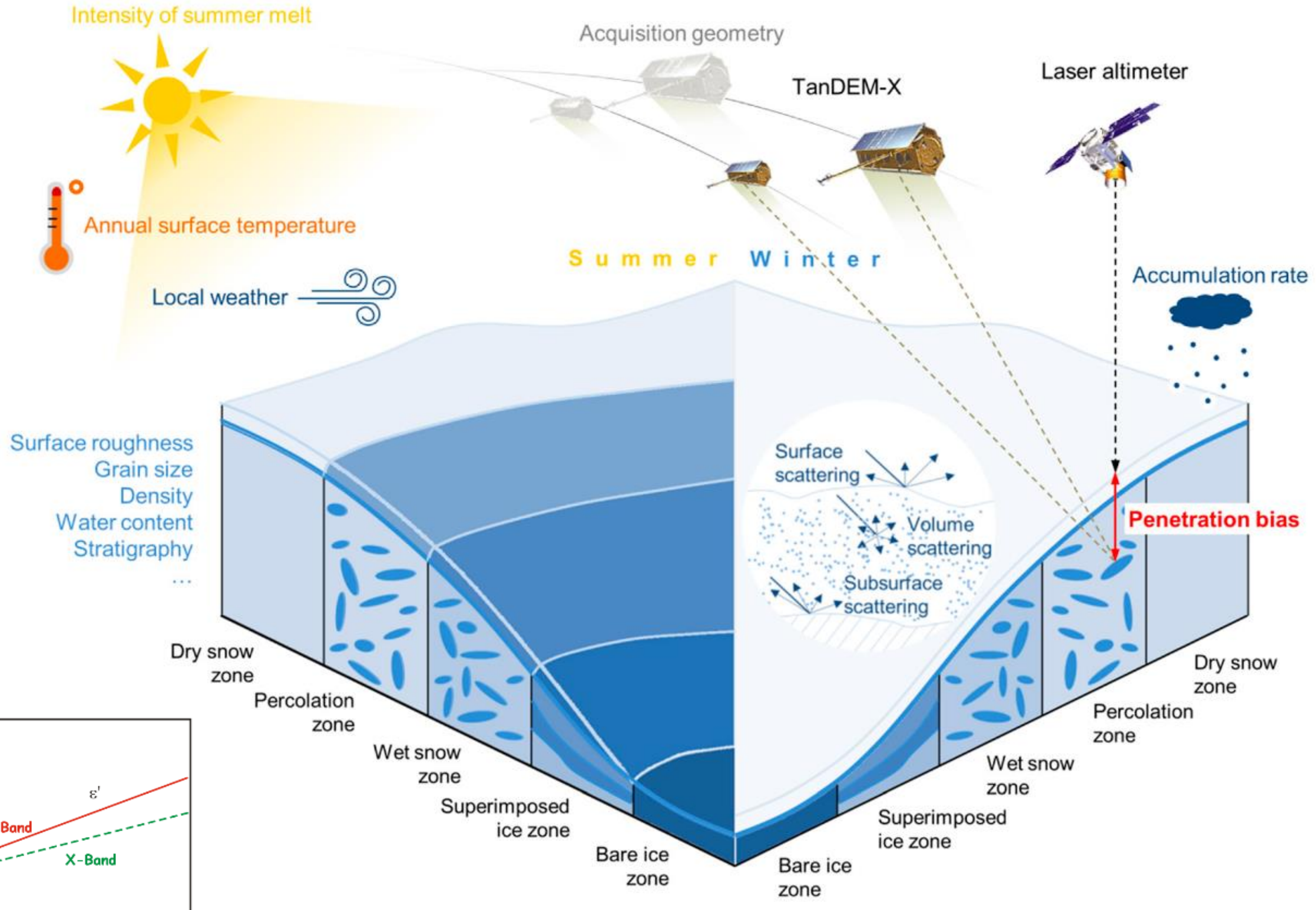


Radar for snow and ice

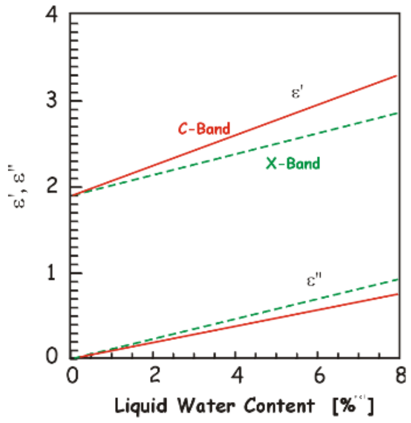
Sensor	*Satellite*	*[GHz].*	*Resolution/Swath*	*Repeat*
AMI	ERS-1,-2(1991-2011)	5.3 VV	25 m - 100 km	35d/1 d
SIR-C/X-SAR	Shuttle (1994)	1.2,5.3,9.6	25 m - 40 km	2 Campaigns
SIR-C/X-SAR	SRTM (Feb.2000)	5.3 & 9.6	50/100 m - 100/200 DEM	
Present				
SAR	Radarsat1(1995-)	5.3	10,30,100 m - 100-500 km	24 d
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



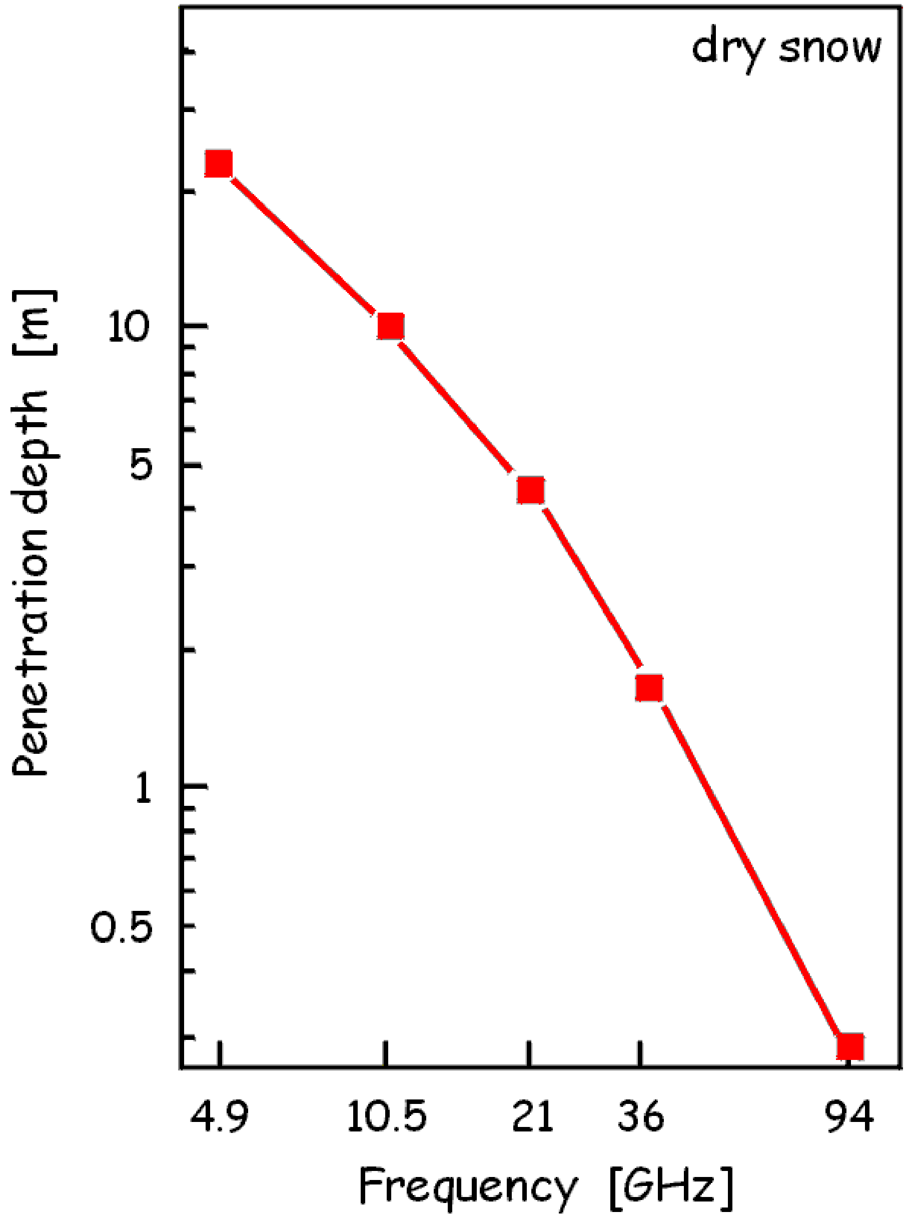
Microwave Permittivity

Microwave Penetration Depth in Dry Snow

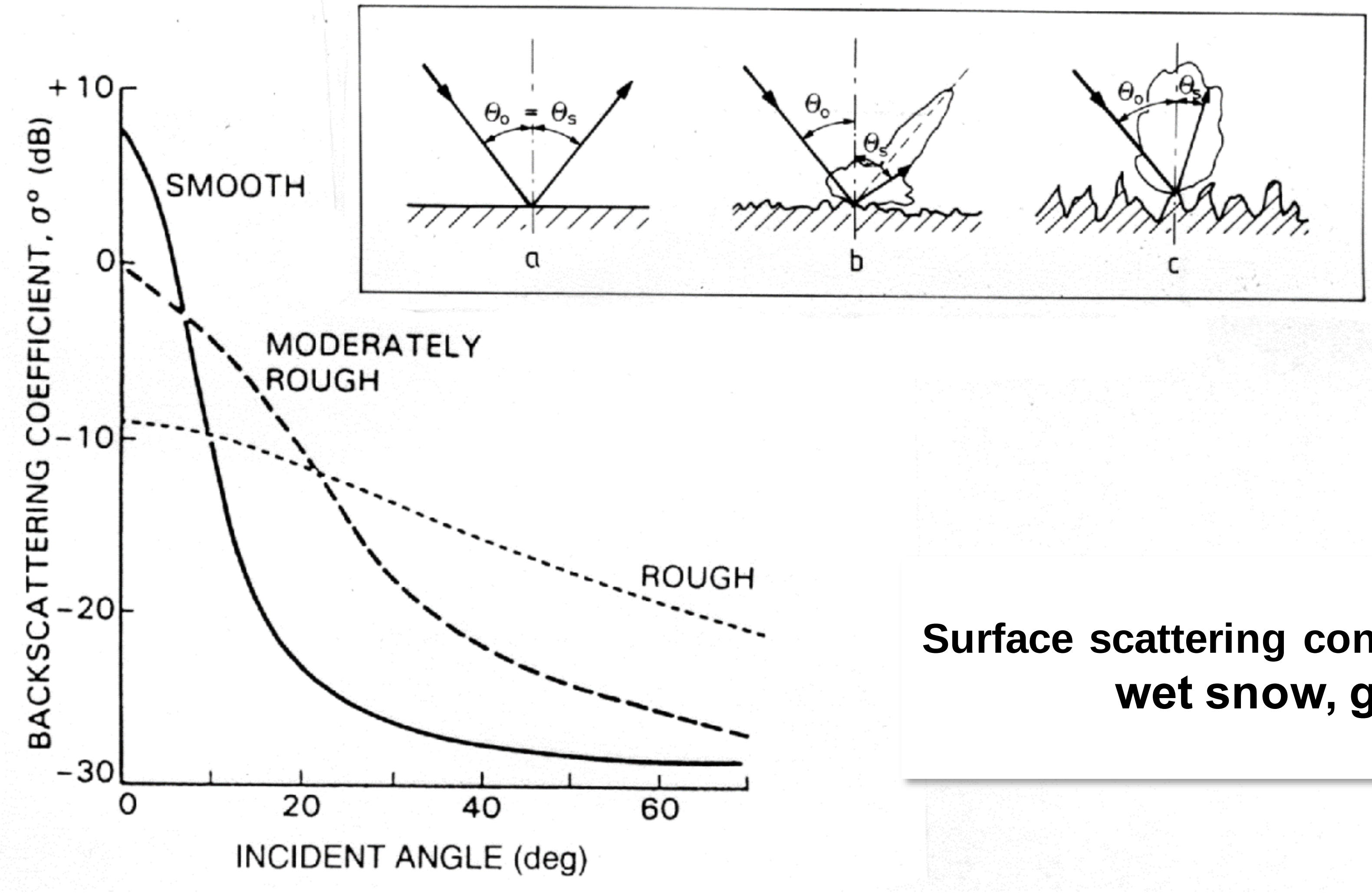
Measured by microwave radiometry:

- 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

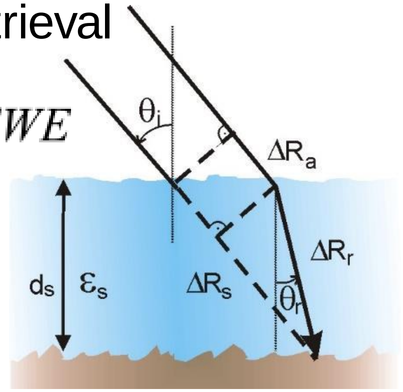
- **Volume inhomogeneities (grains, grain clusters, ice lenses, ice pipes, ..)**
- **Internal interfaces between snow layers of different density**

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

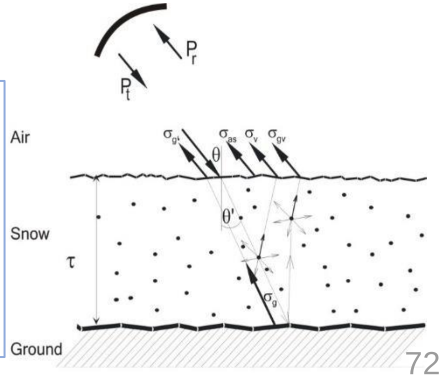
$$\Delta\phi_{snow} = \frac{1.6k}{\cos\theta_i}\Delta SWE$$



Radar (Scat or SAR)

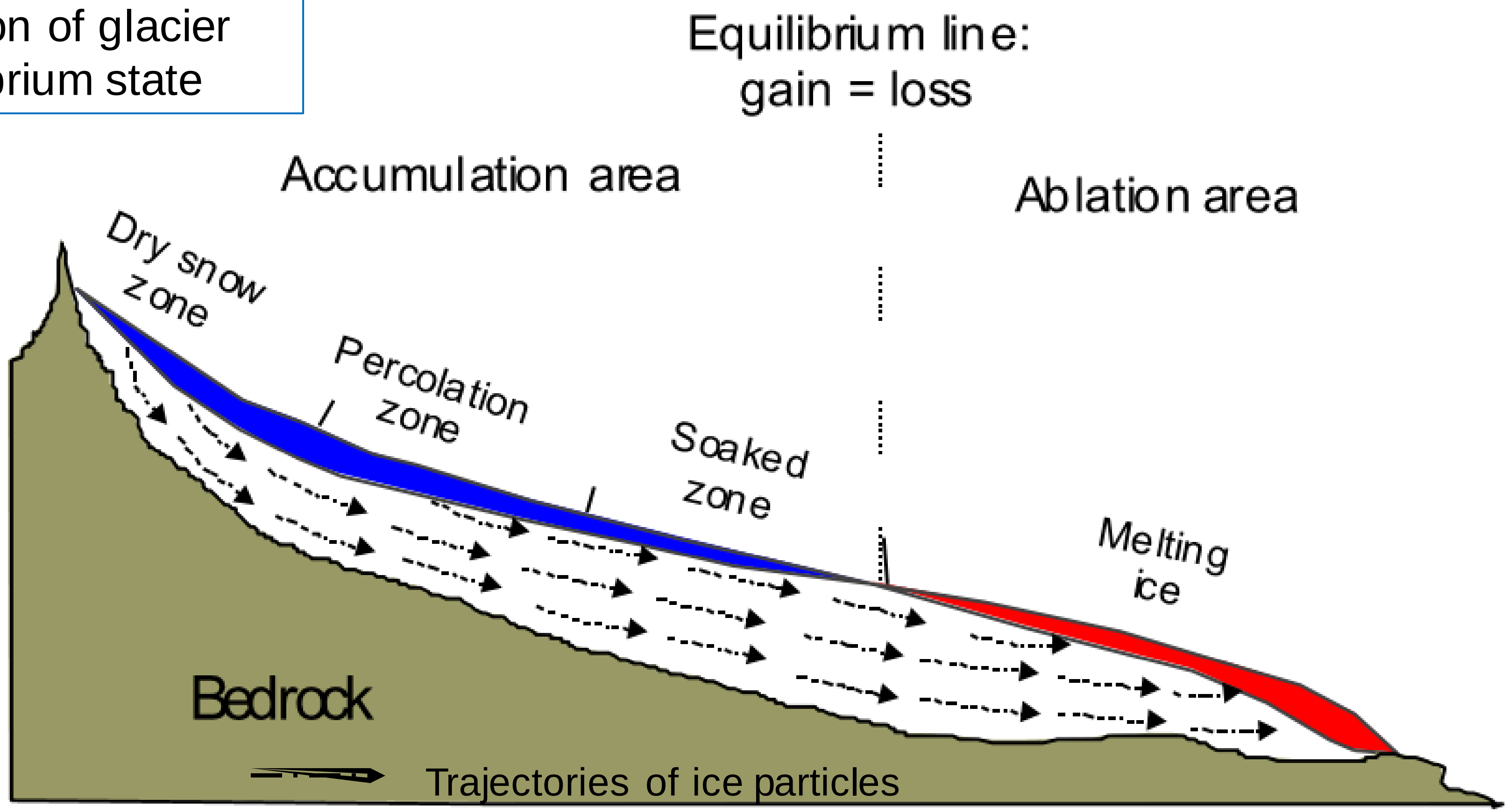
Sensitivity of backscatter to SWE depends on scattering albedo:

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



Glacier Motion by InSAR and Offset Tracking

Ice motion of glacier
in equilibrium state

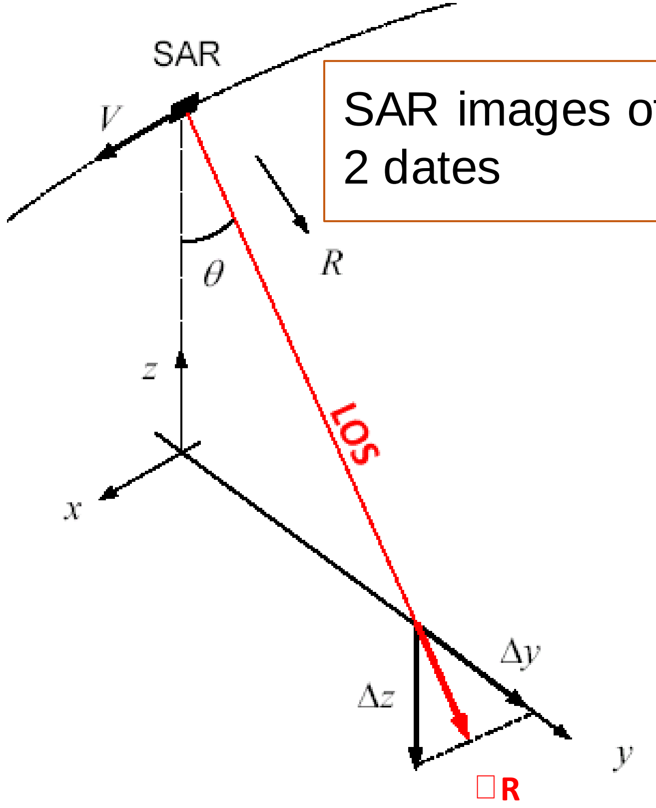


Objectives for mapping Ice Motion:

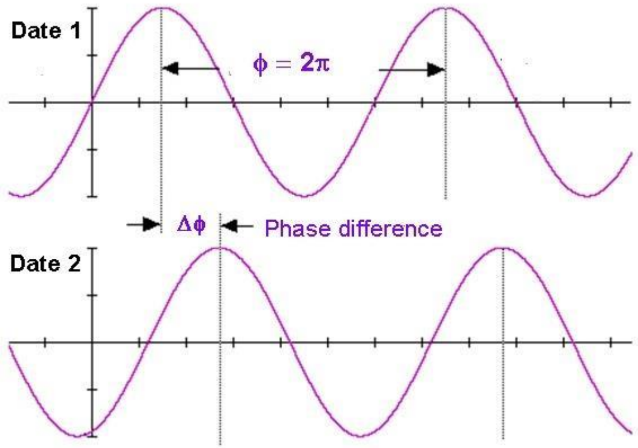
- Retrieving ice export by calving (Input/Output method for mass balance)

Interferometric measurement of displacement

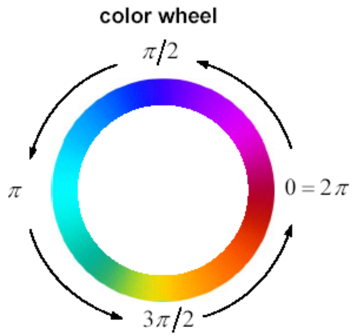
Measurement of Displacement



SAR images of 2 dates

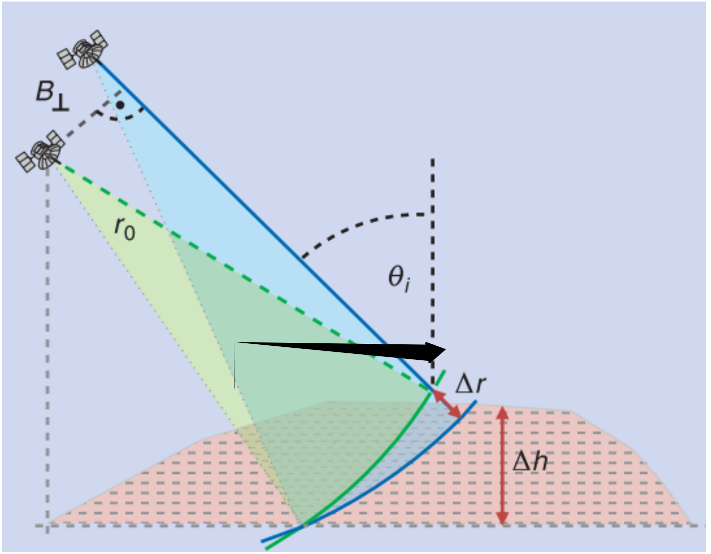


1 Fringe



TanDEM-X

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.

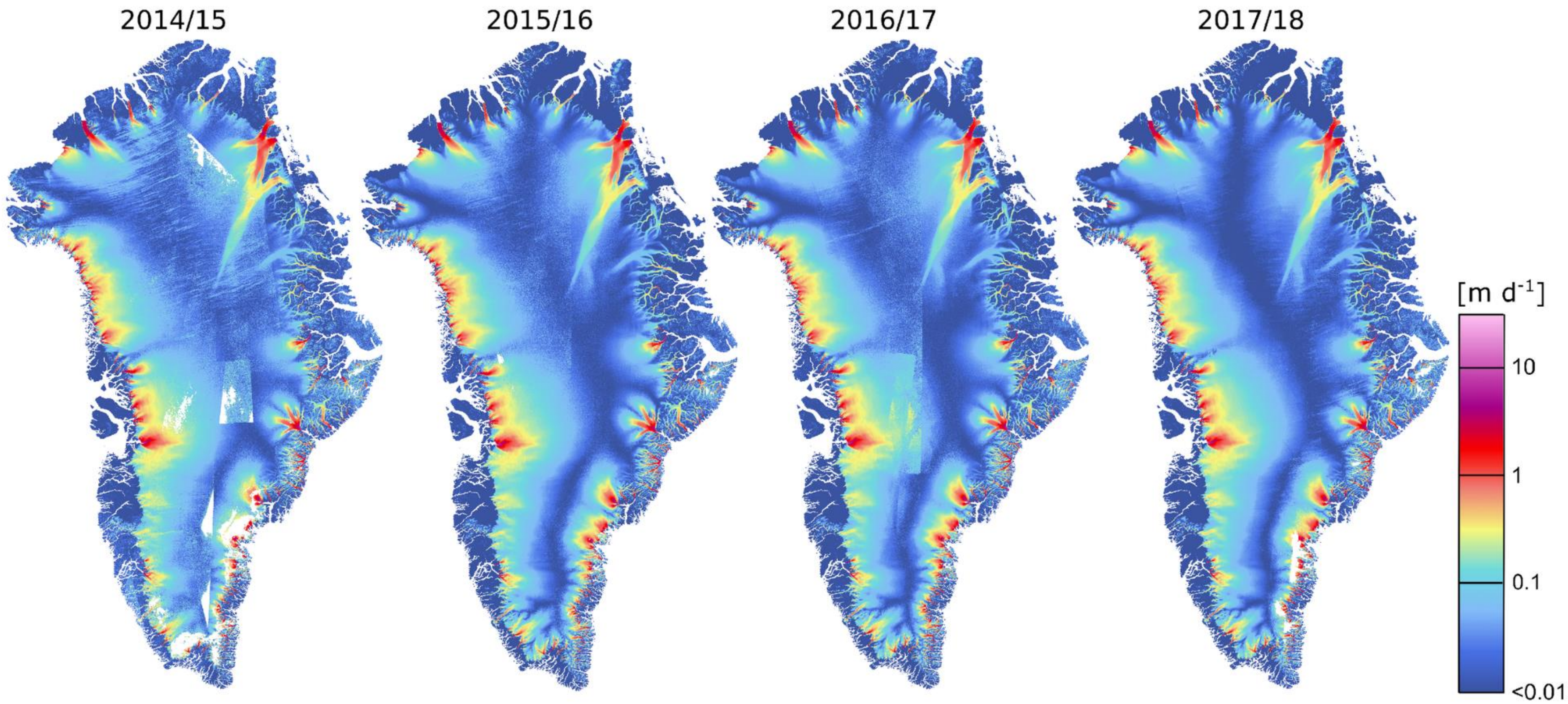
Possibilities for features to be tracked:

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.

