SAR for Soil Moisture

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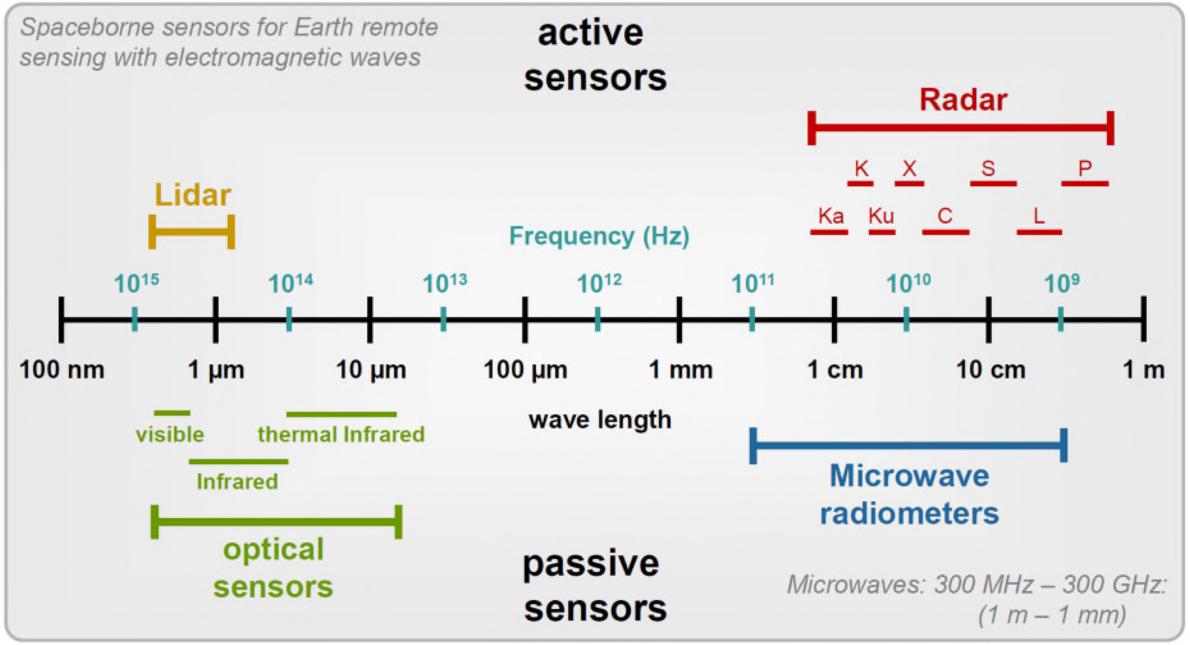
What is SAR?

Approaches for Remote Sensing of Soil Moisture

- Measurement principles
  - No direct measurement of soil moisture possible, only indirect techniques

- Visible to Mid-Infrared (0.4 – 3 μm)
  - Change of soil colour
  - Water absorption bands at 1.4, 1.9 and 2.7 μm
  - Vegetation as indirect indicator of soil wetness
- Thermal Infrared (7-15 μm)
  - Indirect assessment of soil moisture through its effect on the surface energy balance (temperature, thermal inertia, etc.)
- Microwaves (1 mm – 1 m)
  - Change of dielectric properties

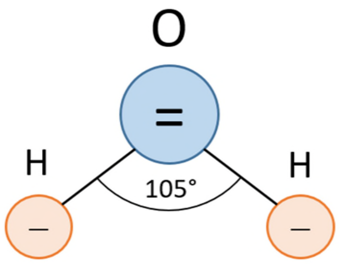
Electromagnetic Spectrum and Sensor Types



https://earth.esa.int/documents/10174/642943/6-LTC2013-SAR-Moreira.pdf

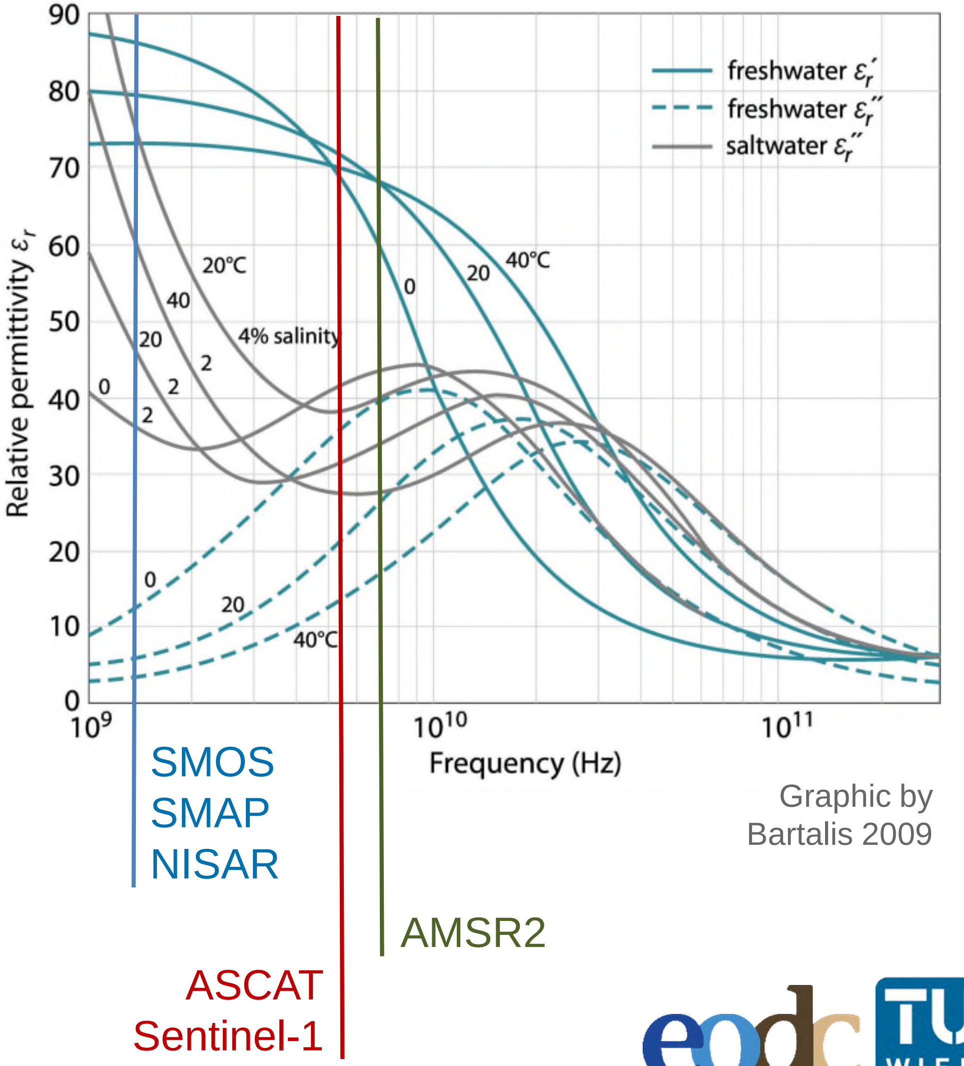
Microwaves

- All-weather, day-round measurement capability
  - No problems with clouds below about 10 GHz
- High penetration into vegetation and soils
  - Longer wavelengths beneficial
- Microwave measurements are sensitive to
  - Geometric structure
    - Roughness
  - Dielectric properties
    - Water



The separation of positive and negative charges in a water molecule causes a water molecule to react strongly to an incoming electromagnetic wave. It starts to "wobble", producing heat and reradiating electromagnetic waves. Technically, it is said that water has a permanent dipole moment that leads to orientational polarisation and a high dielectric constant.

Dielectric properties of water at microwave frequencies

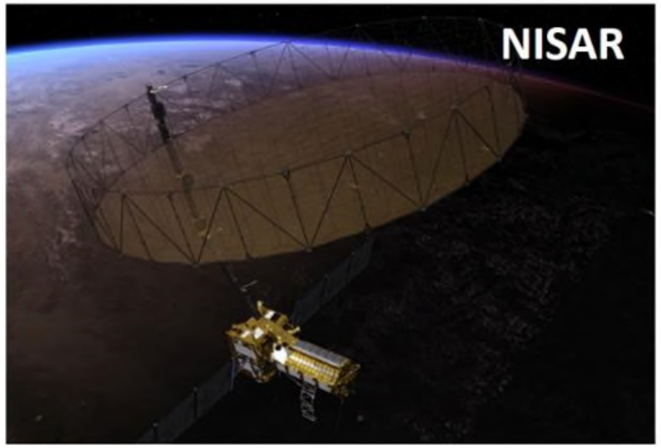


Graphic by Bartalis 2009

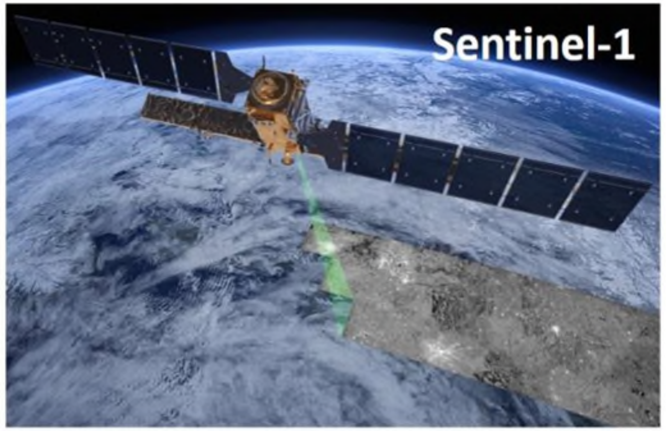
Microwave Satellites for Soil Moisture Monitoring

Radiometers | **Active/Passive Microwave** | **Synthetic Aperture Radar**

L-Band



C-Band



Coarse Resolution

Fine Resolution

Active and Passive Microwave Sensors

Active Sensors

- Active sensor systems transmit pulses and detect the signals scattered by the objects
- Mono-static radars measure the backscattering coefficient σ^0
  - a measure of the reflectivity of the Earth surface

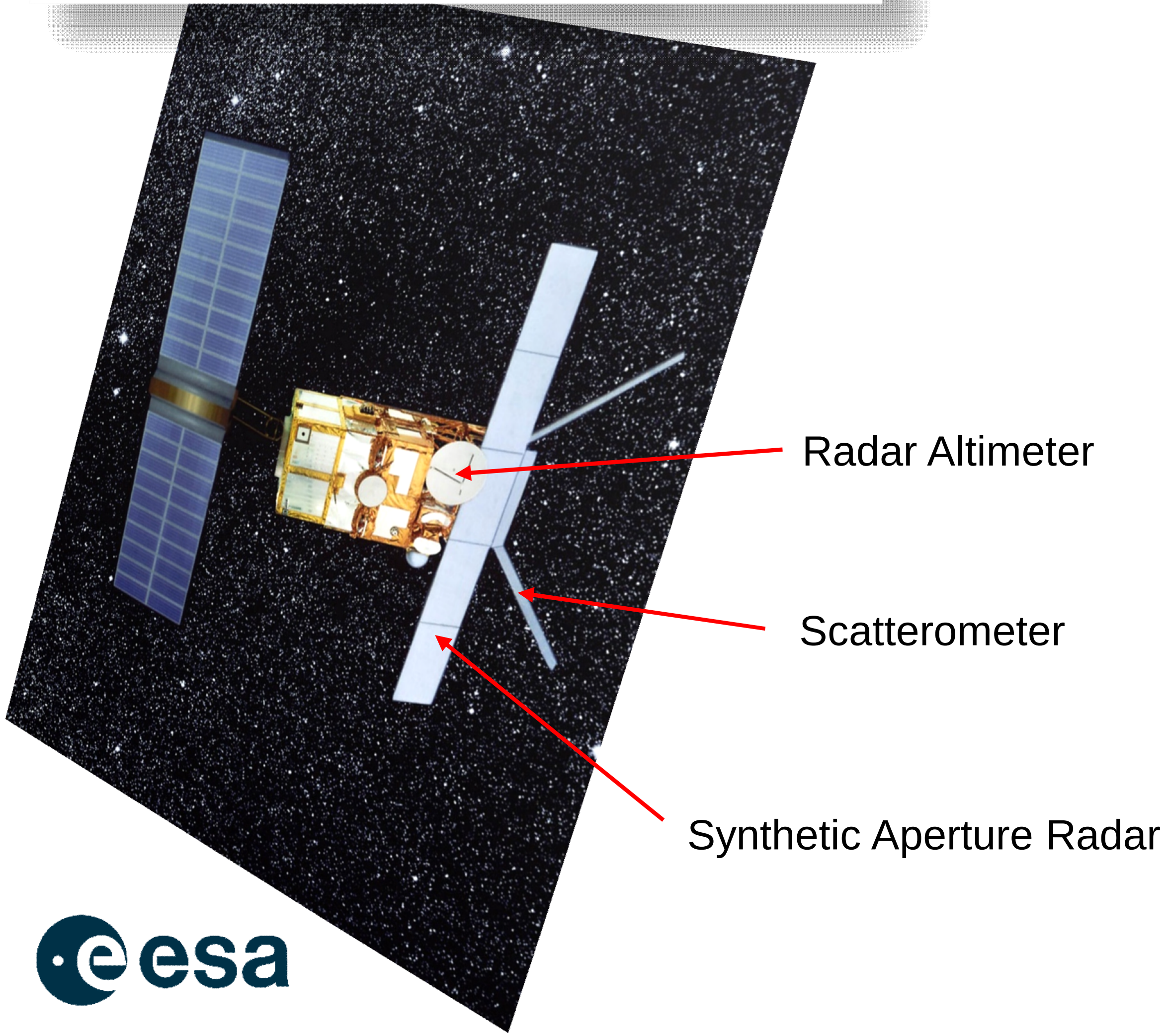
Passive Sensors

- Passive sensors detect the microwave radiation emitted by the objects themselves
- Microwave radiometers measure the brightness temperature T_B
  - $T_B = e \cdot T_s$ where e is the emissivity and T_s the physical surface temperature

- Active measurements are more sensitive to roughness and vegetation structure than passive measurements, but
  - are not affected by surface temperature (above 0°C)
  - have a better spatial resolution
- Despite these differences both active and passive sensors are sensitive to the same variables:
  - Passive and active methods are interrelated through Kirchhoff's law: $e = 1 - r$ where r is the reflectivity

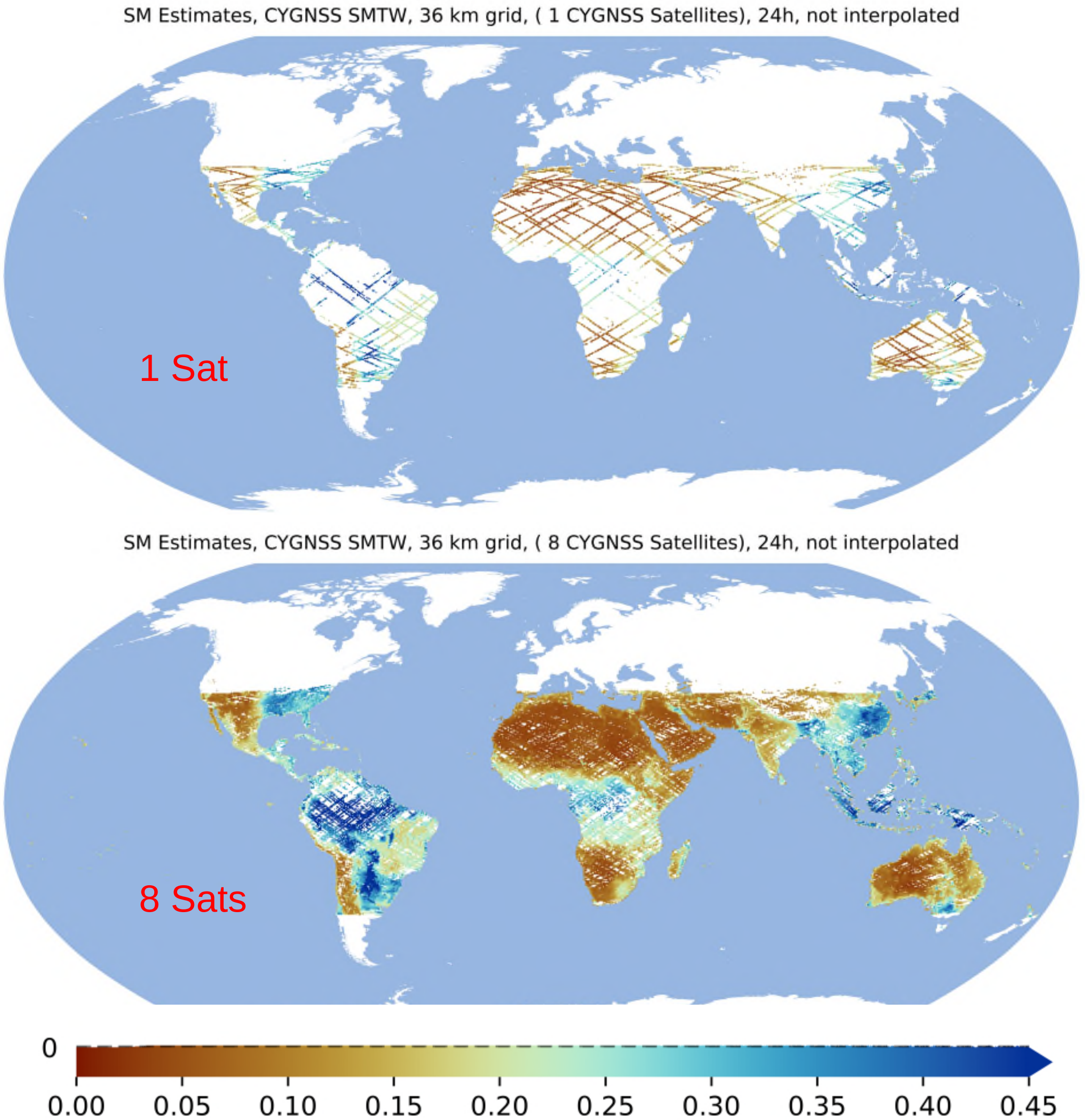
Active Microwave Measurement Techniques

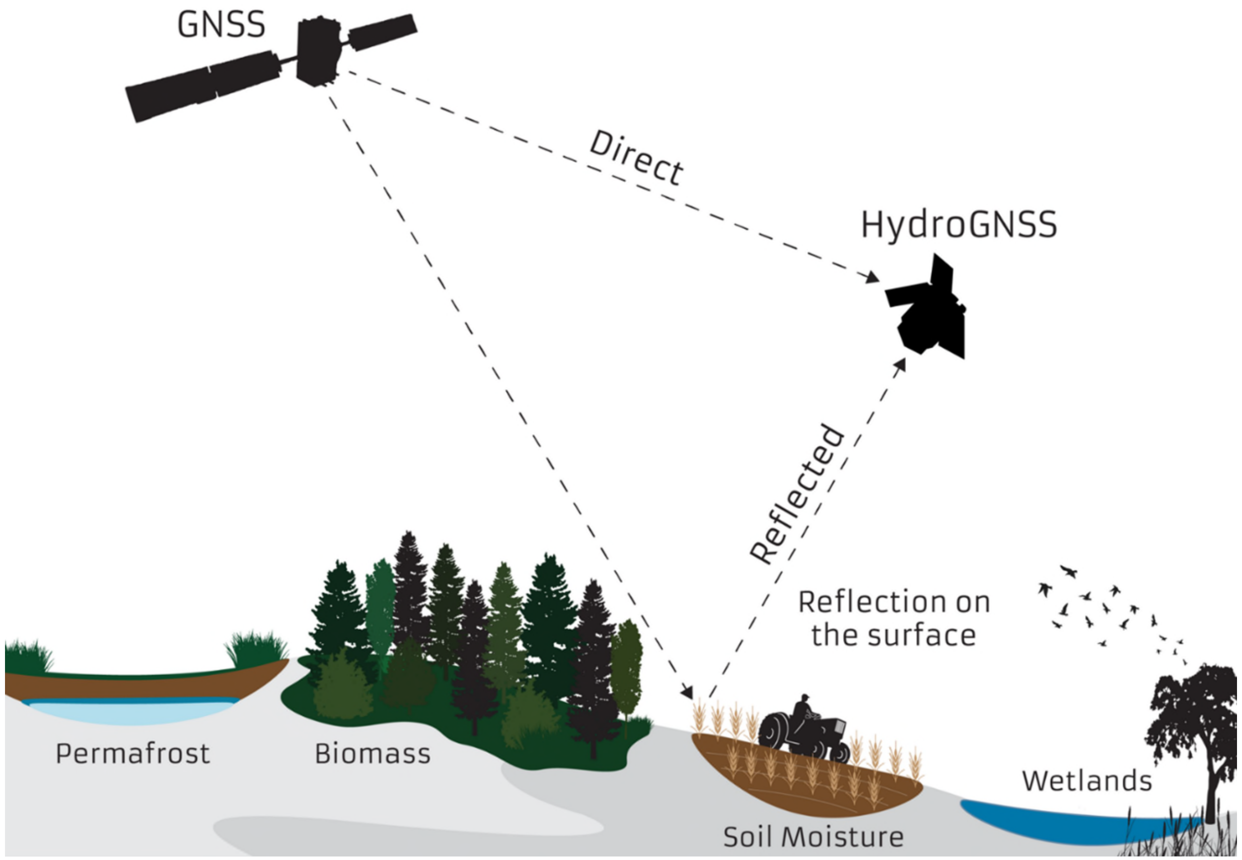
First European Remote Sensing Satellite
ERS-1 (1991-2000)



- Altimeter
  - Measurement of height above surface
- Scatterometer
  - Measurement of backscatter from multiple viewing directions
- Synthetic Aperture Radar (SAR)
  - High-resolution imaging
- Bi-static techniques

Soil Moisture from GNSS Reflectometry





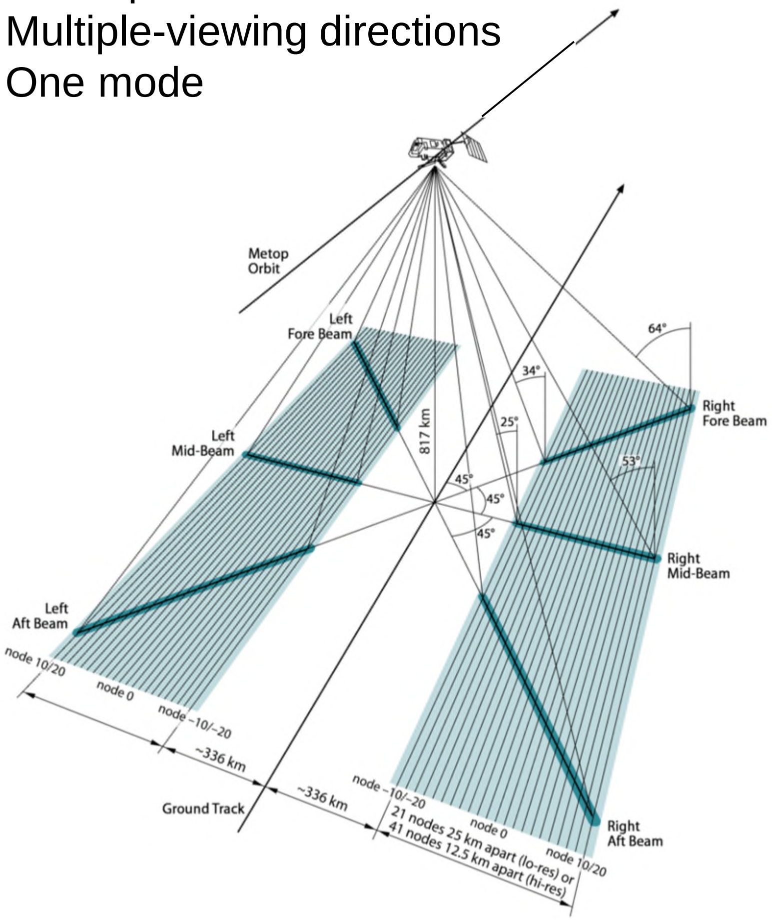
https://www.esa.int/Applications/Observing_the_Earth/Second_Scout_gets_the_go-ahead

CYGNSS soil moisture data from Emanuele Santi, IFAC

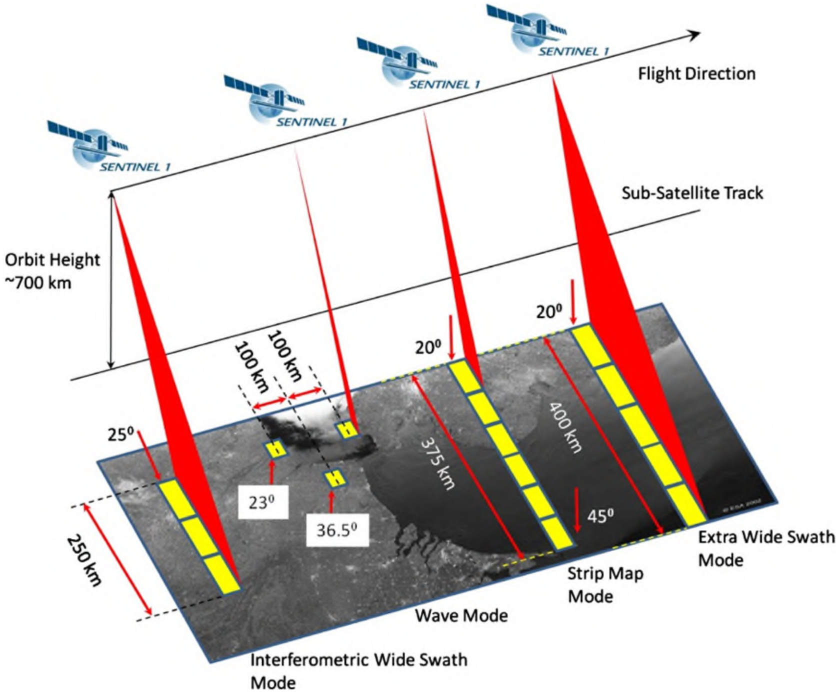
Side-Looking Radars

- SARs and scatterometers are side-looking radars that measure the backscatter coefficient