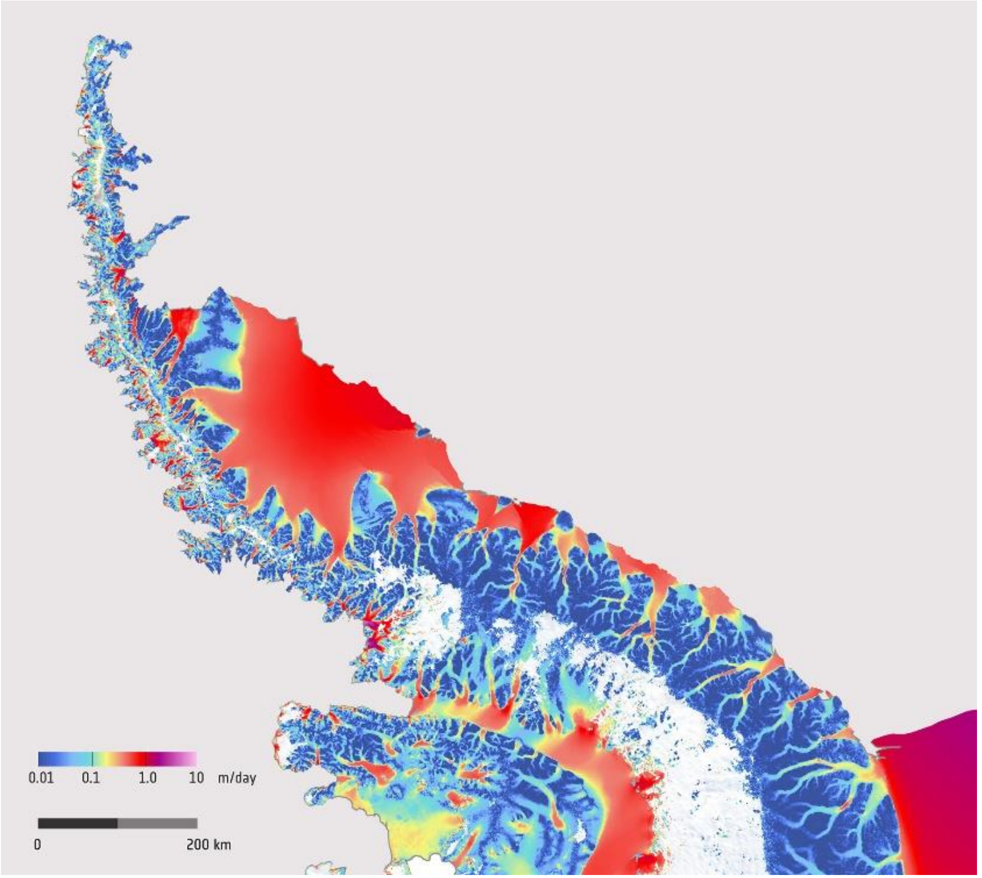
Glacier Velocity Map



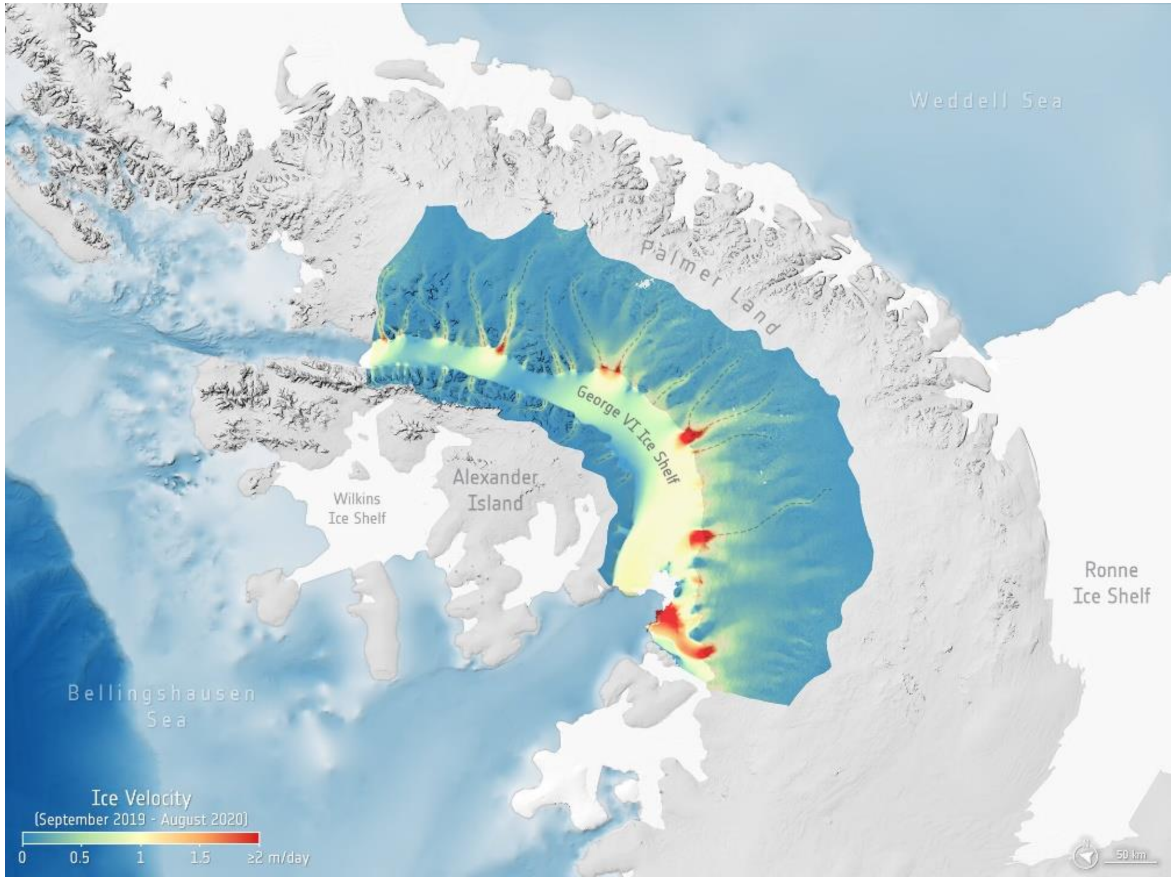
Annual ice velocity maps of Greenland from Copernicus Sentinel-1 2014-17 and winter campaign 2017/18.

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

Ice Flow Map



Antarctic Peninsula ice flow

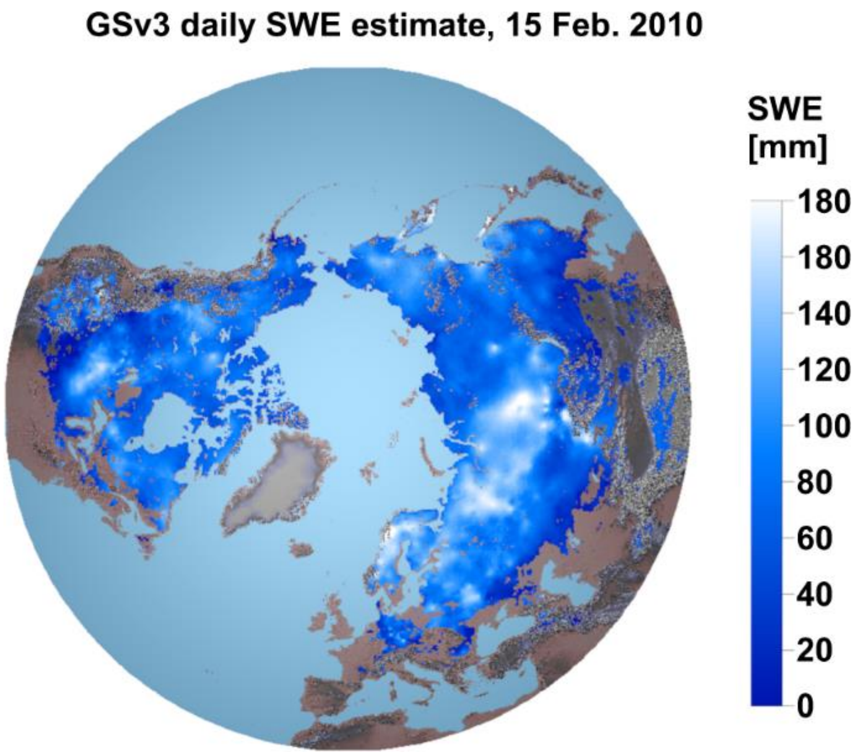


Ice-flow velocity of the George VI Ice Shelf

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 snow and ice

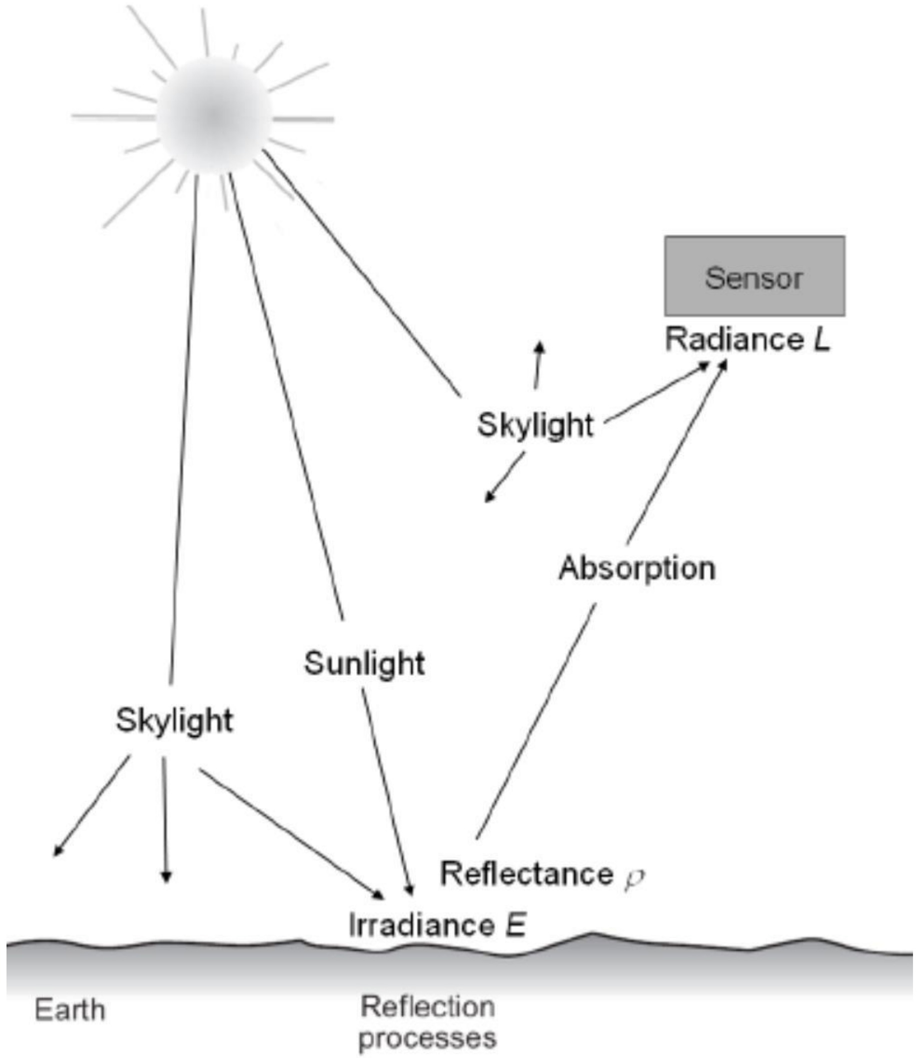
Incoming electromagnetic energy
${}_I(\lambda)$) is affected by:

- 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)

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

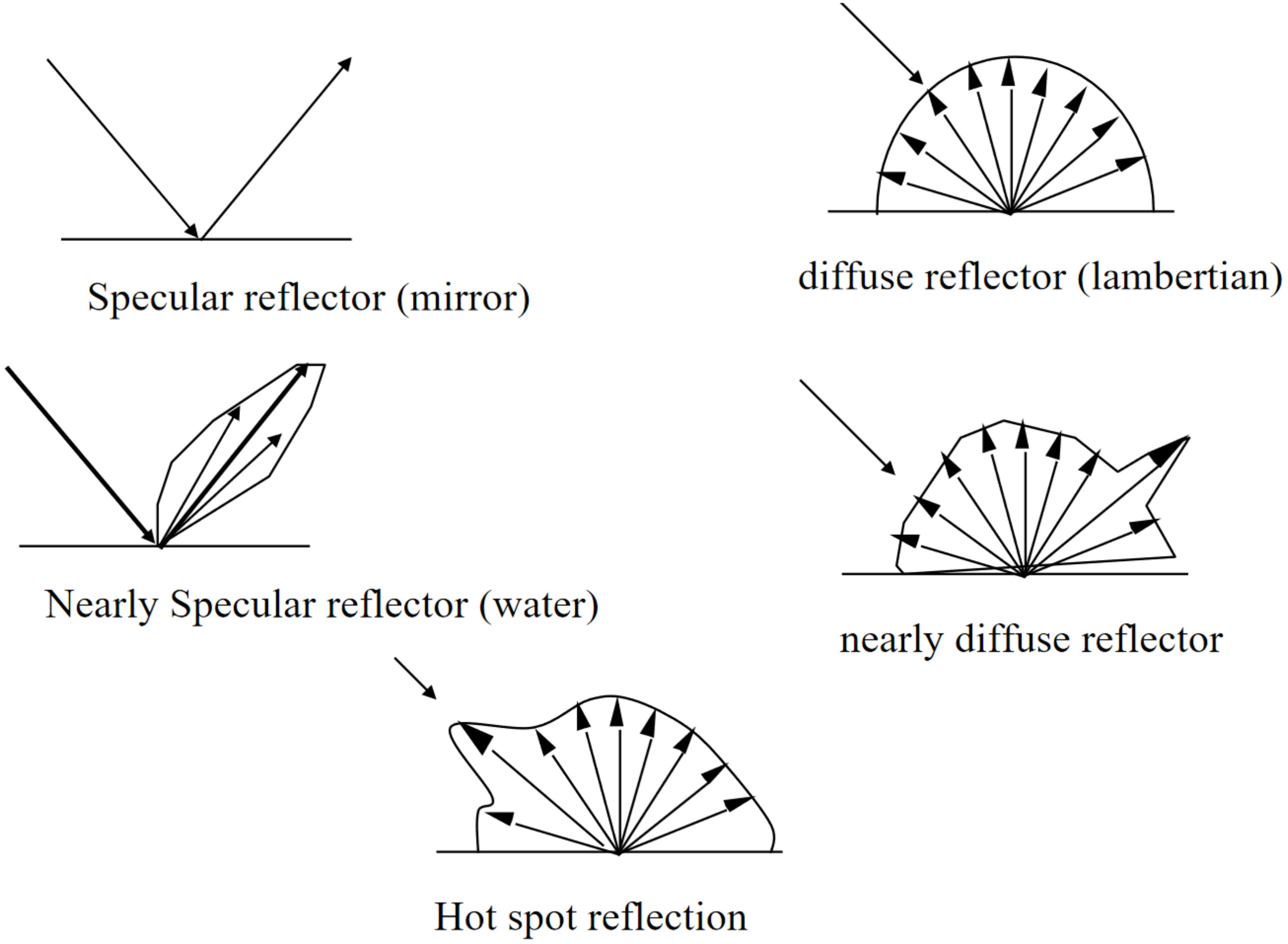
Optical sensors measure the amount of light receiving the satellite (= at-satellite radiance L), which is often converted to



Optical for snow and ice

Reflectance depends on

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



Selected Optical Sensors for Snow and 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*

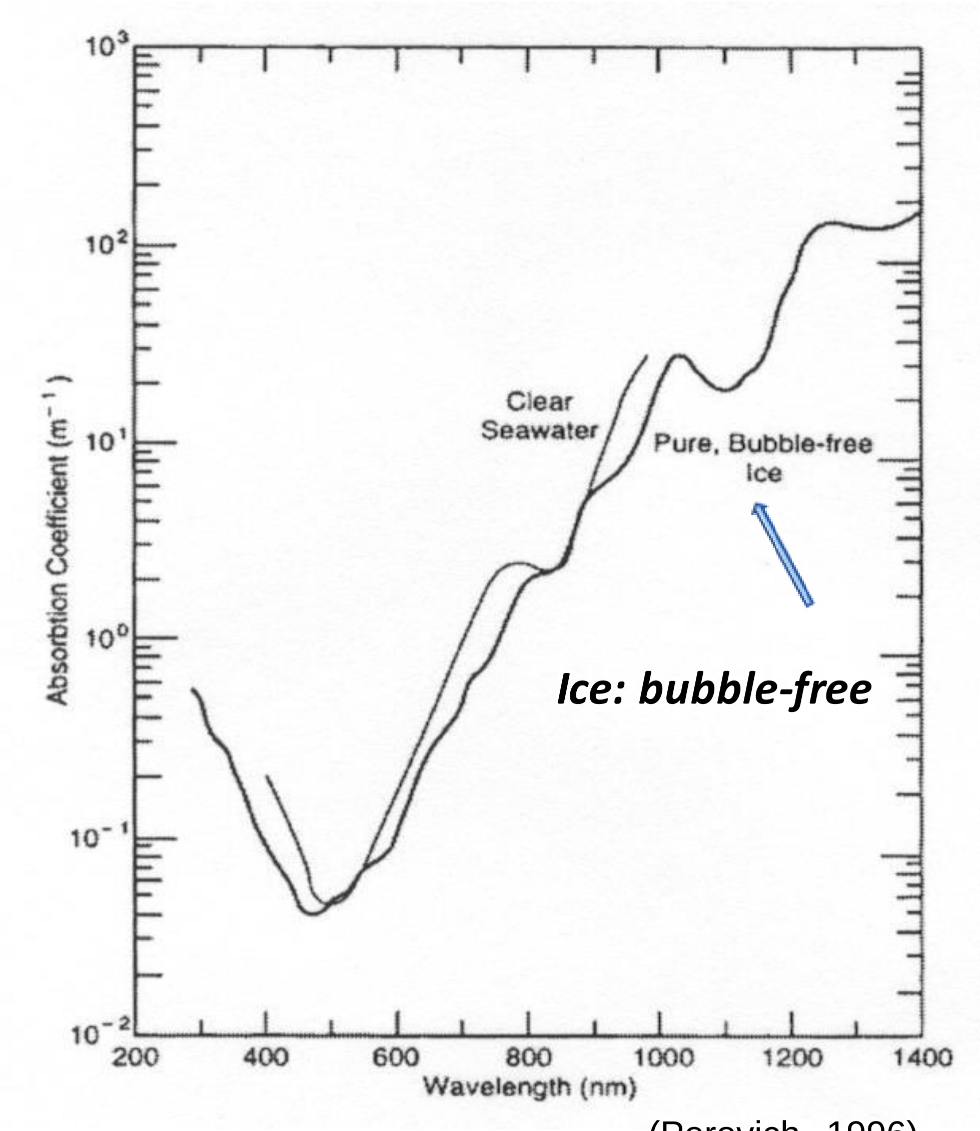
Extinction Coefficient of pure ice and sea water

Penetration depth (for intensity)

$d_p = 1/K_e$

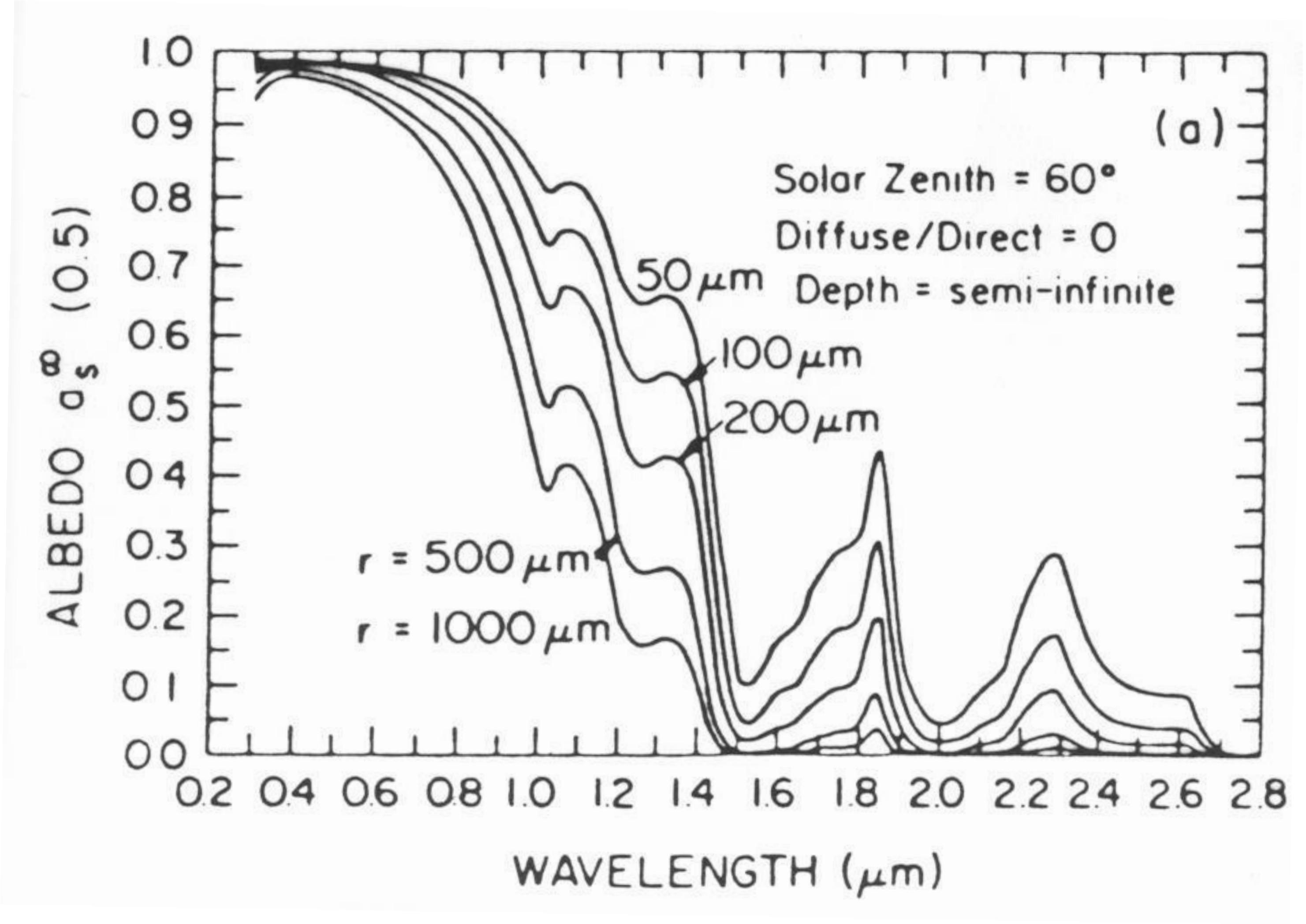
$K_e[m^{-1}]$ extinction coefficien

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



(Perovich, 1996)

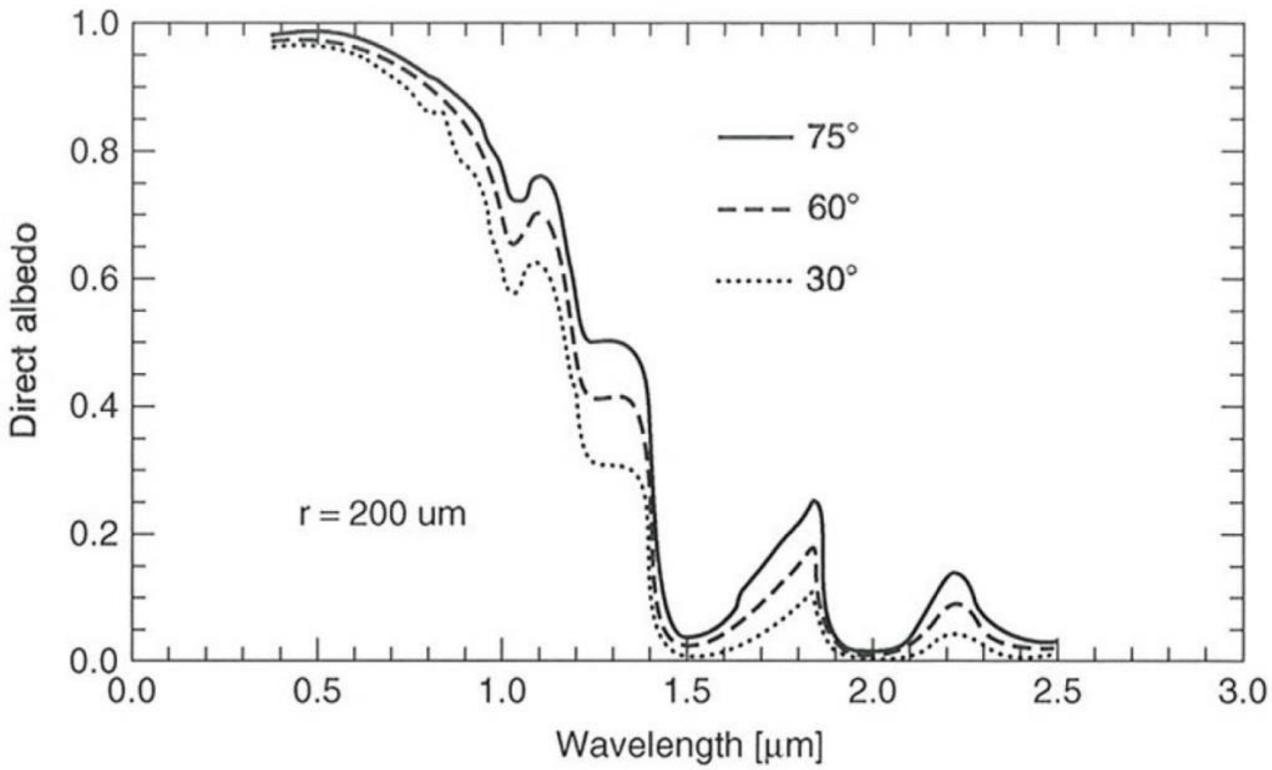
Spectral Reflectivity of Snow: Grain Size



Model Calculation by Wiscomb and Warren (1980)

Strong effect of grain size in near IR

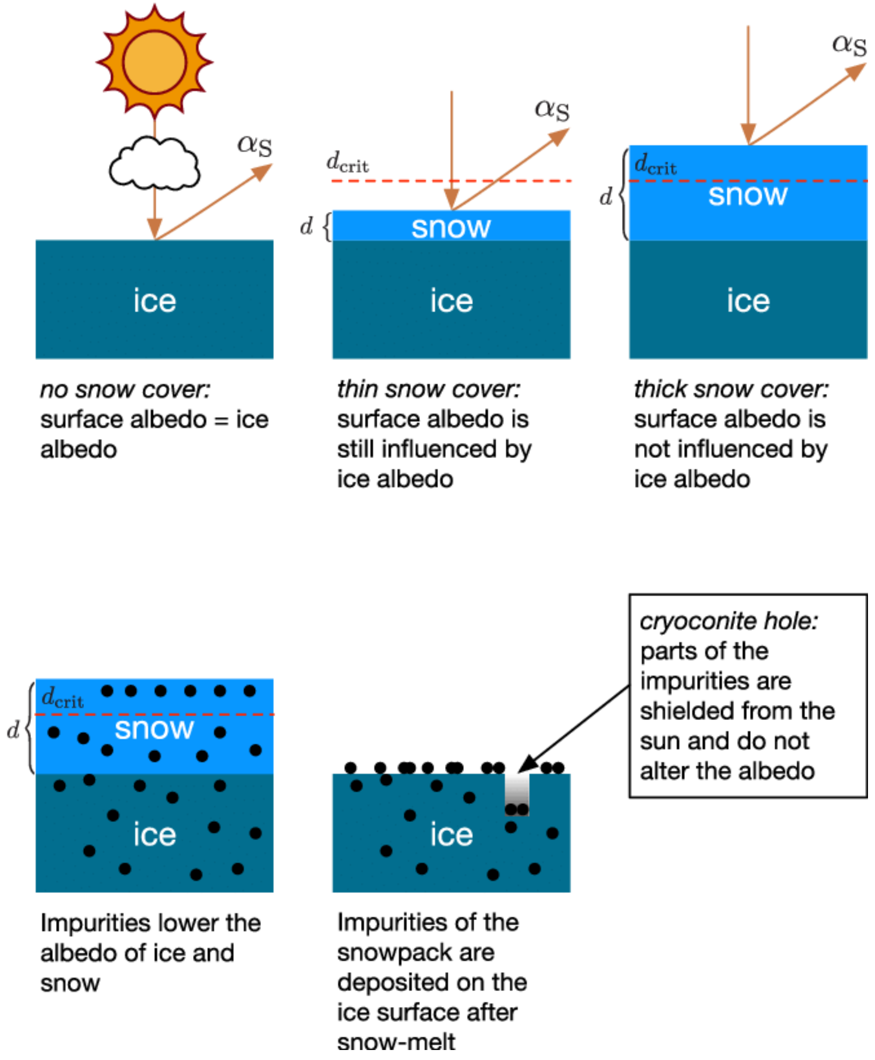
Angular Dependence of Snow Reflectivity



Snow albedo dependence on solar zenith angle

Main Factors for Spectral Reflectance of Snow

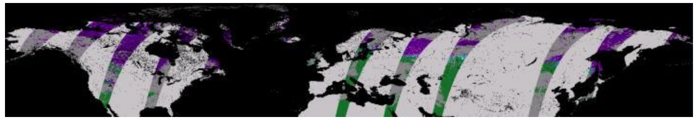
- Impurities (Soot, Dust, ...) - main factor at visible wavelengths
- Grain size; important at $\lambda > \sim 1$ µm
- Liquid water content (relevant in shortwave IR; primarily an indirect effect through grain size)
- Illumination and observation geometry (bi-directional reflectance)
- Surface roughness