METOP ASCAT
Real aperture radar
Multiple-viewing directions
One mode

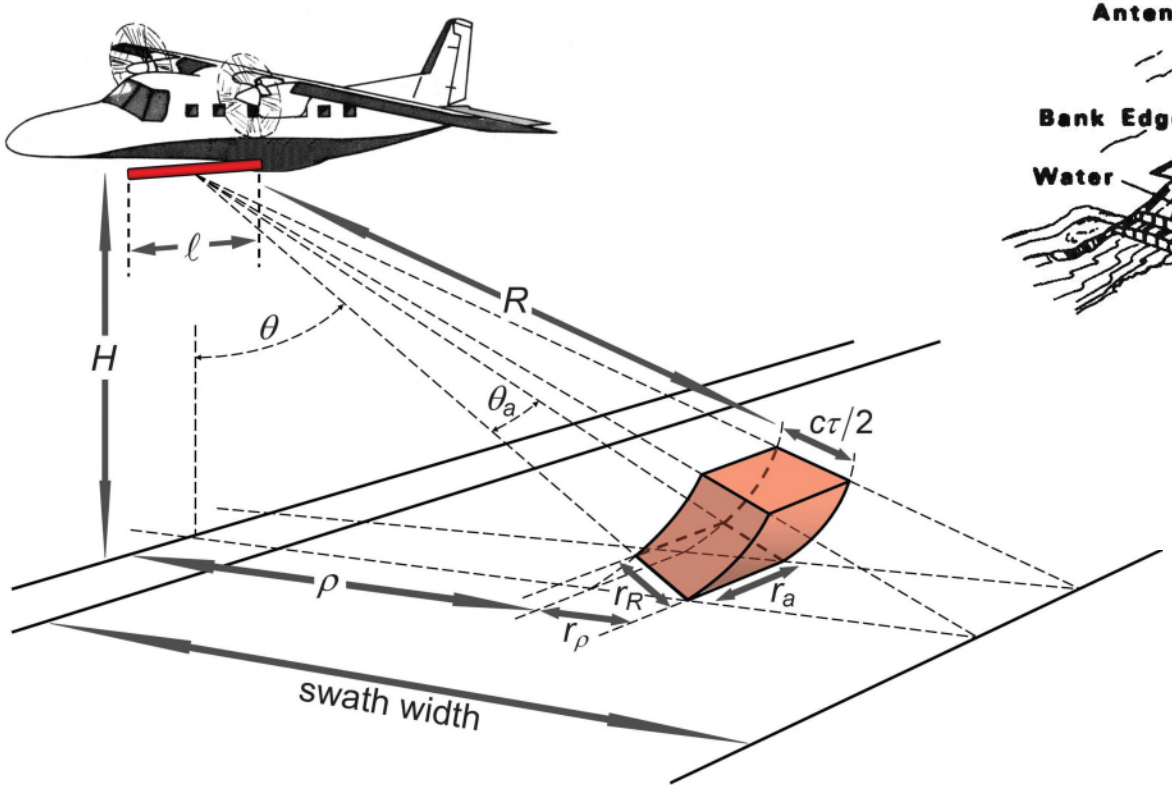


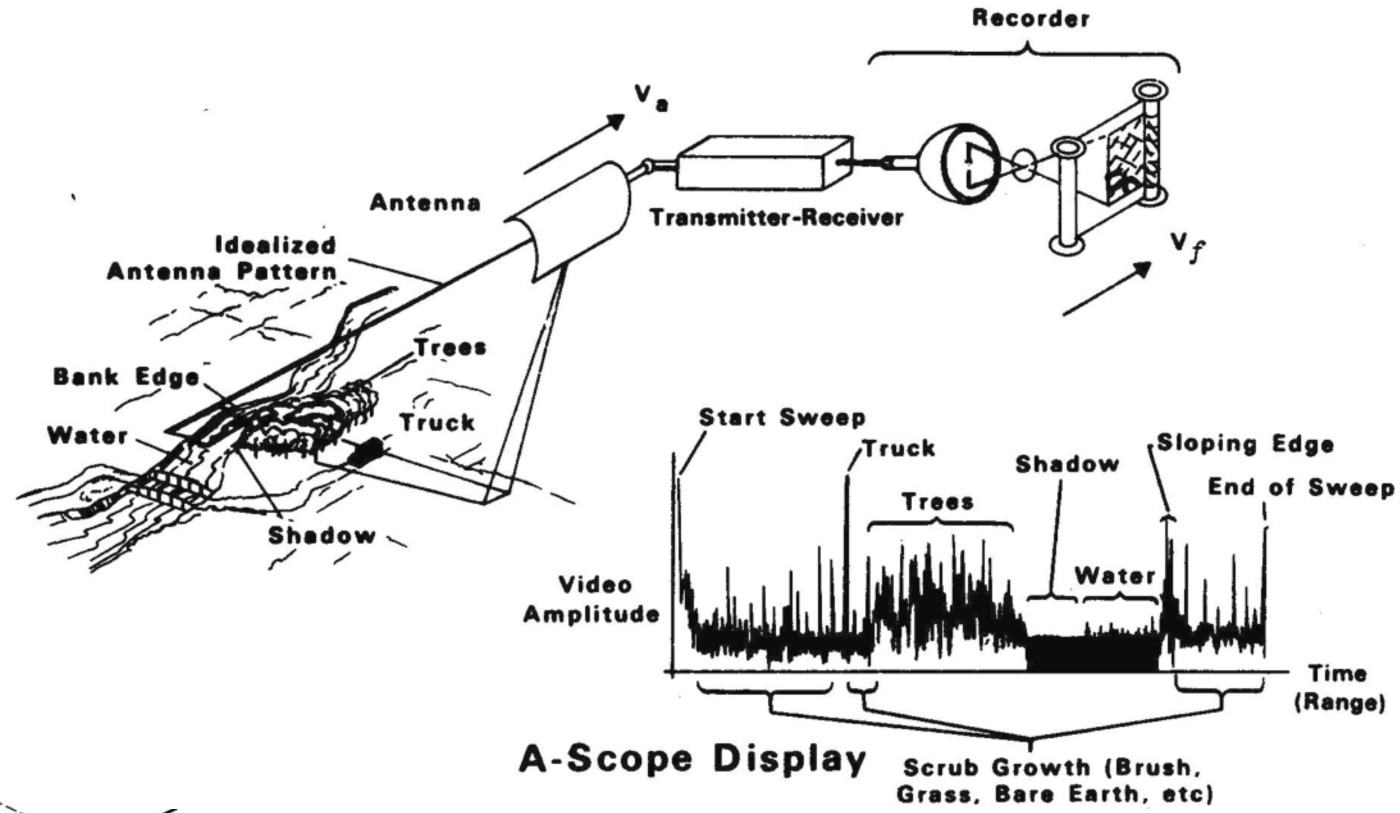
Sentinel-1 SAR
Synthetic aperture radar
Single-viewing direction
Several modes



Measurement Principle of Side-Looking Radars

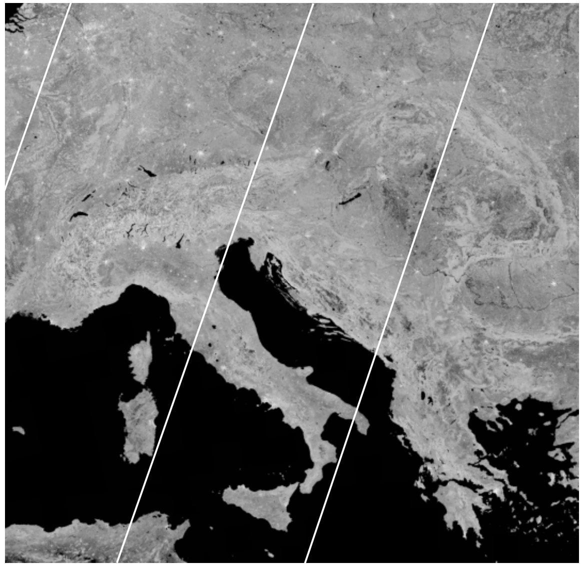
- Side-looking radars use antennas to send out short pulses (chirps) and measure the echoes coming from the objects
- The long wavelength implies a large beamwidth and poor native resolution



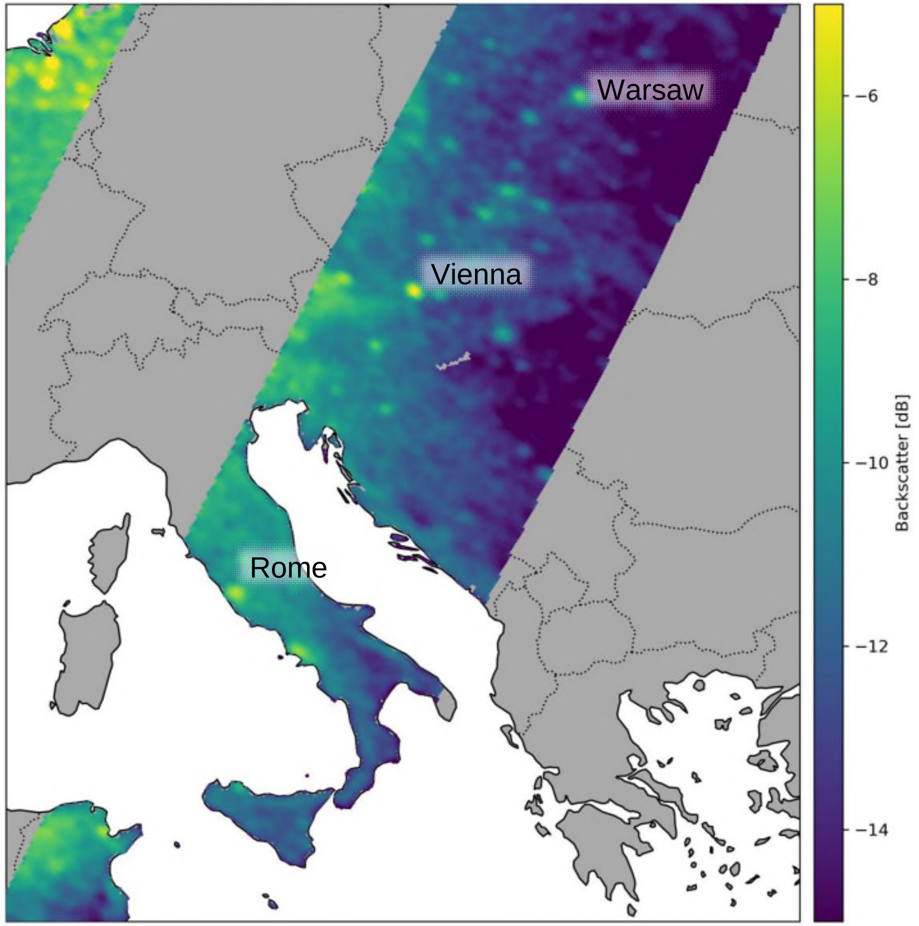


Spatial Resolution of ASCAT

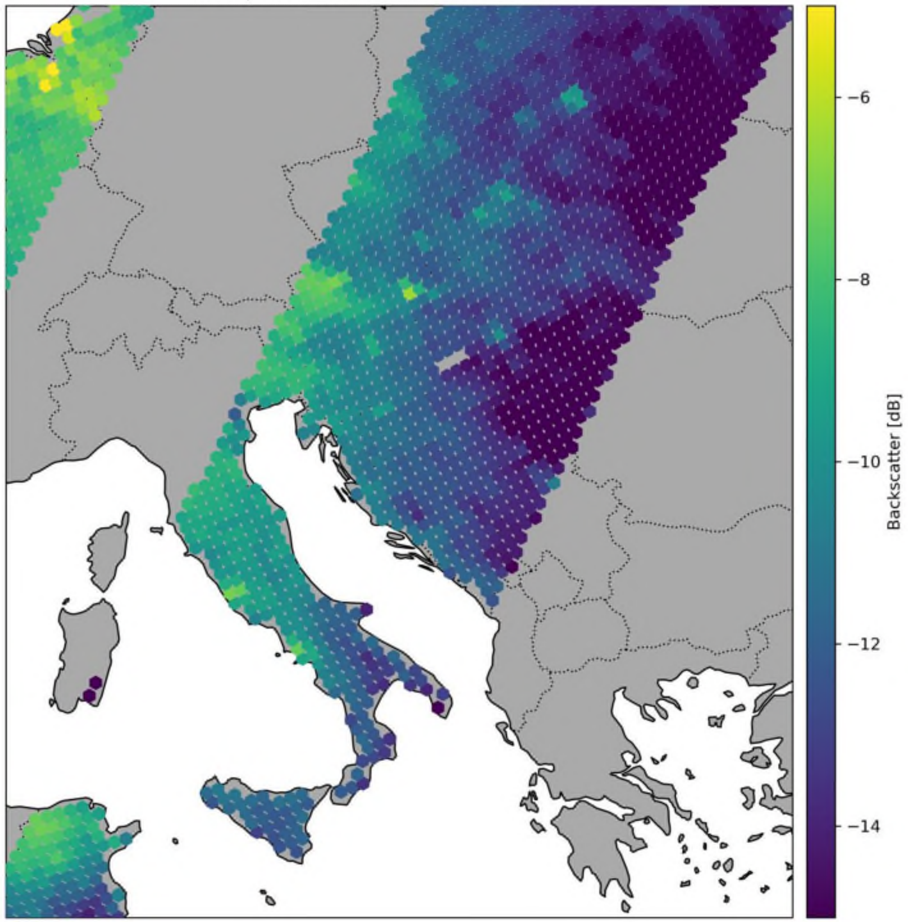
Sentinel-1 Mean Backscatter



METOP-A ASCAT Fore Beam @ 6.25km Grid



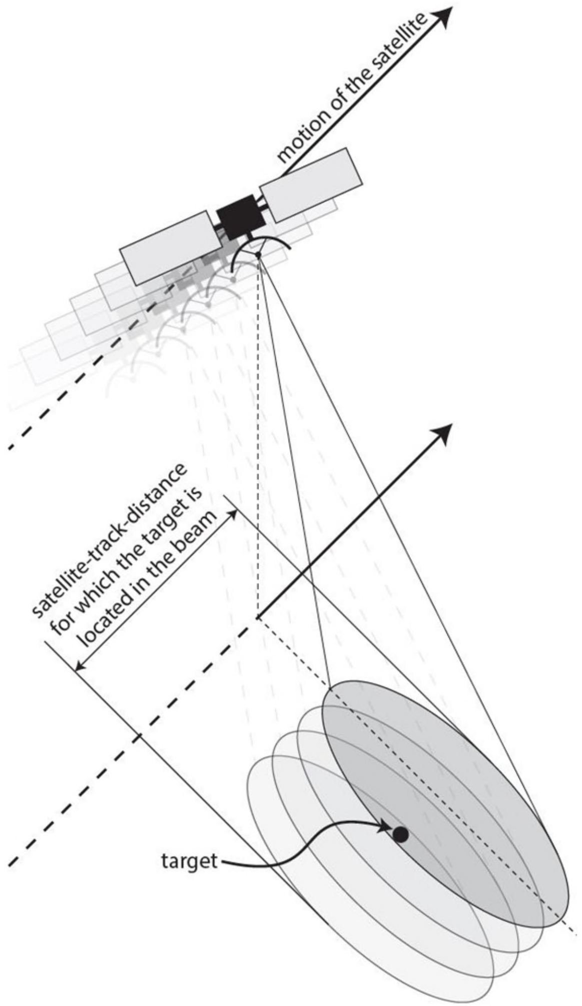
METOP-A ASCAT Fore Beam @ 25km Grid

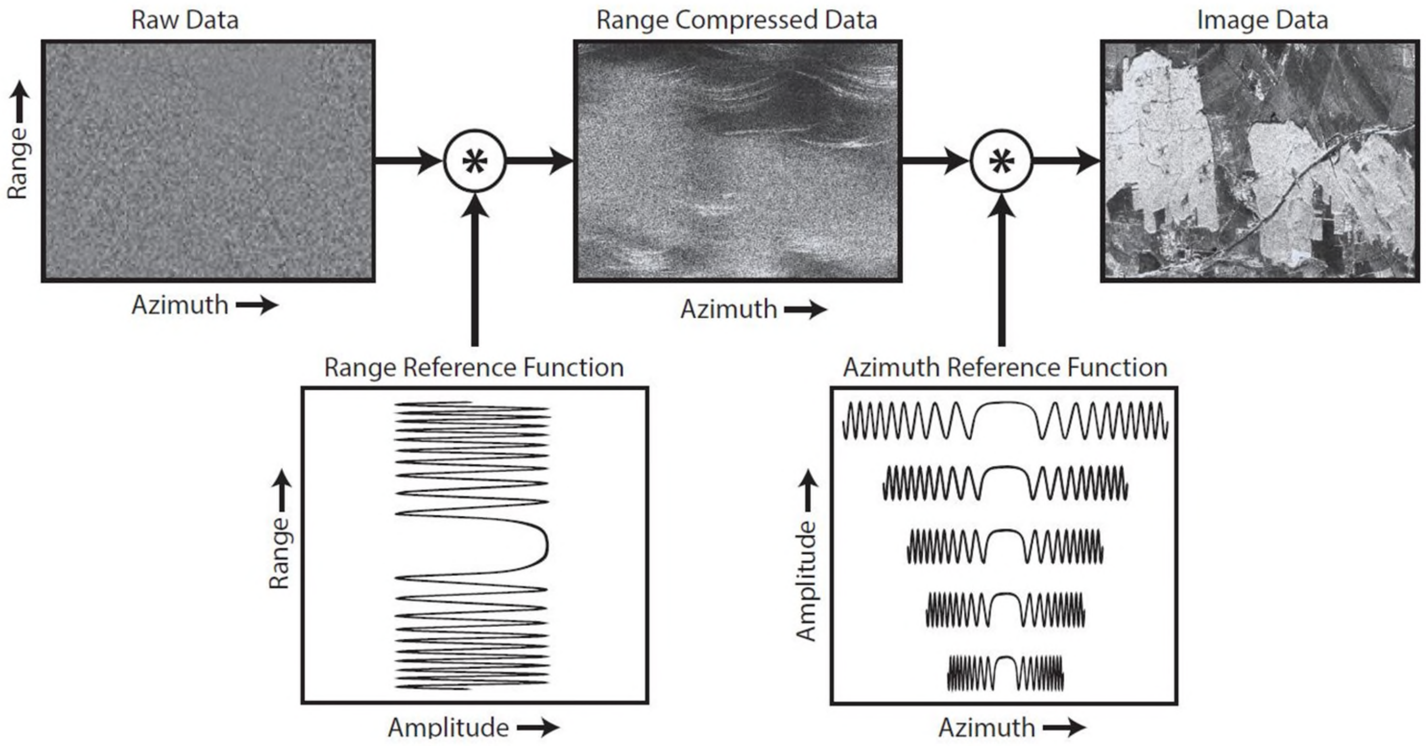


ASCAT Images by Sebastian Hahn

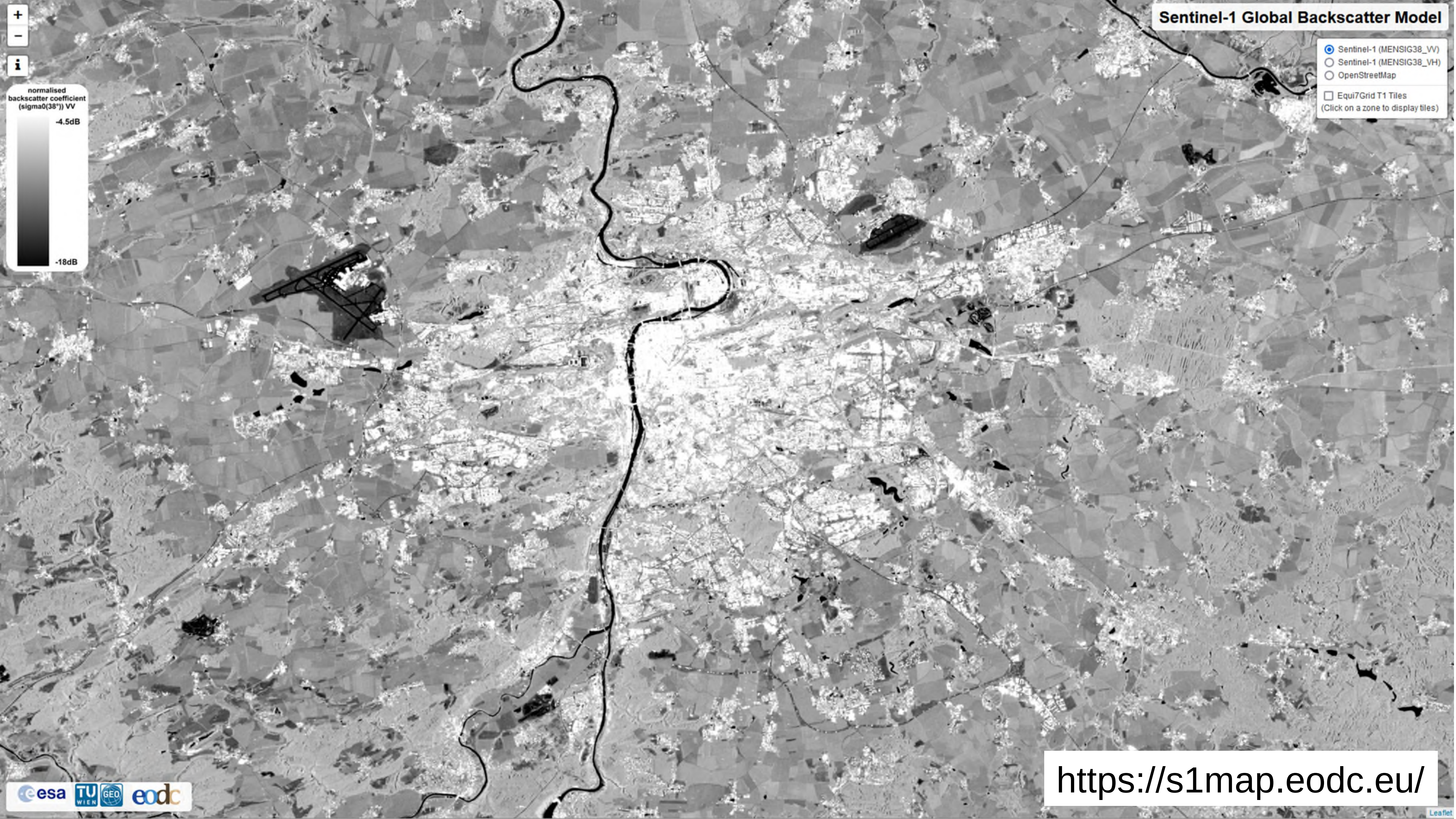
SAR Measurement Principle

- A SAR sends out many short pulses and measures amplitude and phase of the echoes (coherent measurement system)



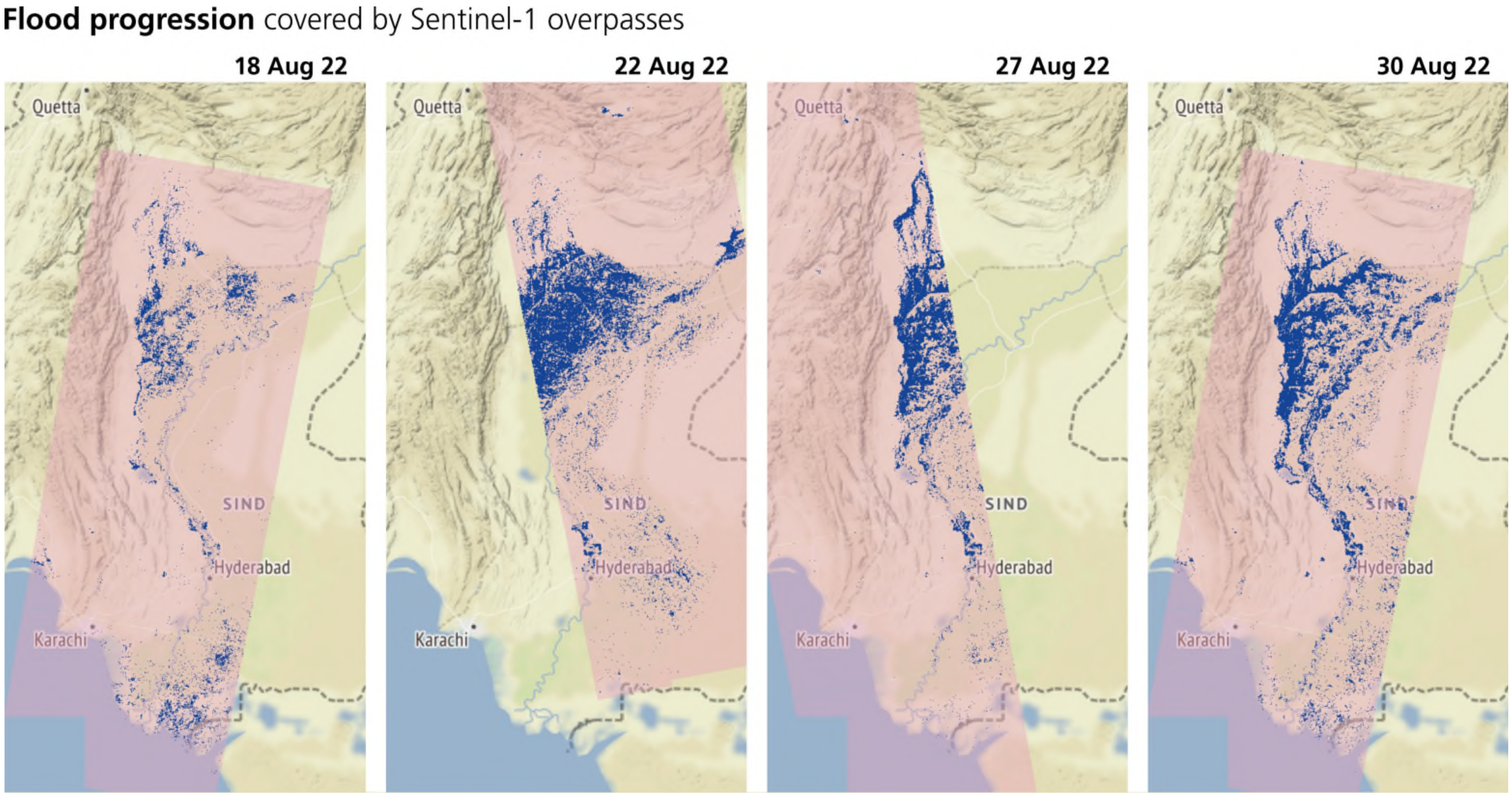


SAR processing steps where the raw data are decompressed by convoluting the data first with a range reference function (chirp) and second with an azimuth reference function (Doppler shifts). From Moreira et al. 2013.



https://s1map.eodc.eu/

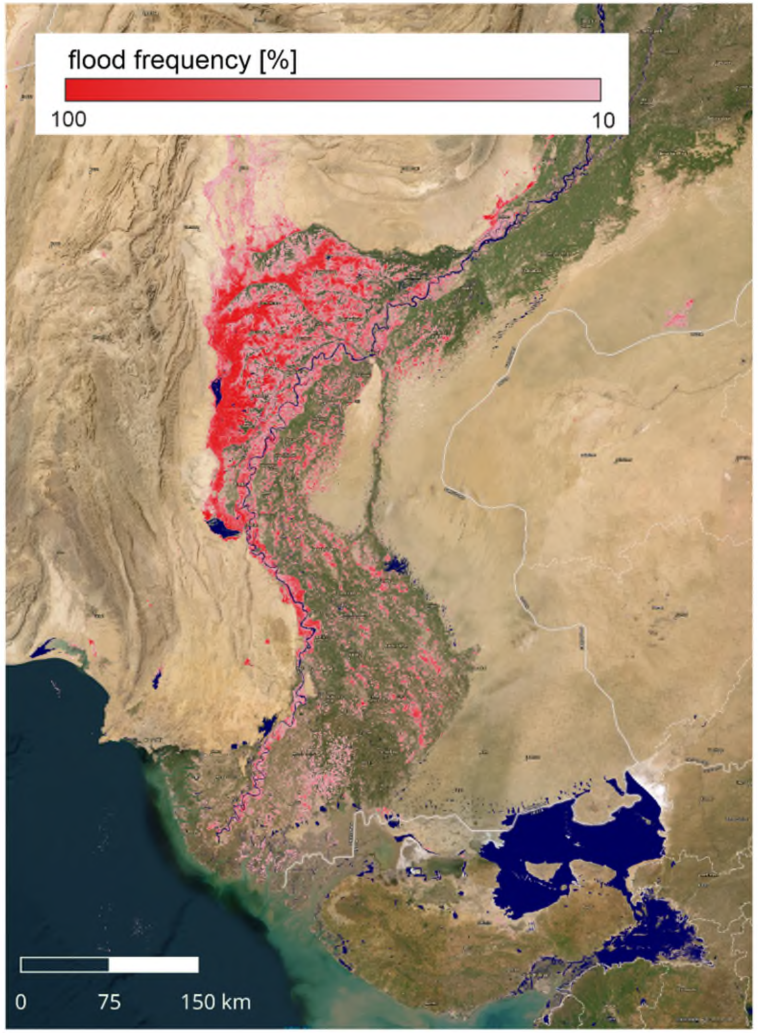
Monitoring of the Flood in Pakistan in 2022



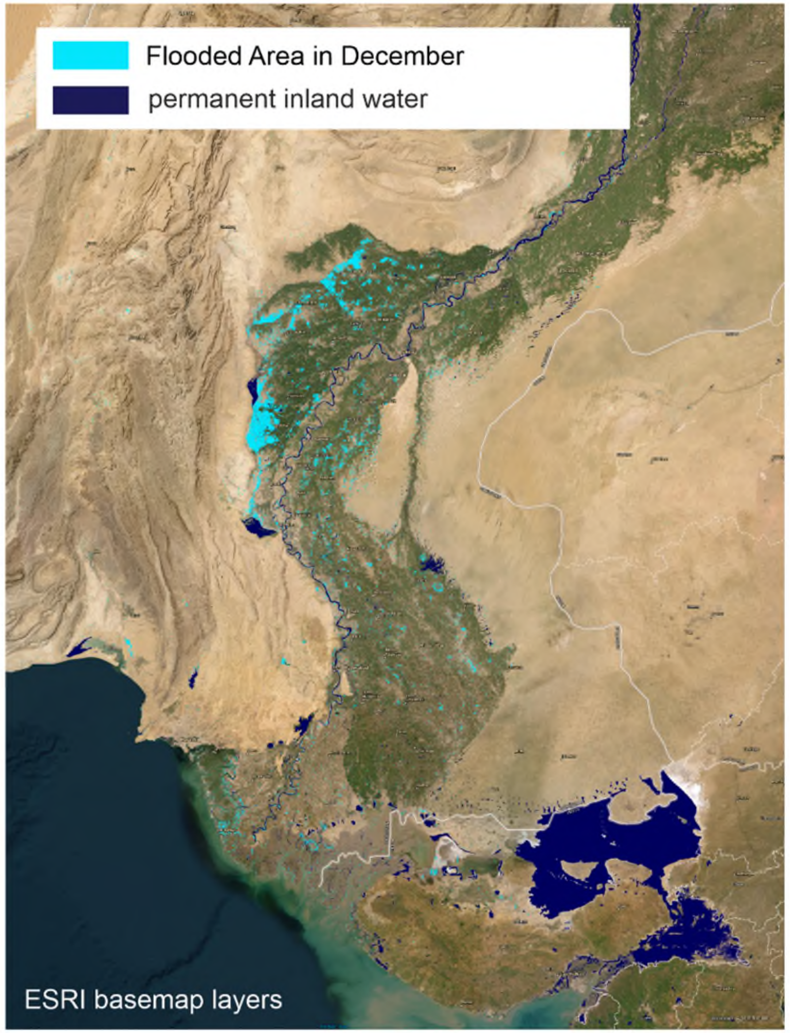
Roth et al. (2022) Sentinel-1 based analysis of the Pakistan Flood in 2022, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-1061.

Pakistan Floods 2022 - Persistence into December

Flood maps based on TU Wien algorithm as part of the **CEMS Global Flood Monitoring (GFM)** ensemble product
which automatically analyses images acquired be the **Copernicus Sentinel-1** radar satellite



flood frequency | Pakistan / Indus Valley
frequency of flood detection in period 18 Aug - 23 Sep 2022



remaining flood area
flood area remaining in period 1 Dec - 15 Dec 2022

Why Soil Moisture?

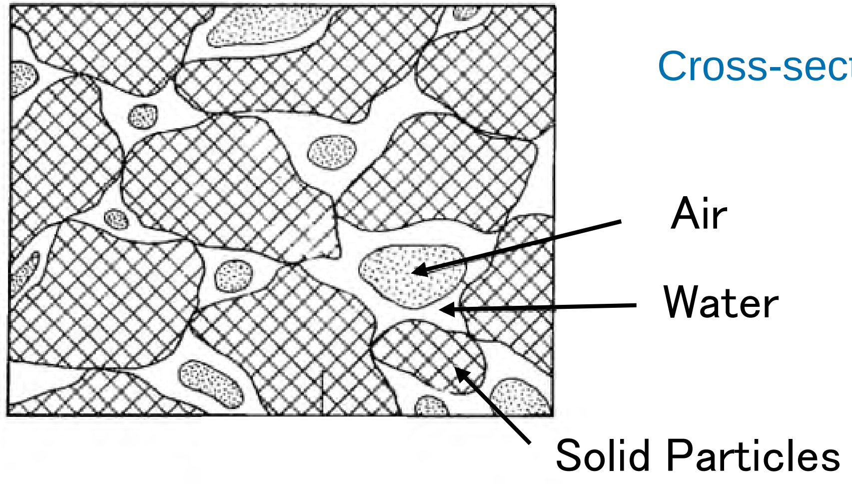
Soil Moisture

- Definition, e.g.

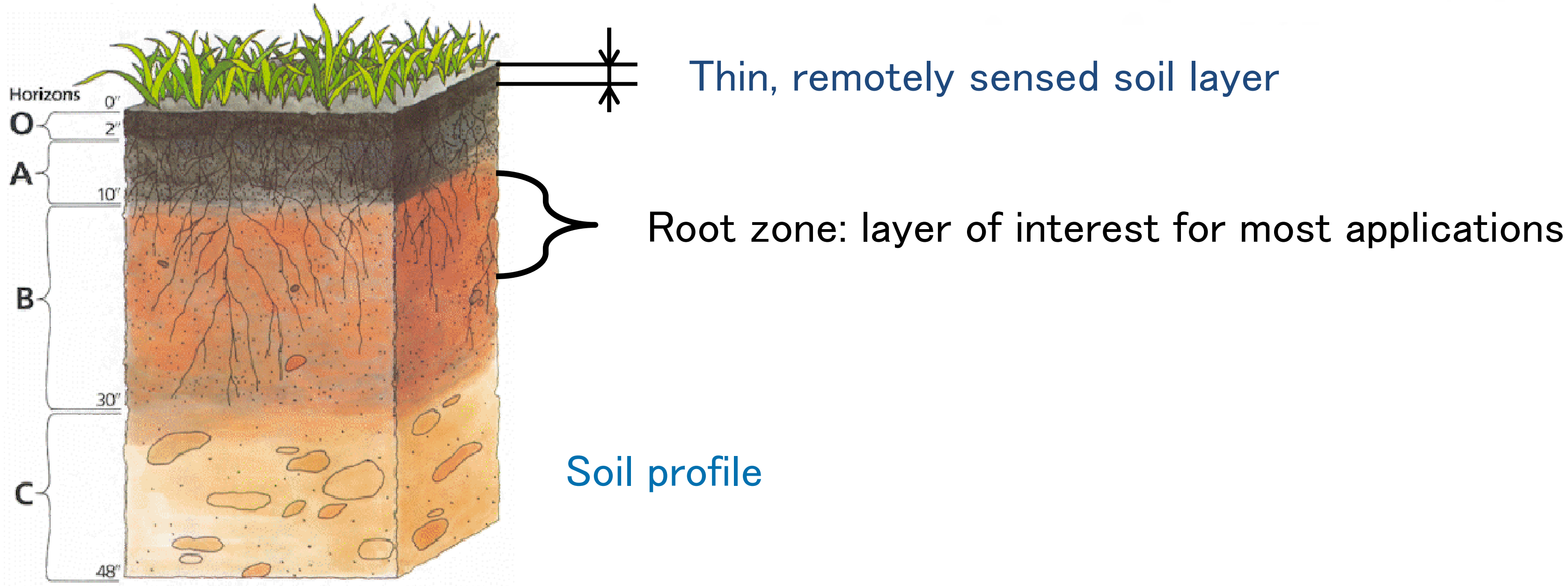
$$\theta = \frac{\text{Water Volume (m}^3)}{\text{Total Volume (m}^3)}$$

- Average

$$\langle\theta\rangle = \frac{1}{Area \cdot Depth} \int_{Area} \int_{Depth} \theta(x,y,z)\,dz\,dx\,dy$$

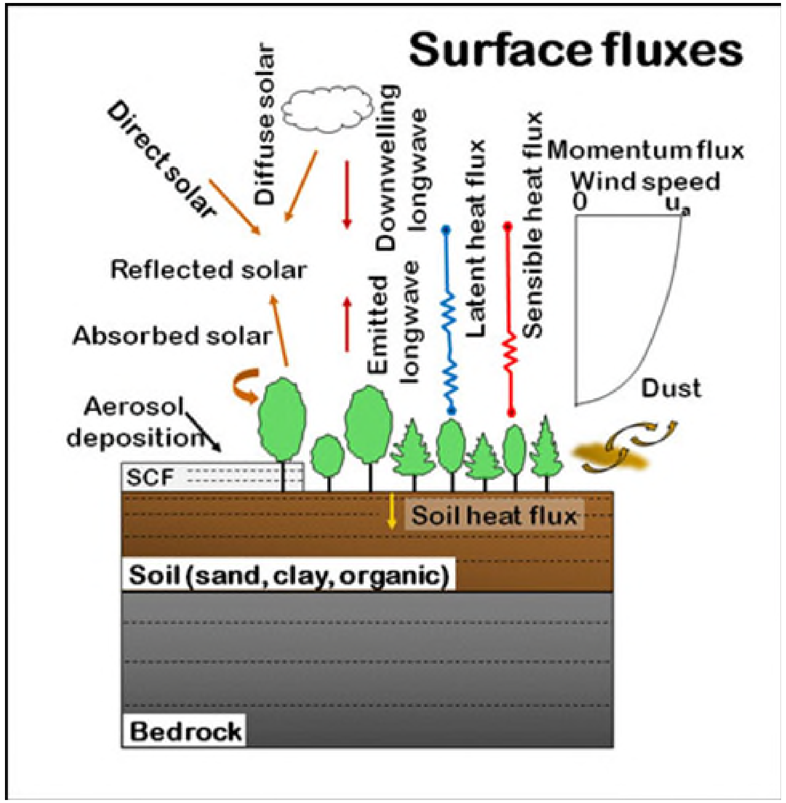


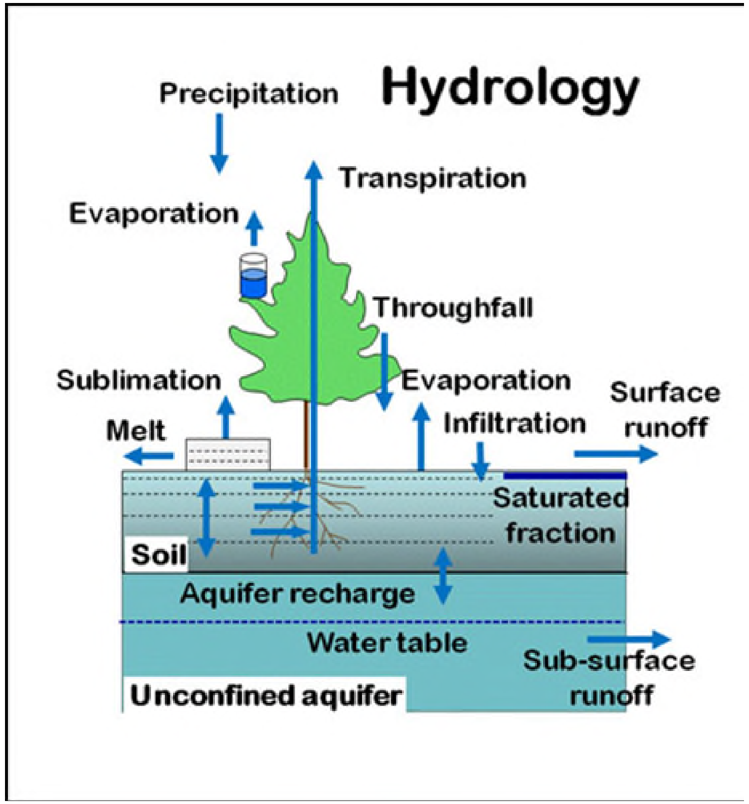
Cross-section of a soil

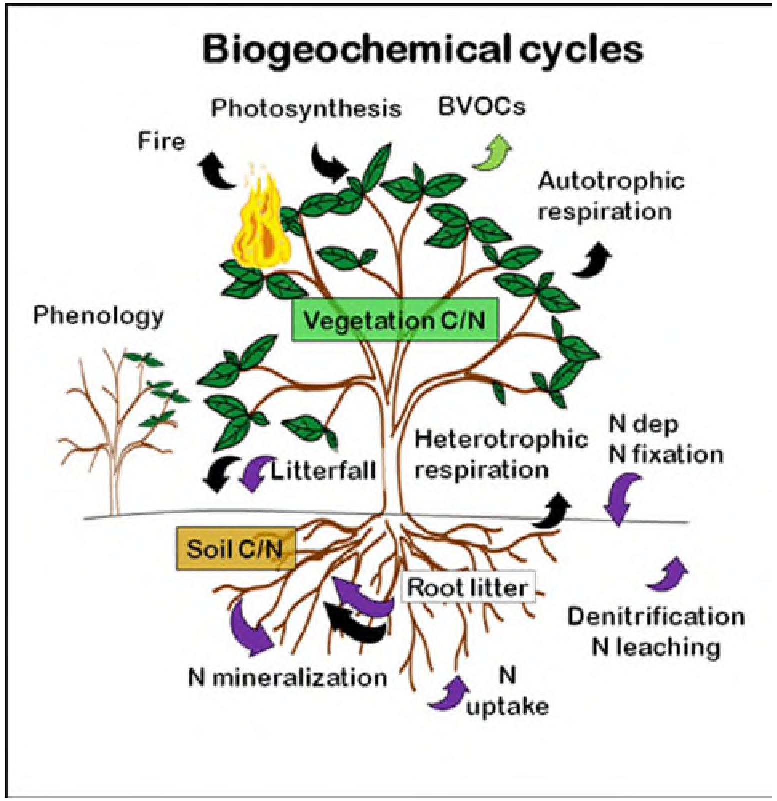


Soil profile

Soil Moisture plays a Key Role in Water, Energy and Biochemical Cycles



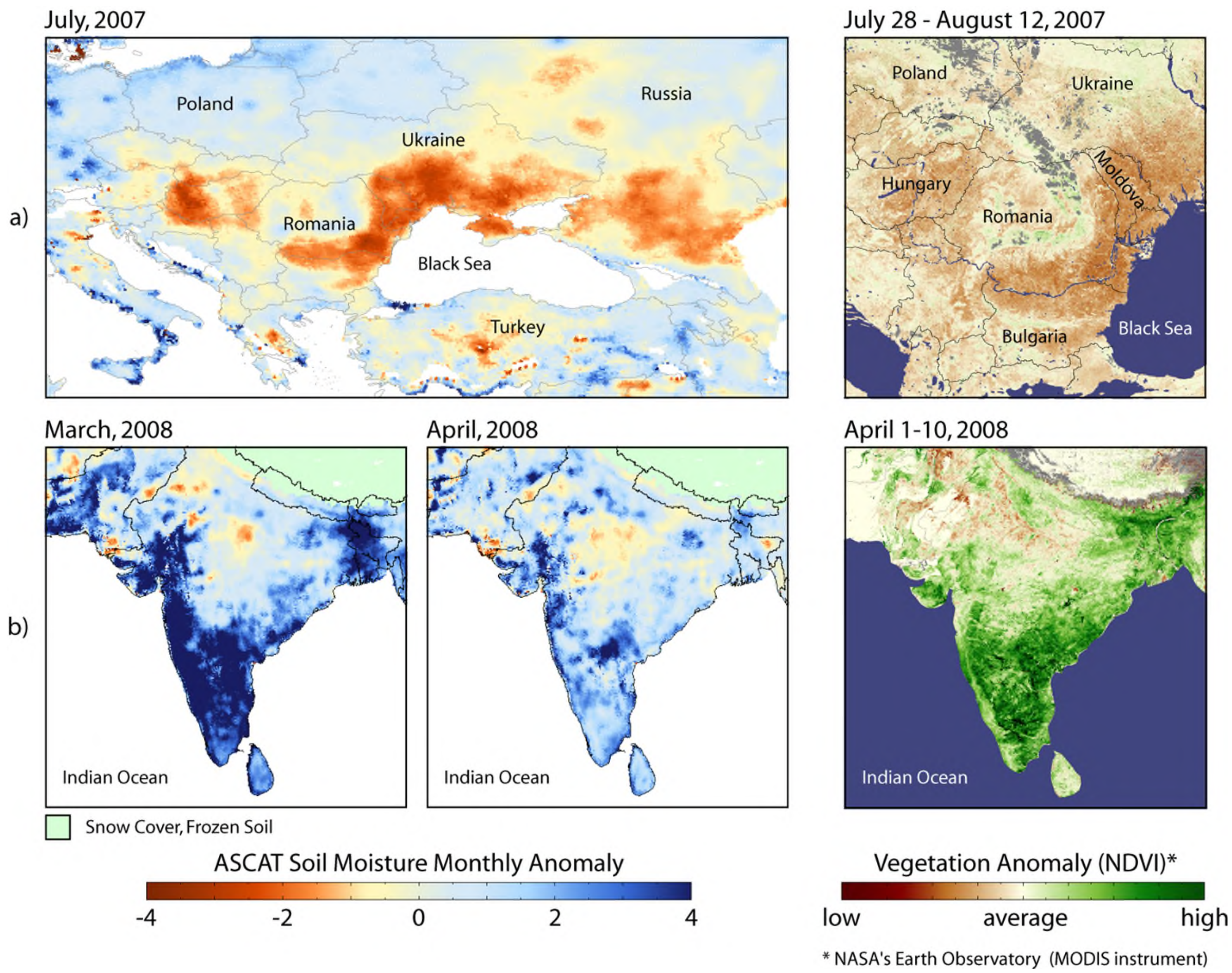




Schematic diagram depicting processes represented in the Community Land Model (http://www.cesm.ucar.edu/models/clm/)

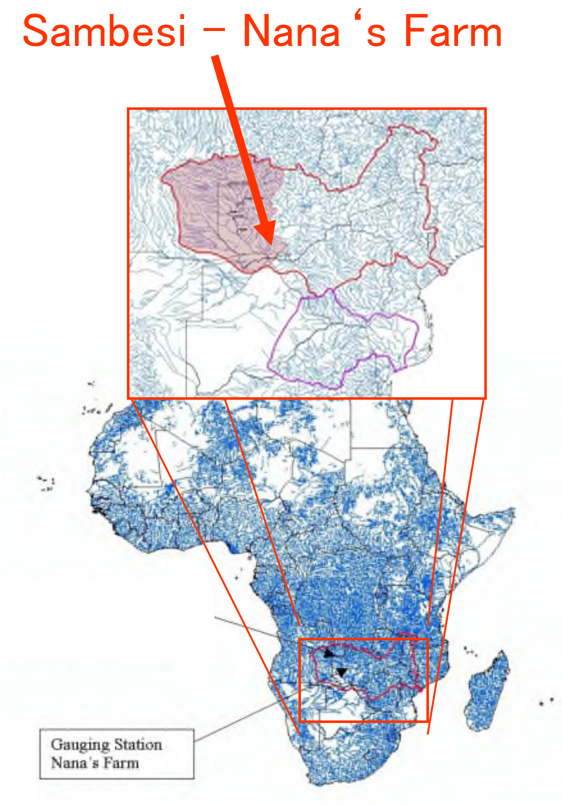
Lawrence and Fisher (2013) The Community Land Model Philosophy: model development and science applications. iLEAPS Newsletter, 13, 16-19.

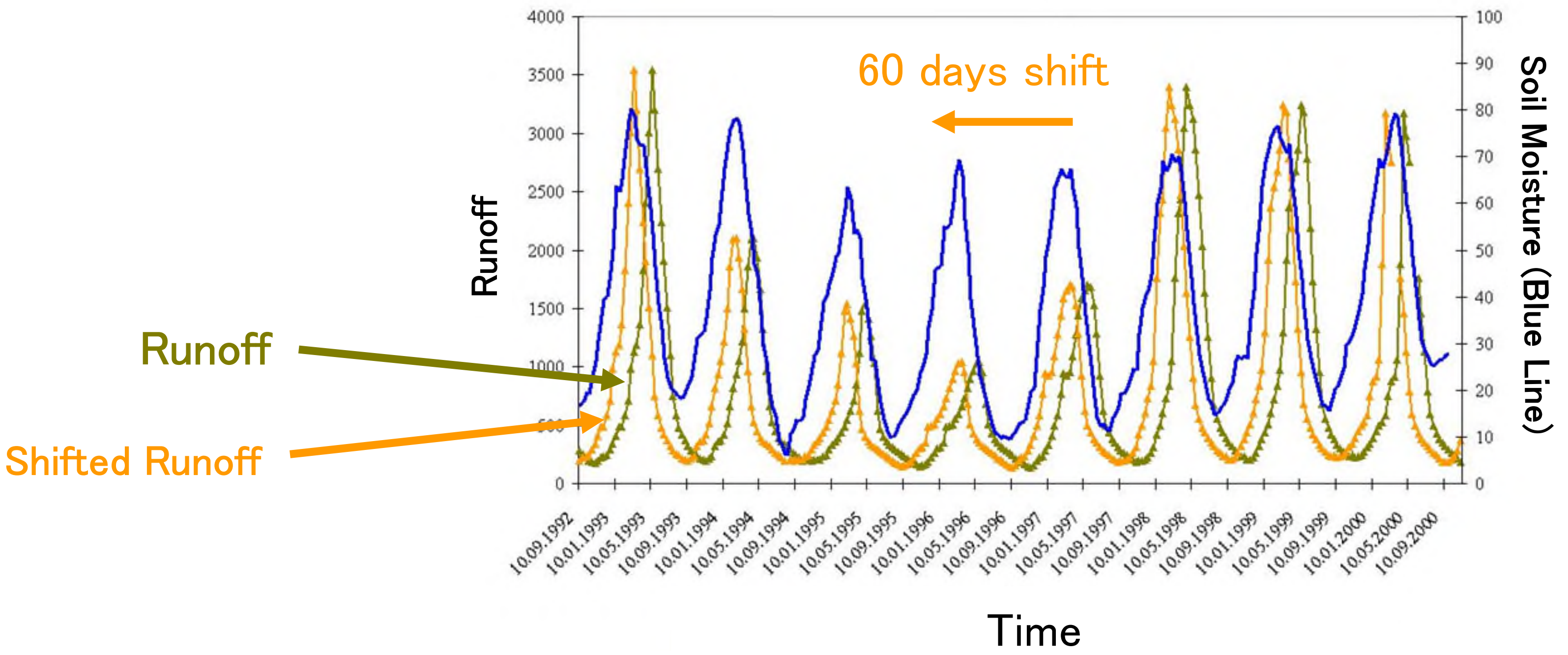
Soil Moisture and Vegetation

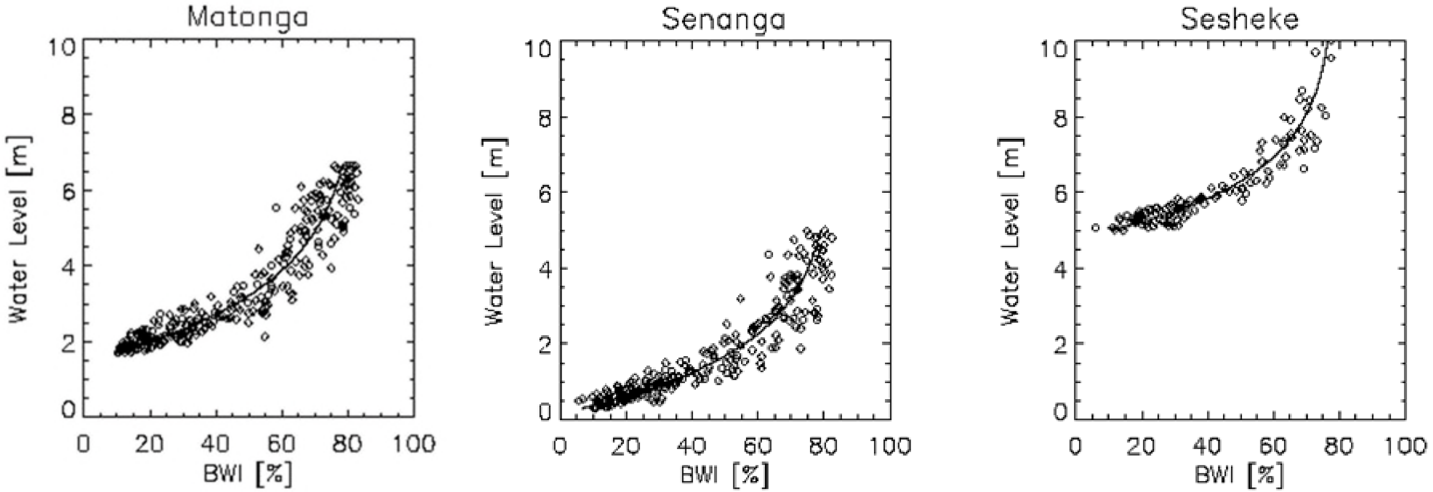


Naeimi and Wagner (2010) C-band Scatterometers and their Applications, Chapter 13 of "Geoscience and Remote Sensing New Achievements", P. Imperatore and D. Riccio (Ed.), INTECH, Vukovar, Croatia, 230-246.