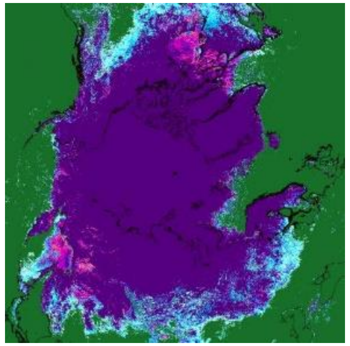
https://www.cambridge.org/core/journals/journal-of-glaciology/article/albedo-reduction-of-ice-caused-by-dust-and-black-carbon-accumulation-a-model-applied-to-the-ktransect-west-greenland/3FE93E004C1793A5DC4D78FD4CD1ECB4

Selected Snow Products from Optical Satellite data

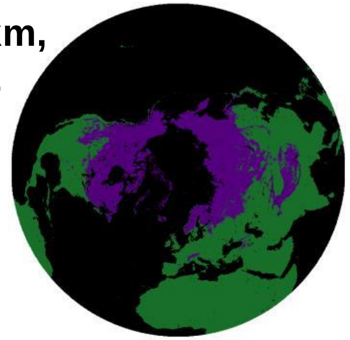
GlobSnow, 1 km, Fractional SE



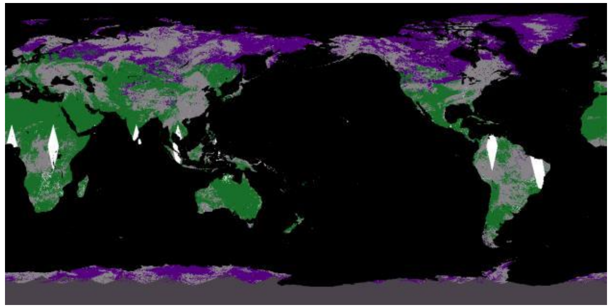
Pathfinder, 5 km, Fractional SE



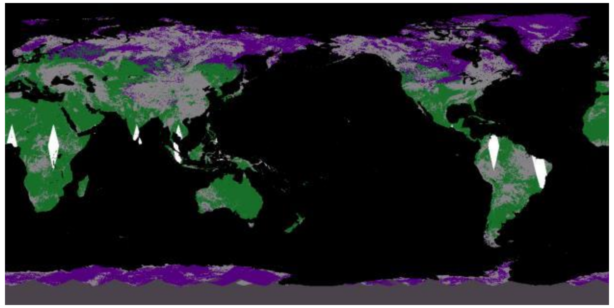
CryoClim, 5 km, Fractional SE



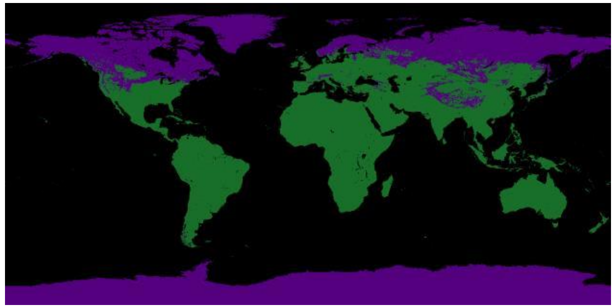
JAXA MDS10C, 5 km, Binary SE



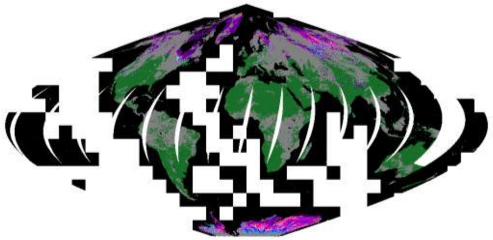
JAXA GHRM5C, 5 km, Binary SE



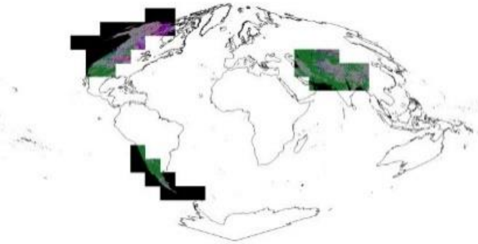
AutoSnow, 4 km, Binary SE



MOD10_C5, 0.5 km, Fractional SE



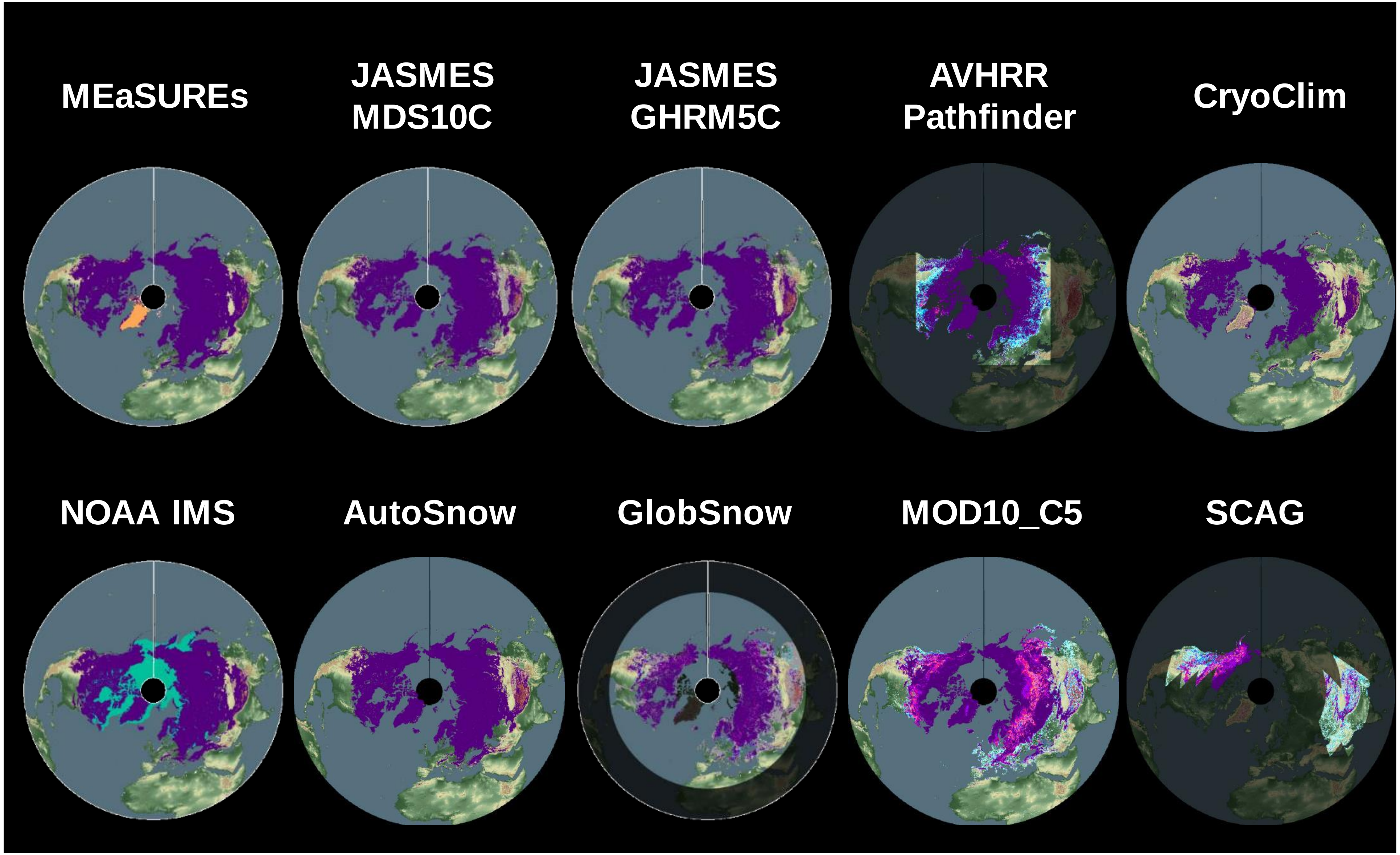
MODSCAG, 0.5 km, Fractional SE



MEaSUREs, 25 km, Binary SE

IMS, 4 km, Binary SE

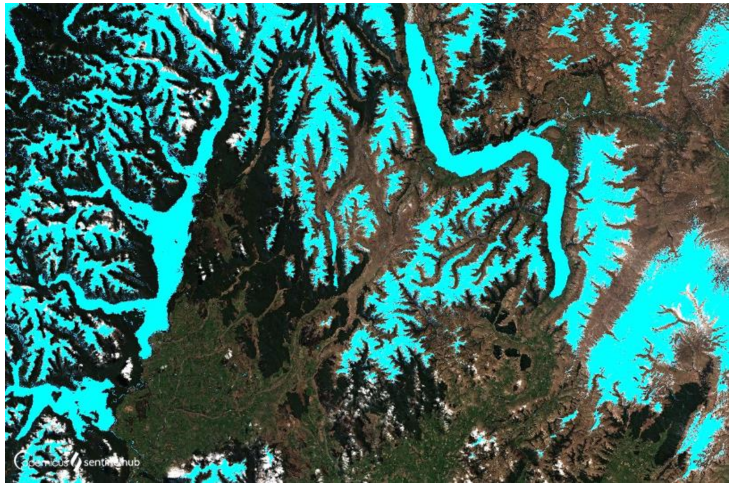
Hemispheric snow products reprojected in EASE-GRID 2.0



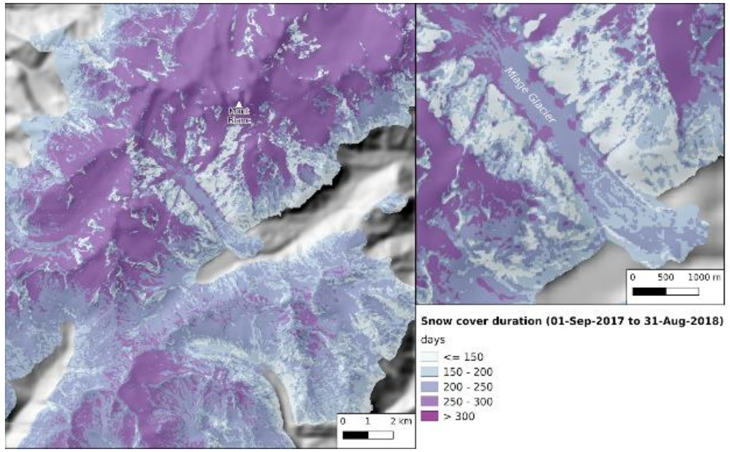
Applications in Cryosphere: Optical Sensors

- 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

For more information, see the tutorial:
[11. Generating high resolution binary and fractional snow maps from Sentinel-2 data using SNAP software]



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



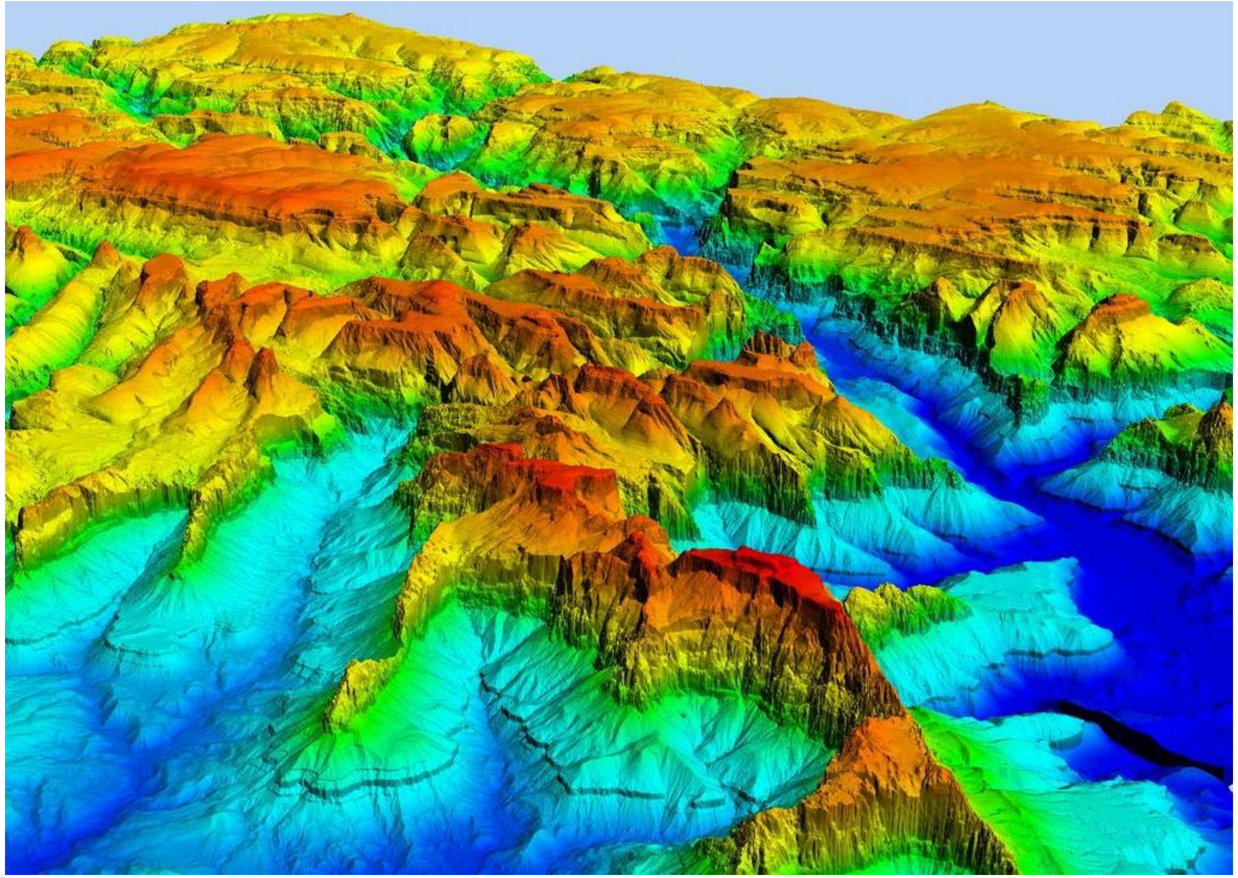
Snow Cover Duration for Mont-Blanc area during an hydrological year (1 September 2016 to 31 August 2017) produced by synthesis of Theia snow-covered surface products.

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

12. Retrieval of digital elevation model (DEM) from ESA EO data and comparison with LiDAR outputs

What is DEM?

- 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).

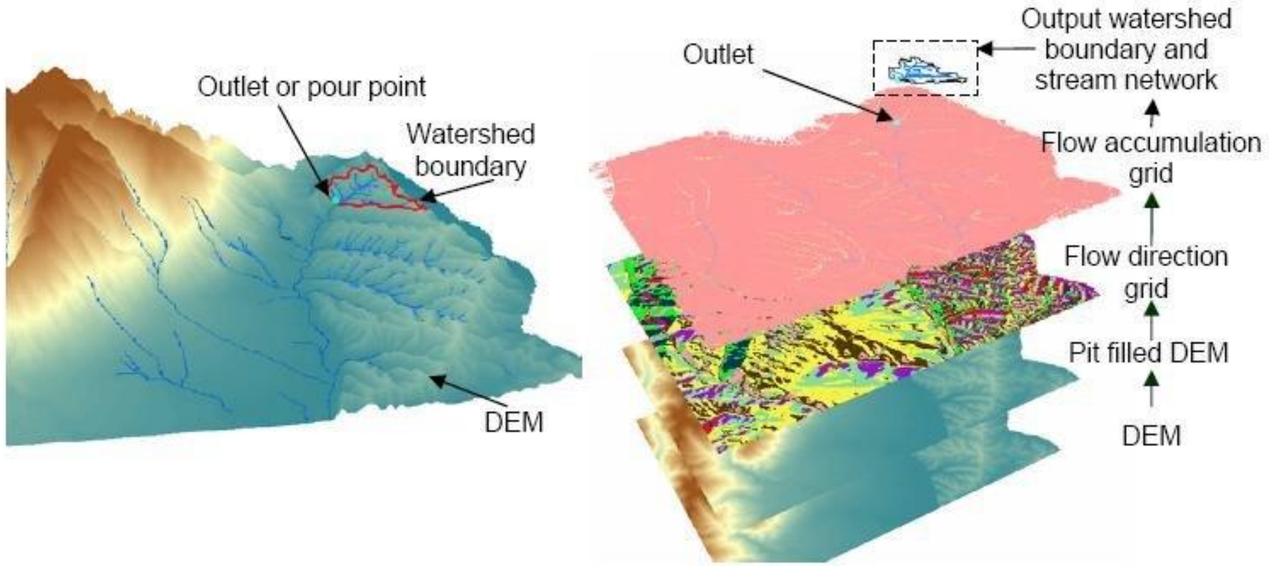


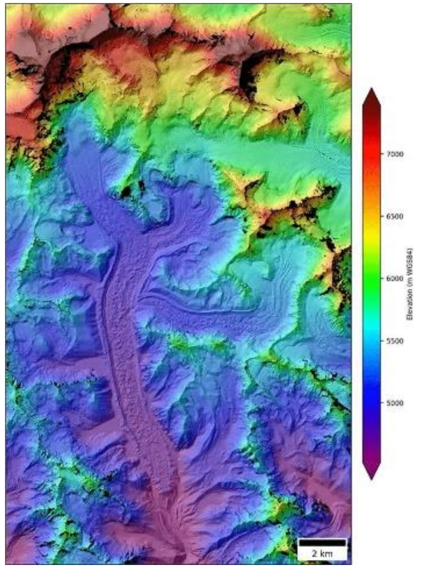
Source: https://www.surveyinggroup.com/dsm-dem-dtm-elevation-models-in-gis/

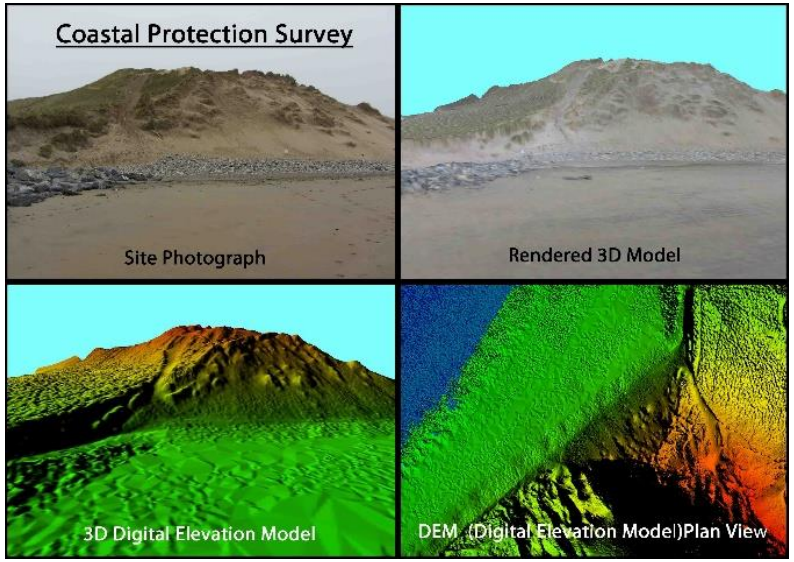
Use of DEM

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. ...

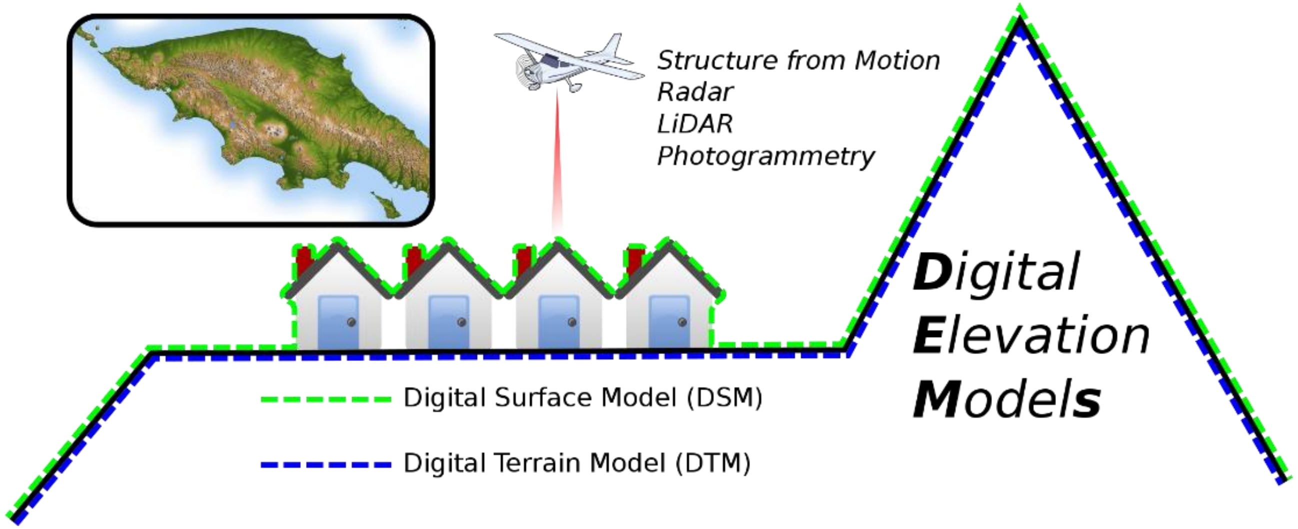






Types of DEM

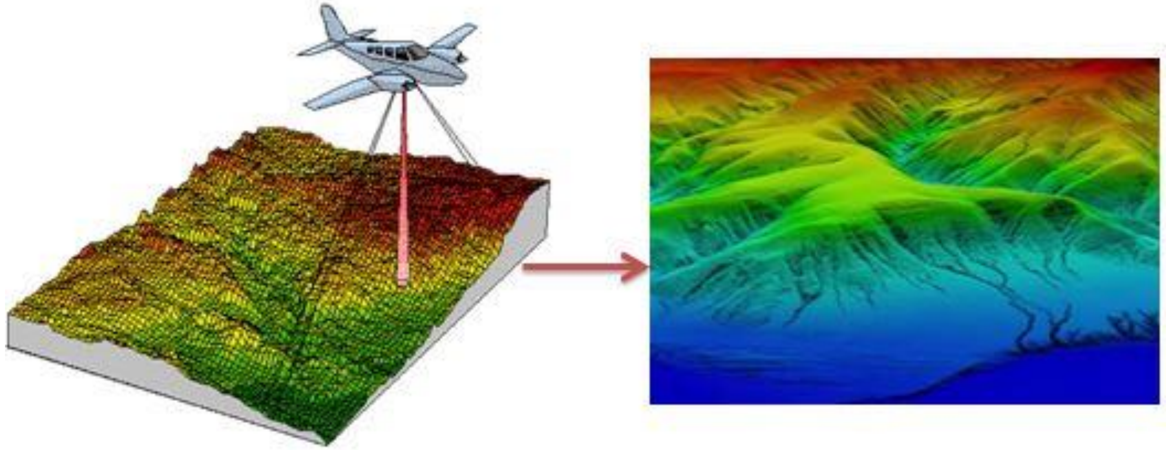
- **Digital Terrain Models (DTM)** - the height of the earth's surface in relation to otherpoints
- **Digital Elevation Models (DEM)** - the height of the earth's surface specifically in relation to a standard global/regional elevation (normally sea level).
- **Digital Surface Models (DSMs)** - the height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

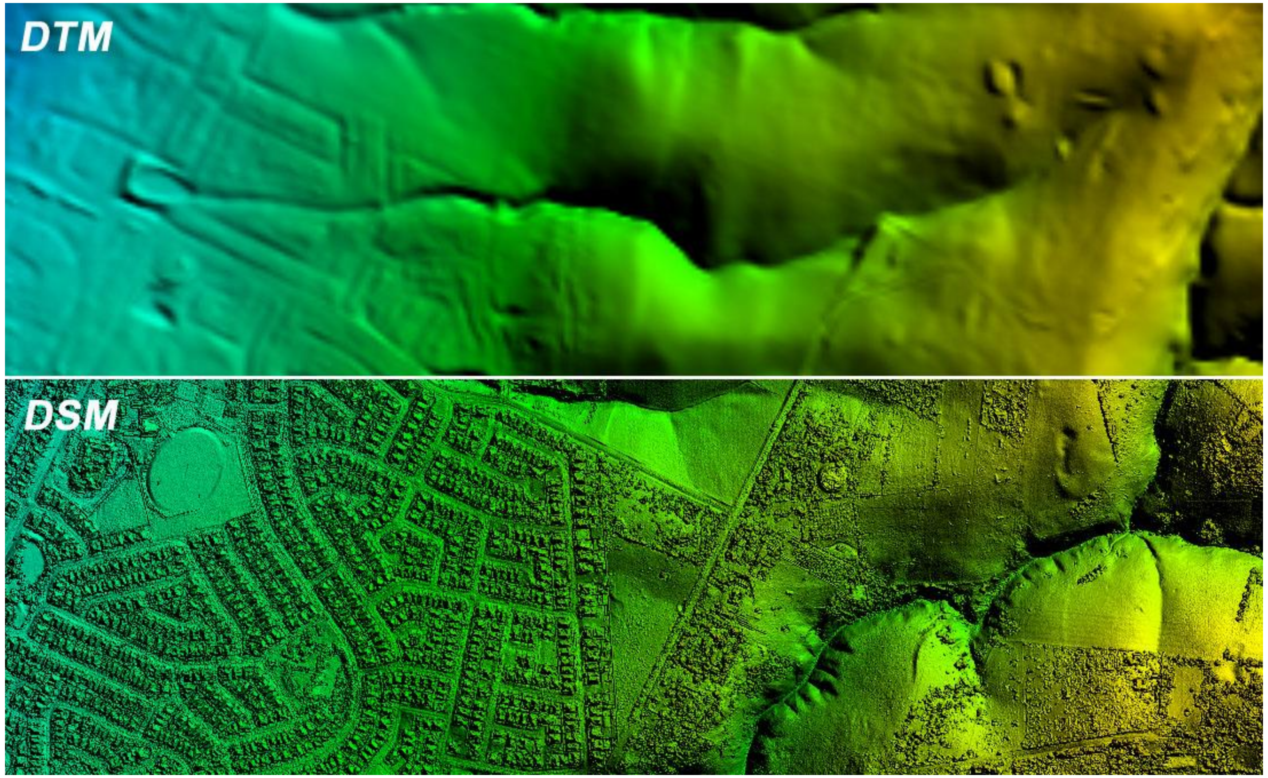
DEM Retrieval

- 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 photogrammetry and LIDAR, but they may also be built from land surveying.