Soil Moisture and River Runoff



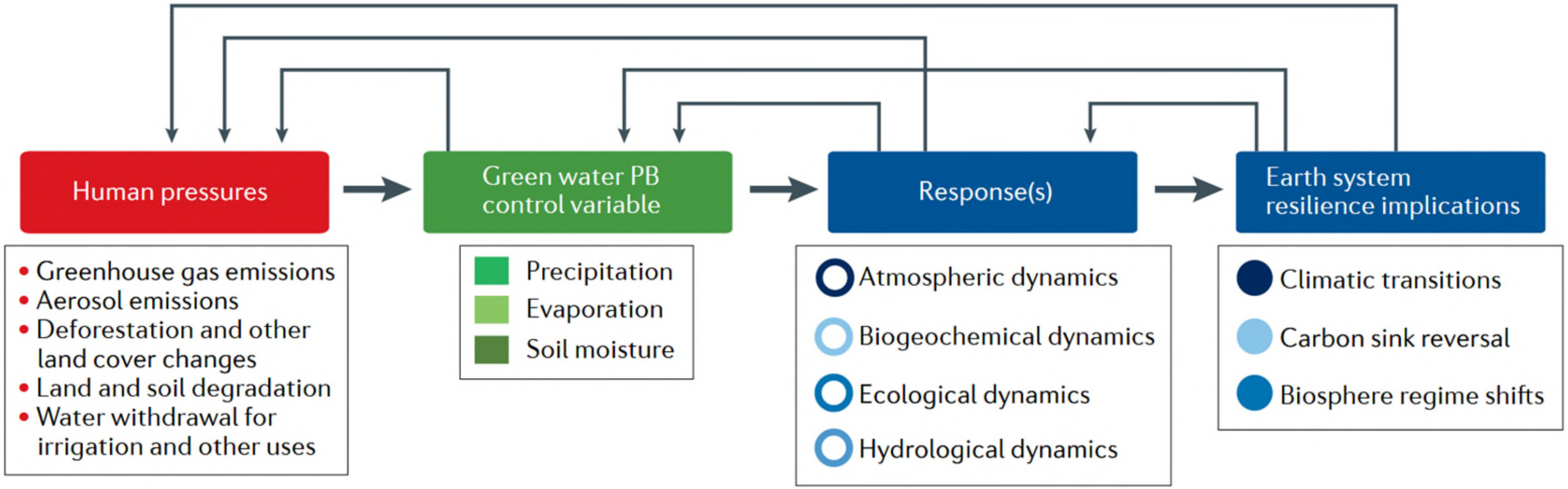




Scipal et al. (2005) Soil moisture-runoff relation at the catchment scale as observed with coarse resolution microwave remote sensing, Hydrology and Earth System Sciences, 9(3), 173-183.

Soil Moisture as a Planetary Boundary

- Green water - terrestrial precipitation, evaporation and soil moisture - is fundamental to Earth system dynamics and is now extensively perturbed by human pressures
- Wang-Erlandsson et al. (2022) recently proposed a green water planetary boundary
  - percentage of ice-free land area on which root-zone soil moisture deviates from Holocene variability for any month of the year.

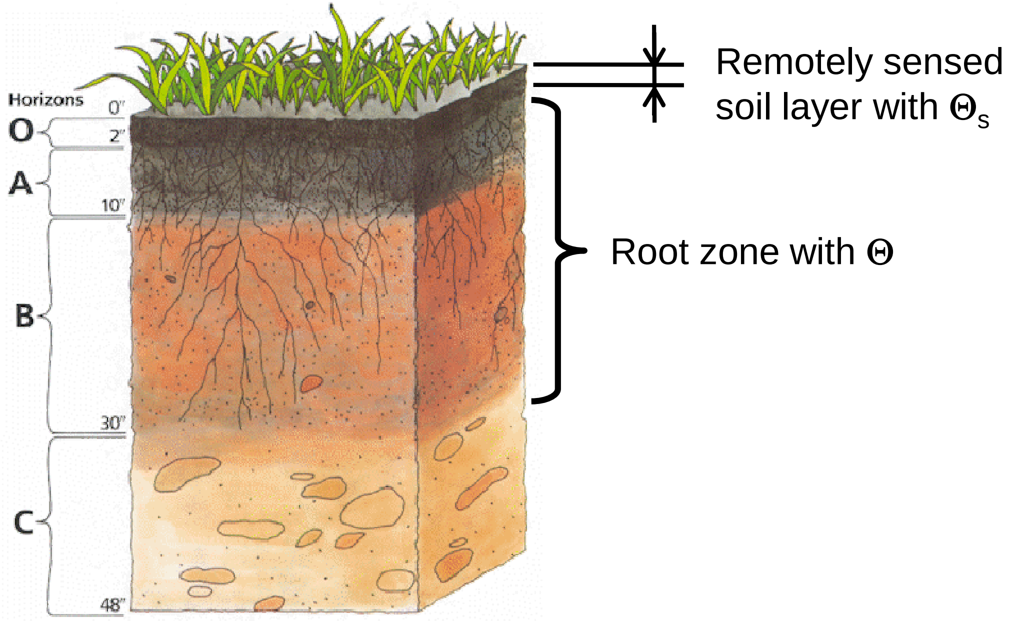


Wang-Erlandsson et al. (2022) A planetary boundary for green water. Nature Reviews Earth & Environment, 3(6), 380-392.

Estimating Root Zone Soil Moisture from Surface Time Series

- The method rests upon simple differential model for describing the exchange of soil moisture between surface layer (Θ_s) and the “reservoir” (Θ)
  - T … characteristic time

$$\frac{d\Theta}{dt} = \frac{1}{T}\left(\Theta - \Theta_s\right) \quad \Longrightarrow \quad \Theta(t) = \frac{1}{T}\int_{-\infty}^{t} \Theta_s(t')\exp\left[-\frac{t-t'}{T}\right]dt'$$



- Mathematically, this model corresponds to a first-order Markov process
- The autocorrelation function of $\Theta(t)$ is given by $r(t) = e^{-t/T}$
  - First suggested theoretically for soil moisture by Delworth and Manabe in 1988
  - Confirmed with in situ observations by Robock, Vinnikov, and collaborators in the 1990s

Wagner, W., G. Lemoine, H. Rott (1999) A Method for Estimating Soil Moisture from ERS Scatterometer and Soil Data, Remote Sensing of Environment, 70, 191-207.

Some Applications of Remotely Sensed Soil Moisture Data

- Runoff forecasting
- Numerical Weather Prediction
- Vegetation monitoring
- Agricultural monitoring
- Tree-Ring studies
- Landslide monitoring
- Epidemiological prediction
- GHG budget
- Climate studies
- Ground water modelling
- Drought monitoring
- Rainfall estimation
- Etc.

How are the data used?

Model validation

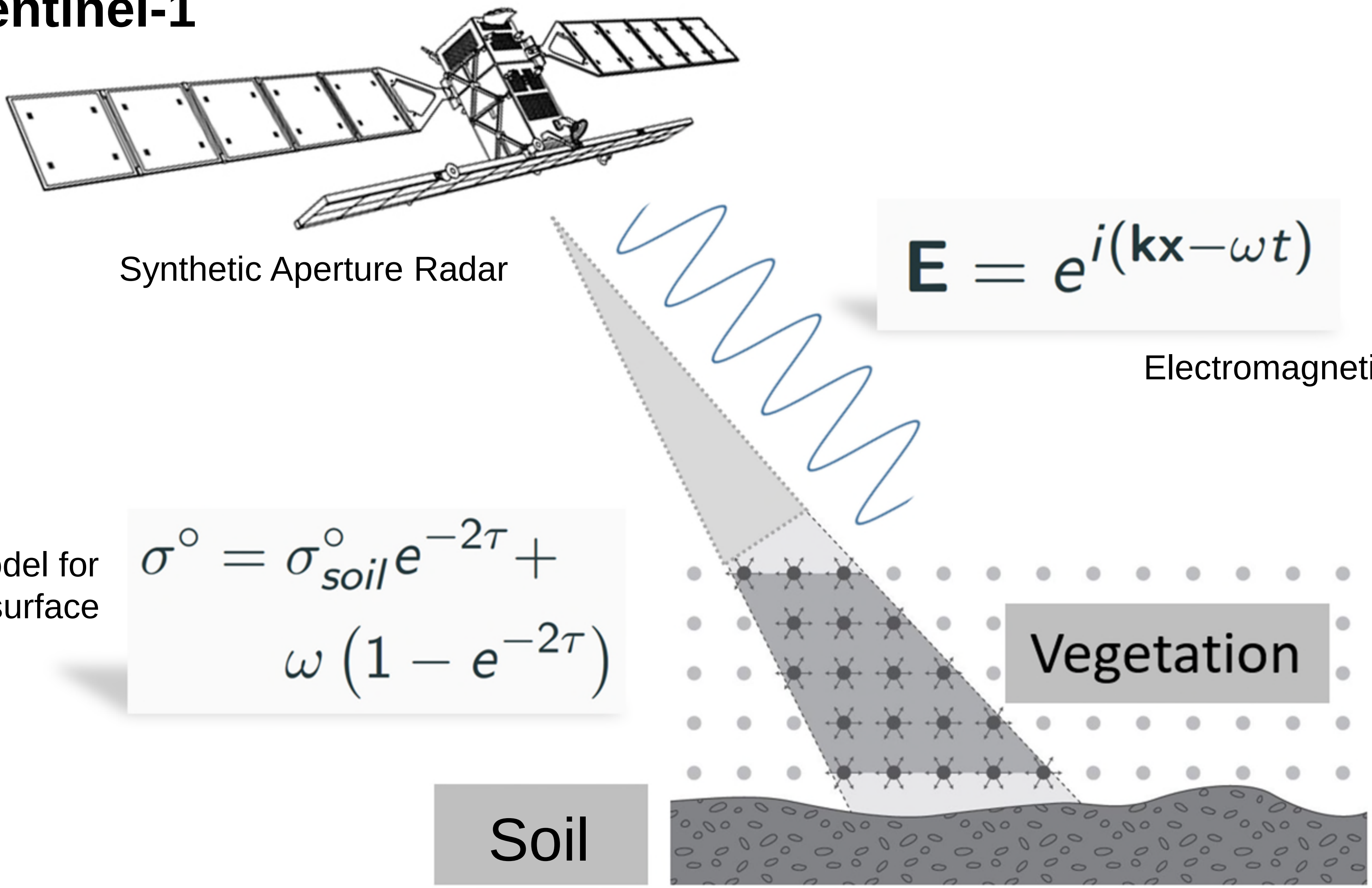
Model calibration

Direct model input

Data assimilation

Soil Moisture Retrieval

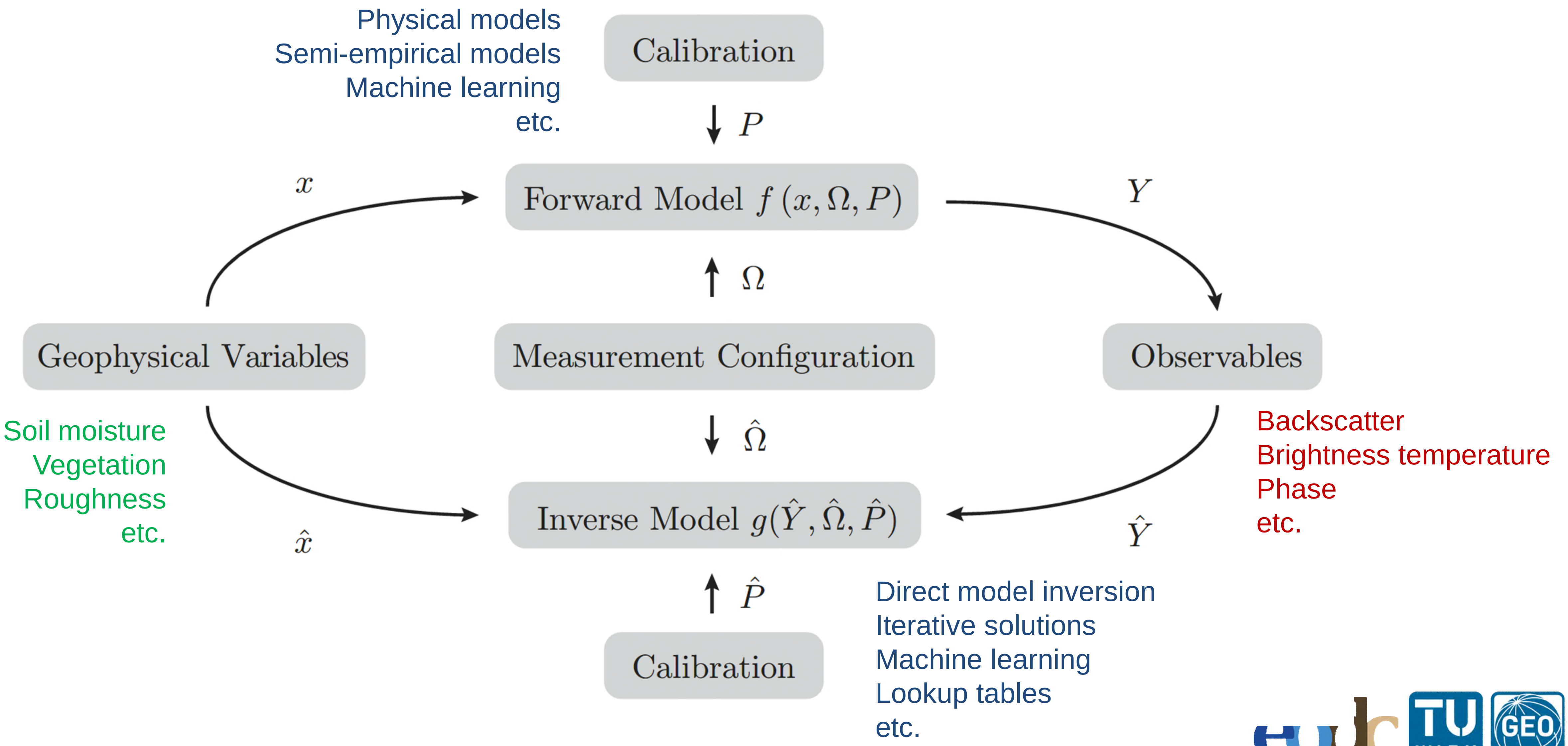
Active Microwave Remote Sensing of Soil and Vegetation



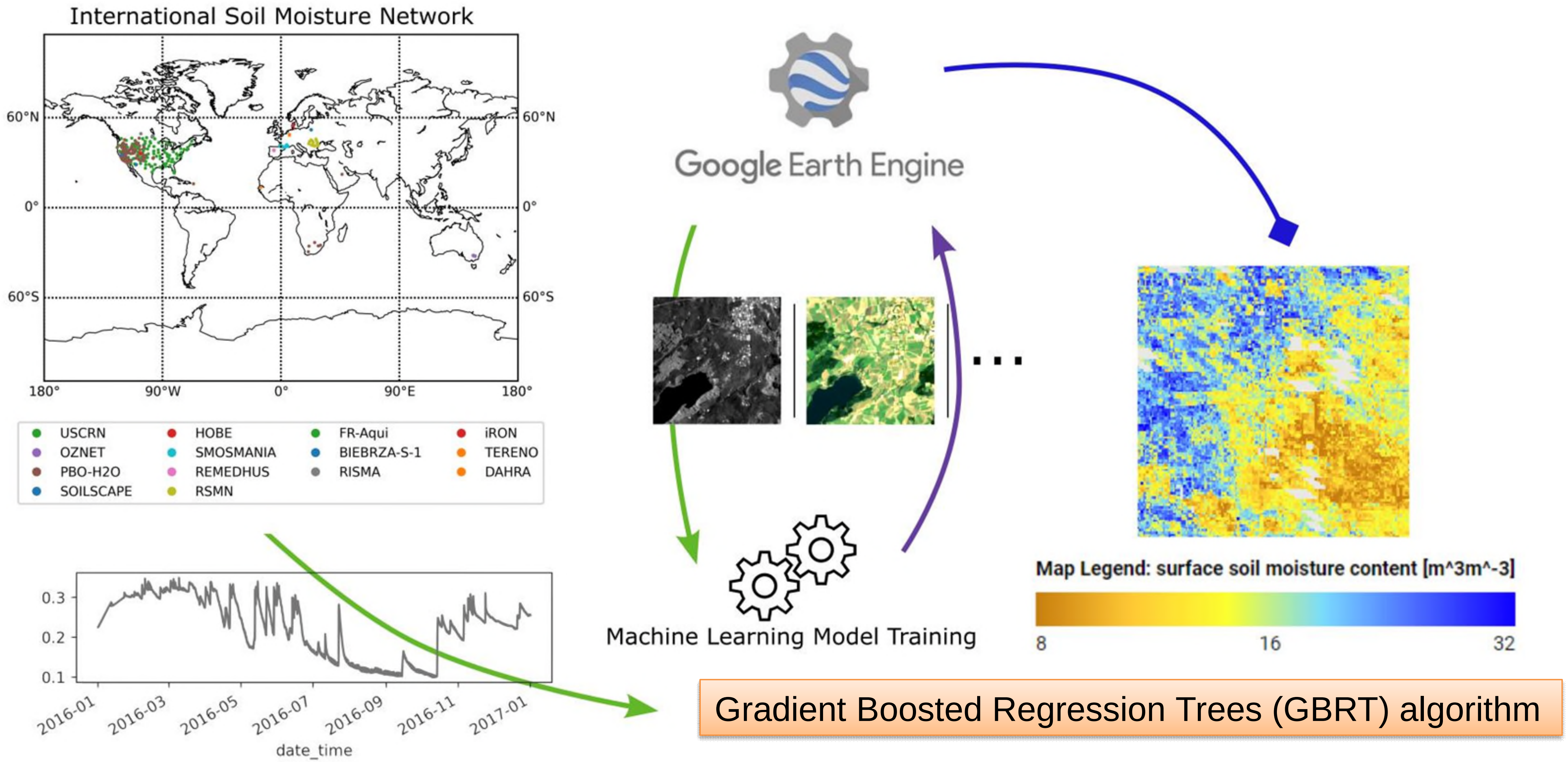
$$\mathbf{E} = e^{i(\mathbf{kx} - \omega t)}$$

$$\sigma^{\circ} = \sigma^{\circ}_{soil} e^{-2\tau} + \omega \left(1 - e^{-2\tau}\right)$$

Soil Moisture Data Retrieval



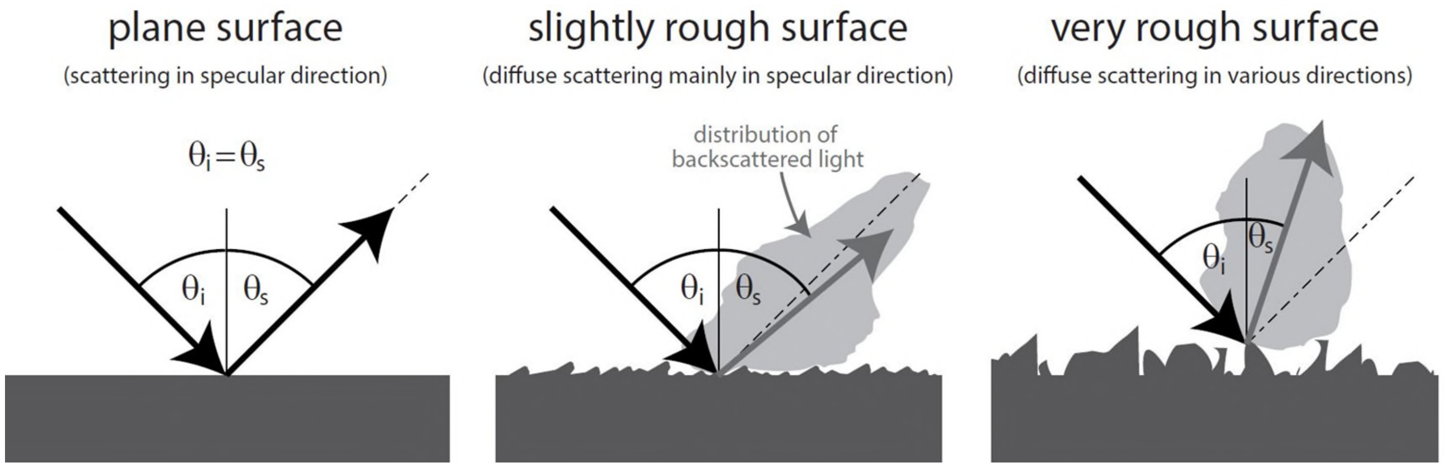
Sentinel-1 Soil Moisture Retrieval using Machine Learning



Greifeneder et al. (2021) A machine learning-based approach for surface soil moisture estimations with Google Earth Engine, Remote Sensing, 13, 2099, 21p.

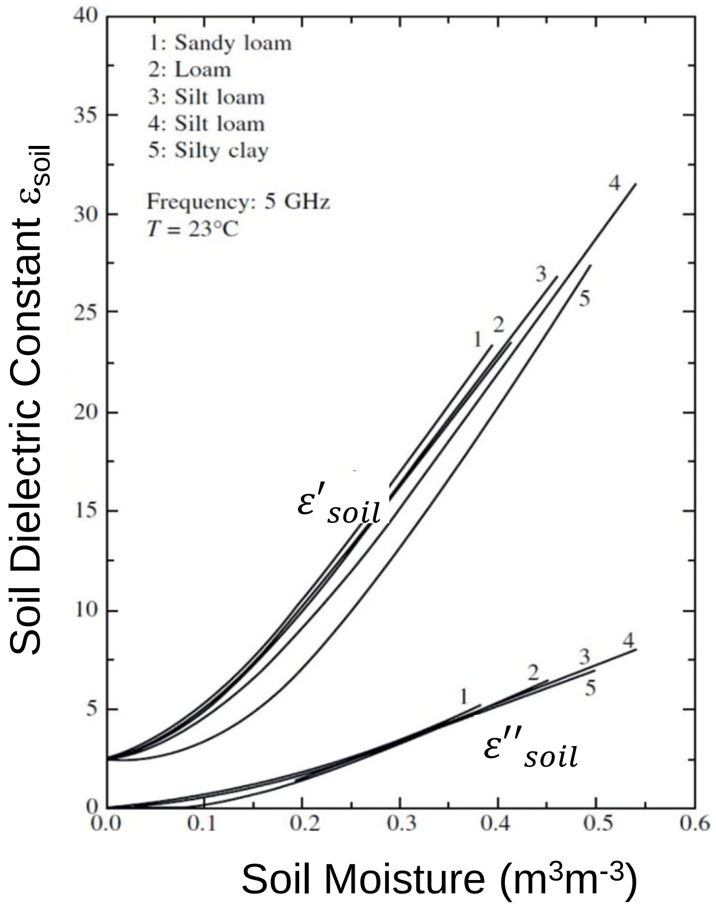
Soil Scattering

- Soil scattering is principally driven by
  - Soil dielectric constant
    - Soil moisture
    - Texture
  - Soil surface "roughness"
    - Relative to wavelength
    - Dependent on soil moisture

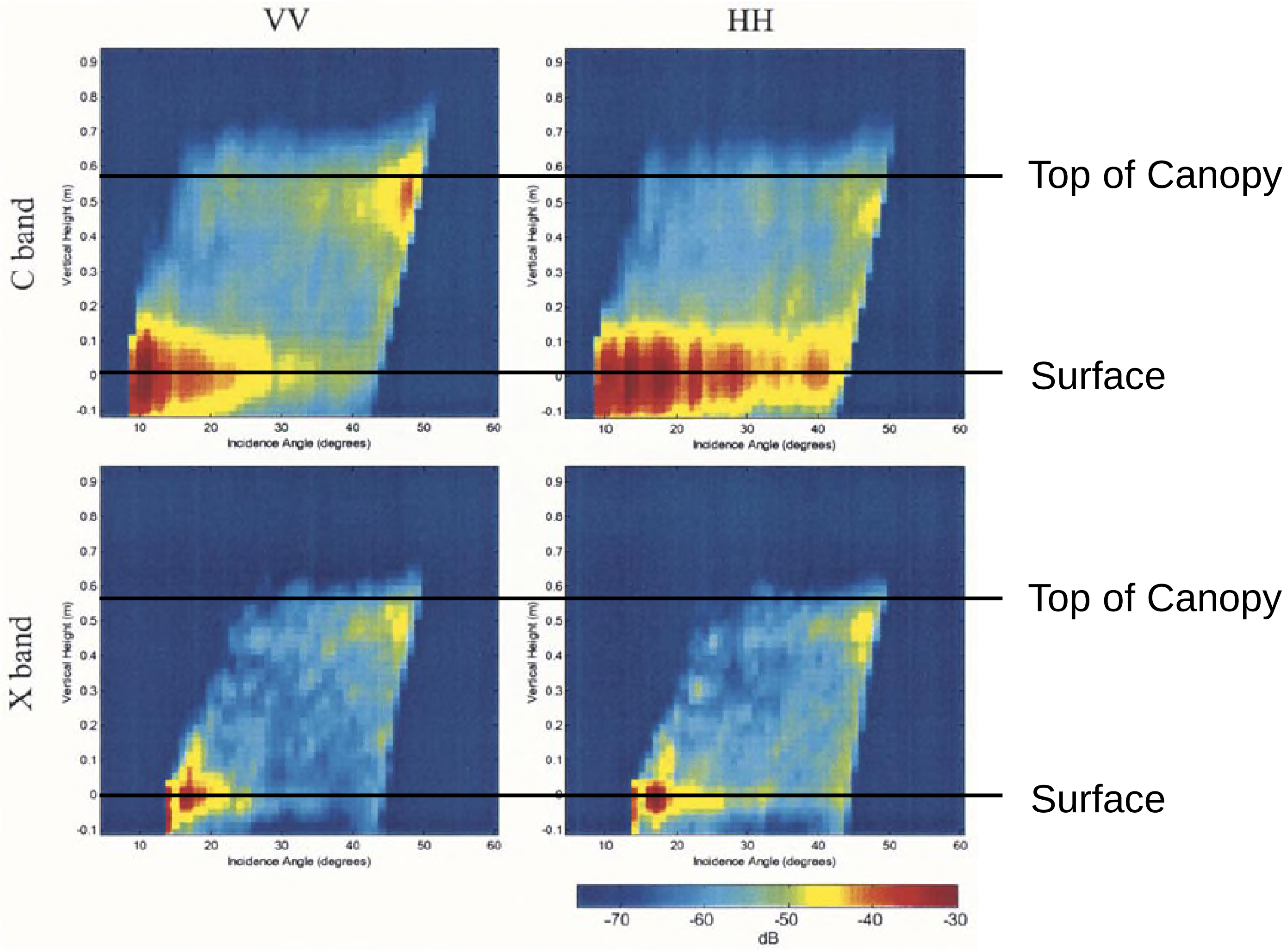


Graphic by R. Quast, TU Wien

Behari (2005) Microwave dielectric behaviour of wet soils, Springer, 164 p.