DEM Retrieval

- Since the early 21st century, the development of LiDAR technology and point-cloud processing methods has enabled the derivation of both Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) from a single data source.

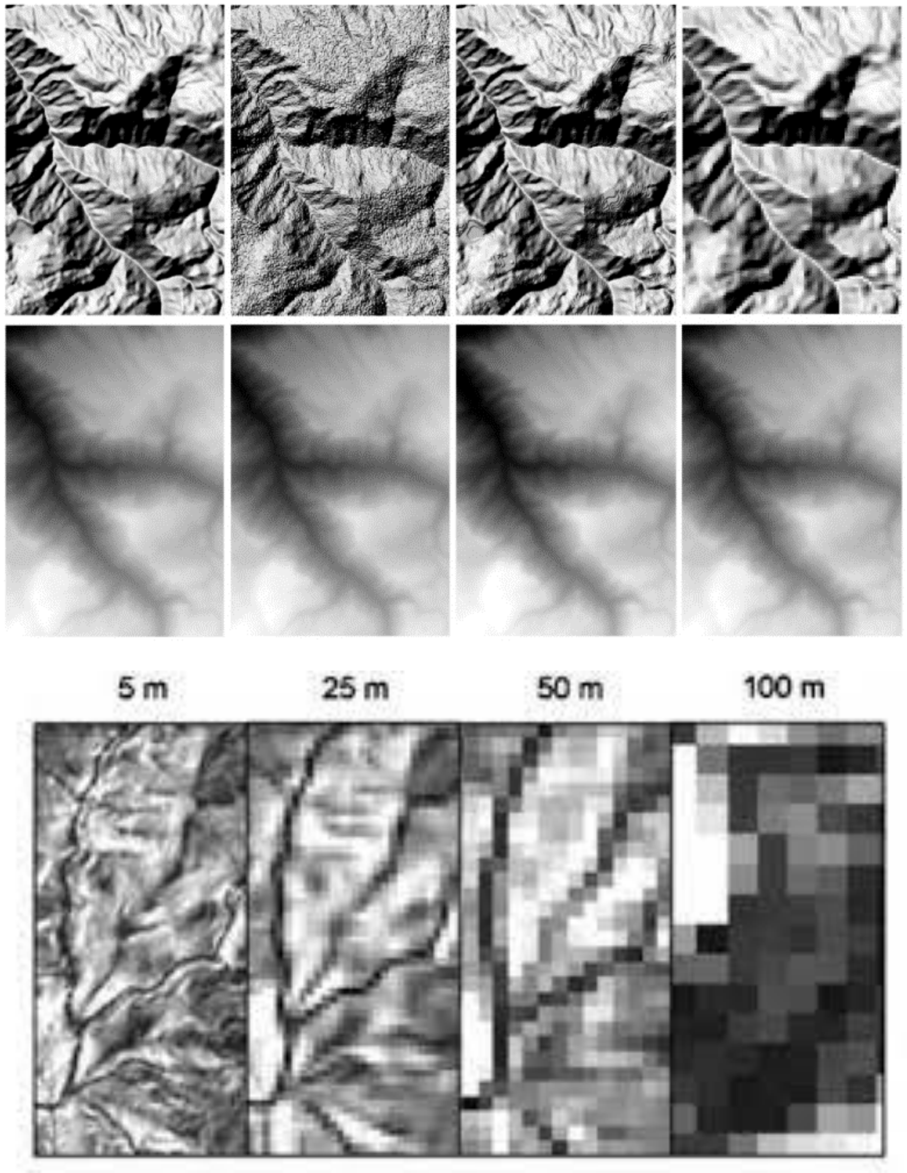


DEM Quality

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

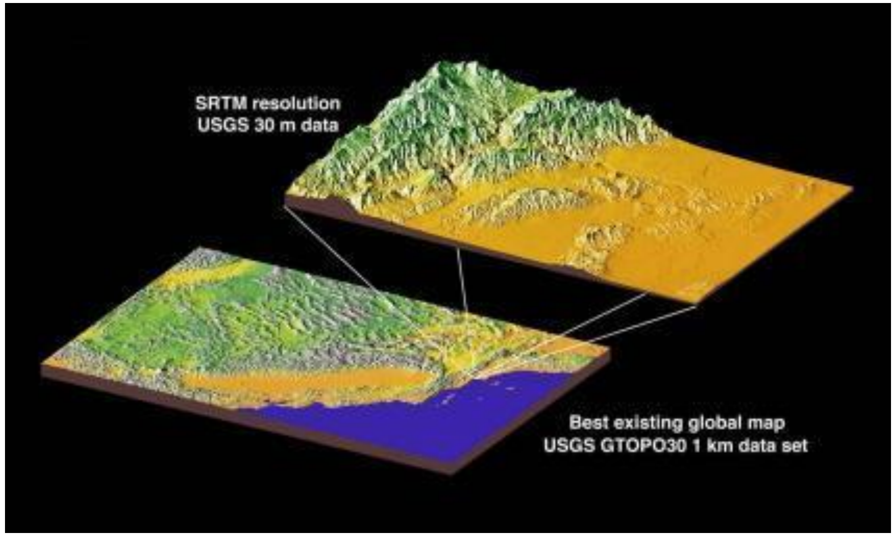
- A joint operation between NASA and Japan was the birth of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)
- ASTER GDEM boasted a global resolution of 90 meters with a resolution of 30 meters in the United States
- You can download the ASTER DEM data for free from the USGS EarthExplorer

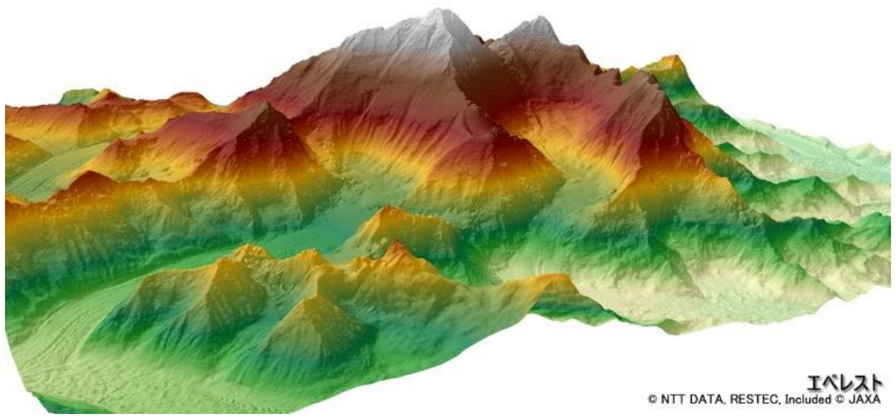
3. JAXA's Global ALOS 3D World

- 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

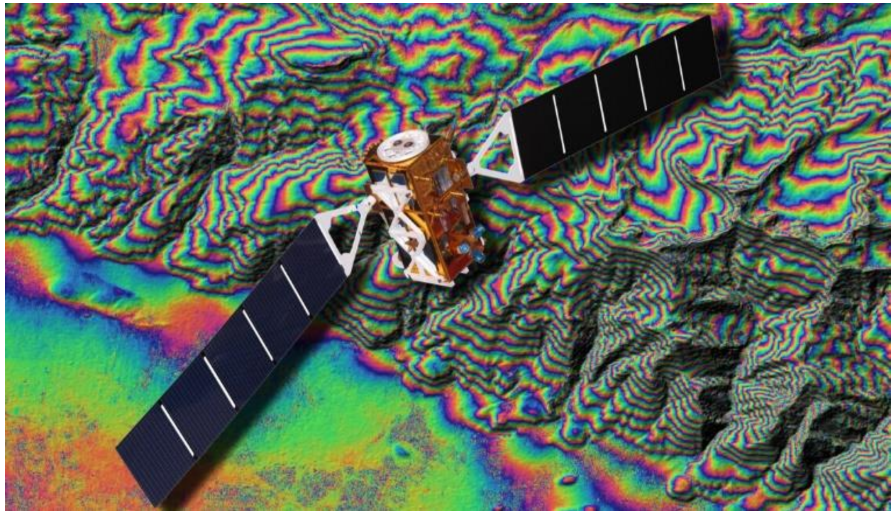
- CARTOSAT 1 and 2 derived stereo DEM, available for entire India freely

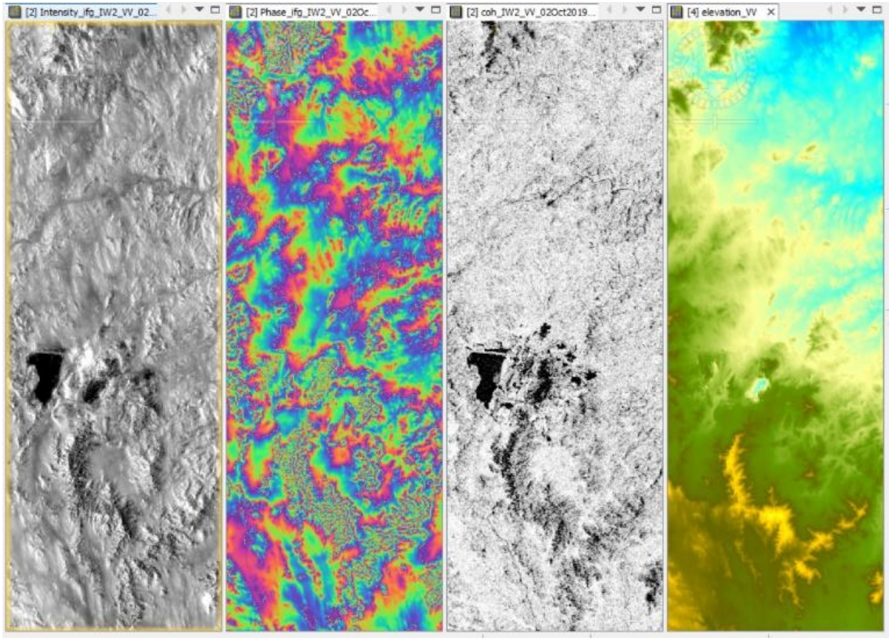




Retrieval of DEM using Sentinel-1 radar data

- 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.



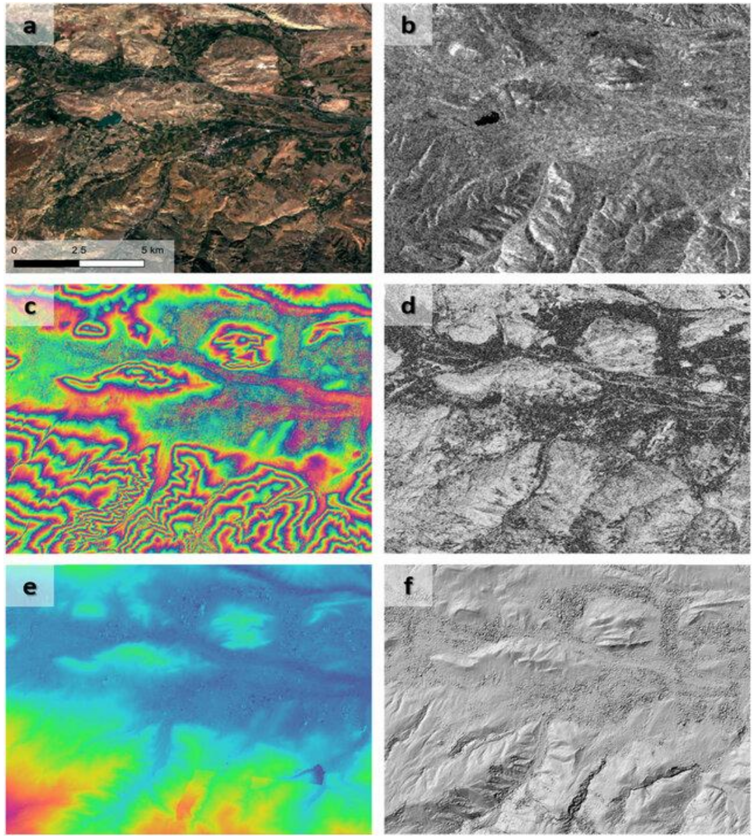


Create a DEM using Sentinel-1 radar data

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

For more information, see the tutorial:
12. Retrieval of digital elevation model (DEM) from Sentinel-1/DEM generation with Sentinel-1, comparison with LiDAR outputs, using SNAP software



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

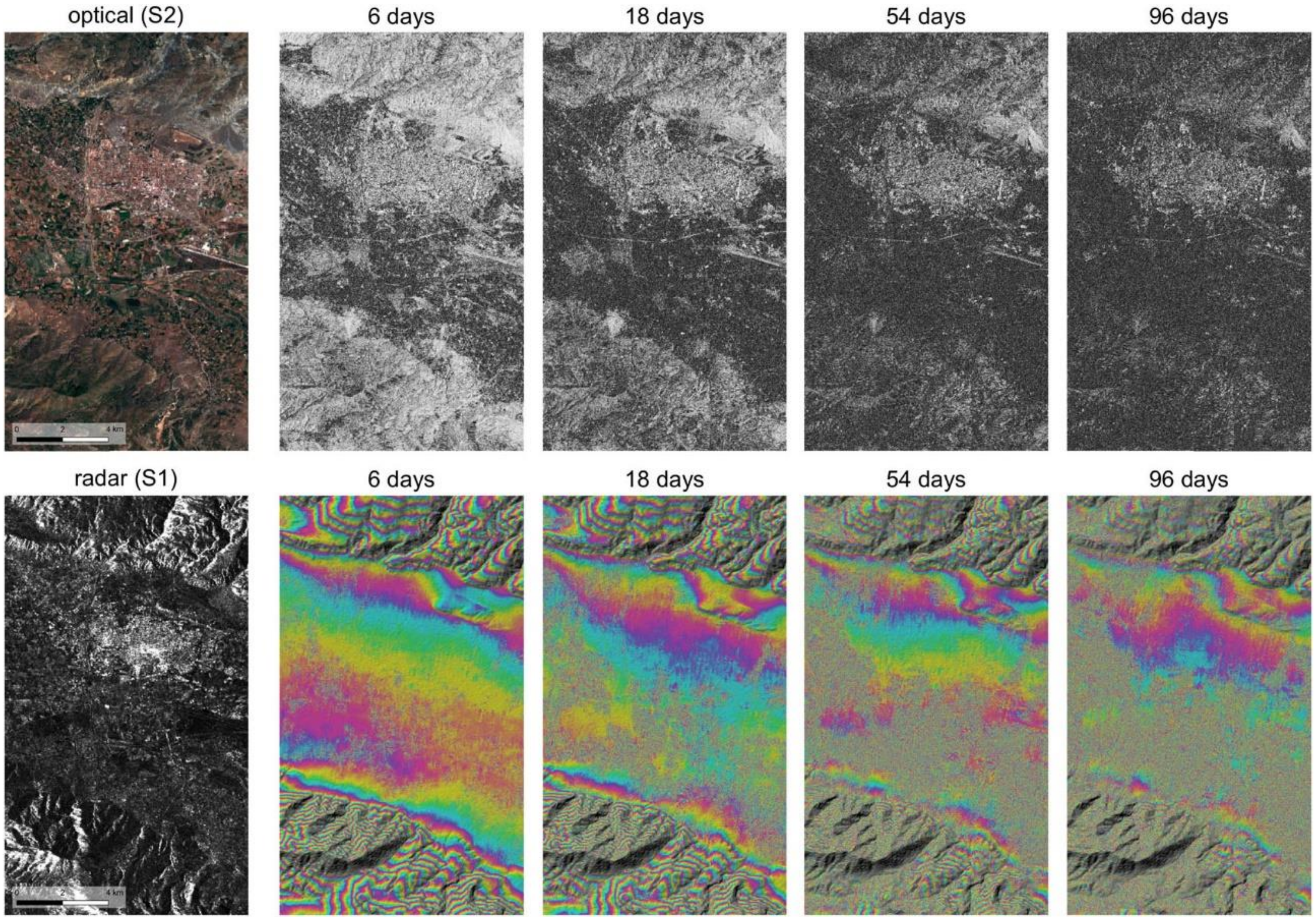
Preparation

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

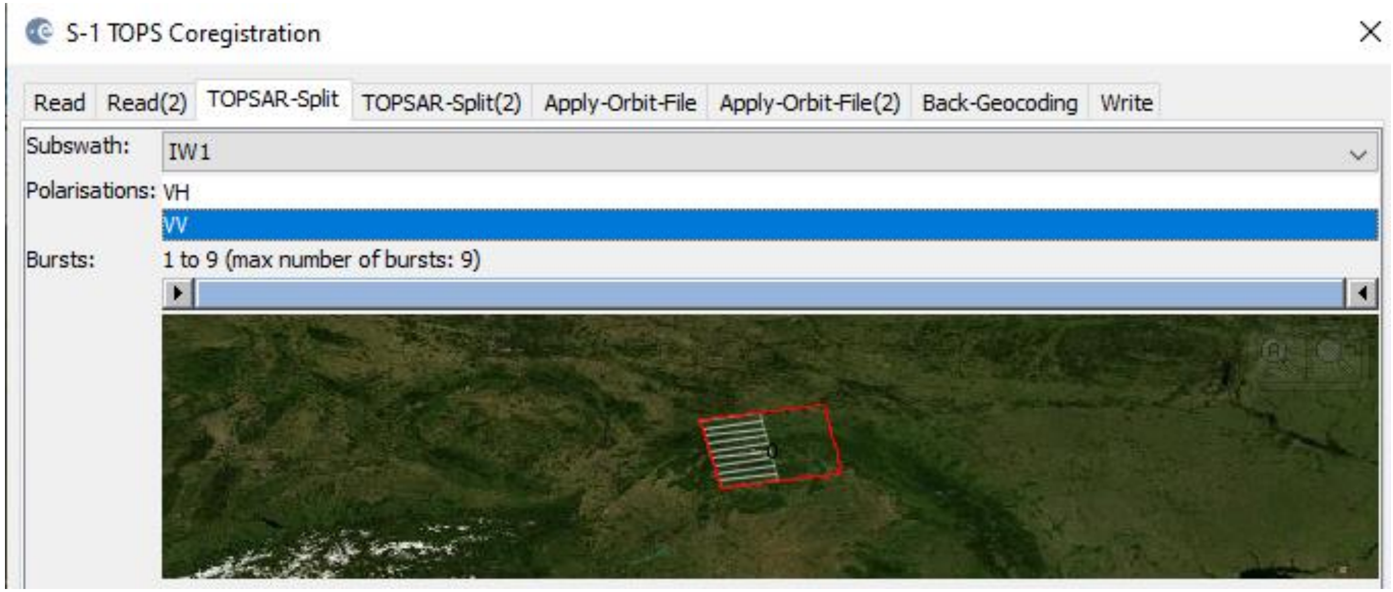
In order to utilize the phase difference between the acquisitions, it is necessary to first create a stack containing both products. Coregistration involves aligning both products with sub-pixel accuracy using image statistics.

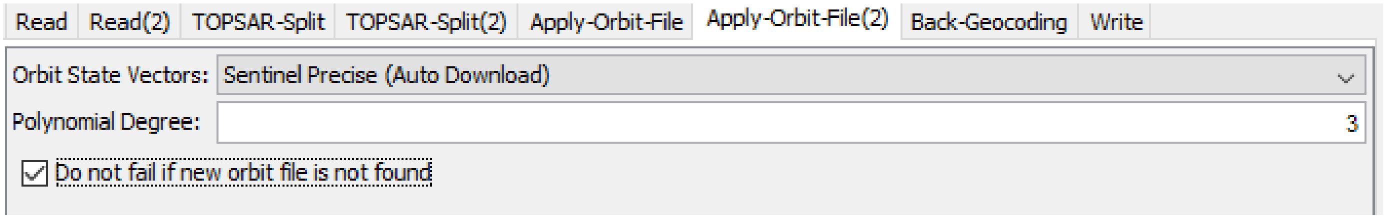
TOPS Split

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.

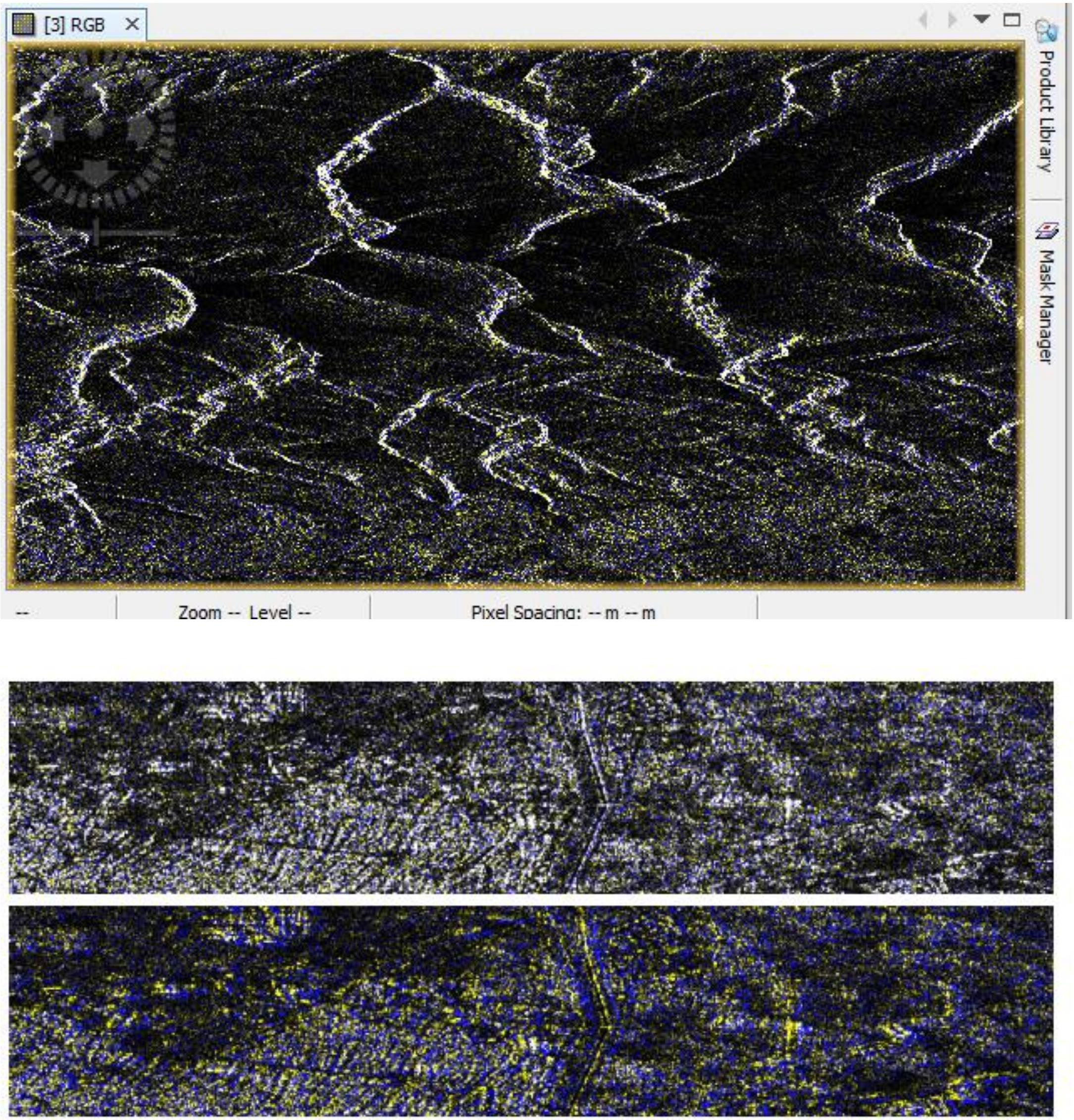


Figure 15: Successful (top) vs. failed (bottom) coregistration in an RGB image

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.

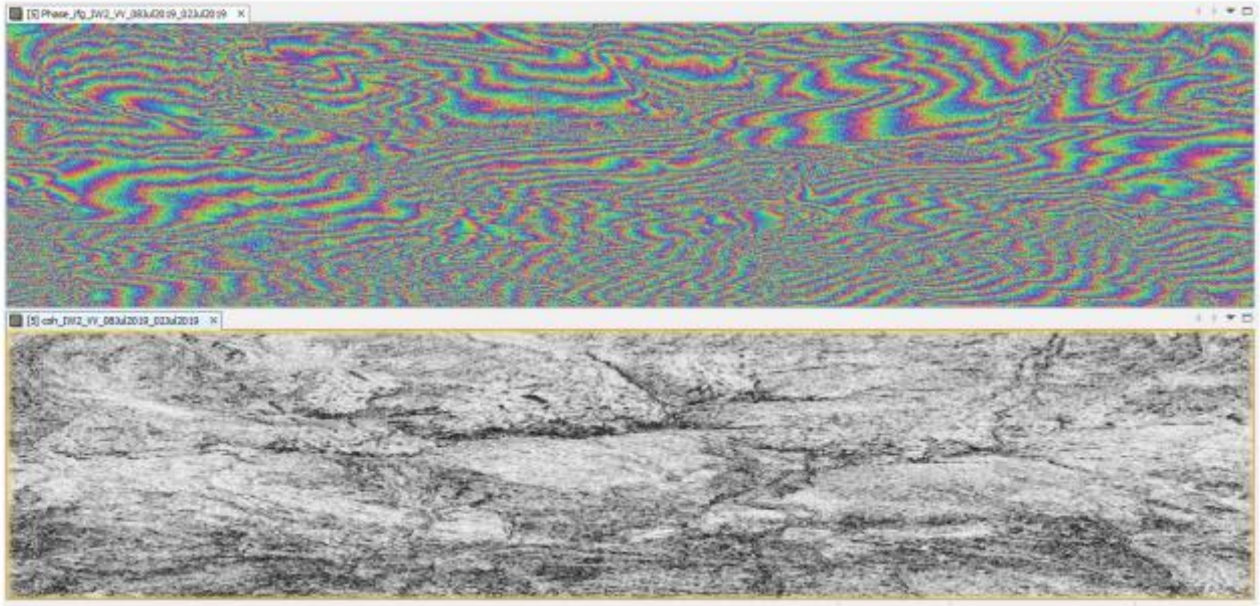


Figure 18: Interferogram (top) and coherence (bottom)

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.