Vegetation Scattering



3D radar measurements of a 58 cm high wheat canopy

Brown et al. (2003) High-resolution measurements of scattering in wheat canopies - Implications for crop parameter retrieval. IEEE Transactions on Geoscience and Remote Sensing, 41(7), 1602-1610.

Three Backscatter Models

- Change detection backscatter model
  - Developed for ENIVSAT ASAR and adopted for Sentinel-1
  - Used in Copernicus

Bauer-Marschallinger et al. (2019) Towards global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles, IEEE Transactions on Geoscience and Remote Sensing, 57(1), DOI 10.1109/TGRS.2018.2858004

- Zero-order radiative transfer model RT0
  - Modified water cloud model developed for studying subsurface scattering

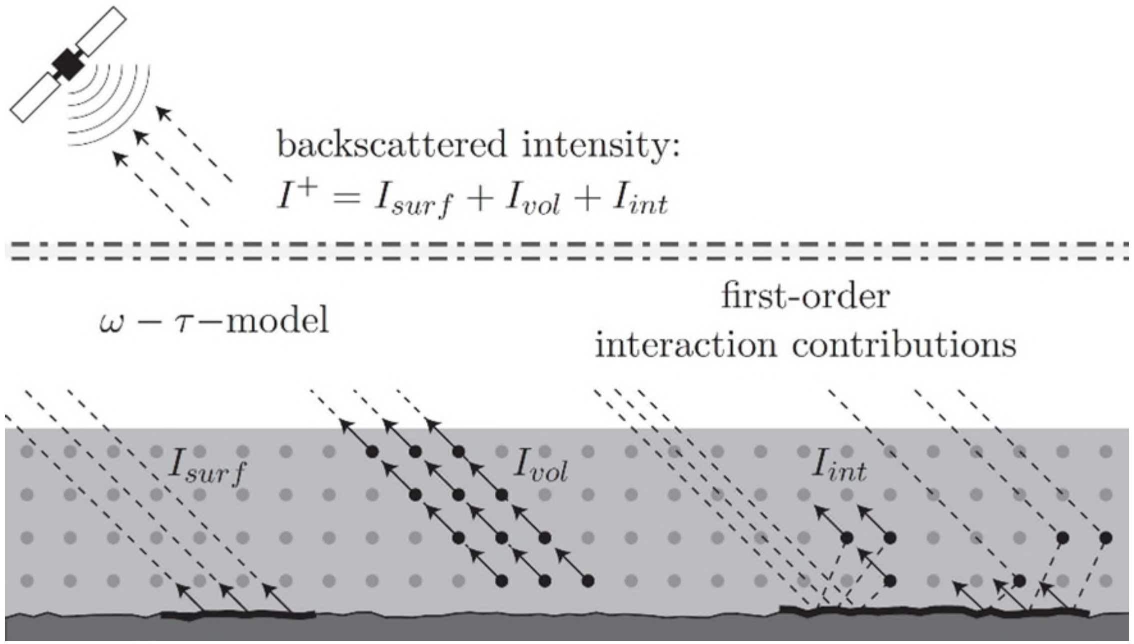
Wagner et al. (2022) Widespread occurence of anomalous C-band backscatter signals in arid environments by subsurface scattering, Remote Sensing of Environment, 276, 113025, DOI 10.1016/j.rse.2022.113025.

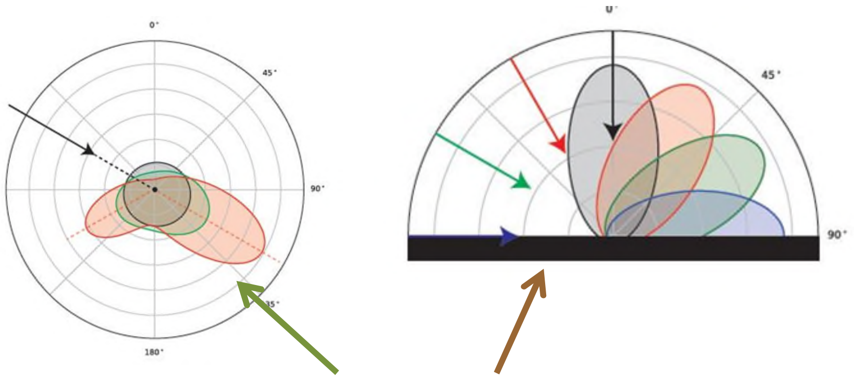
- First-order radiative transfer model RT1
  - Developed to describe soil-vegetation interaction mechanisms and a new way of modelling soil scattering

Quast et al. (2023) Soil moisture retrieval from Sentinel-1 using a first-order radiative transfer model - a case-study over the Po-Valley, Remote Sensing of Environment, 295, 113651, DOI 10.1016/j.rse.2023.113651

RT-1 Model: Scattering by Vegetation and Soil

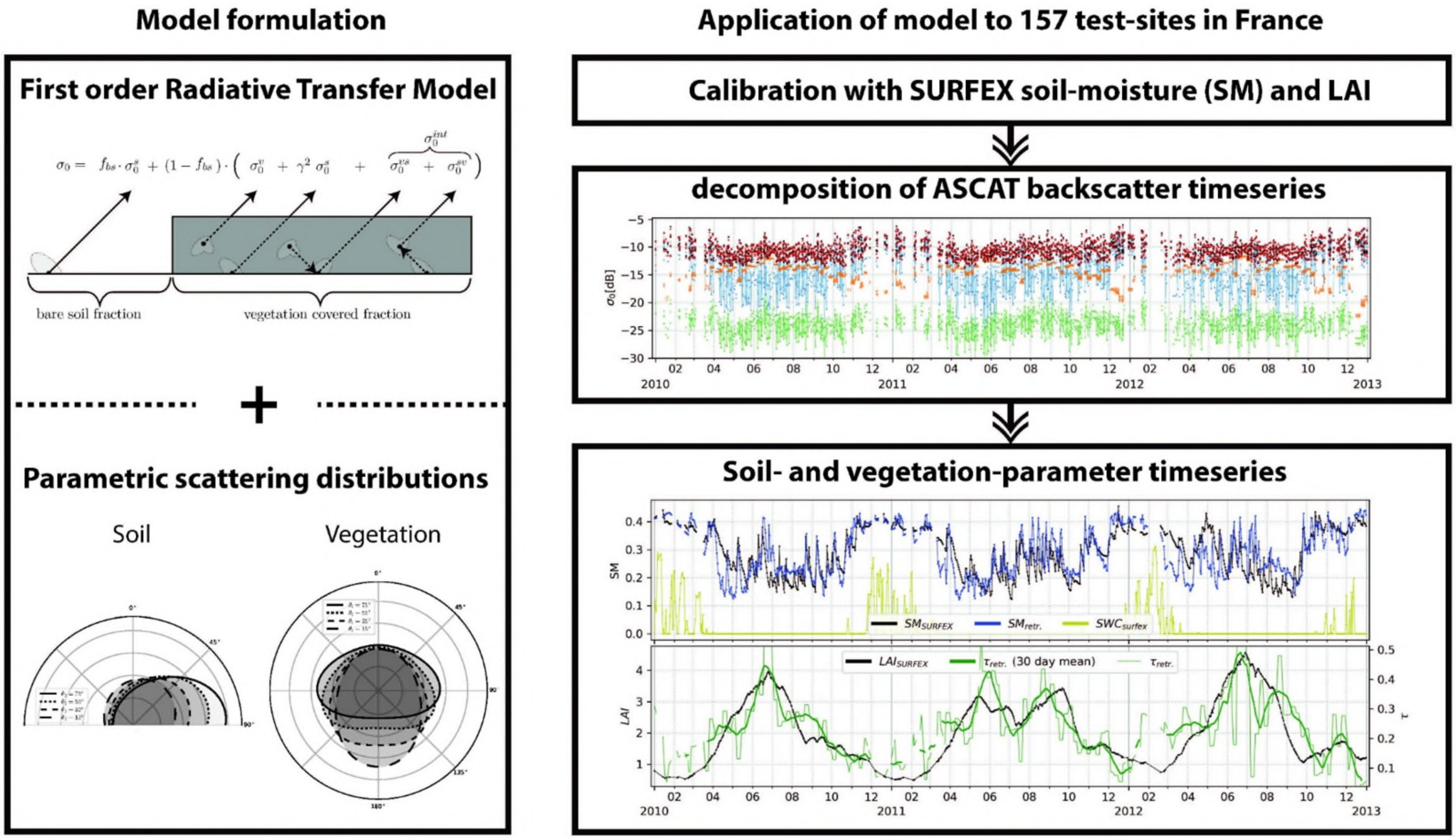
- Radiative transfer model for bi- and monostatic scattering
- Generalised phase functions for modelling surface-volume interactions
- Available on GitHub: https://github.com/TUW-GEO/rt1





$$I_{int} \propto \iint \cdots \mathcal{P}_{vol} \cdot \mathcal{P}_{surf}\, d\mu\, d\varphi$$

Quast et al. (2019) A generic first-order Radiative Transfer modelling approach for the inversion of soil- and vegetation parameters from scatterometer observations, Remote Sensing, 11, 285, 24p.

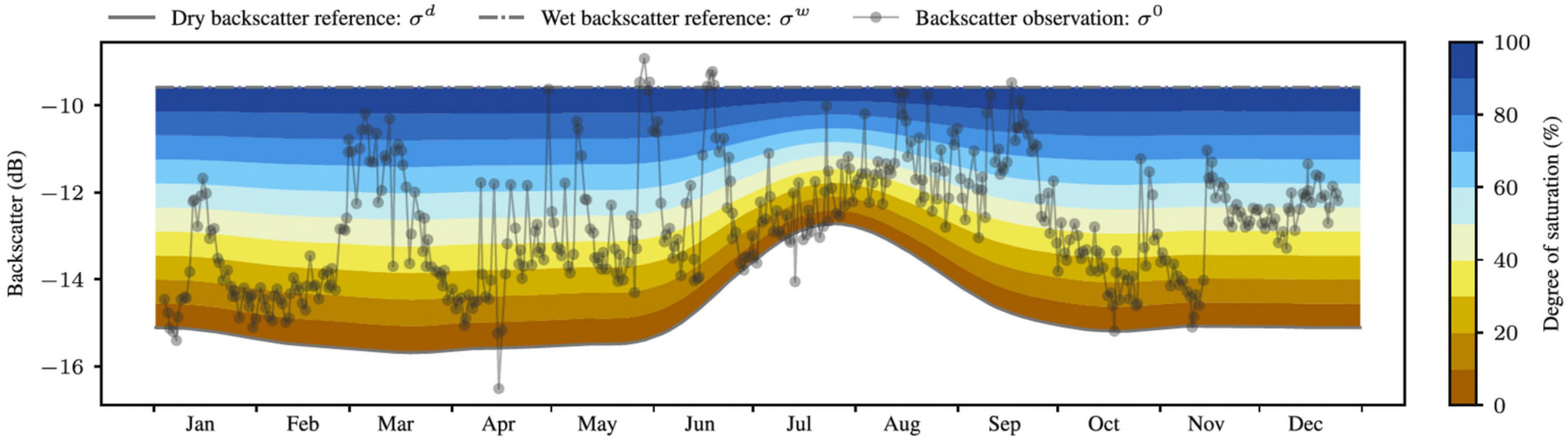


Quast et al. (2019) A generic first-order Radiative Transfer modelling approach for the inversion of soil- and vegetation parameters from scatterometer observations, Remote Sensing, 11, 285, 24p.

Soil Moisture Retrieval using a Change Detection Model

- For the EUMETSAT H SAF ASCAT soil moisture data product a change detection model is used which separates changes in backscatter due to soil moisture variations and seasonal vegetation phenology

Soil moisture $$\theta(t) = \frac{\sigma^0(t) - \sigma^0_{dry}(t)}{\sigma^0_{wet}(t) - \sigma^0_{dry}(t)}$$

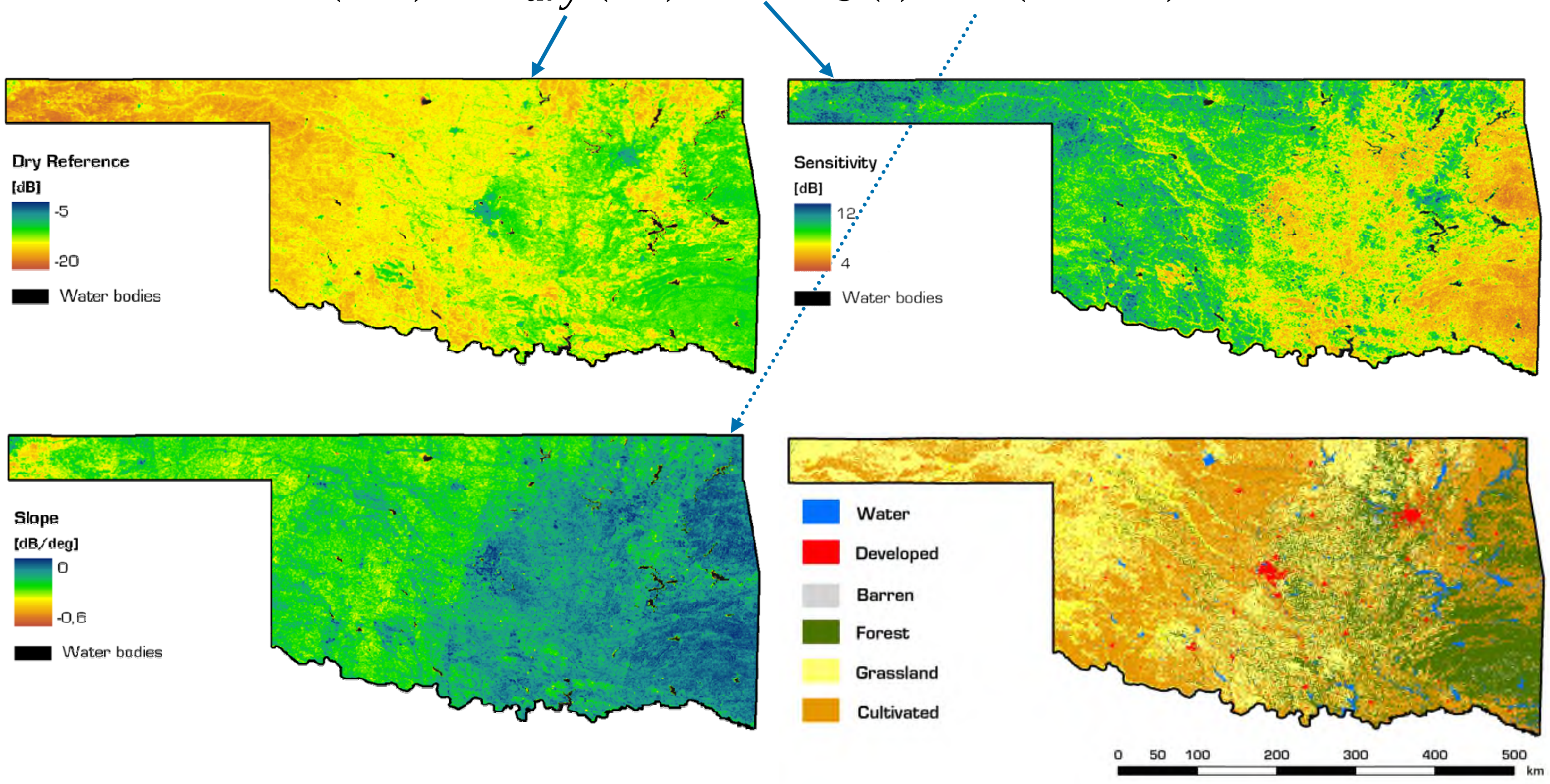


Hahn et al. (2021) Improving ASCAT soil moisture retrievals with an enhanced spatially-variable vegetation parameterization, IEEE Transactions on Geoscience and Remote Sensing, 10, 8241-8256.

SAR Backscatter Model

- Retrieval method is based on a backscatter model originally developed for the ERS scatterometer and later adopted to ENVISAT ASAR and Sentinel-1

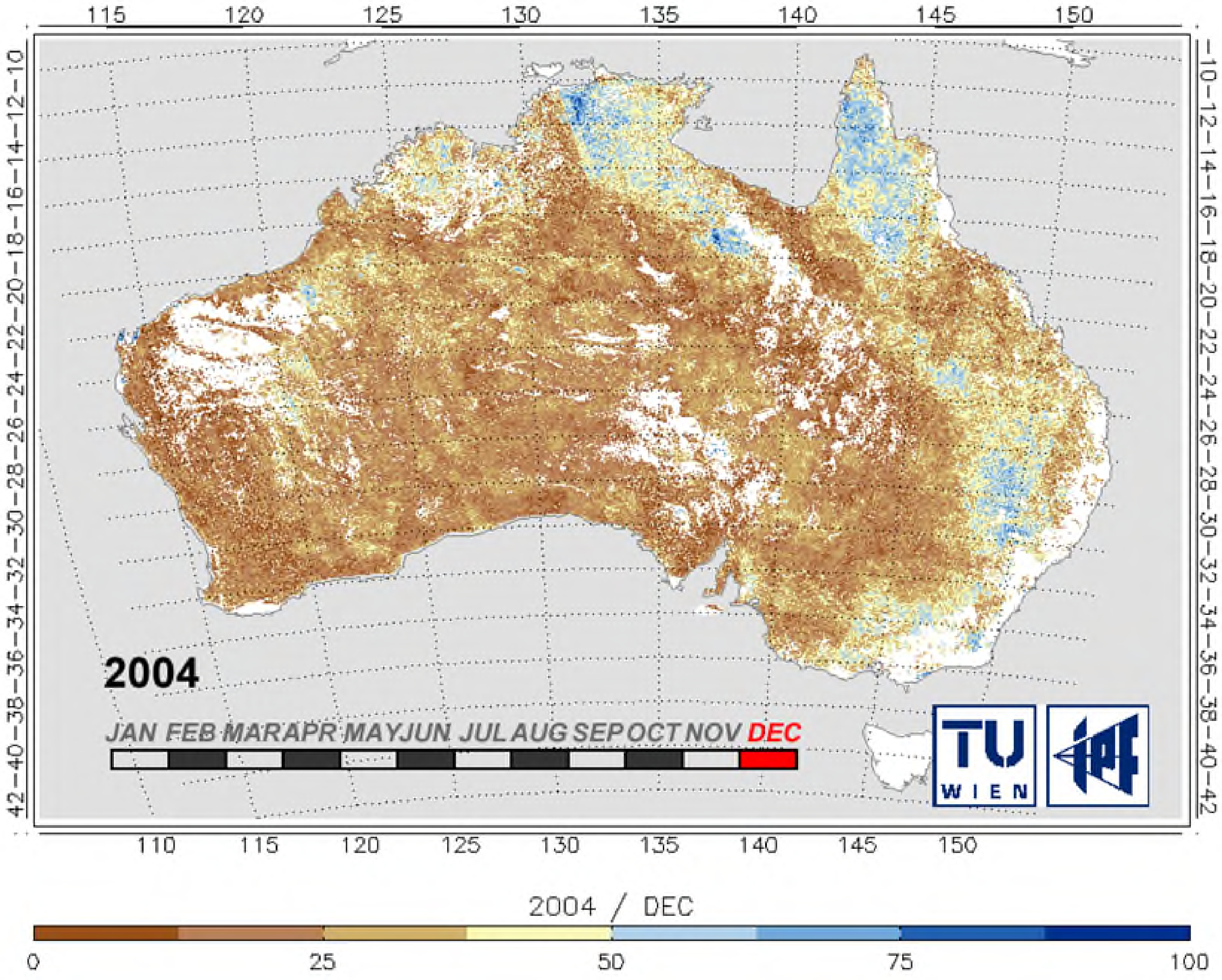
$$\sigma^0(t,\theta) = \sigma^0_{dry}(30) + S \cdot m_s(t) + \beta(\theta - 30)$$



ASAR backscatter model parameters and land cover map of Oklahoma, USA.

Pathe et al. (2009) Using ENVISAT ASAR Global Mode data for surface soil moisture retrieval over Oklahoma, USA, IEEE Transactions on Geoscience and Remote Sensing, 47(2), 468-480.