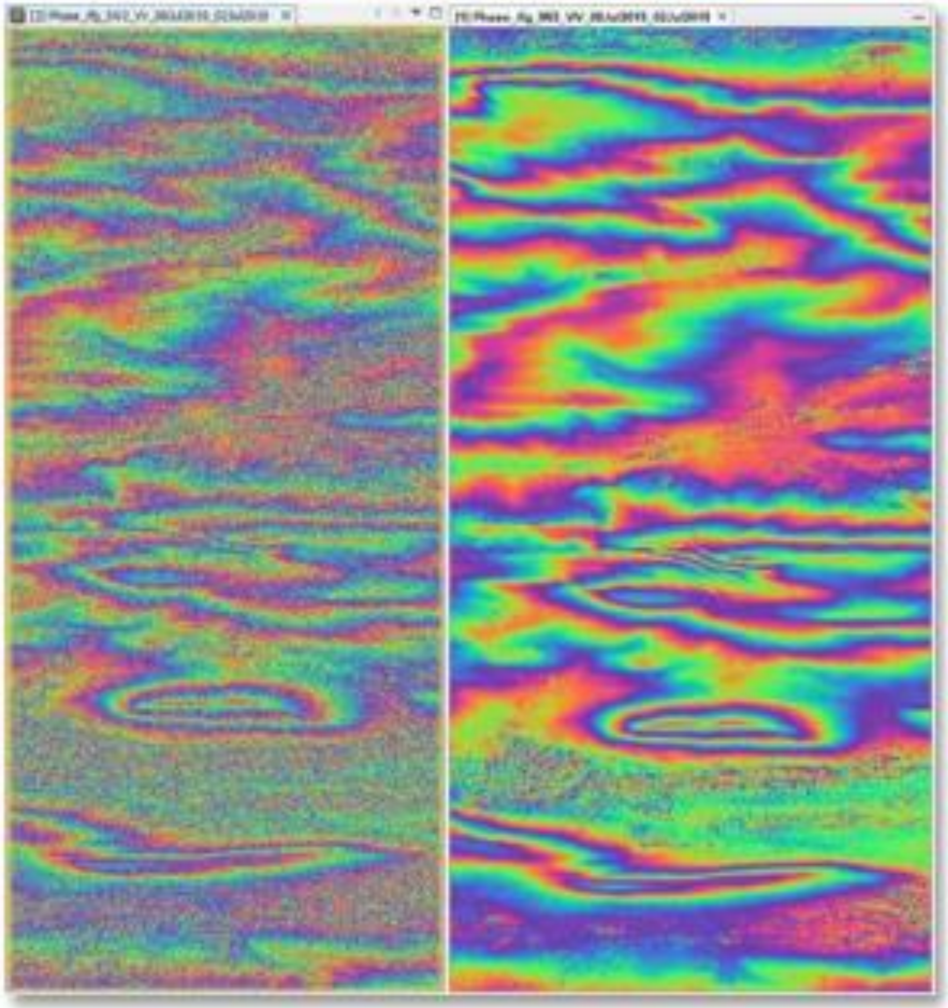


Figure 21: Interferogram before (left) and after (right) Goldstein phase filtering

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.

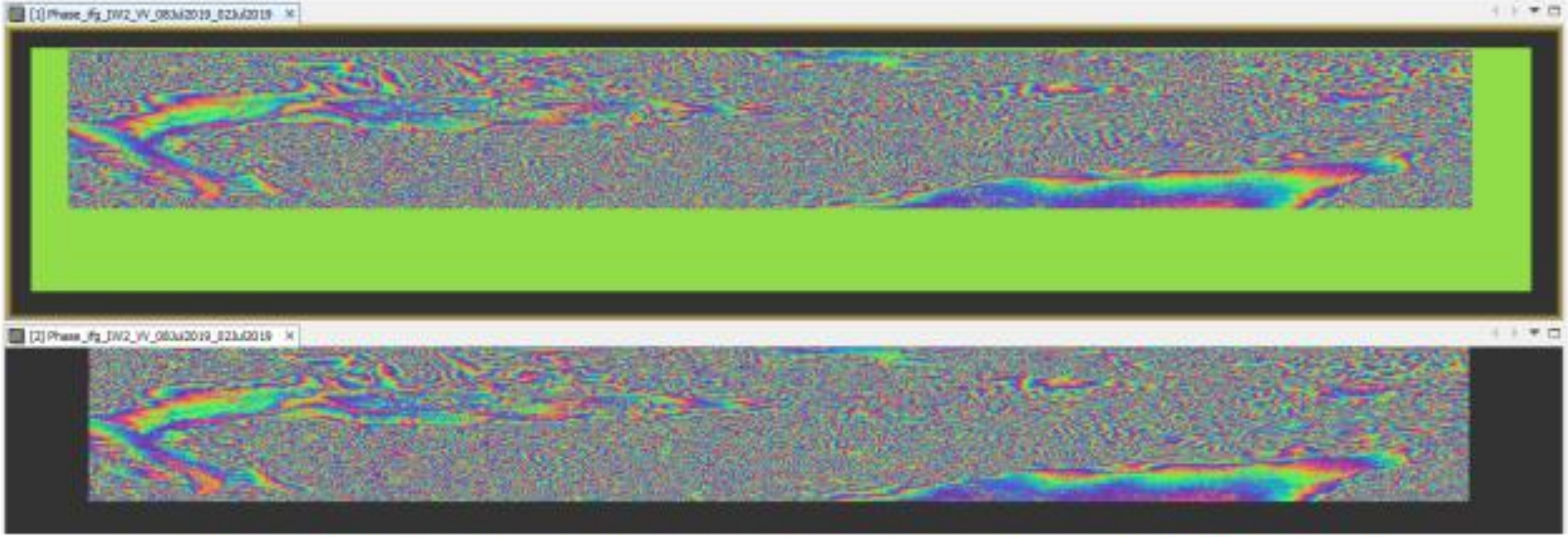


Figure 23: Interferogram before (top) and after (bottom) creating the subset

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.

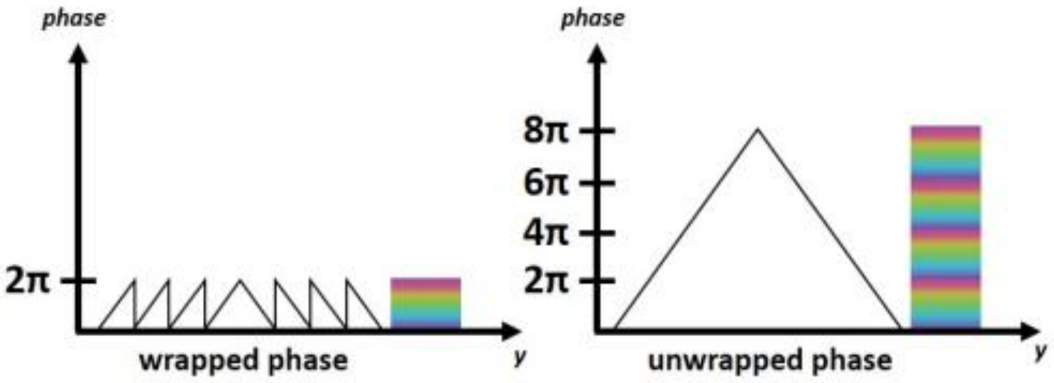


Figure 24: Principle of phase unwrapping

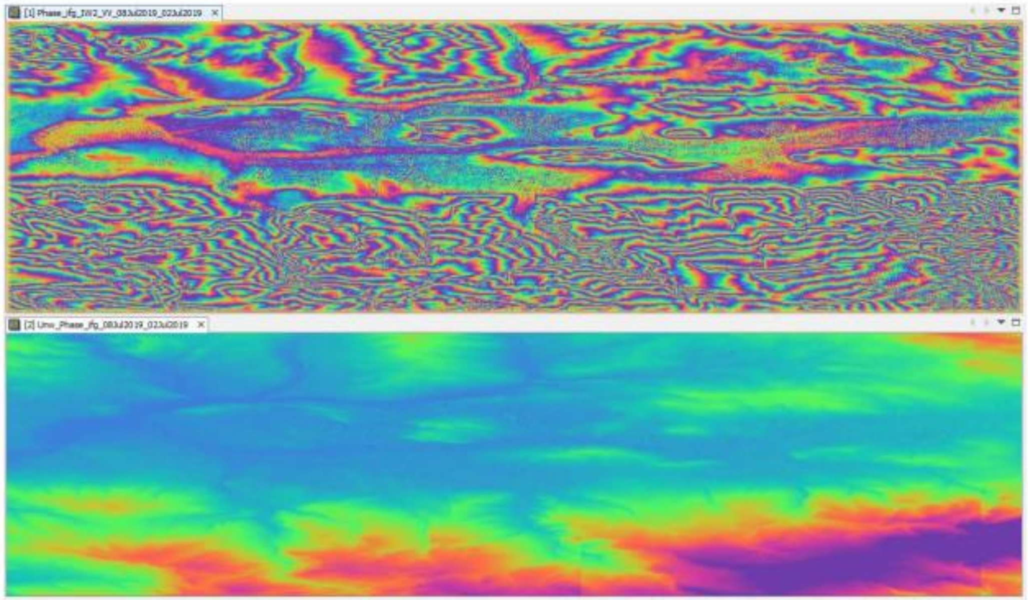
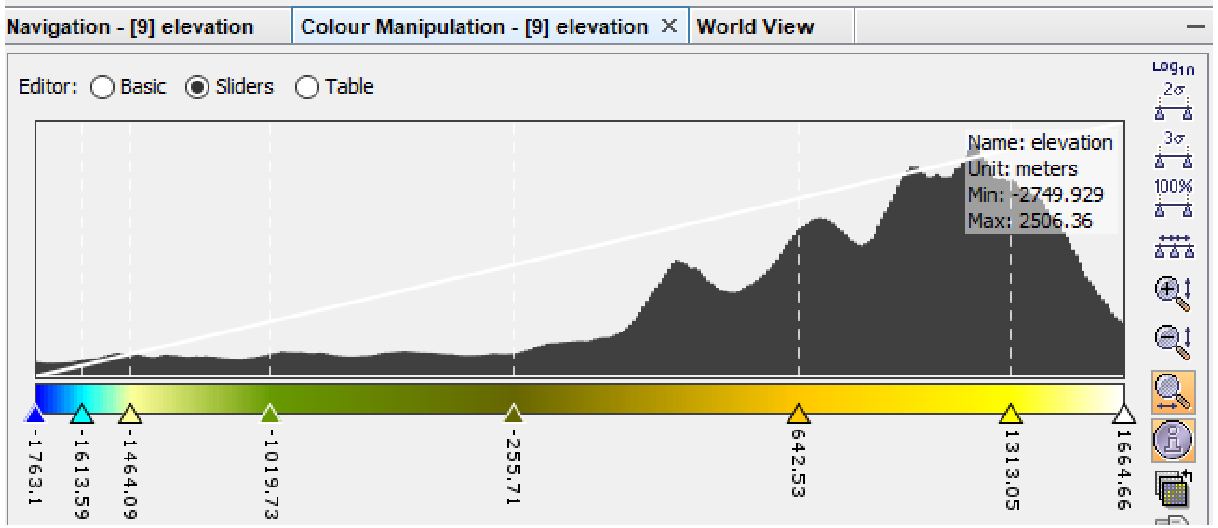


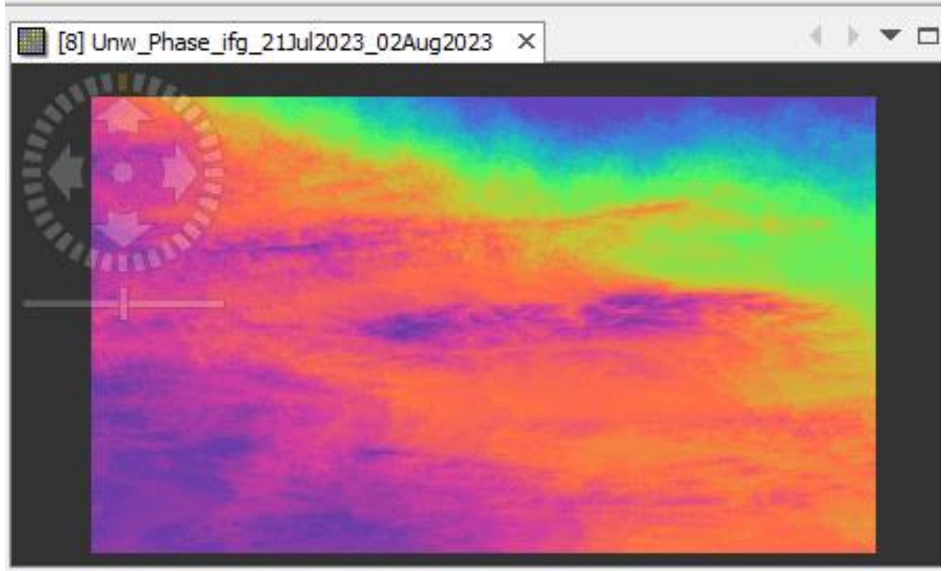
Figure 28: Phase before (top) and after (bottom) unwrapping

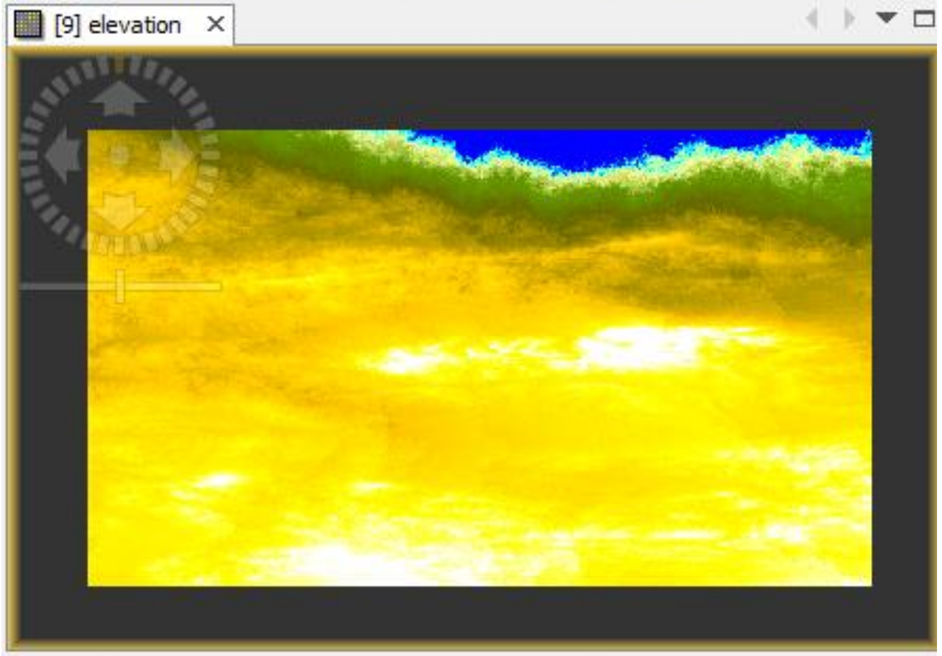
Create a DEM using Sentinel-1 radar data

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

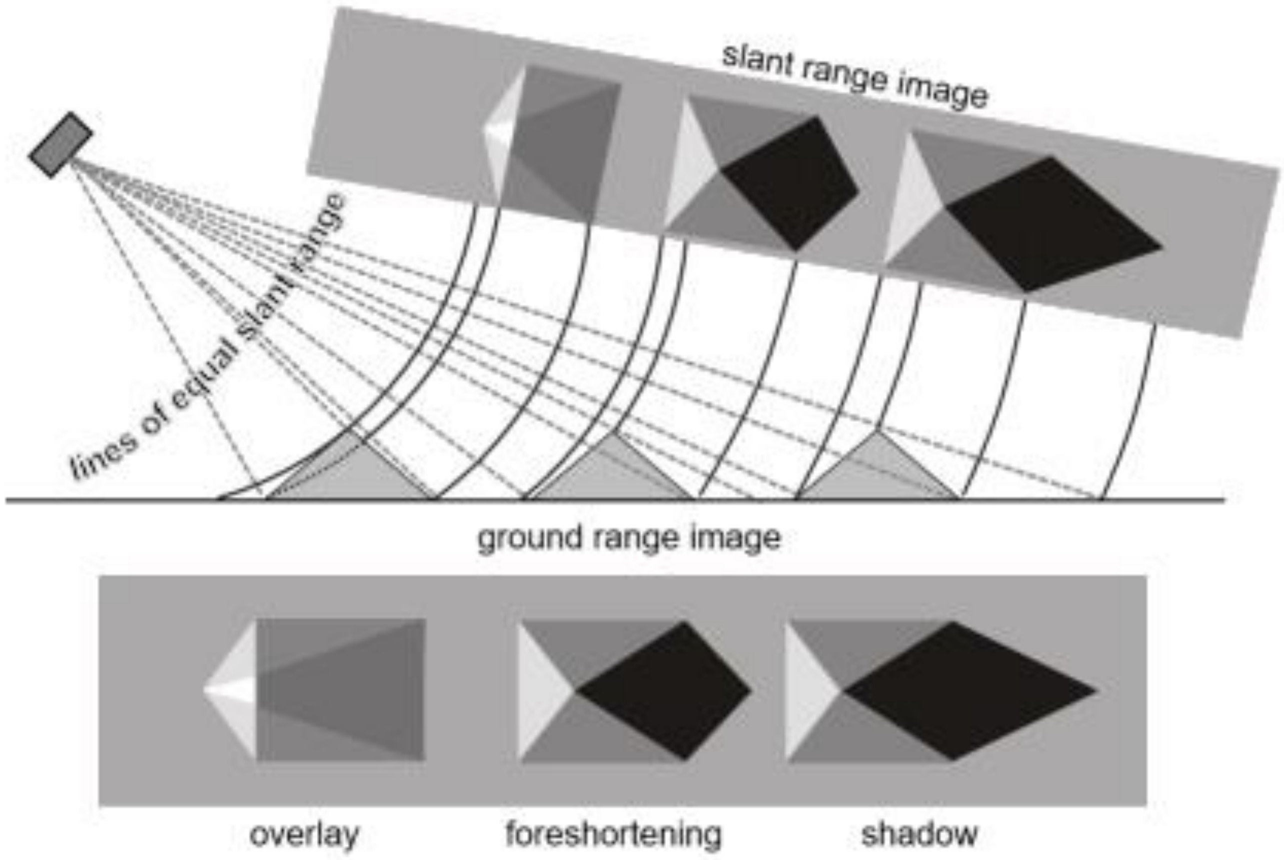
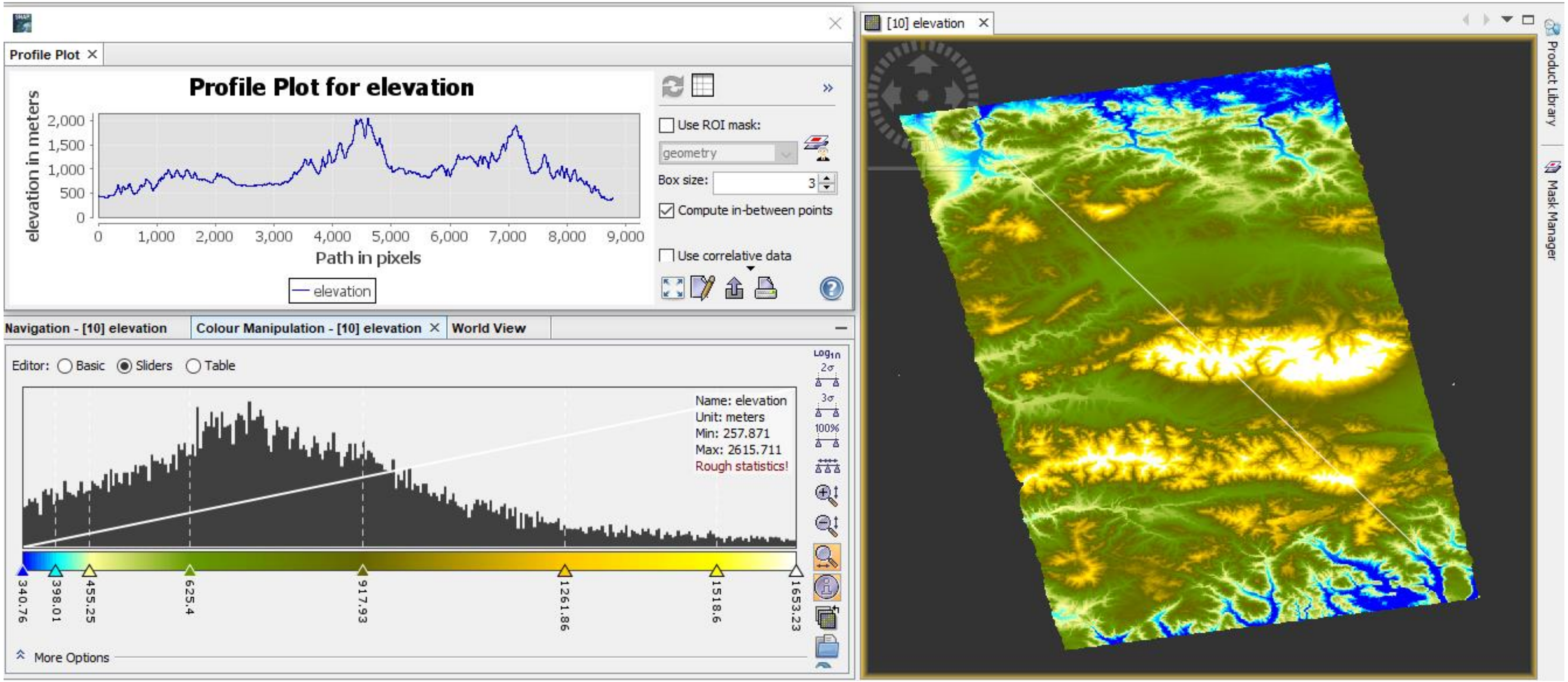


Figure 33: Geometric distortions in radar images (Braun 2019)

Create a DEM using Sentinel-1 radar data

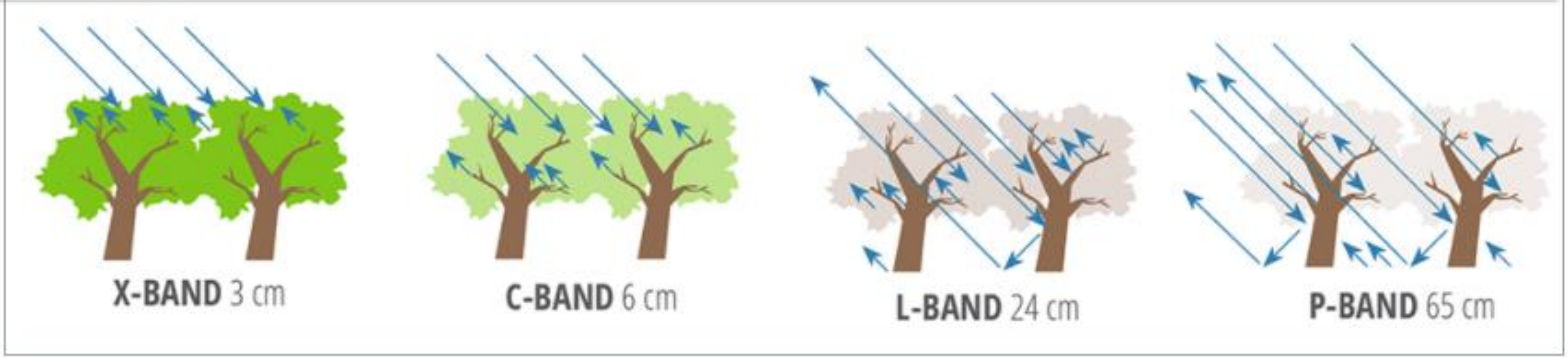
Final DEM

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



Tradeoffs of DEMs created with Sentinel-1 C-band

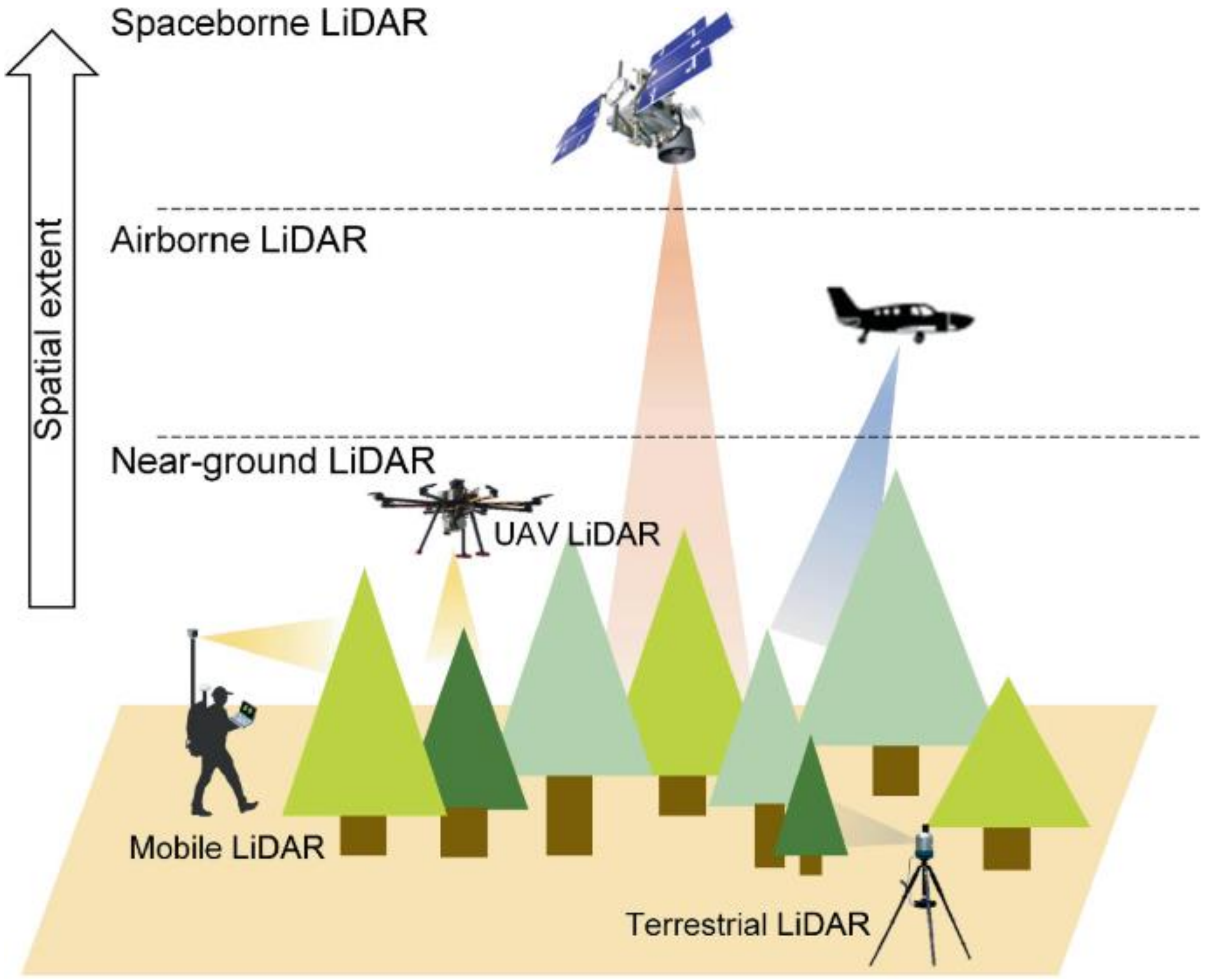
- Unfortunately, the C-band used by Sentinel-1 doesn't penetrate through vegetation. Consequently, DEMs derived from C-band radar don't directly measure the Earth's surface but instead depict the top of the canopy. However, Sentinel-1 offers excellent temporal coverage, resulting in lower temporal decorrelation 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.