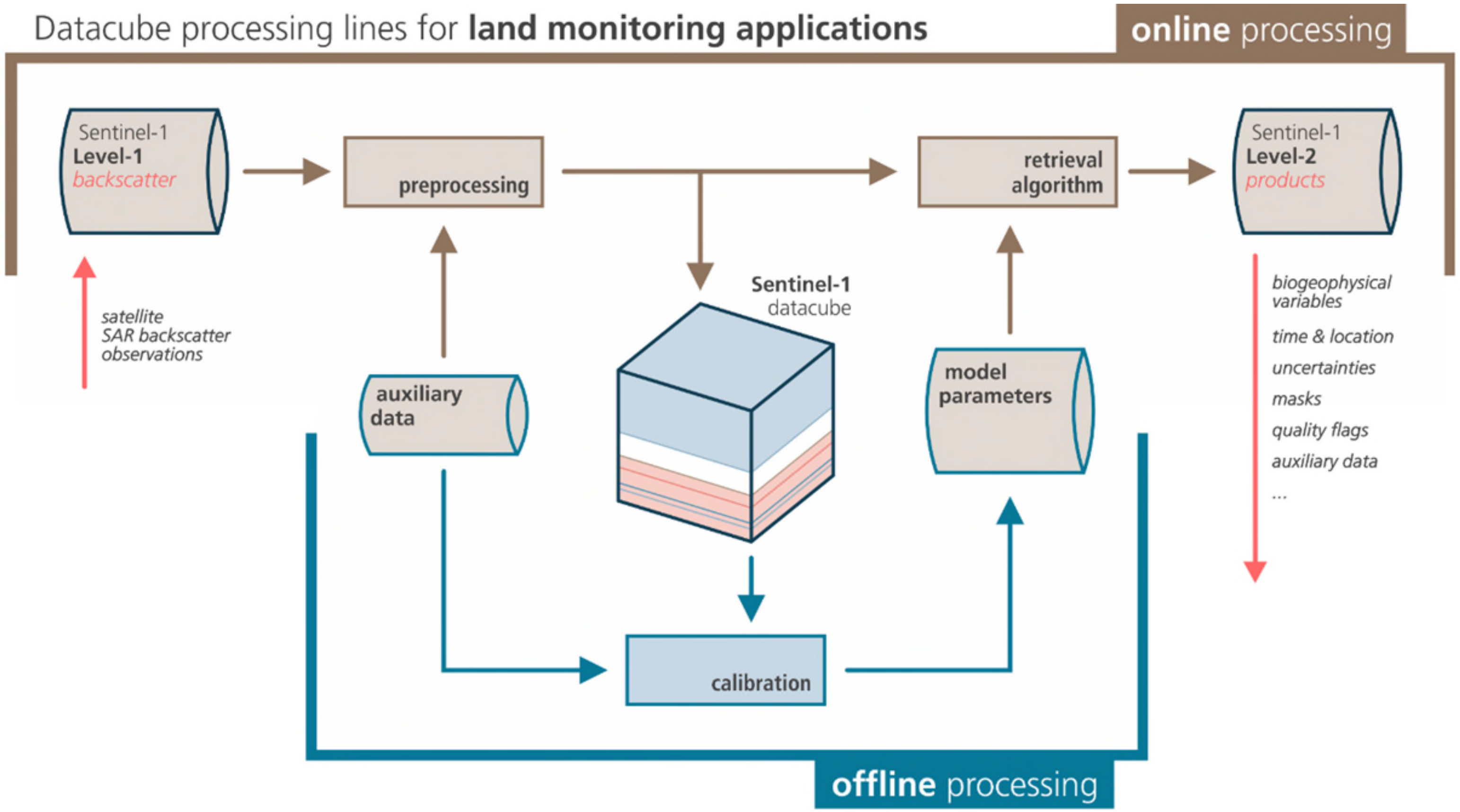
ENVISAT ASAR SSM



Sentinel-1 Pre-Processing

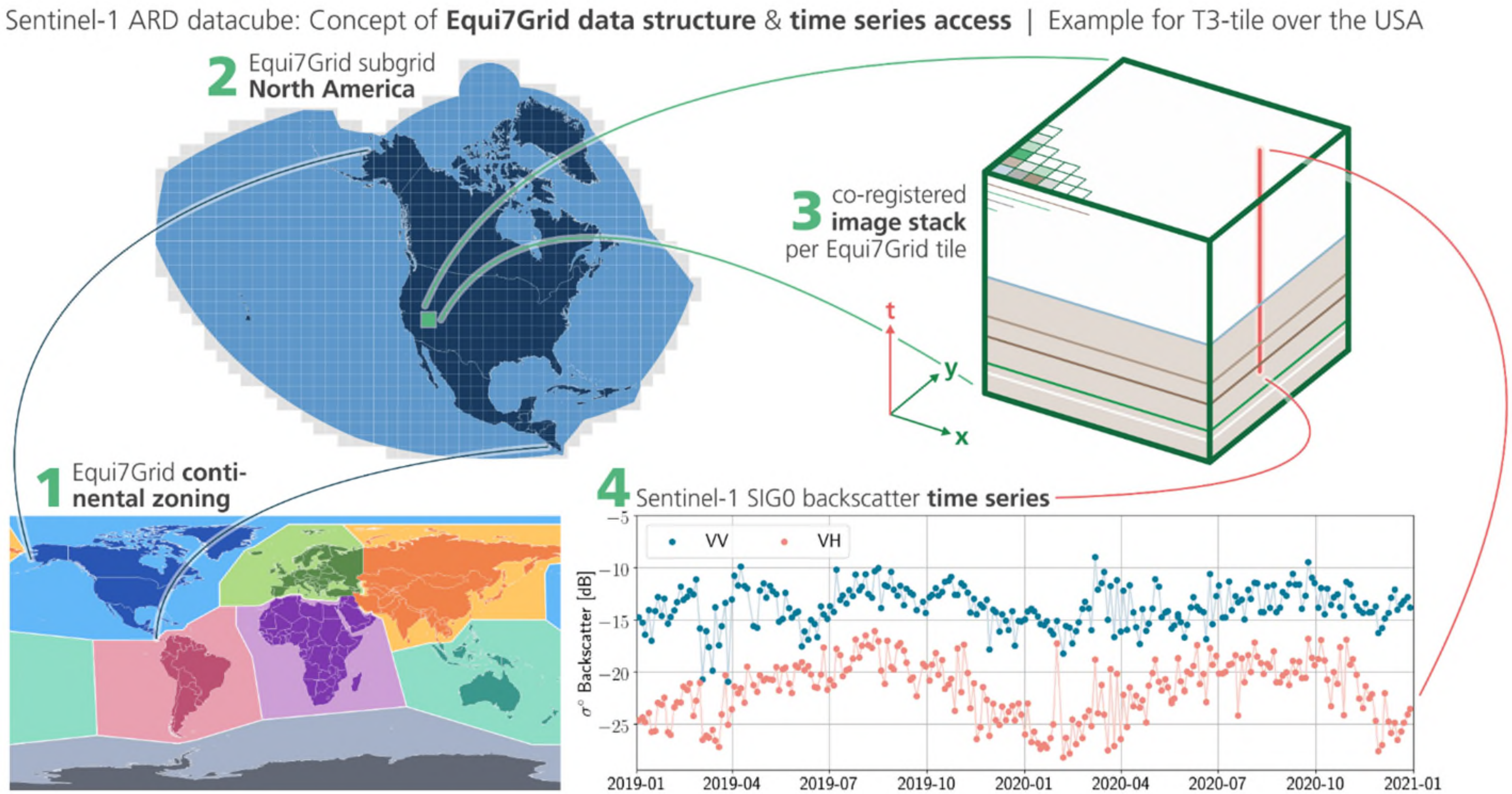
Datacube Processing Architecture

- From offline scientific analysis and model calibration to online operations



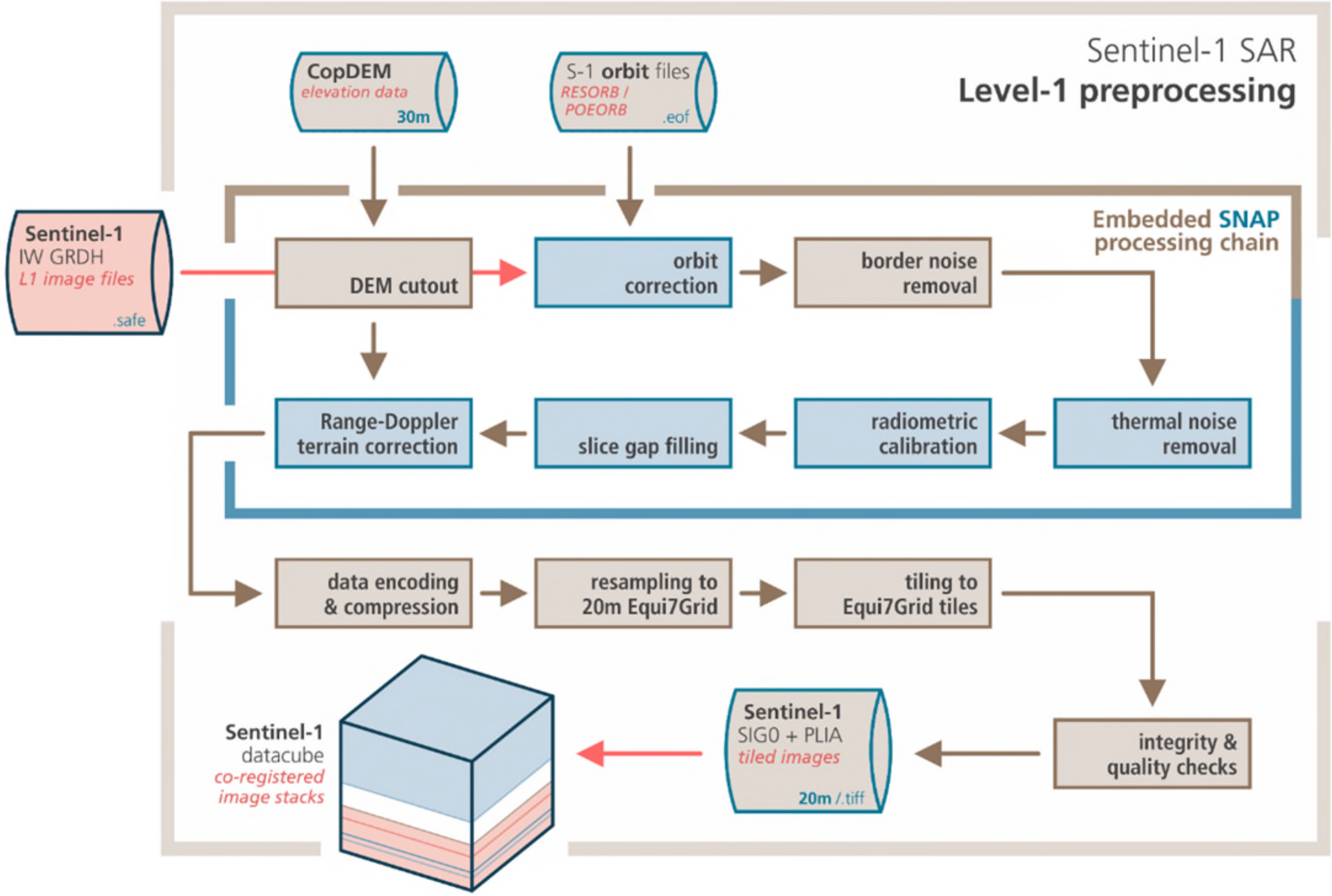
Wagner et al. (2021) A Sentinel-1 Backscatter Datacube for Global Land Monitoring Applications, *Remote Sensing*, 13, 4622.

Datacube System based upon the Equi7Grid



Bauer-Marschallinger et al. (2014) Optimisation of global grids for high-resolution remote sensing data, Computers & Geosciences, 72, 84-93. Figure from Wagner et al. (2021) A Sentinel-1 Backscatter Datacube for Global Land Monitoring Applications, *Remote Sensing*, 13, 4622.

Sentinel-1 Preprocessing



Data Volume in TB

Level-1 Sentinel-1 IW GRD data

Year	Africa	Asia	Europe	NA	Oceania	SA	Total
2015	12.7	15.1	22.0	6.2	4.9	5.3	66.2
2016	20.6	19.2	31.9	11.5	6.6	9.0	98.8
2017	45.0	53.9	71.8	31.4	18.4	23.1	243.6
2018	48.0	58.1	70.3	35.3	20.2	24.7	256.6
2019	94.4	61.1	119.9	38.5	21.1	26.9	361.9
2020	97.3	63.3	130.7	41.4	21.3	28.6	382.6
Total	318.0	270.7	446.6	164.3	92.5	117.6	1409.7

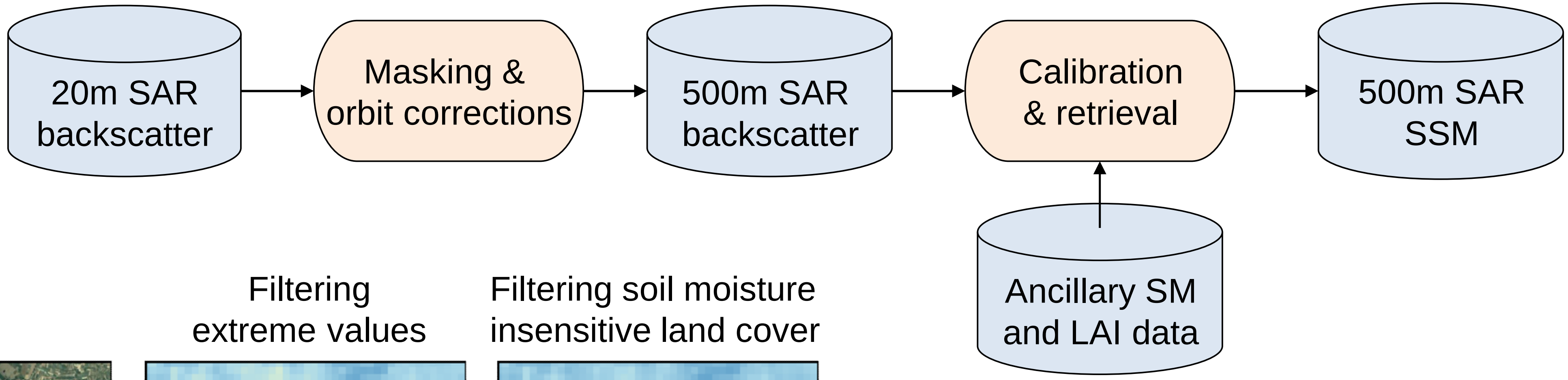
20 m Sentinel-1 datacube

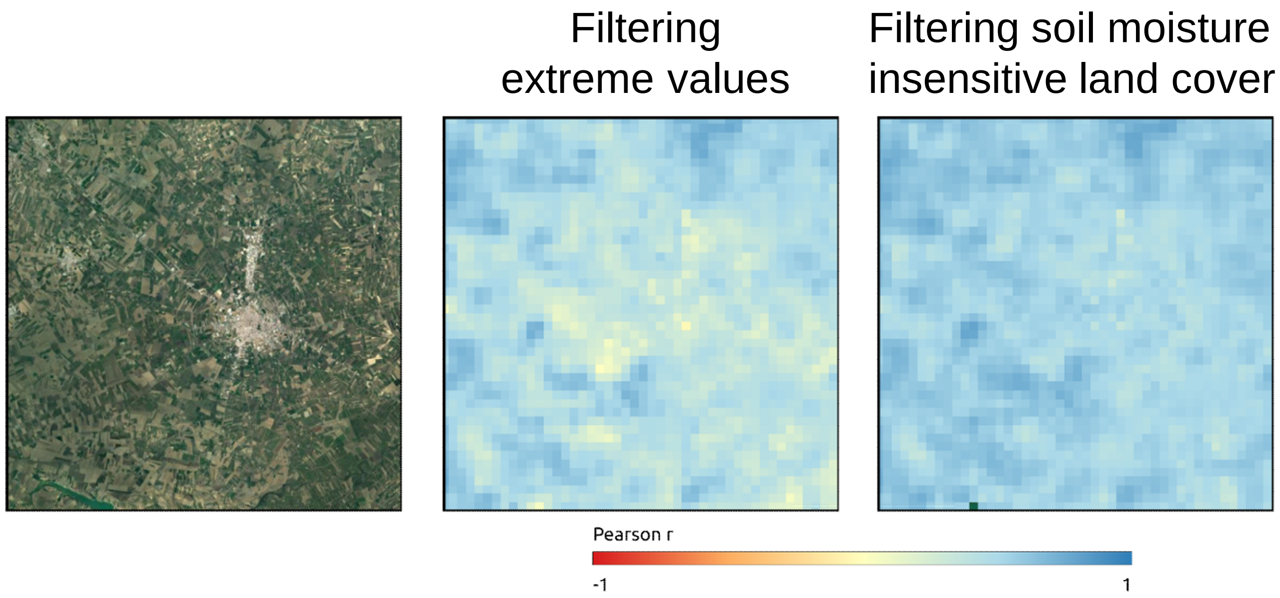
Year	Africa	Asia	Europe	NA	Oceania	SA	Total
2015	2.5	2.9	4.3	1.2	1.1	1.0	13.0
2016	4.4	4.0	6.4	2.5	1.5	1.9	20.7
2017	9.8	11.9	14.6	6.9	4.3	4.9	52.4
2018	10.3	12.8	12.8	7.6	4.7	5.2	53.4
2019	16.9	19.4	23.5	13.4	7.6	8.6	89.4
2020	17.3	20.1	25.0	14.6	7.7	9.4	94.1
Total	61.2	71.1	86.6	46.1	26.9	31.0	323.0

Wagner et al. (2021) A Sentinel-1 Backscatter Datacube for Global Land Monitoring Applications, *Remote Sensing*, 13, 4622.

From 20m to 1km Sentinel-1 Backscatter Data

- Improving soil moisture retrievals by masking high resolution input
- Correcting orbit and incidence angle effects





Higher correlation to reference ERA5-Land soil moisture by masking extreme values and pixels insensitive to soil moisture, e.g. urban areas

Masking of Non-Soil-Moisture-Sensitive Areas

- Urban areas, dense forests, water bodies/inundated areas, etc.

Without Masking Forests

With Masking Forests

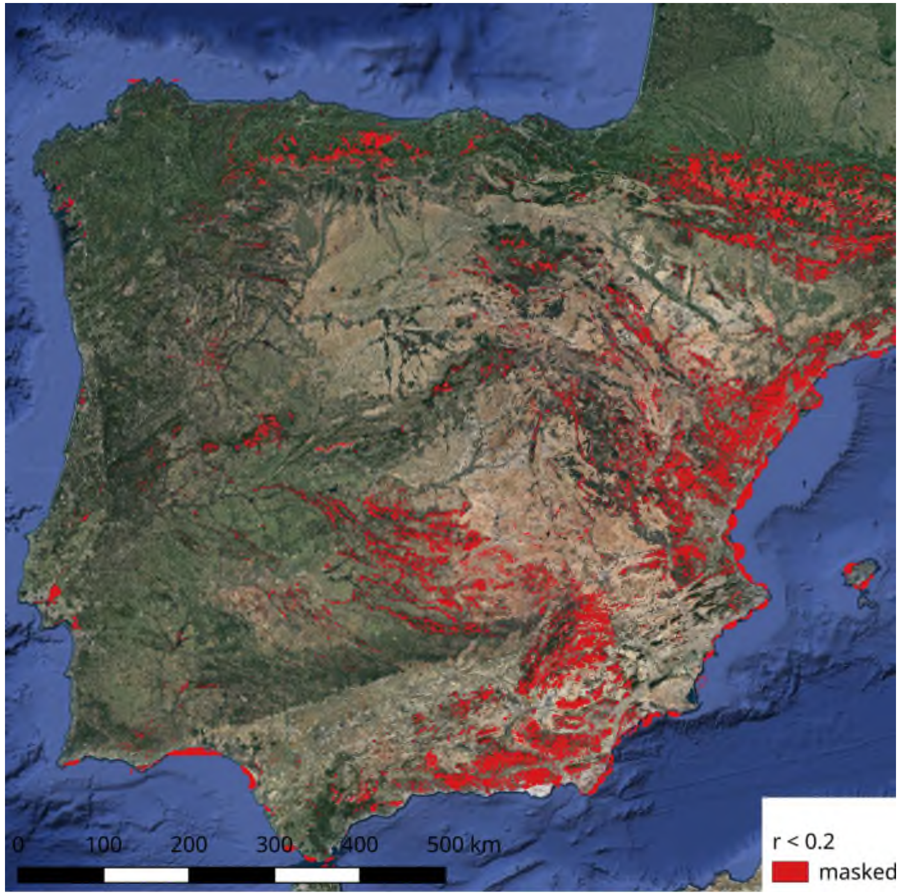
Correlation improves when masking dense forest areas before aggregating to 1 km scale

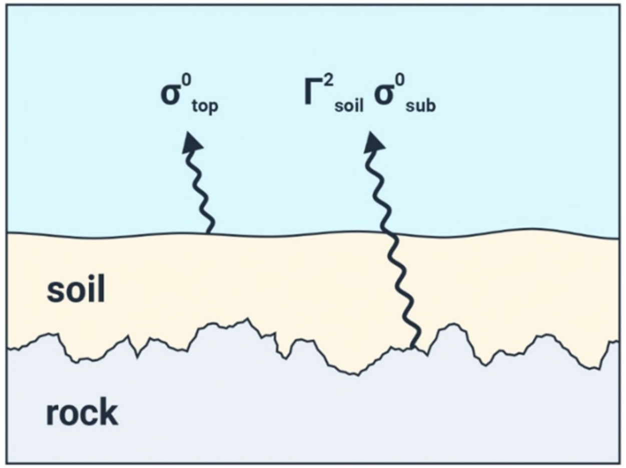
Massart et al. (2023) Mitigating the impact of dense vegetation on theSentinel-1 surface soil moisture over Europe, EGU General Assembly 2023, https://doi.org/10.5194/egusphere-egu23-12269, 2023.

Masking was done based on the Sentinel-1 derived forest map by Dostálová et al. (2021) European wide forest classification based on Sentinel-1 data, Remote Sensing, 13, 337, 10.3390/rs13030337

Subsurface scattering in Arid Regions

- Backscatter may increase due to near-surface rocks and stones when soil dries





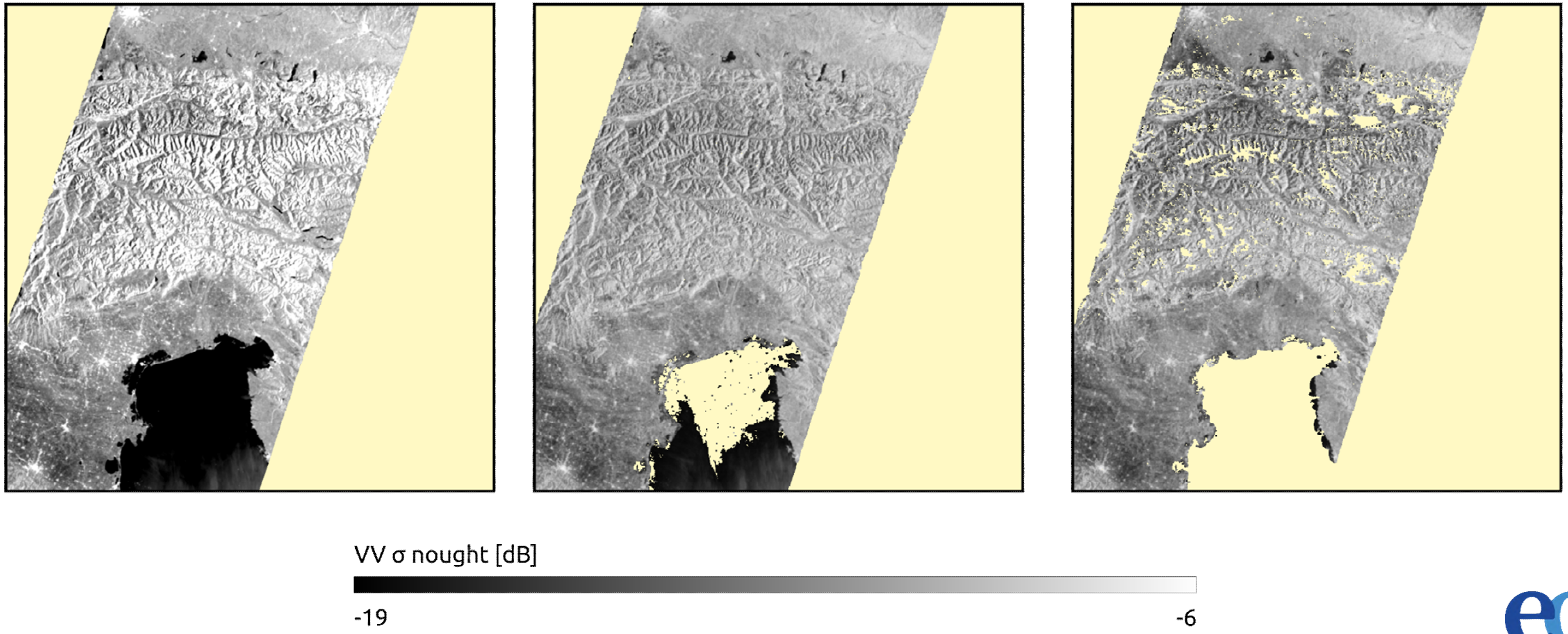
Red pixels indicate subsurface scattering areas. Processing by Bernhard Raml

Wagner et al. (2022) Widespread occurence of anomalous C-band backscatter signals in arid environments by subsurface scattering, Remote Sensing of Environment, 276, 113025, DOI 10.1016/j.rse.2022.113025.

1km Backscatter Data Optimised for Soil Moisture Retrieval

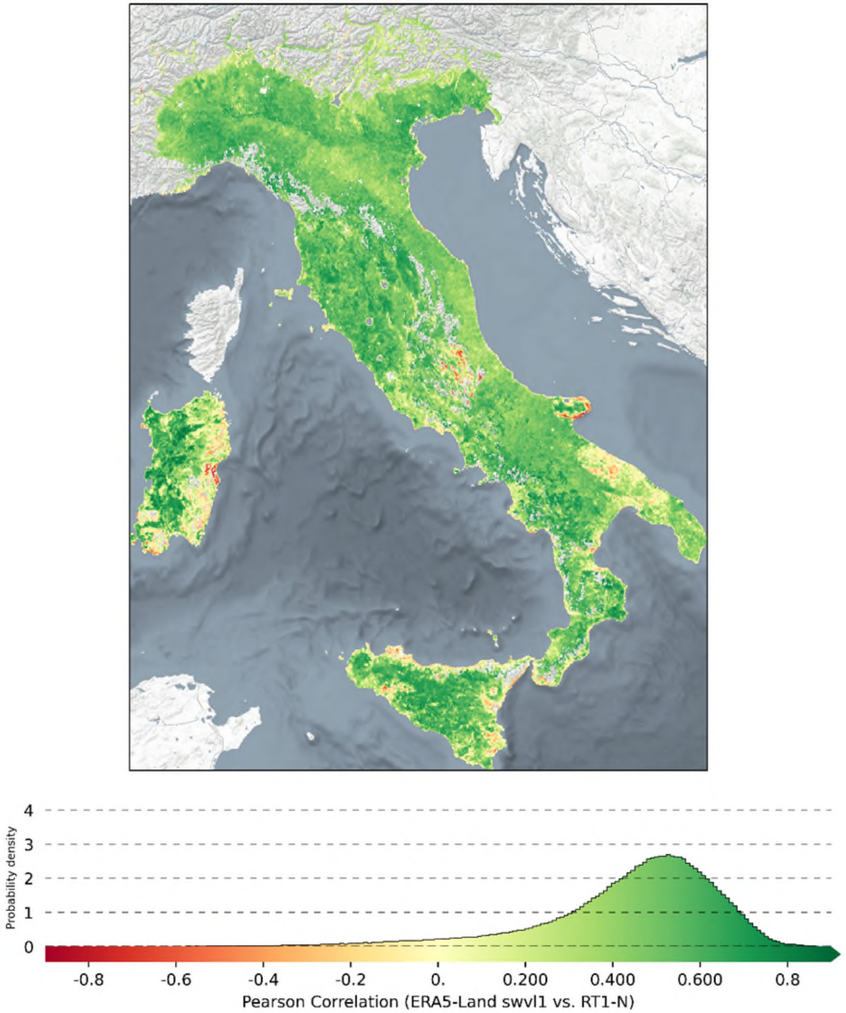
- Aggregate to 500m grid after masking for soil moisture insensitive areas
  - Dense forest, urban areas, water bodies, wetlands, subsurface scattering areas, snow, frost, …
- Efficient processing thanks to optimised I/O operations (“streaming”)

Without filtering | Filtering extreme values | Filtering soil moisture insensitive land cover

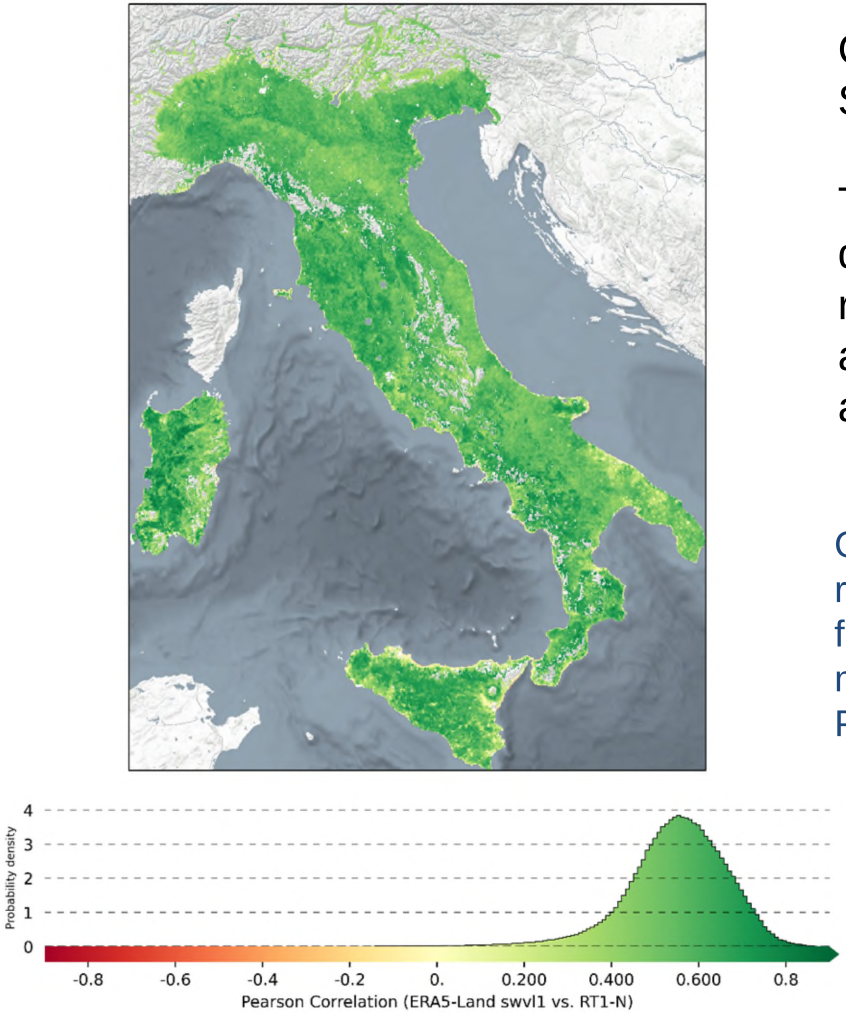


Impact of Masking on Sentinel-1 SSM Retrievals

Without Masking



With Masking



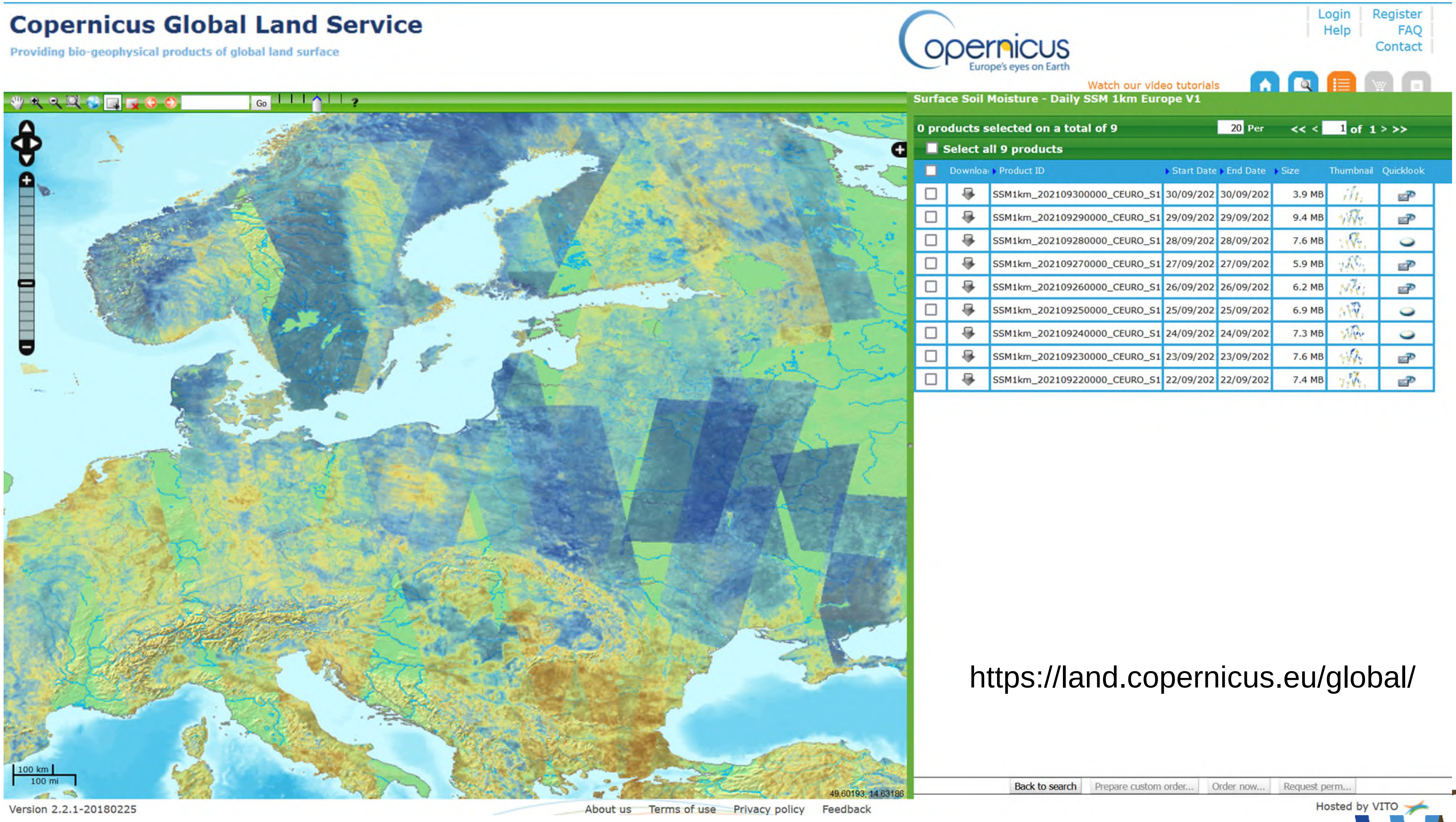
Correlation between Sentinel-1 SSM and ERA5-Land.

The Sentinel-1 SSM were derived with RT1 using a trust-region-reflective least squares algorithm and only LAI as ancillary data set.

Quast et al. (2022) Soil moisture retrieval from Sentinel-1 using a first-order radiative transfer model - a case-study over the Po-Valley, submitted.

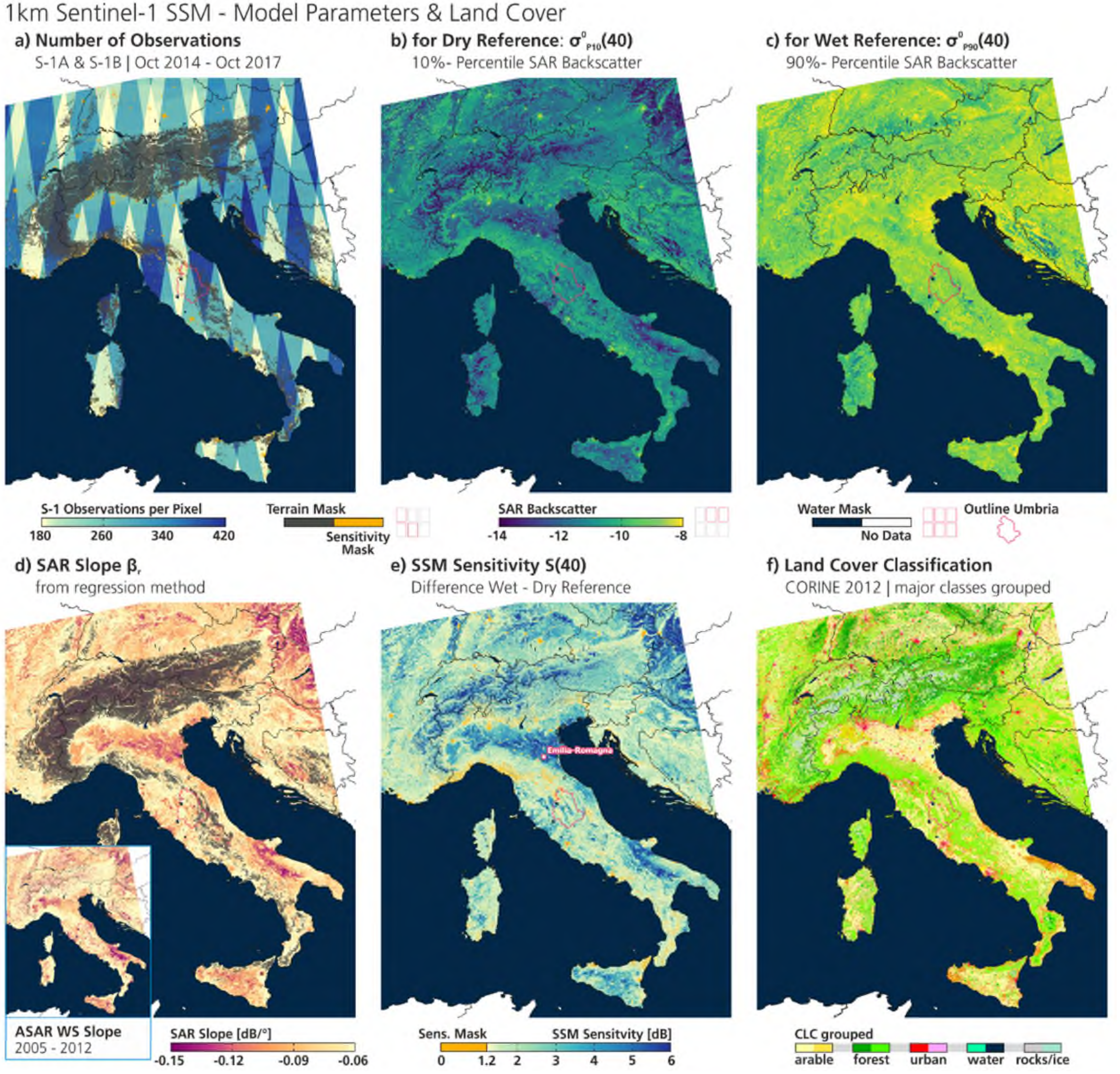
Sentinel-1 Soil Moisture

Operational Sentinel-1 SSM from Copernicus



https://land.copernicus.eu/global/

Sentinel-1 SSM Retrieval



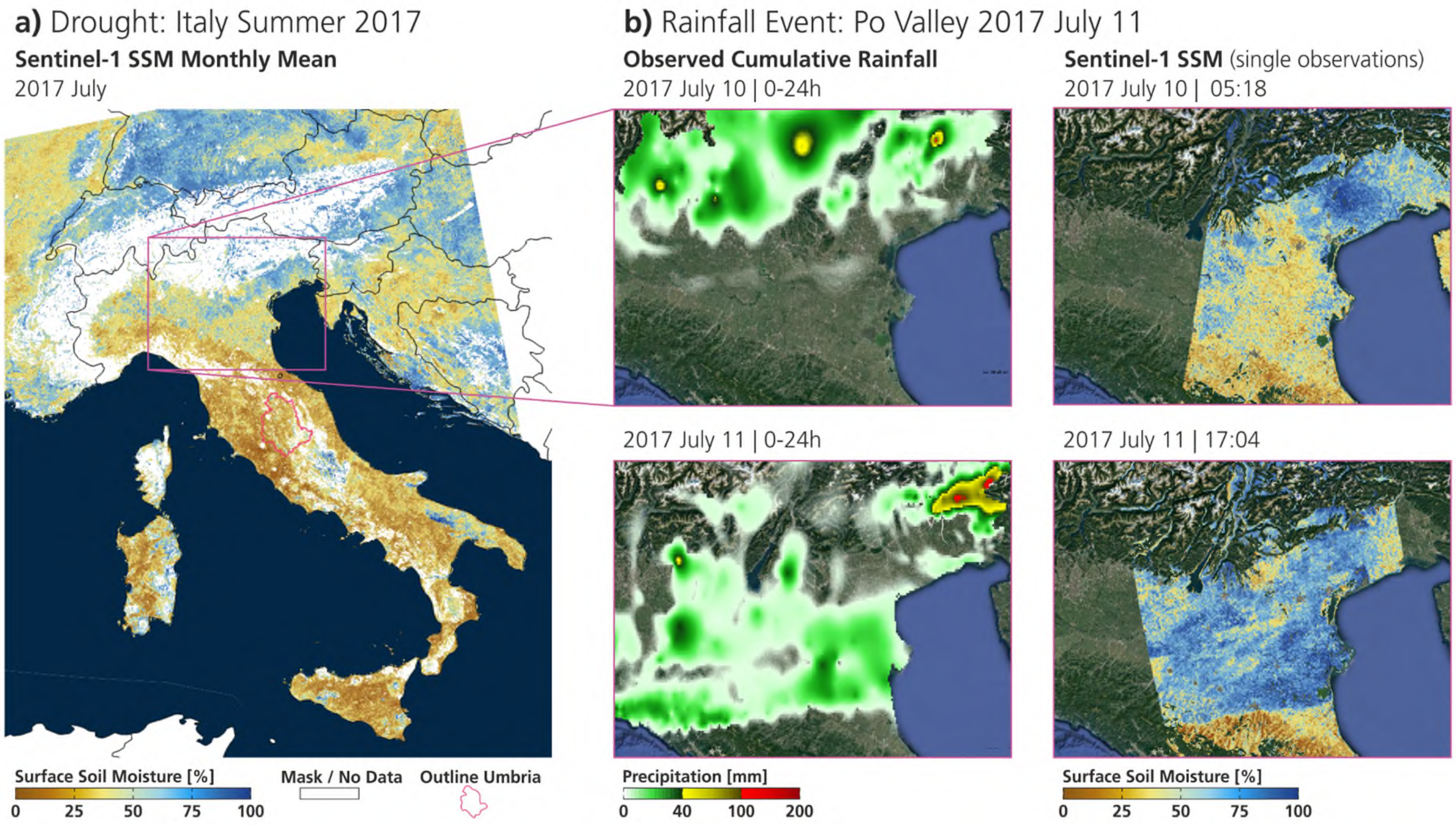
- Use all orbits to maximise temporal coverage
- Pre-processing workflows to produce 1km backscatter data
  - Masking of extreme values: -20dB<σ^0<-5dB
  - Gaussian filtering to resample to 500m grid
  - Standardisation of backscatter σ^0 to 40°
- Adjustment of algorithms
  - Methods for estimating model parameters

Bauer-Marschallinger et al. (2019) Towards global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles, IEEE Transactions on Geoscience and Remote Sensing, 57(1), 520-539.

Copernicus The European Earth Observation Programme

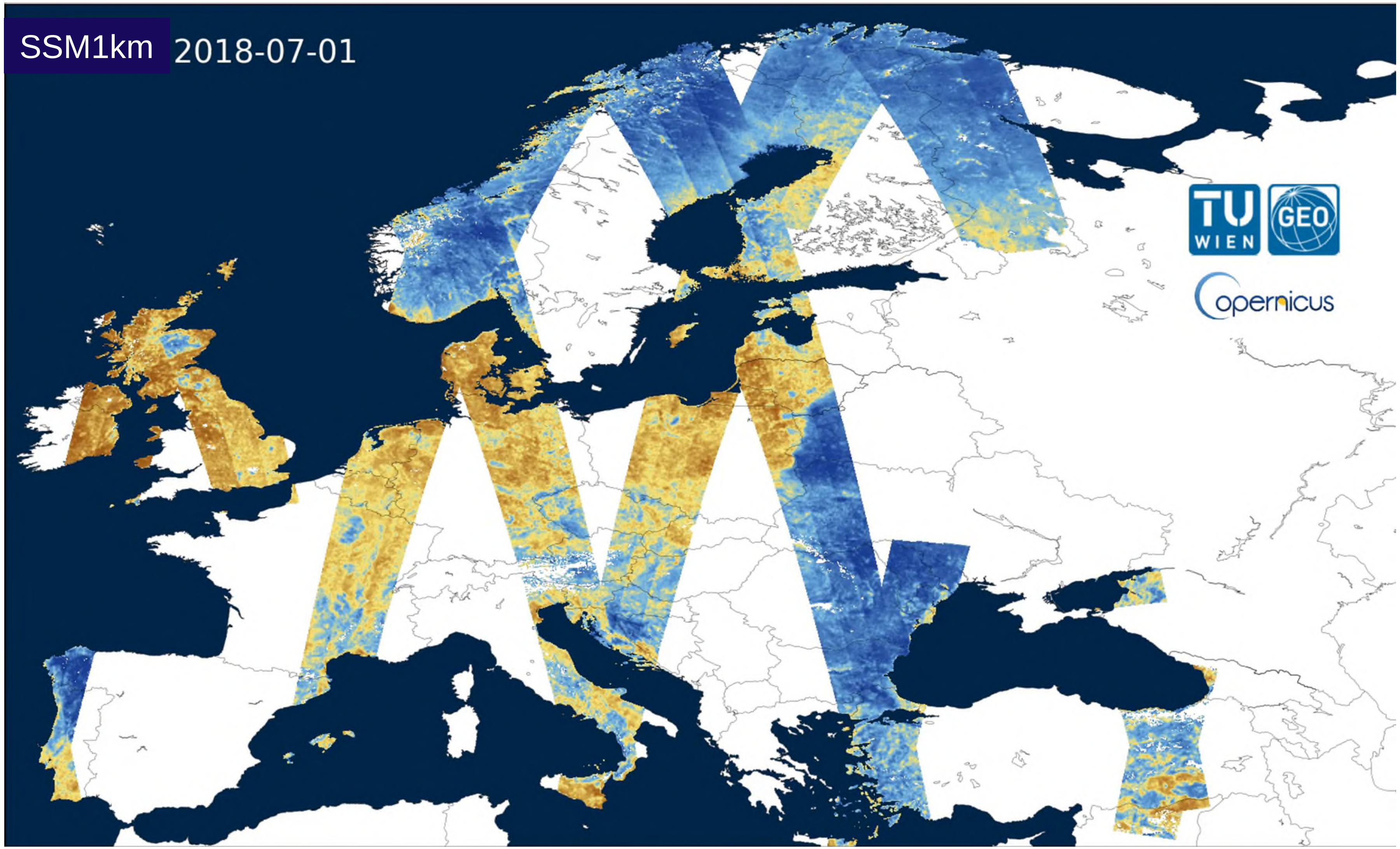
eodc TU WIEN GEO

Sentinel-1 SSM vs Precipitation

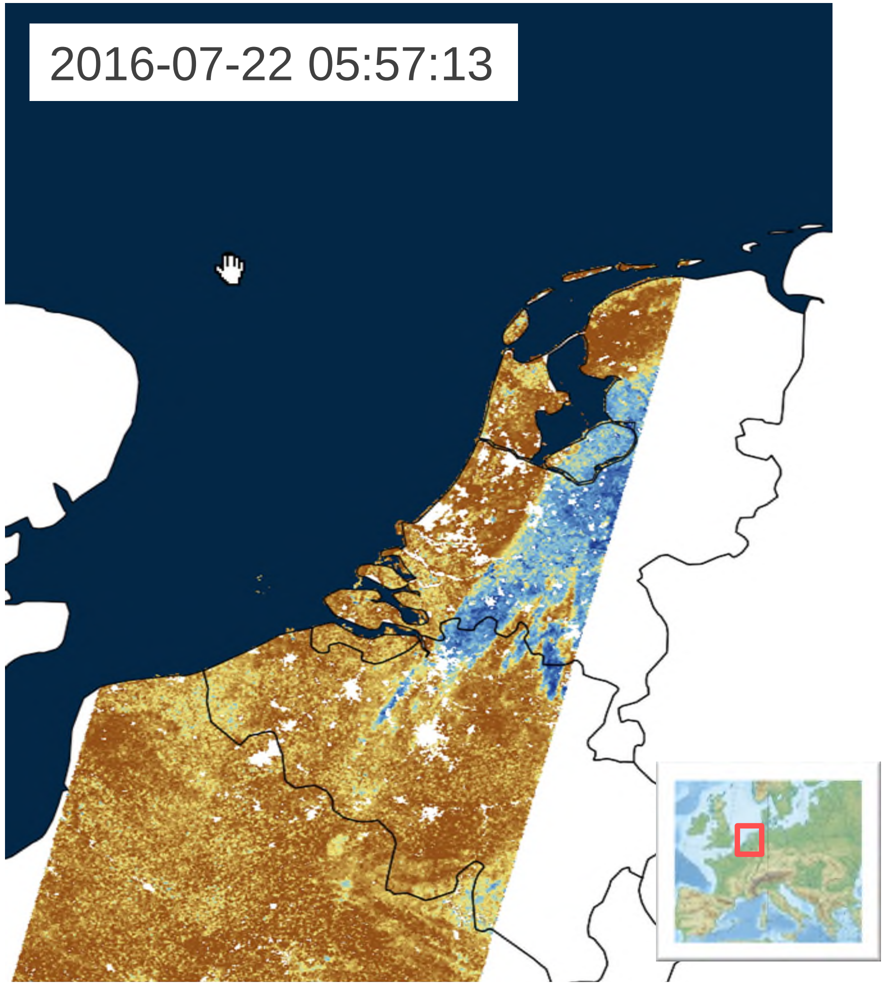


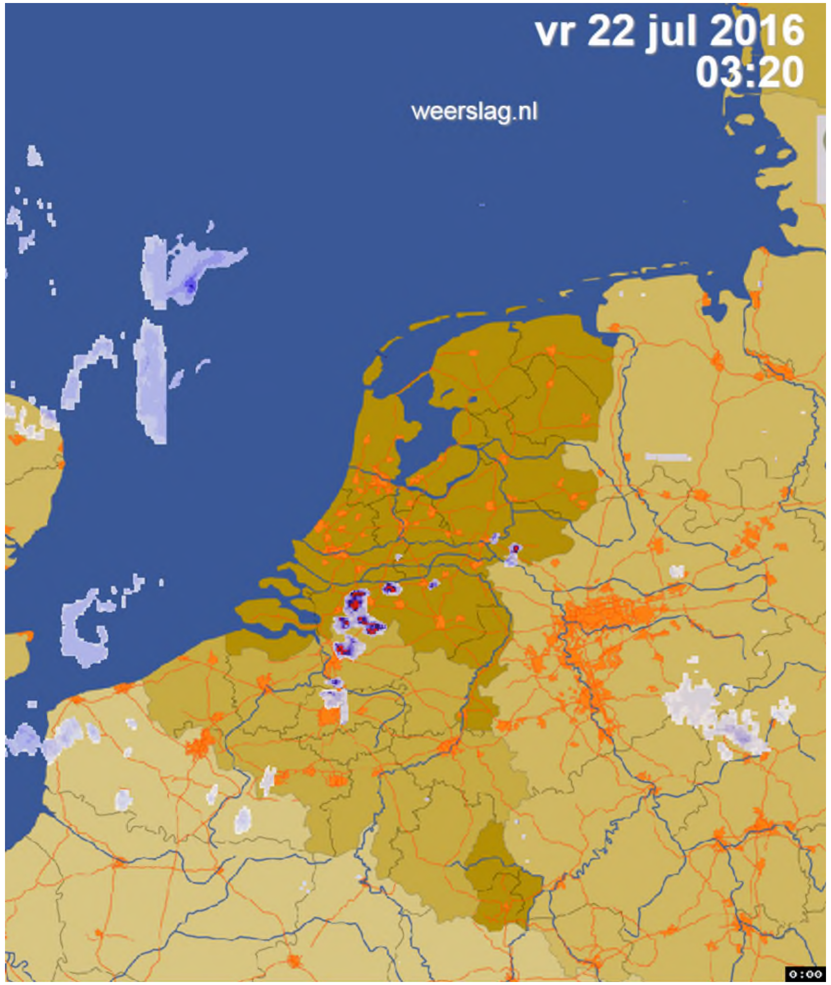
Bauer-Marschallinger et al. (2019) Towards global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles, IEEE Transactions on Geoscience and Remote Sensing, 57(1), 520-539.