Retrieval of DEM using LiDAR

- **Lidar — Light Detection and Ranging — is a remote sensing method used to examine the surface of the Earth.**
- LiDAR employs pulsed laser light to measure distances to the Earth's surface, generating precise three-dimensional data about its shape and surface features.
- A typical LiDAR setup includes a laser, scanner, and specialized GPS receiver. Aircraft are commonly used to collect LiDAR data over large areas. There are two main types of LiDAR: topographic, which uses near-infrared lasers to map land features, and bathymetric, which uses green light to measure water depth and seafloor elevations.

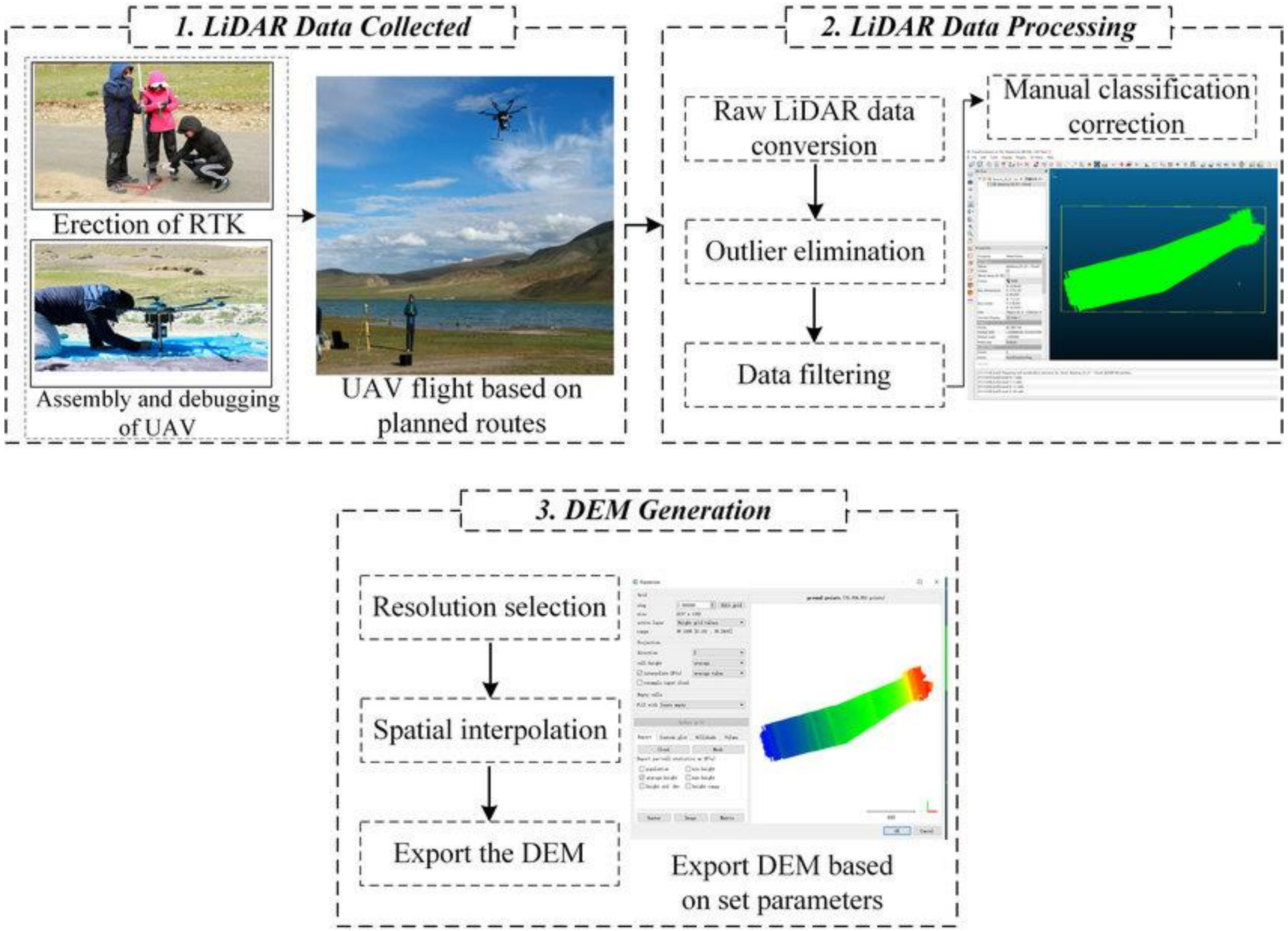


https://link.springer.com/chapter/10.1007/978-981-19-3816-0_24

Retrieval of DEM using LiDAR

Retrieval of DEM using LiDAR involves:

- **Data Acquisition:** LiDAR systems measure surface elevation by emitting laser pulses.
- **Point Cloud Generation:** LiDAR data creates a dense point cloud representing terrain features.
- **Filtering and Classification:** Algorithms remove noise and classify ground points.
- **Surface Interpolation:** Interpolation methods generate a continuous surface from ground points.
- **DEM Generation:** The interpolated surface forms the basis for creating a Digital Elevation Model.
- **Validation:** The accuracy of the LiDAR-derived DEM is assessed for quality assurance.



Comparison of Optical, SAR and LiDAR parameters

Characteristics/ Properties	Optical	SAR	LiDAR
Electromagnetic range	0.4µm to 1mm	1mm to 1m	250 nm to 10 µm Mostly monochromatic wavelength is used. Recently some systems like Optech Titan started the use of multiband data
Sensor direction for the receiving of electromagnetic radiation	Near vertical	Oblique	Near vertical
Information in pixel	Spectral reflection of the particular band.	Amplitude and phase	Not applicable because 3D point cloud is formed that contains the planimetric, altitude and intensity data.
Range Resolution (Weijie and Xiaojie, 2016)	Ground range is used.	Slant range is used.	3D point cloud is formed.
Dielectric constant	Independent	Highly dependent	Independent
Coverage Area	Large	Large	Small
Type of errors (Devapal et al., 2019)	Skew distortion, panoramic distortion, haze, error due to varying solar illumination conditions and error due to unstable platform.	Speckle, layover and foreshortening.	Error due to unstable platform, multipath error, calibration errors of GPS and inertial measurement unit.
Classification error due to self and cast shadow (Lin et al., 2019)	It is affected by the shadow that leads to the misclassification of pixel into low reflectance objects like water.	It is affected from the shadow that leads to the misclassification.	Its integration with other data helps to identify the shadow that improves the classification.

Source: https://isprs-archives.copernicus.org/articles/XLII-5-W3/1/2019/isprs-archives-XLII-5-W3-1-2019.pdf

Comparison of Optical, SAR and LiDAR parameters

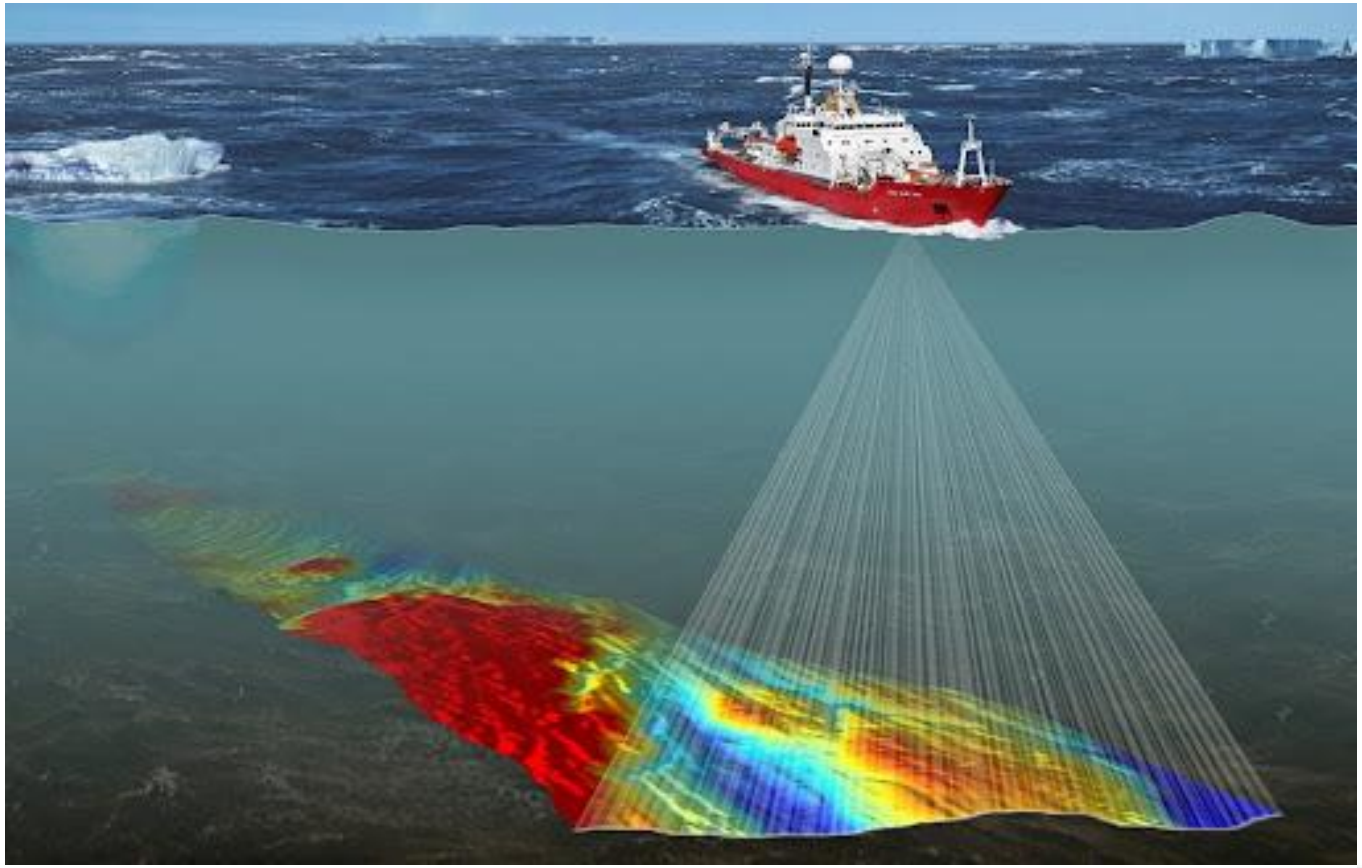
Weather dependence (Liu et al., 2019)	Cannot penetrate through clouds; therefore, image is acquired only in clear weather.	Microwaves can penetrate through clouds; therefore, image is acquired in any weather.	Scanning should be performed in cloud free condition.
Cost	Free to expensive. Prize varies according to images resolution. Most of the high resolution images are not free of cost.	Free to expensive Prize varies according to images resolution	High cost Very small amount of data is freely available.
Survey Customization	Only aerial photography can be customized.	Not possible	Airborne and terrestrial scanning can be customized.
Terrain mapping continuity	Provides a continuous mapping of terrain.	Provides a continuous mapping of terrain.	Does not provide a continuous mapping of terrain. Sampling is done at a certain interval through laser pulses.
Displacement detection	Horizontal	Horizontal and vertical	Horizontal and vertical
Bathymetry	Visible and IR waves cannot transmit through water	Microwaves can transmit through water.	Green light is used that can transmit through water.
DEM (Joyce et al., 2009; Polat et al., 2015)	It can be generated by using photogrammetry on stereo pair. Terrain slope effects the DEM generation.	The interferogram is generated by using two complex SAR images and then by using phase unwrapping technique DEM is generated.	Raw data contains the elevation information. Filtering is applied on it to remove the non-ground points. Interpolation is then applied to generate the DEM.
Parallax measurement	Parallax measurement accuracy is usually from centimeters to meters, in the order of the resolution of the imagery.	The accuracy of InSAR parallax measurement is typically ranges from several millimeters to centimeters, in the fraction of SAR wavelength	Not applicable.
Maturity	High. Instruments and algorithms are available and well tested	Medium	Low, it is still in the conception stage.

Source: https://isprs-archives.copernicus.org/articles/XLII-5-W3/1/2019/isprs-archives-XLII-5-W3-1-2019.pdf

13. Marine applications: nearshore bathymetry, sea surface monitoring

What is Bathymetry?

- Bathymetry is the study of underwater depth of the oceans and the topography of the sea/ocean floor
- It involves measuring and recording water depths to create maps, which provide valuable information about underwater features
- Bathymetric data is essential for various applications, including marine navigation, oceanographic research, coastal zone management, marine resource exploration, engineering work, port management, pipeline laying and fishing

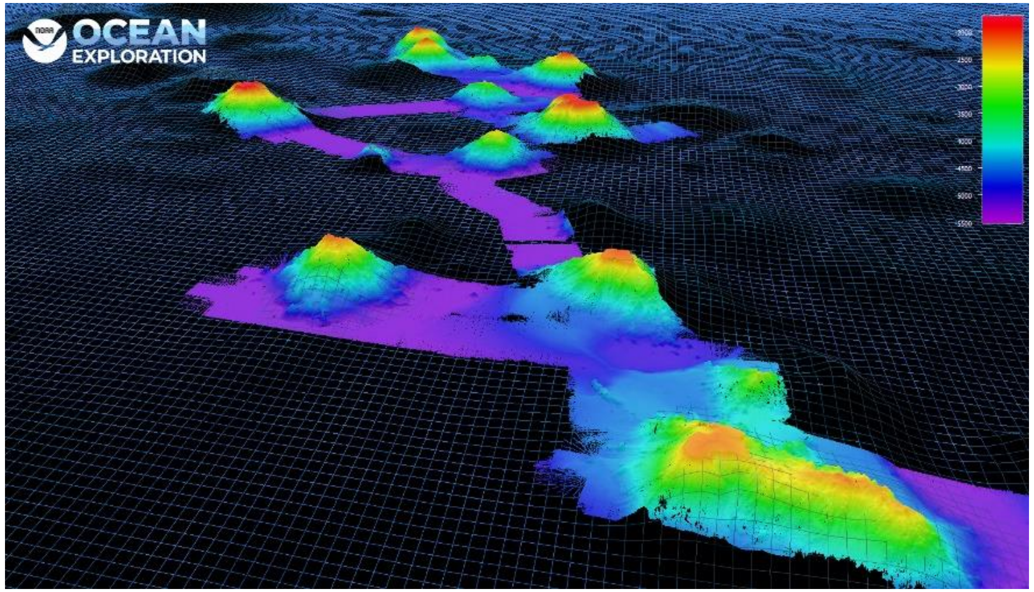


Source: http://digielitetechnologies.com/services/hydrographic-bathymetric-survey/

For more information, see the tutorial:
13. Marine applications: deriving nearshore bathymetric model with Sentinel 2 data using SNAP software

Evolution of Bathymetric mapping

- **Historically** - methods like premeasured ropes or cables to measure seabed depth - slow and inefficient approach
- **Acoustic echo-sounding** (single-beam and multi-beam) - faces limitations in turbid waters due to sound wave absorption
- **Airborne laser bathymetric (ALB) LiDAR systems** - effective but costly
- **Remote sensing -** has emerged as a promising tool for ocean bathymetry mapping due to its wide coverage, low cost, and repeatability
  - recent launches of satellites like Sentinel-1 or Ikonos, QuickBird, WorldView-2 provide high-resolution imagery

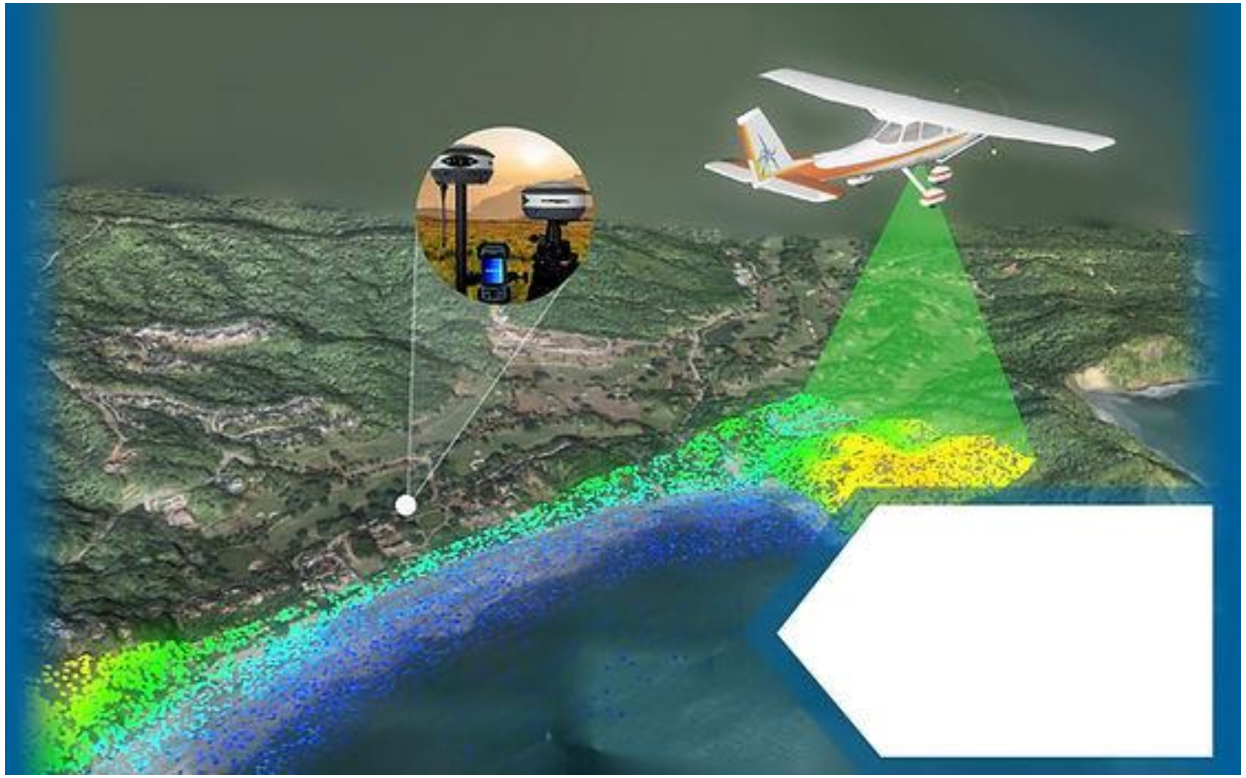


BATHYMETRIC METHODS				
Acoustic methods	Lidar	Remote sensing methods (EM spectrum)		
		SDB	Gravity	SAR radar
Pros: High quality data (IHO standard + high resolution)	Cons: Time and/or money consuming especially in shallow areas	Pros: Time and money efficient		
		Cons:		
		Depth limitation (up to 30 meters)	Resolution and accuracy	Depth limitation (10 m to 70 m)

Source:https://fig.net/resources/proceedings/fig_proceedings/fig2021/ppt/ts04.1/TS04.1_vrdoljak_kilic_10940_ppt.pdf

Approach for satellite imagery

- **Interactive/empirical methods**
  - Relative brightness to water depth
- **Photogrammetric/stereo approach**
  - Find matching points on seafloor
- **Multispectral, physics based approach**
  - Resolve light-transfer and retrieve optical properties



Source: https://www.lidar-america.com/aerial-bathymetry-lidar

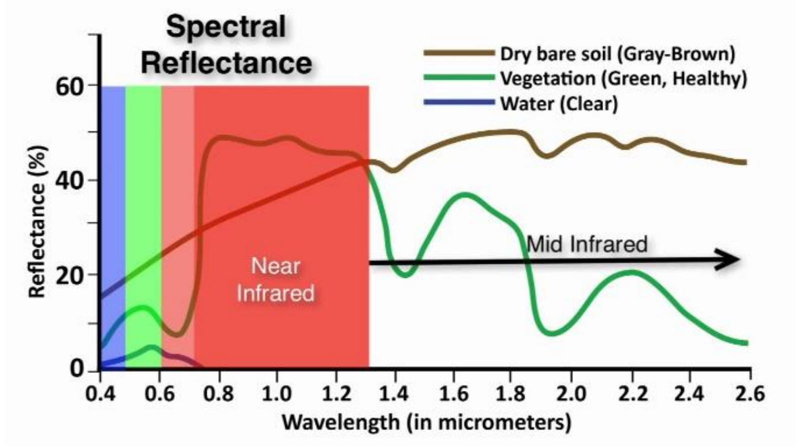
Common bands used in bathymetry

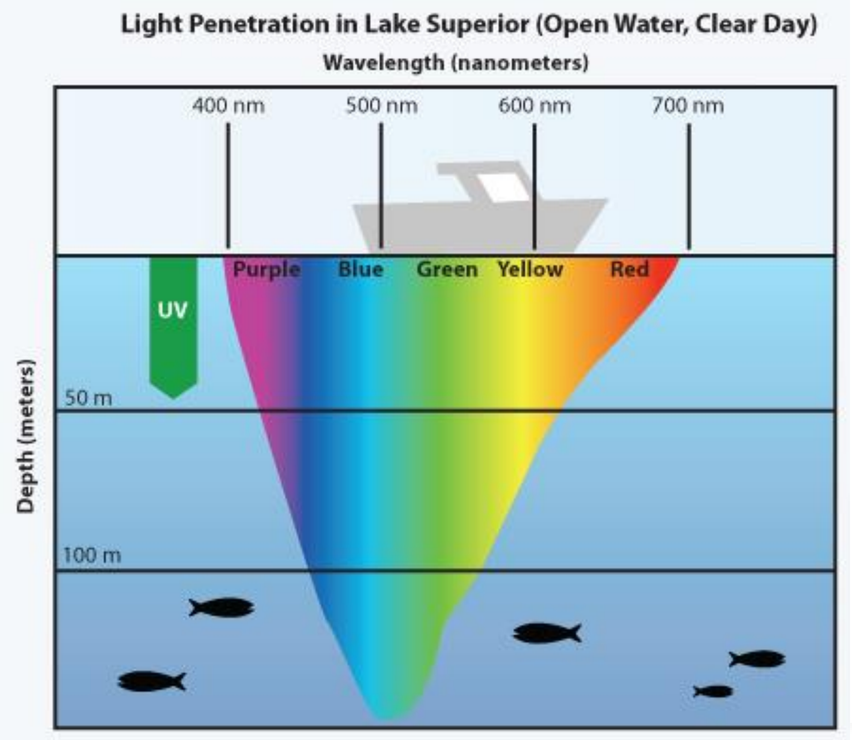
Bathymetry is typically conducted using sensors that operate within specific wavelength ranges:

- **Optical remote sensing:** blue (0.45–0.5 µm), green (0.5–0.57 µm), red (0.61–0.7 µm), NIR (0.7–1.3 µm) and SWIR (1.5–3 µm, sometimes also referred as middle infrared, MIR) bands have been commonly used in water-related applications

- **Bathymetric LiDAR systems:** typically operate in the near-infrared spectrum

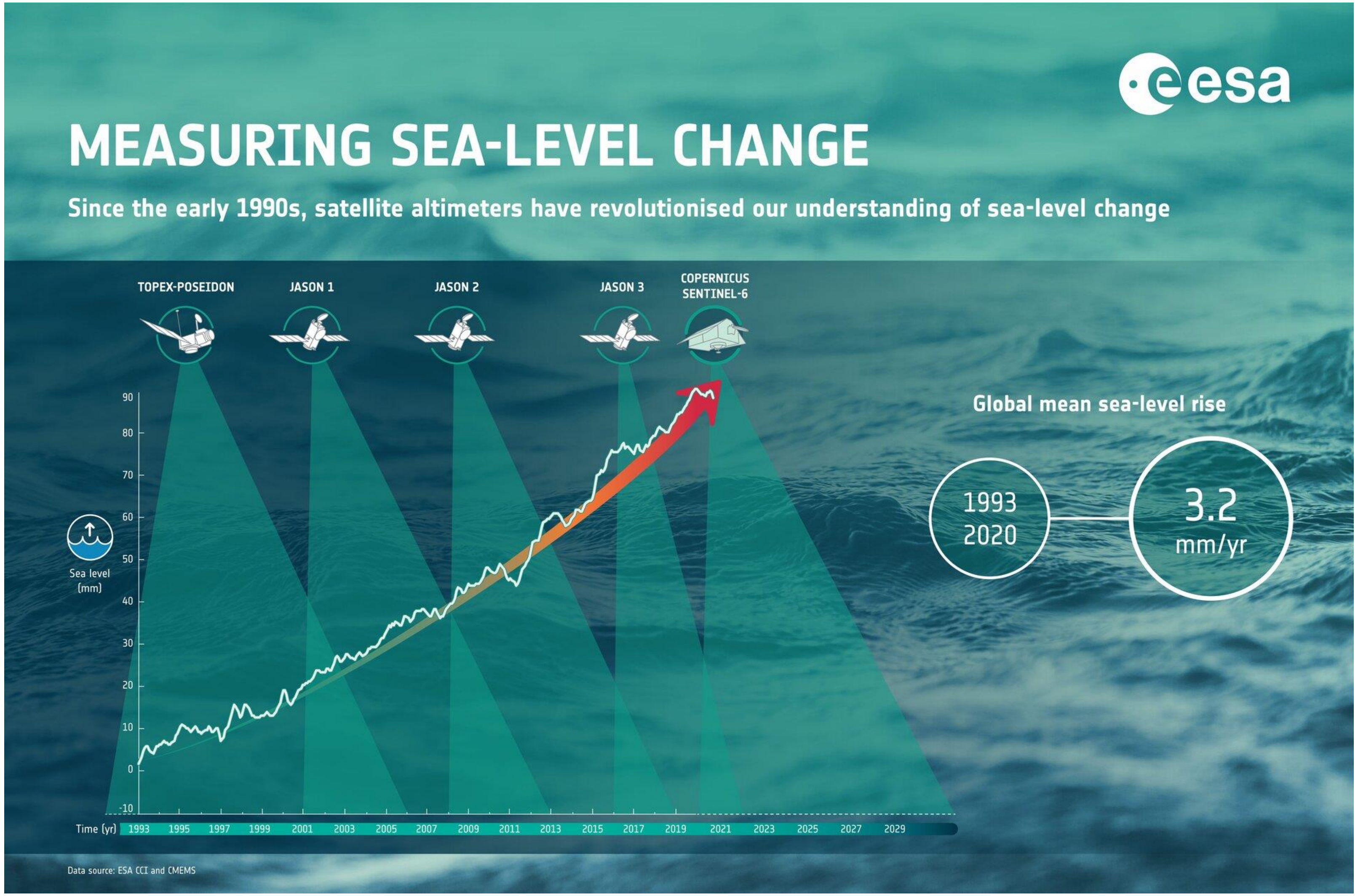
- **Synthetic Aperture Radar (SAR):** operating in the microwave spectrum. The C-band and X-band SAR sensors have been utilized for bathymetry studies





Source: https://www.youtube.com/watch?app=desktop&v=KF2j4sH7pkE, seagrant.umn.edu

Satellites for mapping seas and oceans



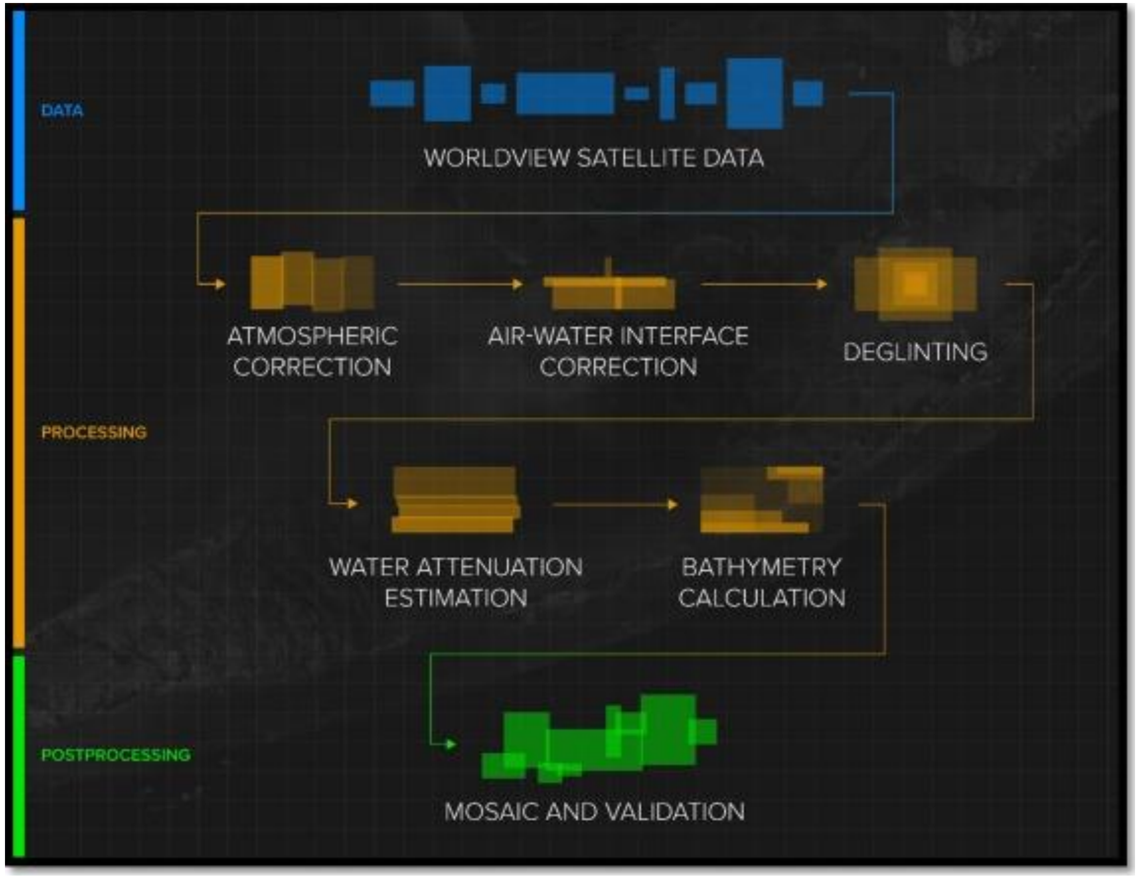
Since the early 1990s, **satellite altimeters** have revolutionised our understanding of sea-level change.

Satellites equipped with radar altimeters capture surface topography along their path over the Earth's surface. These instruments precisely determine the satellite's elevation above various features such as water, land, or ice by measuring the time taken for radar pulses to travel to the surface and back. This technology is crucial for monitoring changes in sea level globally.

Credit: ESA

Satellite-derived bathymetry (SDB)

- Satellite-derived bathymetry (SDB) has existed in practice since at least the 1970s to estimate water depth in clear, shallow water
- The process is based on the observation of water-leaving radiance, knowledge of light attenuation with depth in clear water, and a model calibrated using in-situ depth measurements
- More complex approaches use radiative transfer modeling of the water body's inherent optical properties (IOPs)
- The remote sensing of aquatic properties includes many challenges, such as detecting and correcting for sun glint, wave action, high suspended sediment, or type of bottom

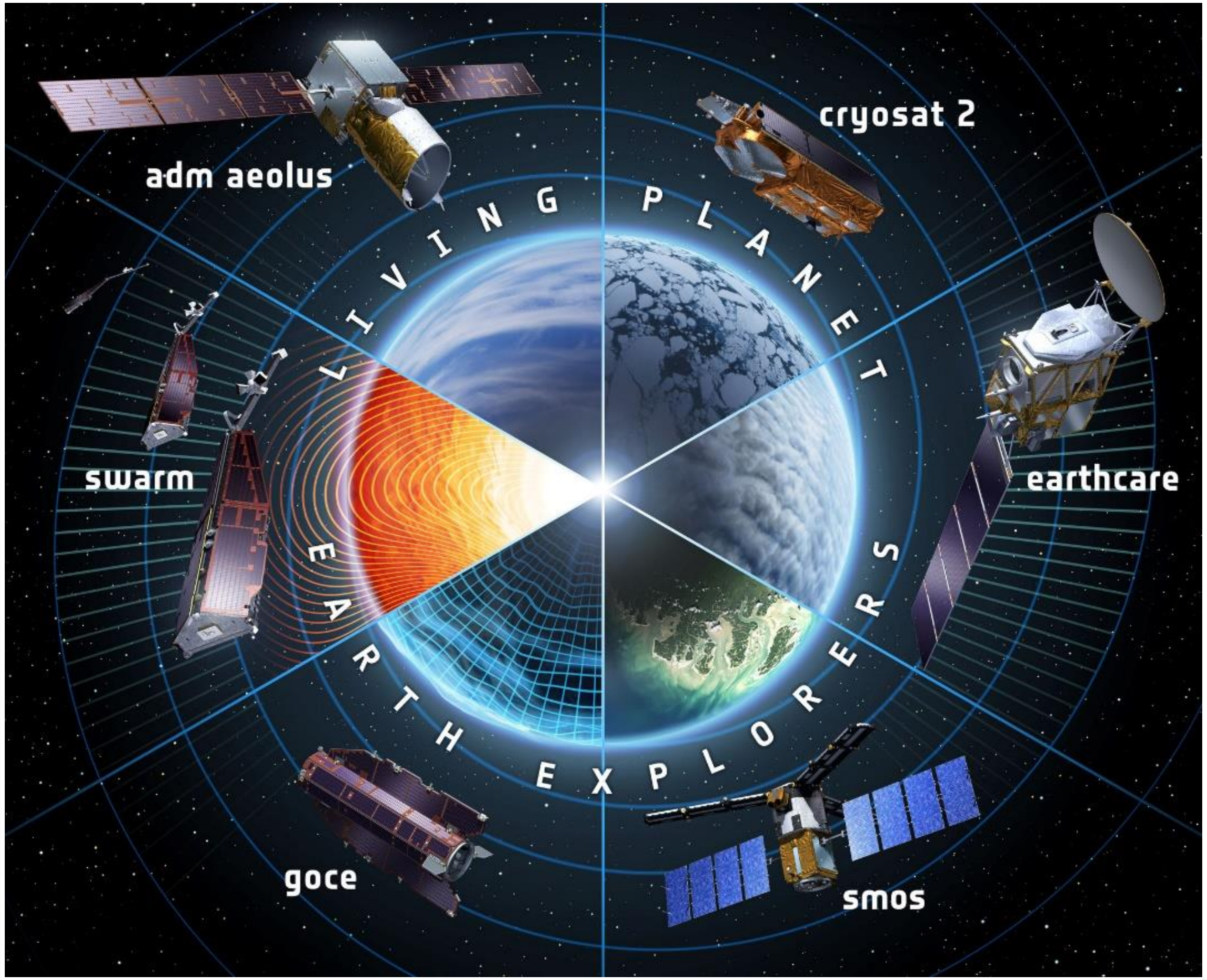


Source:https://www.sciencedirect.com/science/article/pii/S0303243422000198

ESA´s Earth Explorers for mapping sea and ocean

Several Earth Explorer missions launched by the European Space Agency (ESA) provide data that can be utilized for mapping seas and oceans:

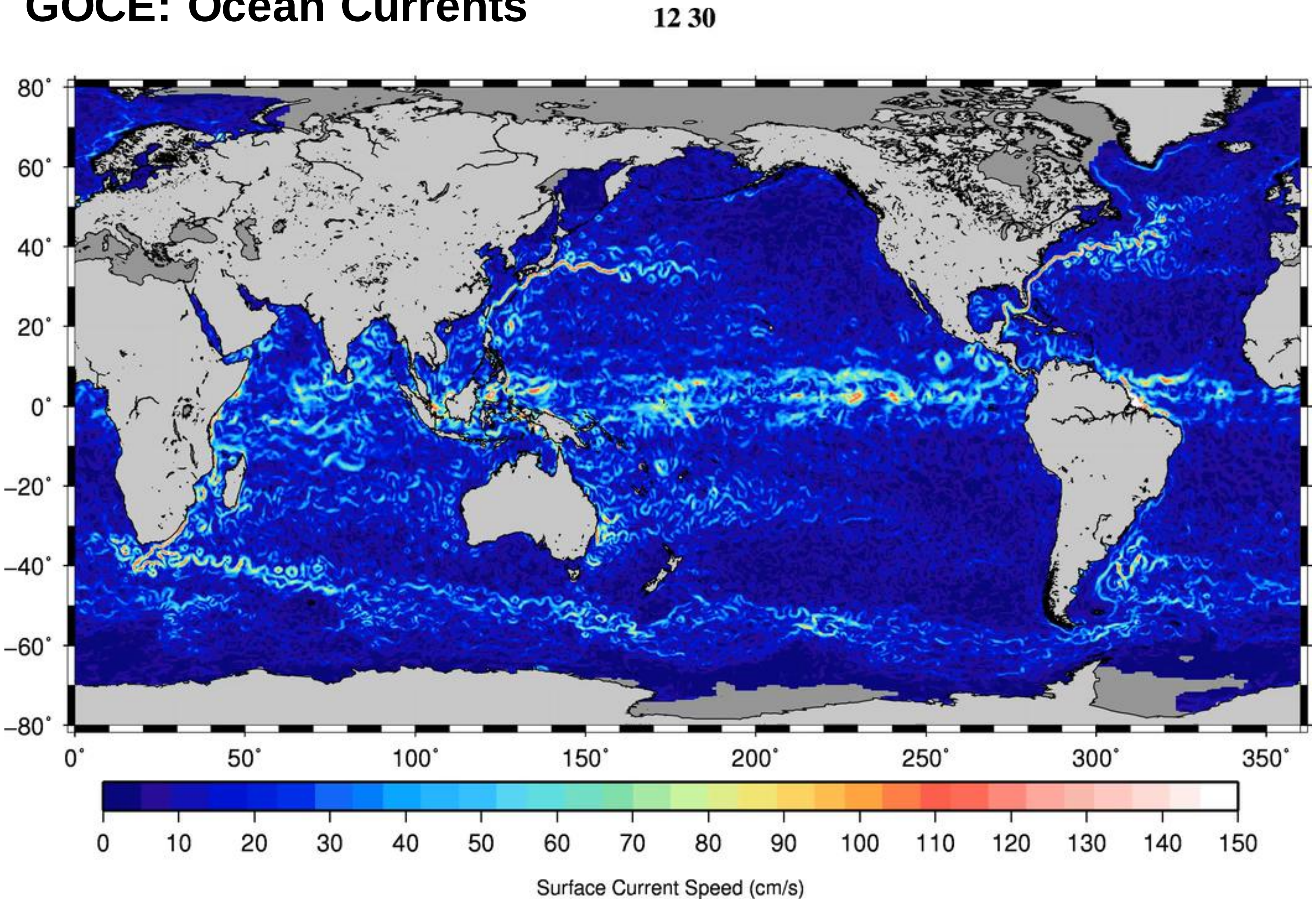
- **GOCE:** provides valuable data for studying ocean currents, sea level changes, and ocean circulation patterns
- **CryoSat:** provides valuable data on sea ice thickness and changes in sea level, which contribute to understanding ocean dynamics
- **Swarm:** provides data on ocean circulation and currents by measuring variations in the Earth's magnetic field caused by oceanic processes
- **SMOS:** can be used to study ocean dynamics and surface currents



Source:https://www.esa.int/ESA_Multimedia/Images/2012/11/ESA_s_Earth_Explorers_satellites

ESA´s Earth Explorers for mapping sea and ocean

GOCE: Ocean Currents



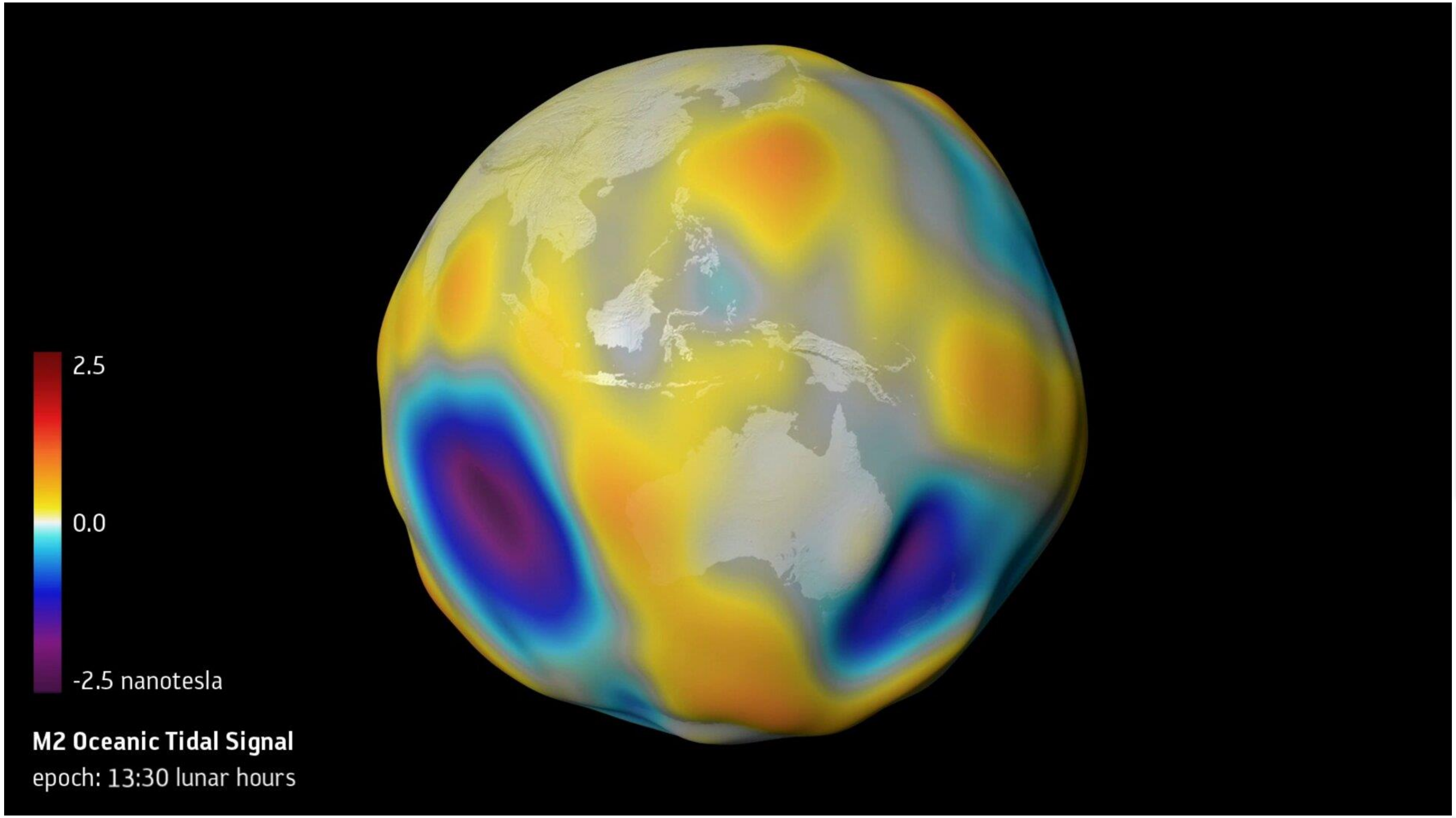
Weekly evolution of ocean surface currents from January 1993 to December 2011.

Gravity data from GOCE geoid & sea altimetry data

Source: https://www.esa.int/ESA_Multimedia/Images/2014/11/Ocean_currents_from_GOCE

ESA´s Earth Explorers for mapping sea and ocean

SWARM: Magnetic tides



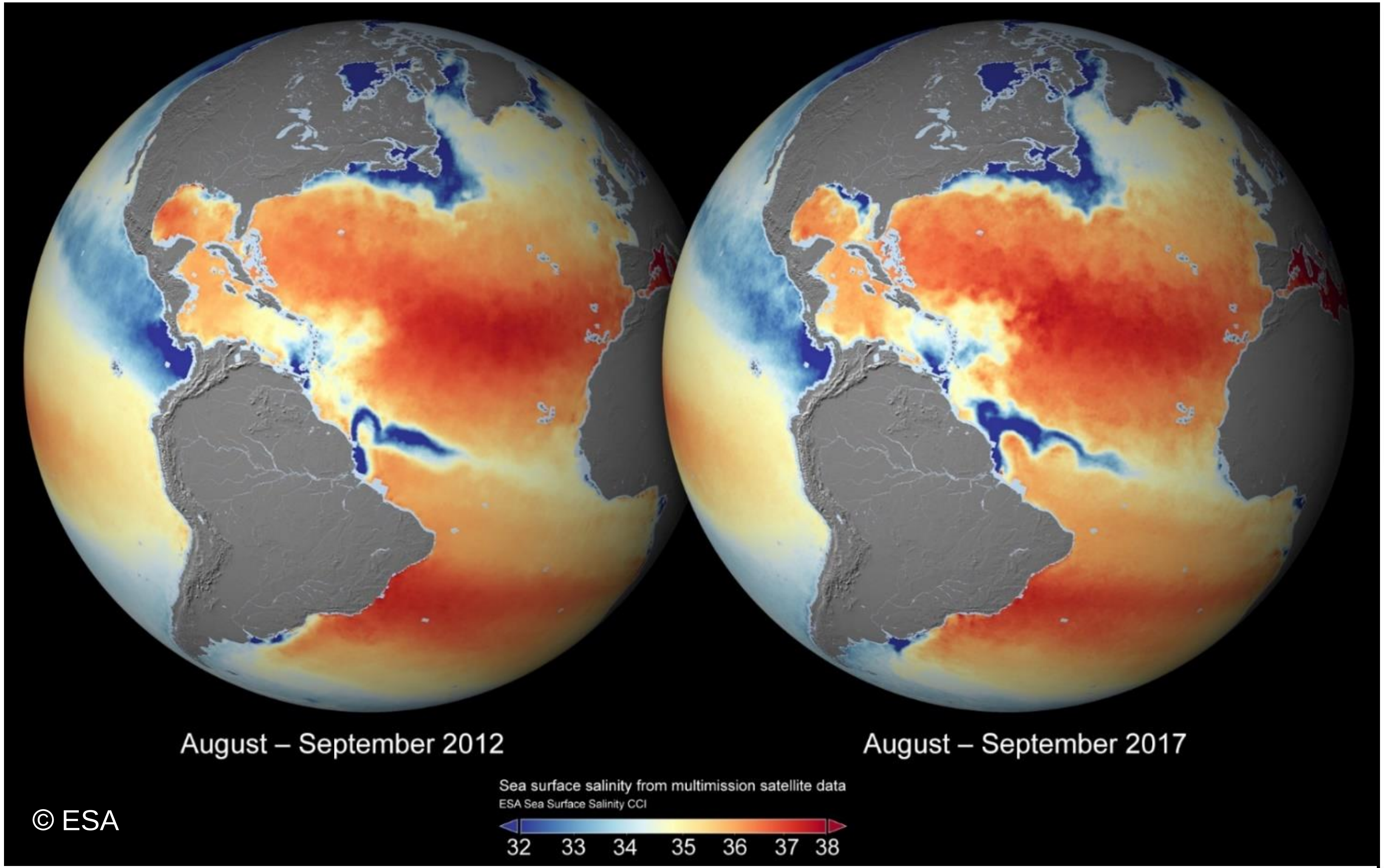
Source: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Swarm/Swarm_tracks_elusive_ocean_magnetism

The magnetic tidal signal measured by Swarm is important for ocean and climate modelling, and is used to determine the electrical properties of the Earth's lithosphere and upper mantle.

Source: ESA

ESA´s Earth Explorers for mapping sea and ocean

SMOS: Sea-ice change

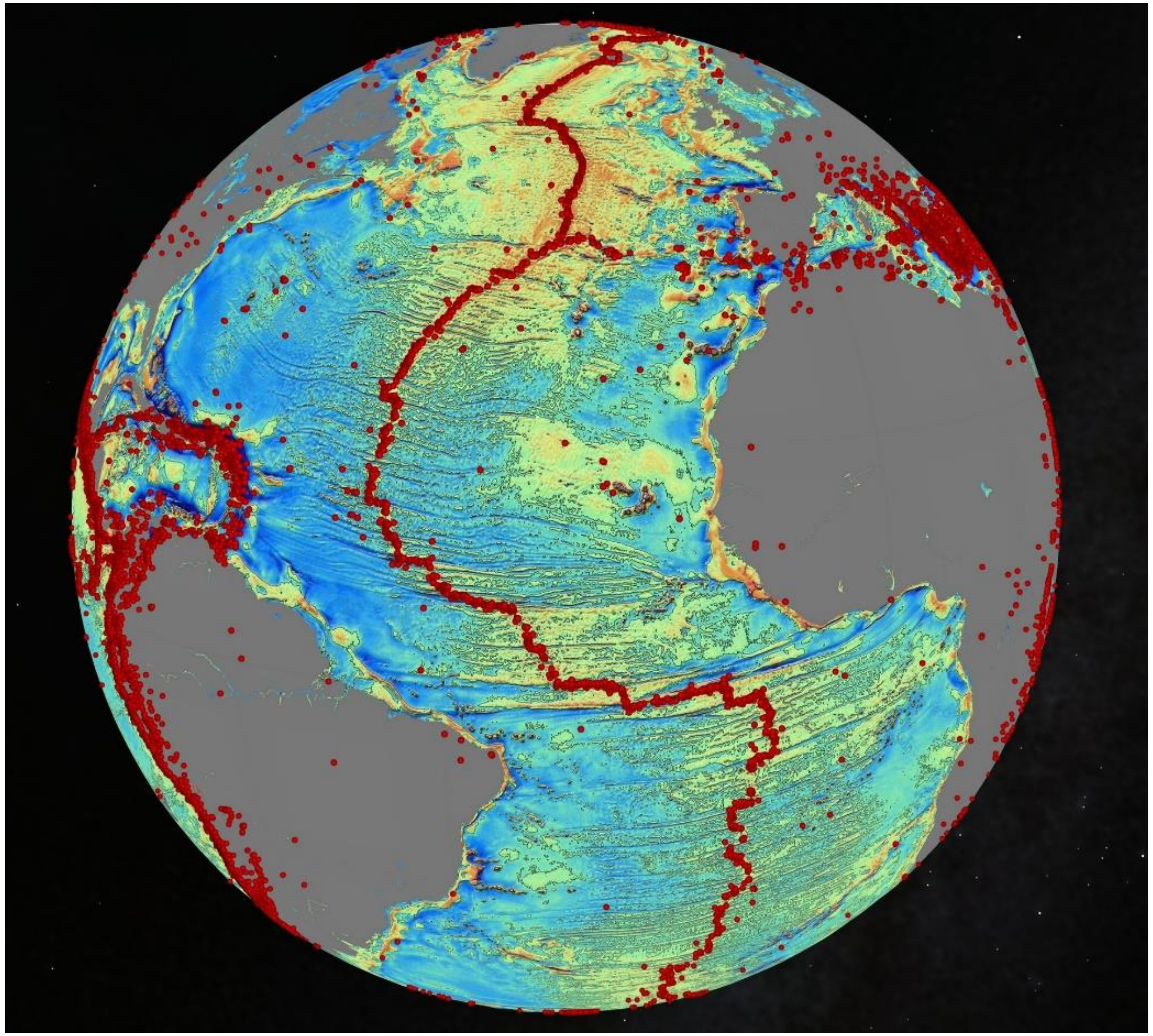


Global sea-surface salinity maps from ESA's Climate Change Initiative showing the difference for the same period in 2012 and in 2017. Note the differences in the spreading of the Amazon and Mississippi River plumes.

Source: https://www.esa.int/ESA_Multimedia/Images/2019/11/Global_sea-surface_salinity_2012_and_2017

ESA´s Earth Explorers for mapping sea and ocean

CRYOSAT: Marine gravity map



- Scientists from Scripps Institute of Oceanography at University California San Diego used altimetry measurements from ESA's CryoSat mission and from the CNES–NASA Jason-1 satellite to create a new marine gravity map – twice as accurate as the previous version produced nearly 20 years ago.

- CryoSat's main task is to measure the elevation of the world's ice but its altimetry measurements acquired over oceans measure sea-surface height, and this can be used to create global marine gravity models and, from them, eventually derive maps of the seafloor.