Copernicus Sentinel-1 SSM Animation

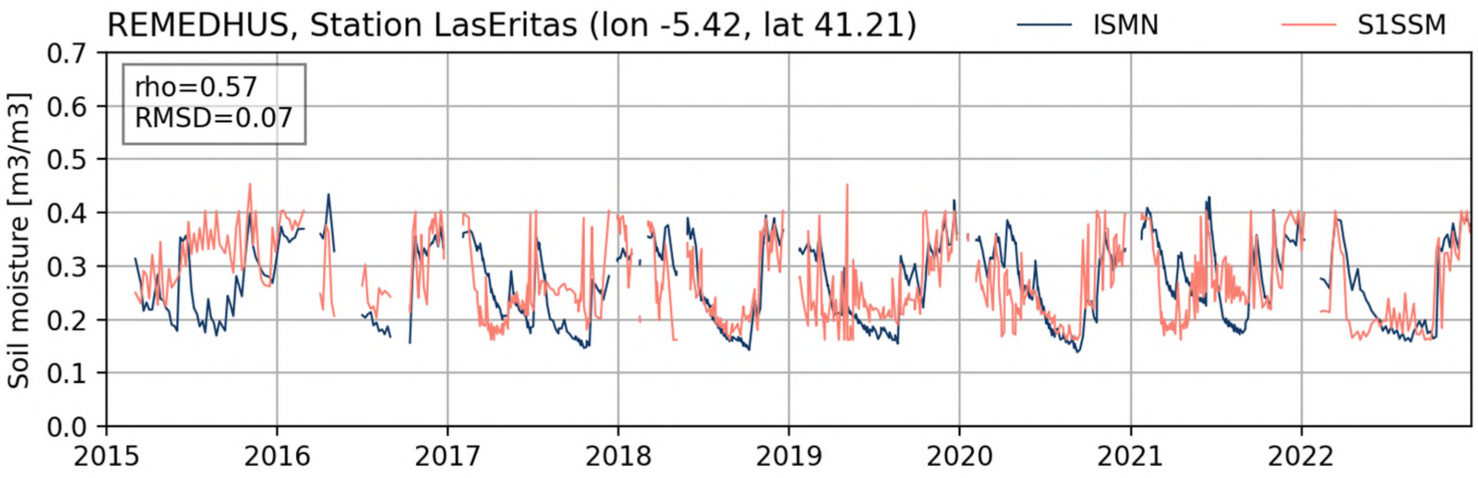


Sentinel-1 Soil Moisture & Precipitation Radar

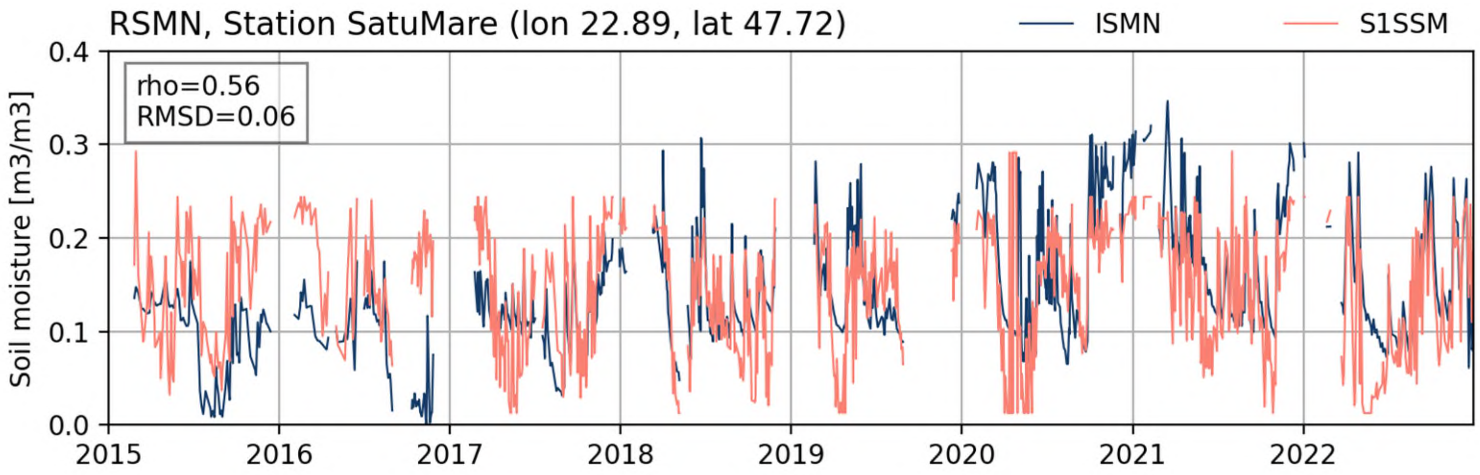




Sentinel-1 versus in situ SSM Time Series



REMEDHUS Network, Spain

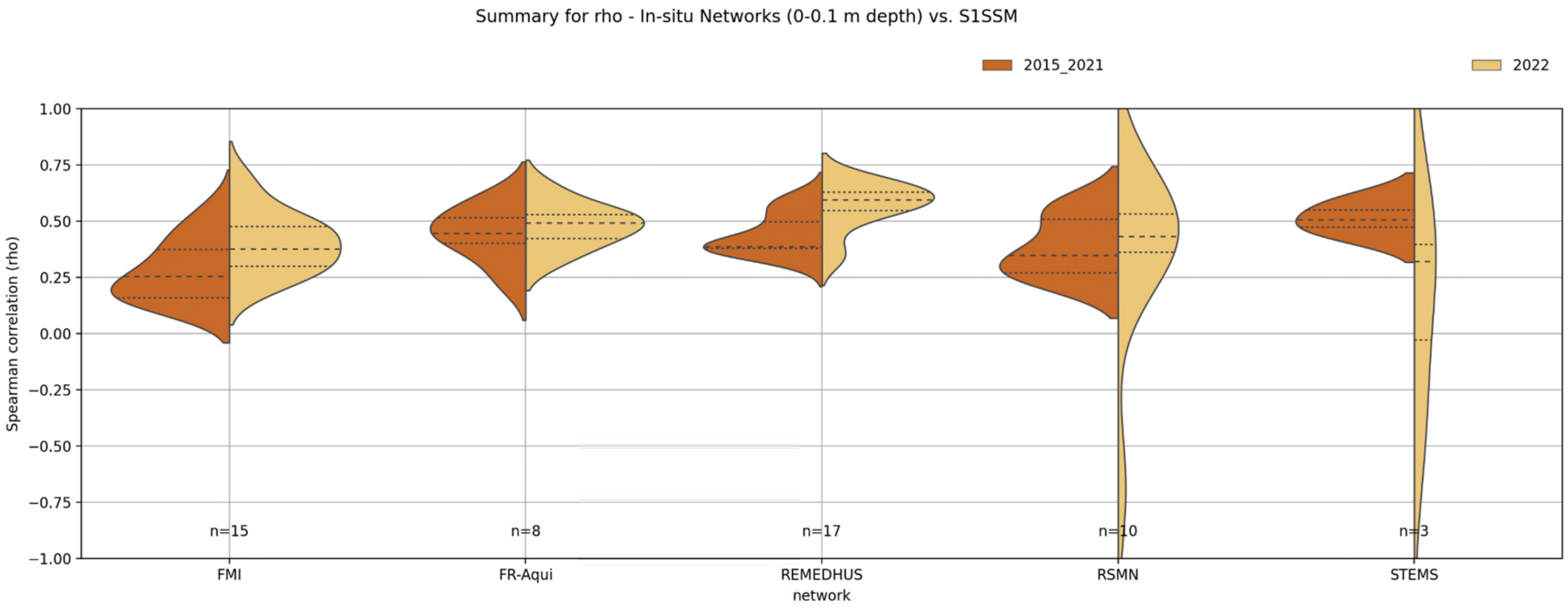


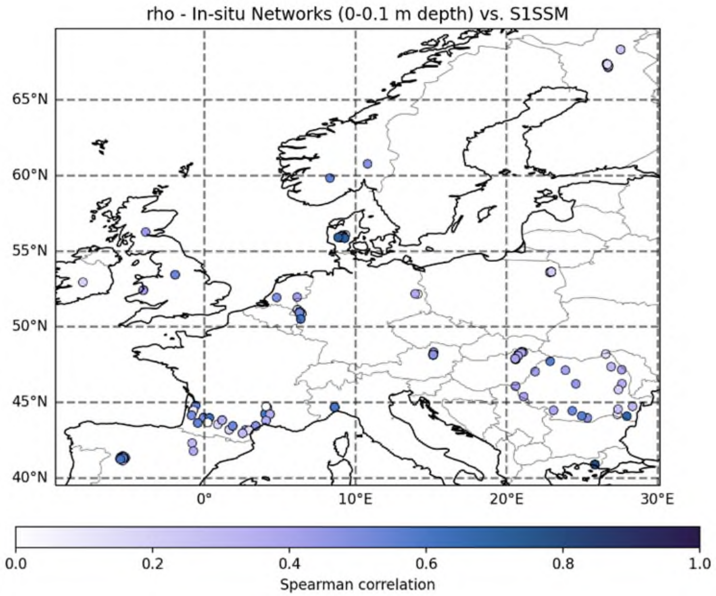
RSMN Network, Romania

Bauer-Marschallinger & Massart (2023) Surface soil moisture collection 1km Version 1.0, Quality Assessment Report Update 2022, Copernicus Global Land Operations “Vegetation and Energy” (CGLOPS-1), Service Contract N° 941115 - ISP- 2021 (JRC).

Sentinel-1 versus in situ SSM Time Series

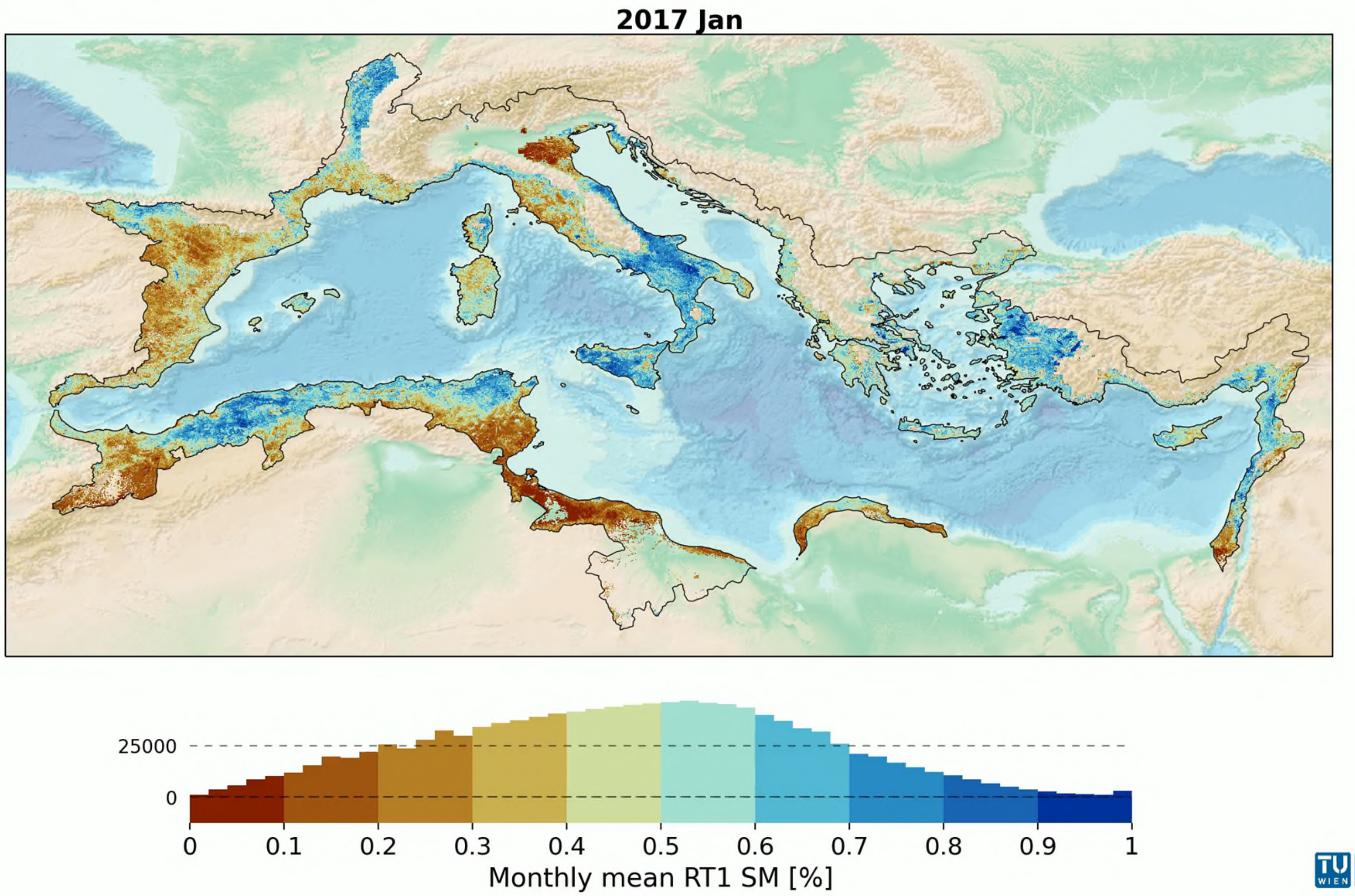
- Due to a mismatch of spatial and temporal scales and retrieval errors correlation values are low to modest
  - There may be differences from year to year (e.g. due to crop rotation)





Bauer-Marschallinger & Massart (2023) Surface soil moisture collection 1km Version 1.0, Quality Assessment Report Update 2022, Copernicus Global Land Operations "Vegetation and Energy" (CGLOPS-1), Service Contract N° 941115 - ISP- 2021 (JRC).

New RT-1 based 1km Sentinel-1 Surface Soil Moisture Retrievals



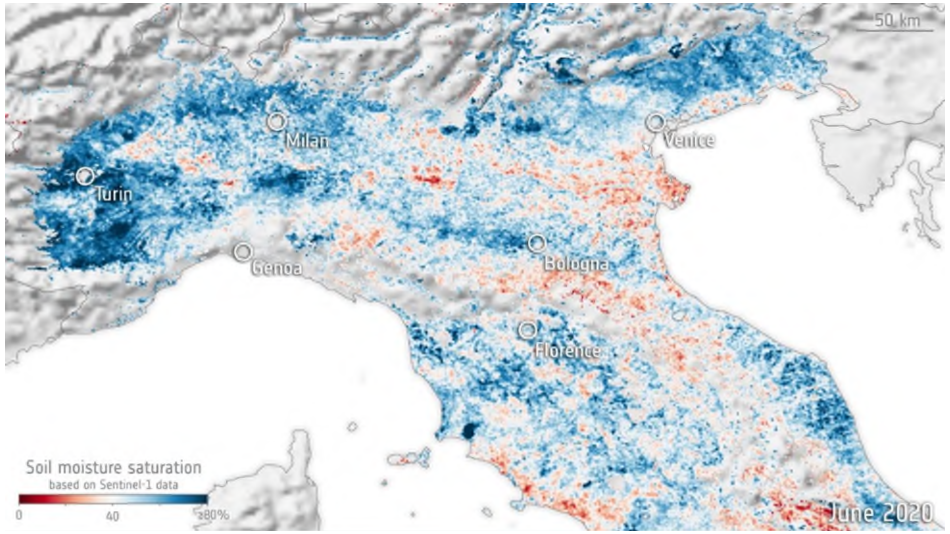
Mean-monthly Sentinel-1 surface soil moisture retrievals for the Mediterranean region from 2017 to 2021.

Sentinel-1 retrievals and animation from Raphael Quast.

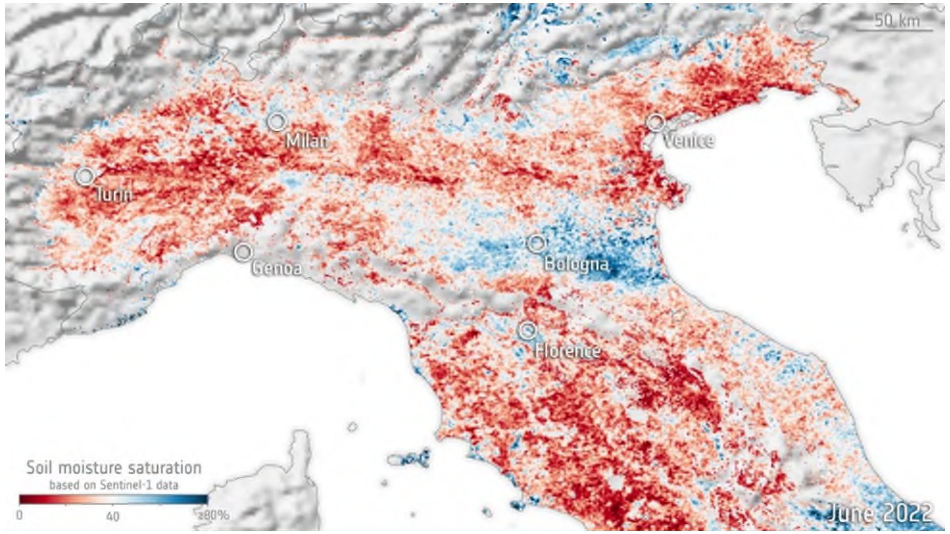
Quast et al. (2023) Soil moisture retrieval from Sentinel-1 using a first-order radiative transfer model - a case-study over the Po-Valley, Remote Sensing of Environment, 295, 113651, DOI 10.1016/j.rse.2023.113651

Dought in Italy in 2022

Mean Sentinel-1 Soil Moisture in June 2020



Mean Sentinel-1 Soil Moisture in June 2022



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


Hydrology IRPI-CNR
@Hydrology_IRPI

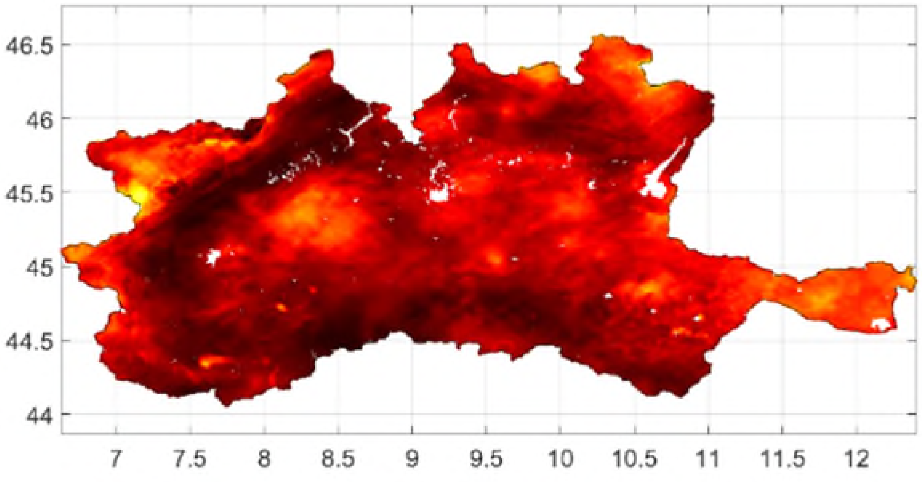
Fantastica novità TOP
Siamo in grado di fornire mappe di #siccità alla risoluzione di 500 m ecco la mappa di anomalia per Giugno 2022
Impressionante nel nordovest e centro
@ESA_EO #Sentinel1
Elab @jetvreugdenhil R Quast
@Giulio_Firenze @LArcidiaco @DPCgov
@CopernicusEU

Twitter Tweet by Luca Brocca (IRPI) on drought seen by Sentinel-1 reached over 60000 views within a day.

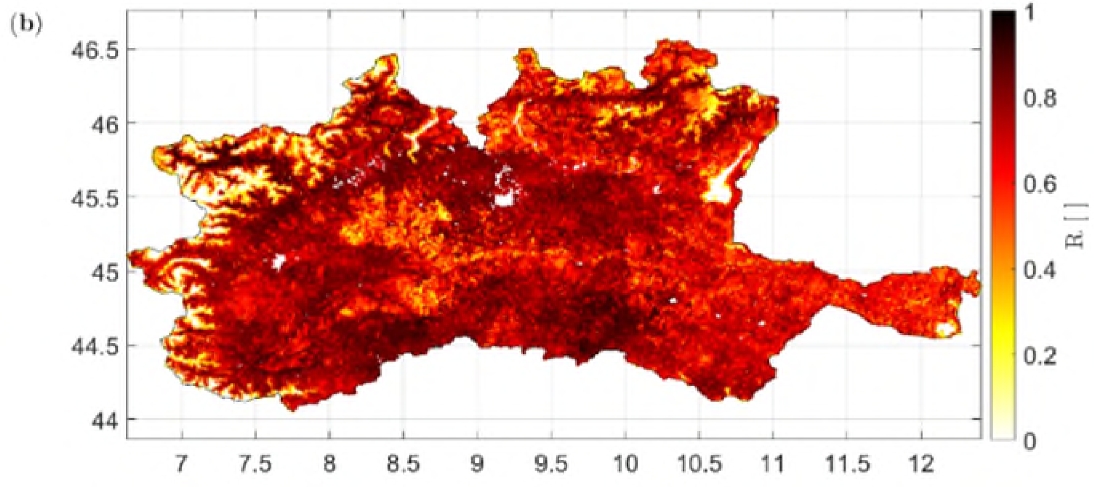
Rainfall Estimation with SM2Rain

- By inverting the water balanace of the land surface rainfall can be estimated by analysing soil moisture changes
  - „Bottom-up method“

SM2Rain for ASCAT



SM2Rain for Sentinel-1

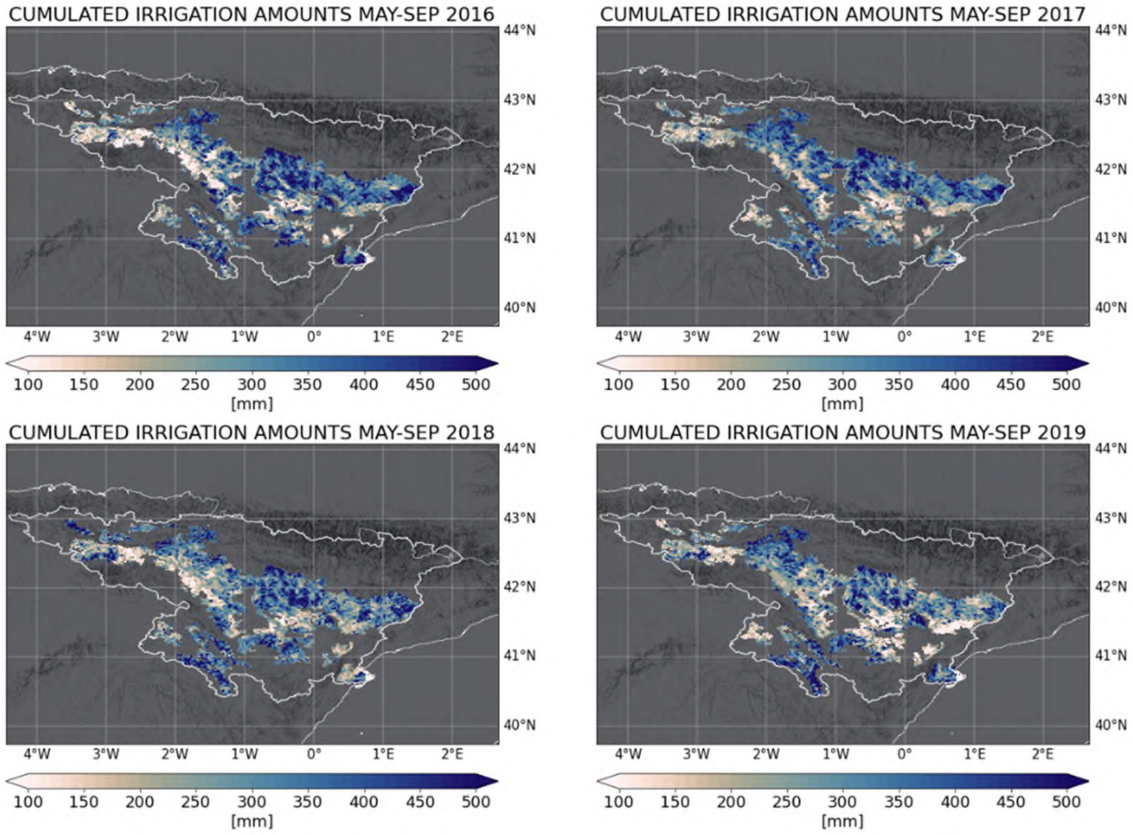


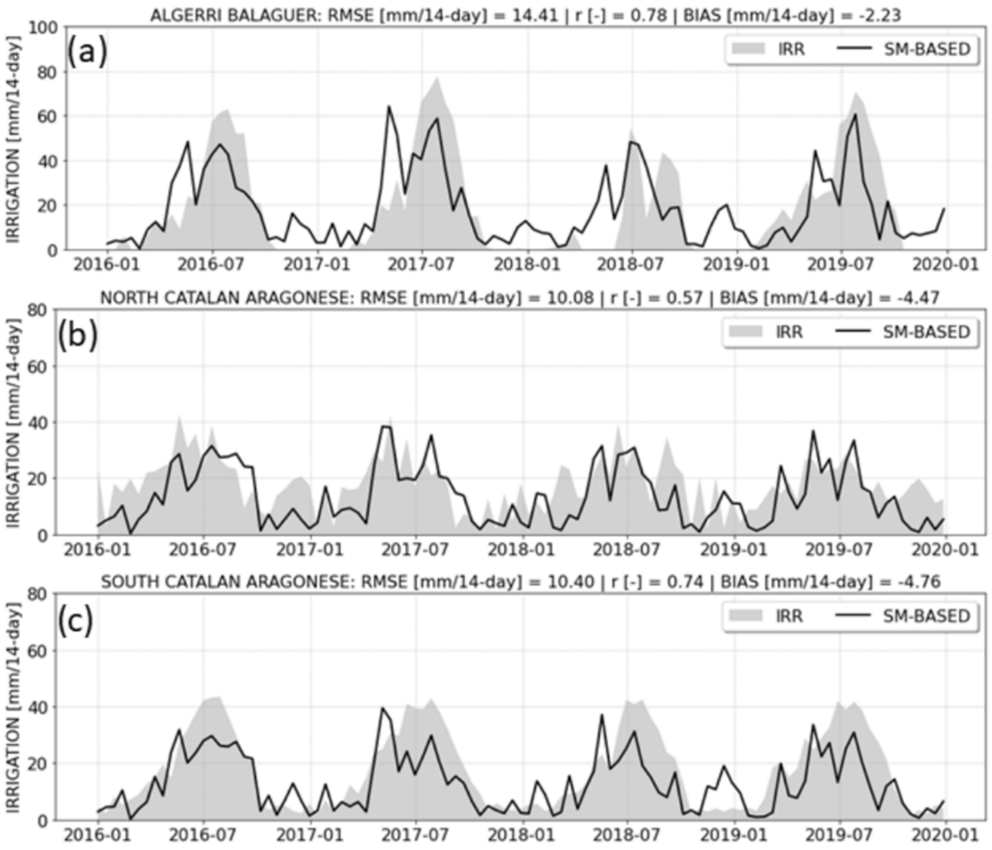
Correlation SM2Rain with gauge measurements, Northern Italy, Po catchment.

Filippucci et al. (2022) High-resolution (1 km) satellite rainfall estimation from SM2RAIN applied to Sentinel-1: Po River basin as a case study. Hydrology and Earth System Sciences, 26(9), 2481-2497.

Estimation of Irrigation

- Irrigation is estimated by comparing SM2Rain with observed rainfall



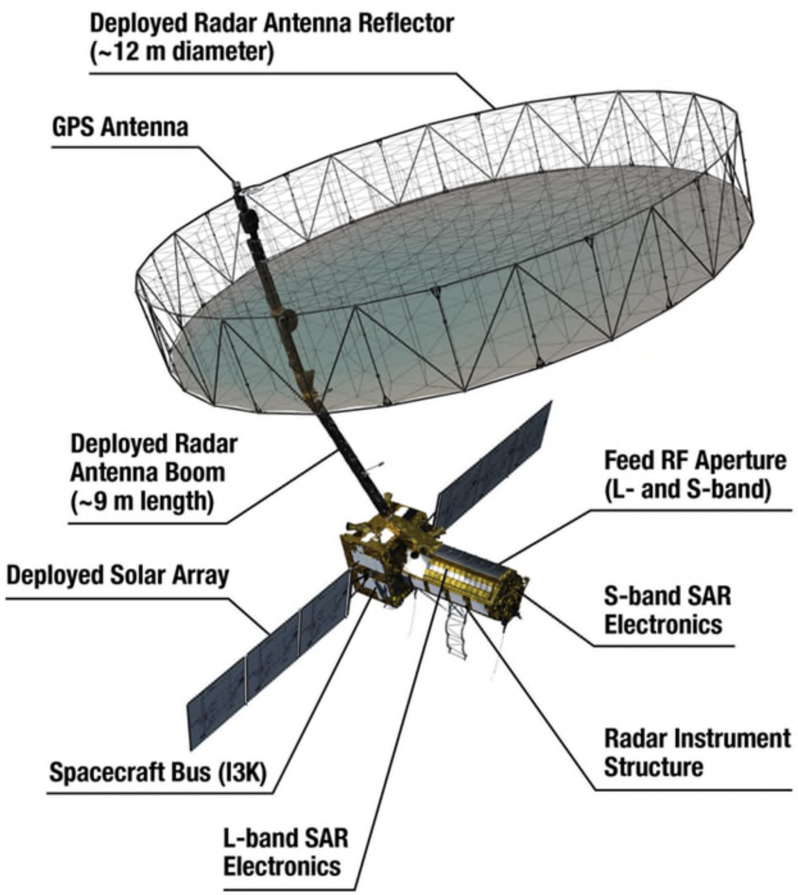


Ebro catchment, Spain

Dari et al. (2023) Regional data sets of high-resolution (1 and 6 km) irrigation estimates from space. Earth System Science Data, 15(4), 1555-1575.

Outlook

- The number of soil moisture products with a sampling of 1km or better is increasing
  - Many of these products are oversampled, i.e. only the sampling is fine but the effective spatial resolution (information) is much coarser
- SAR-only based soil moisture products are becoming operational for
  - Sentinel-1
  - NISAR (from 2024 onwards)
- The validation and application of SAR-only soil moisture products is an emerging research field



https://nisar.jpl.nasa.gov/

Acknowledgements

ESA: DTE Hydrology, 4DMED, Irrigation+ / EUMETSAT: H SAF / Copernicus: Global Land Monitoring Service / FFG: ROSSHINI, GHG-KIT / ADA: DrySat / CzechGlobe: SustES