Credits: ESA

ESA´s Sentinels for mapping sea and ocean

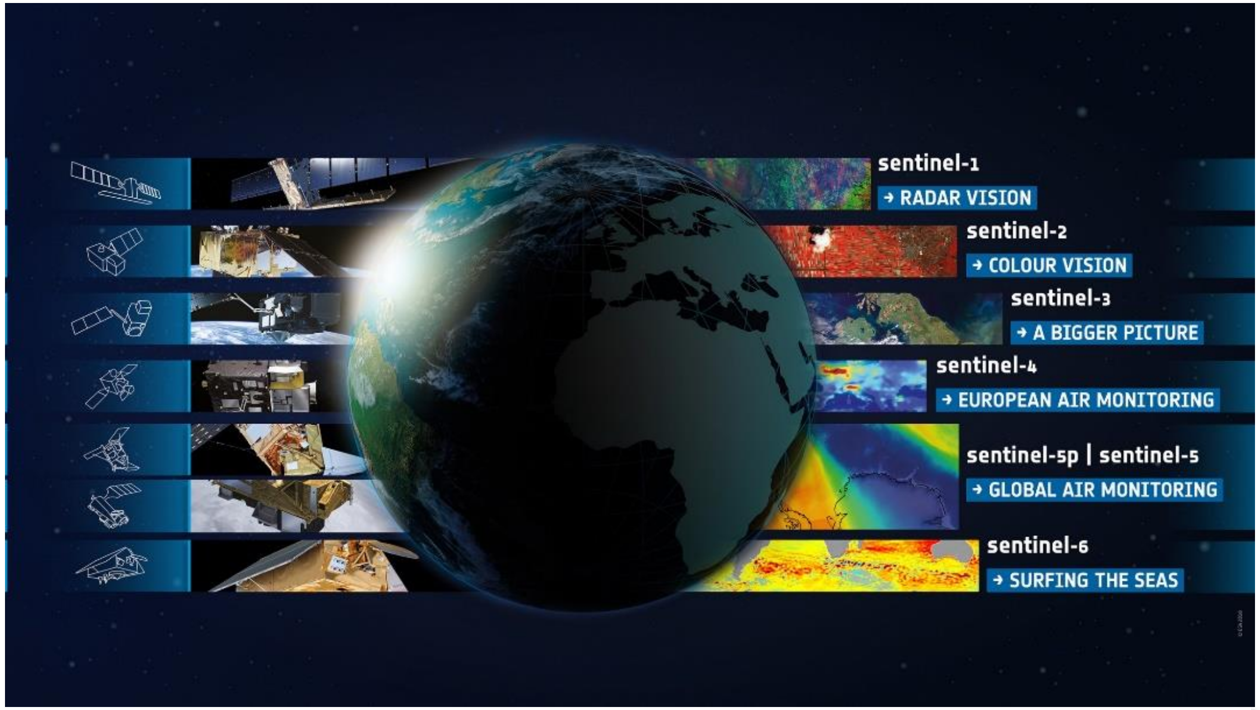
ESA's Sentinel satellite missions, including Sentinel-1, Sentinel-2, Sentinel-3, and Sentinel-6/Jason-CS, provide vital data for mapping and monitoring the Earth's seas and oceans:

Sentinel-1's Synthetic Aperture Radar (SAR) - tracks sea ice extent, ocean surface wind fields, and oil spills

Sentinel-2 offers insights into coastal erosion and coral reef health

Sentinel-3 is dedicated to oceanography, monitoring sea surface temperature, ocean color, and sea level rise

Sentinel-6/Jason-CS continues measuring sea surface height, aiding in understanding ocean circulation and climate change



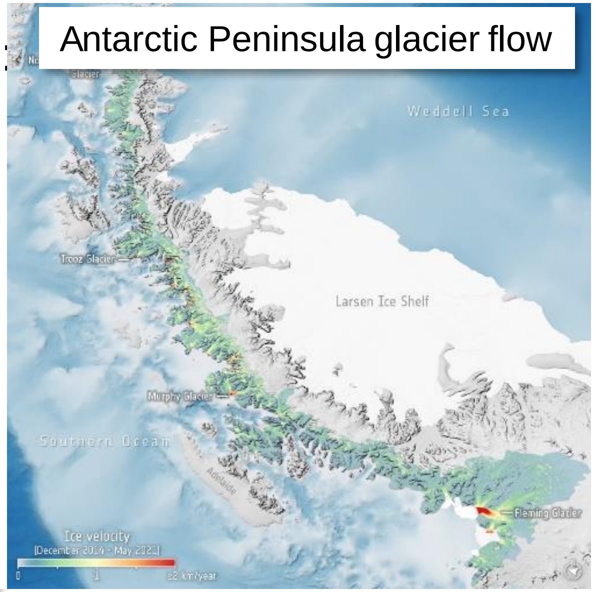
Source:ESA

ESA´s Sentinels for mapping sea and ocean

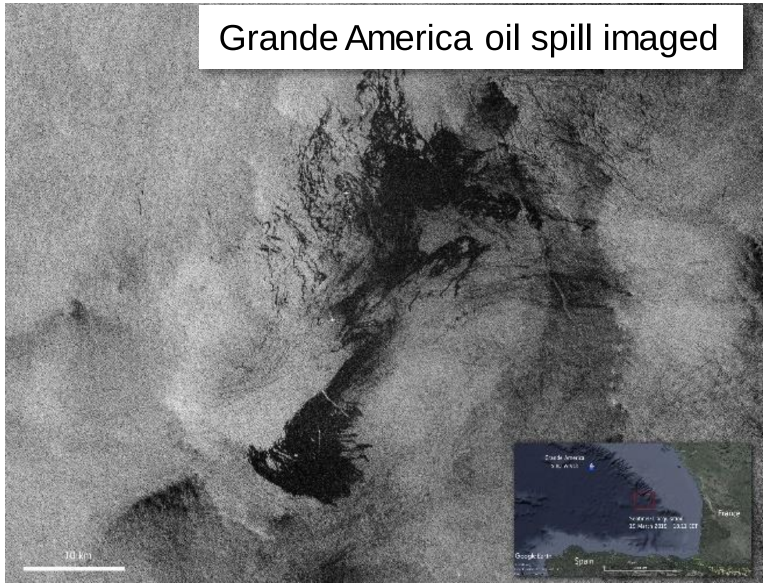
Sentinel-1 – Applications

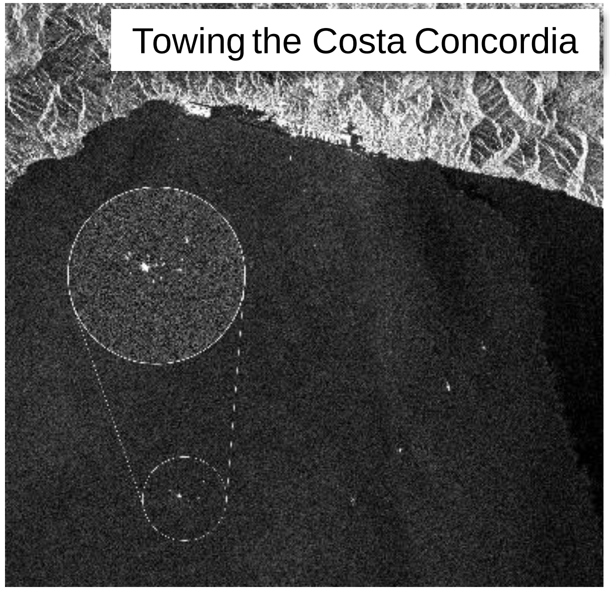
Maritime surveillance:

- Ice Monitoring
- Oil Spill Monitoring
- Ship Detection
- Marine Winds, Etc.



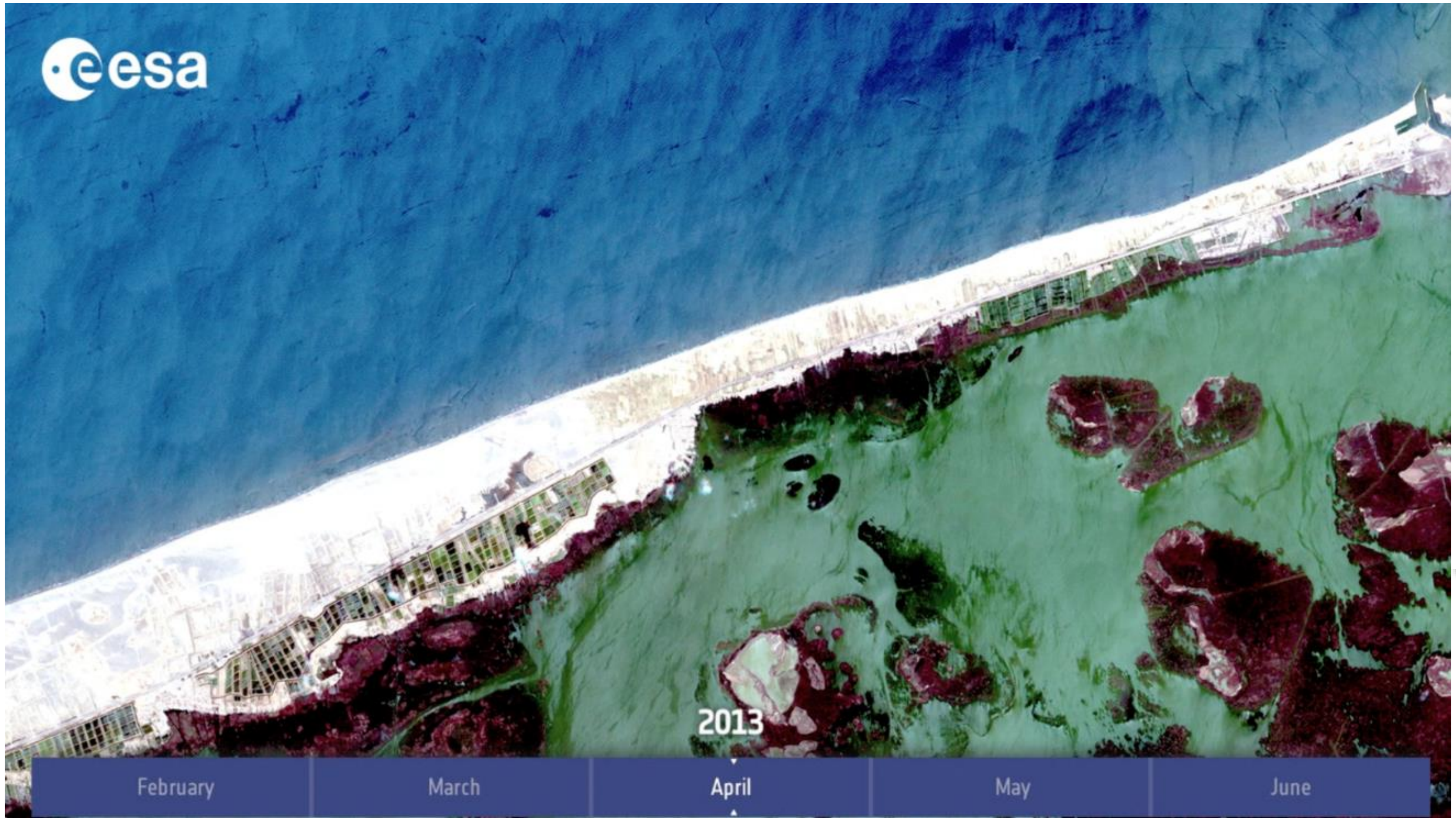
Antarctic Peninsula glacier flow


Grande America oil spill imaged


Towing the Costa Concordia

ESA´s Sentinels for mapping sea and ocean

Sentinel-2 – Applications

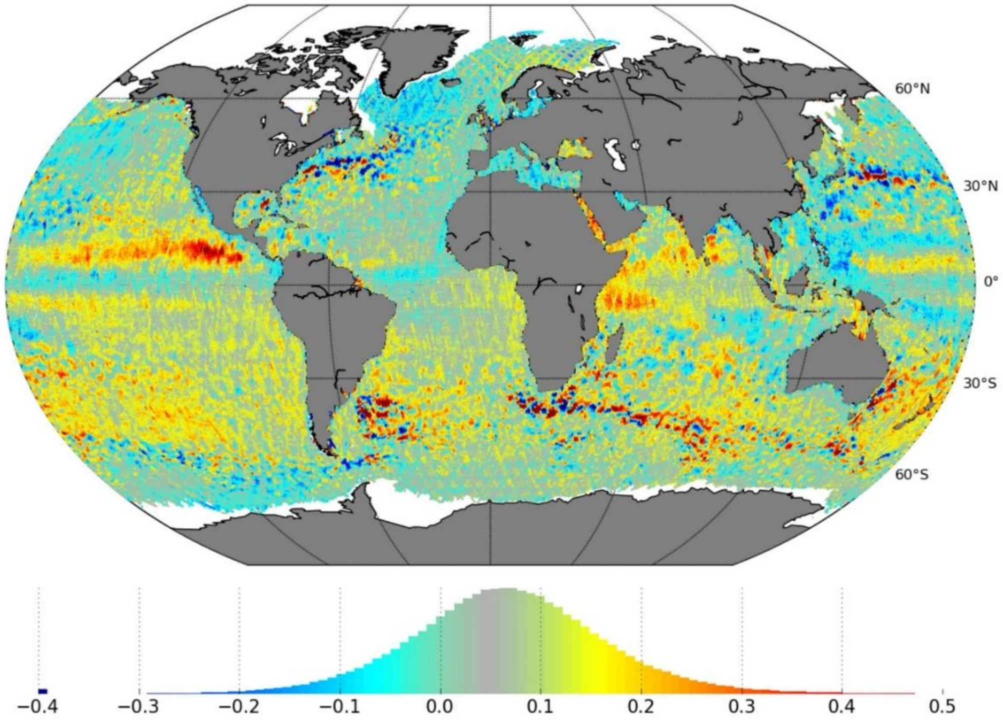


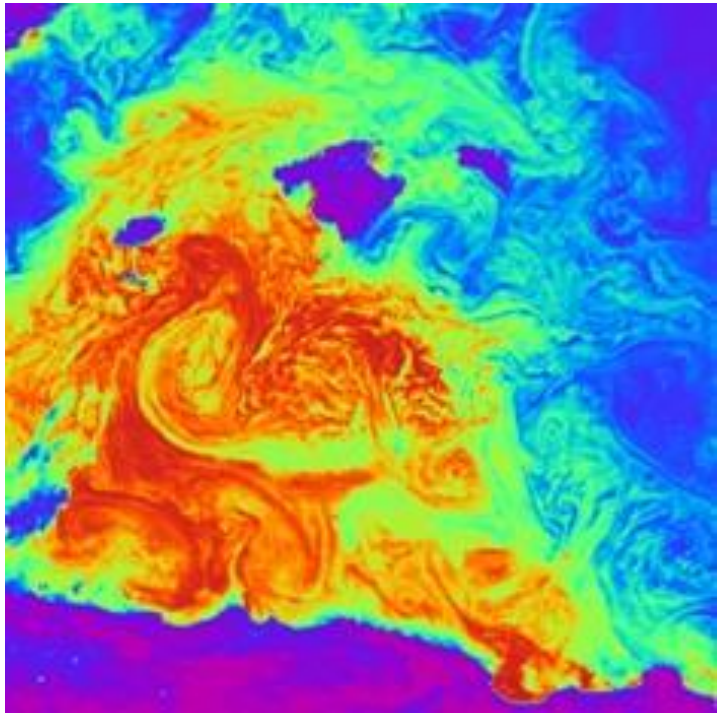
- This animation features imagery from the German RapidEye satellites to demonstrate how the future Sentinel-2 mission will be able to monitor land and coastal zones.

Credits: ESA

ESA´s Sentinels for mapping sea and ocean

Sentinel-3 – Applications



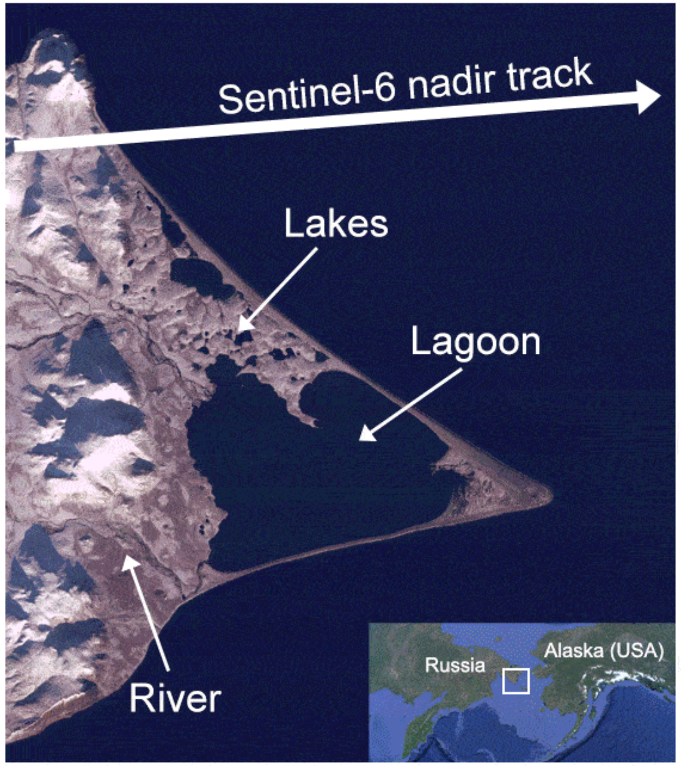


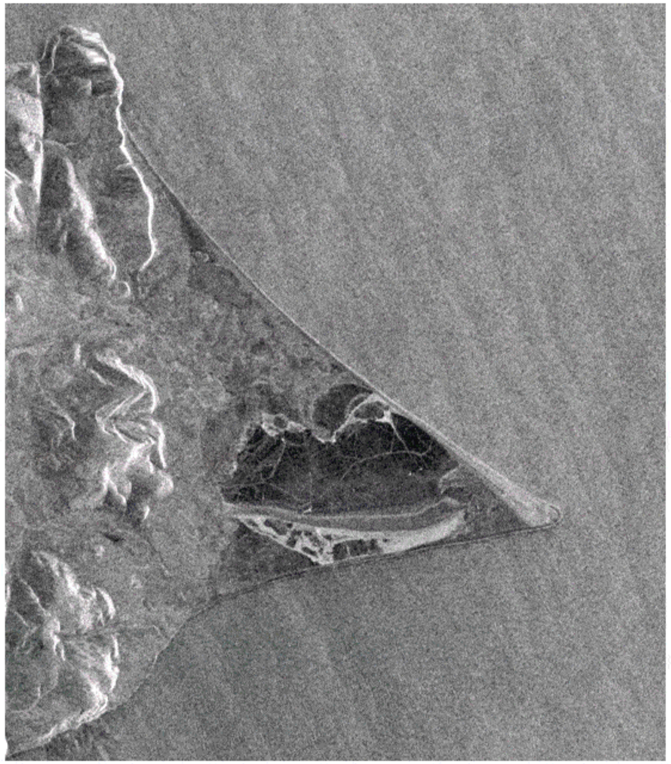
- This new map shows a month of ‘sea-level anomaly’ measurements from Sentinel-3A. The satellite has only been in orbit since 16 February 2016 and is therefore still being commissioned for service. Credits: ESA

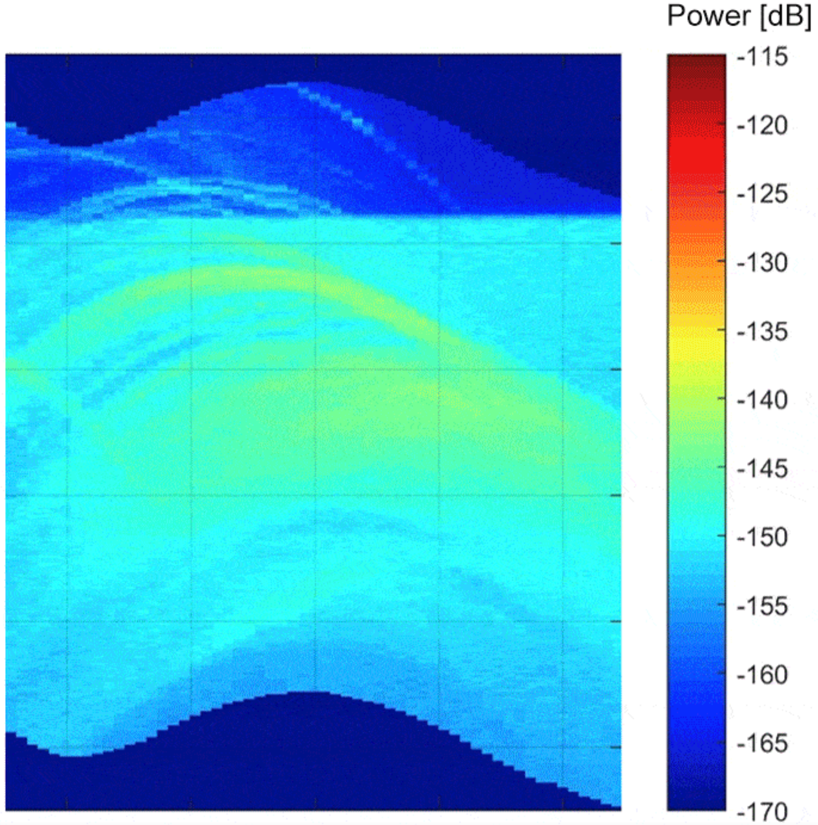
- In this night-time image of SST from AATSR, the coldest areas - which include all the land - are shown in purple and blue, whilst yellow and orange are used to represent successively warmer temperatures over a total range of 280-295 K. Credit: RAL

ESA´s Sentinels for mapping sea and ocean

Sentinel-6/Jason-CS – Surfing the seas







The images of Russia's Ozero Nayval Lagoon and surrounding rivers show multiple views from Copernicus satellites. The first is a 10-m resolution 'camera-like' image captured on 29 October 2020 by Copernicus Sentinel-2. The image is marked with the ground track of Copernicus Sentinel-6 as it crosses the region. The second is a radar image captured on 29 November 2020 by Copernicus Sentinel-1 in interferometric wide swath mode and processed to 10 m resolution. The lagoon has frozen over and numerous cracks are visible in the ice. Ocean swell and wind sea roughness are also seen in the ocean with some wave reflection and refraction on the southern coastal areas. The next image uses Copernicus Sentinel-6 pulse-limited low-resolution mode data for the same area. In this mode, similar to Jason-3, the strongest radar reflections appear as overlapping parabola features, but no discrimination of the ground can be made. Overlying the third image, the Copernicus Sentinel-6 Poseidon-4 fully-focused synthetic aperture radar image reveals features of the Ozero Nayvak Peninsular in fine detail.

Credits: ESA

ESA's Third Party Missions

Many of ESA third party missions also provide datasets for monitoring Earth's water cycle, e.g.:

- **Pléiades Neo:** very high resolution data can be used for both hydrological and bathymetry applications, allowing deeper penetration in water bodies and a clearer understanding of underwater relief

- **Ocean-Sat:** data on ocean chlorophyll can help research into primary production and the monitoring of phytoplankton blooms

- **RADARSAT-2:** data provide valuable information about sea surface conditions, currents, and wave patterns, can be used for bathymetric mapping, particularly in shallow coastal areas or regions with limited optical visibility

Source:https://intelligence.airbus.com/newsroom/case-studies/pleiades-neo/dhi-water-management-from-space/

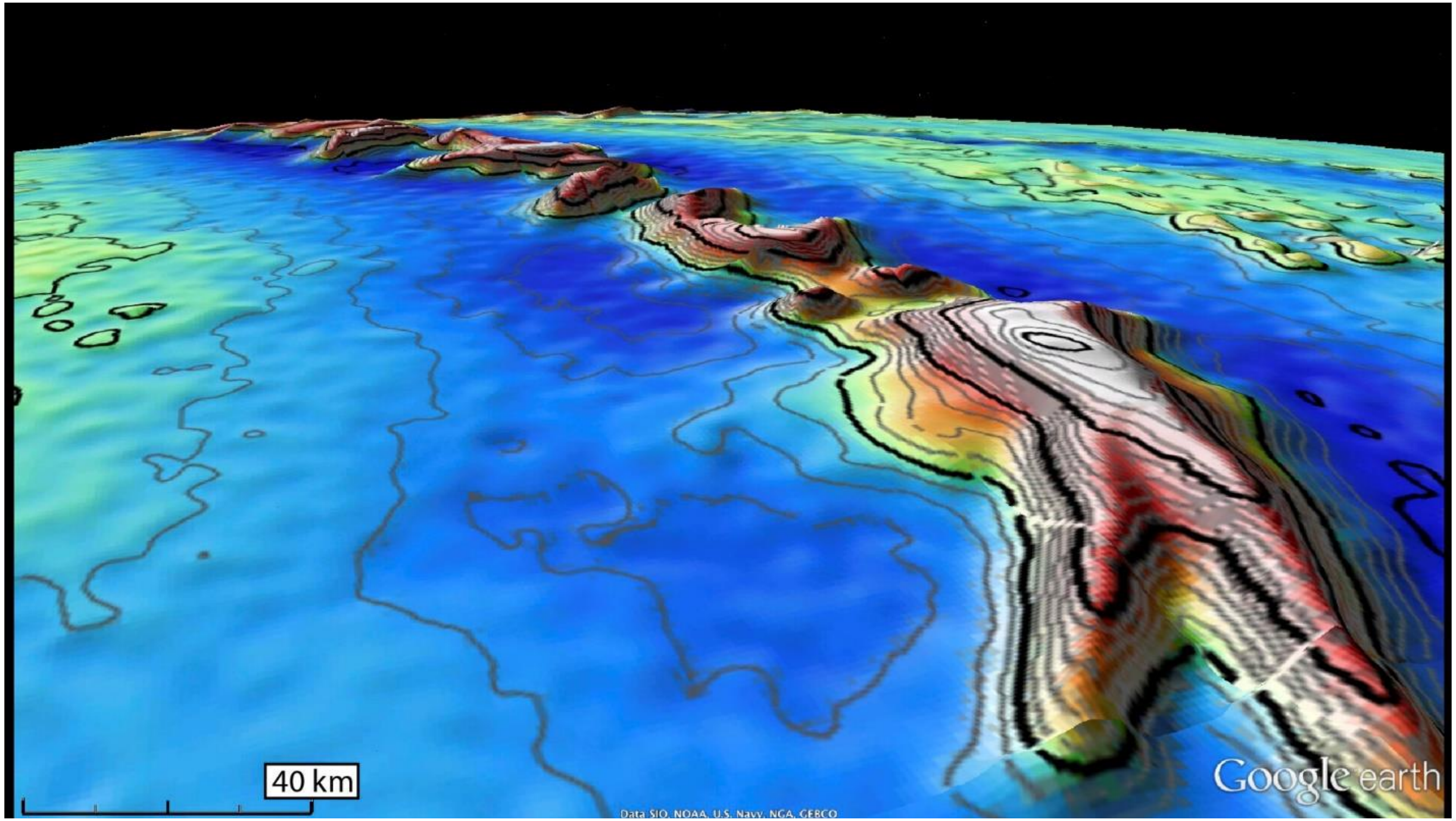
ESA's Heritage Missions

ERS-1 and -2

- data acquired for more than 20 years to track sea surface topography and winds, **moisture transfers**

Envisat

- data on water quality over long time periods



Gravity field over the Pacific Ocean's Emperor Seamounts based on CryoSat, ERS and Geosat satellite altimeter measurements of ocean-surface height.
Source: https://www.esa.int/ESA_Multimedia/Images/2012/05/Improving_bathymetry

esa space solutions

Copernicus Academy

ÚSTAV GEOGRAFIE
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