Overview of Remote Sensing Soil Moisture Data Products

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Topics

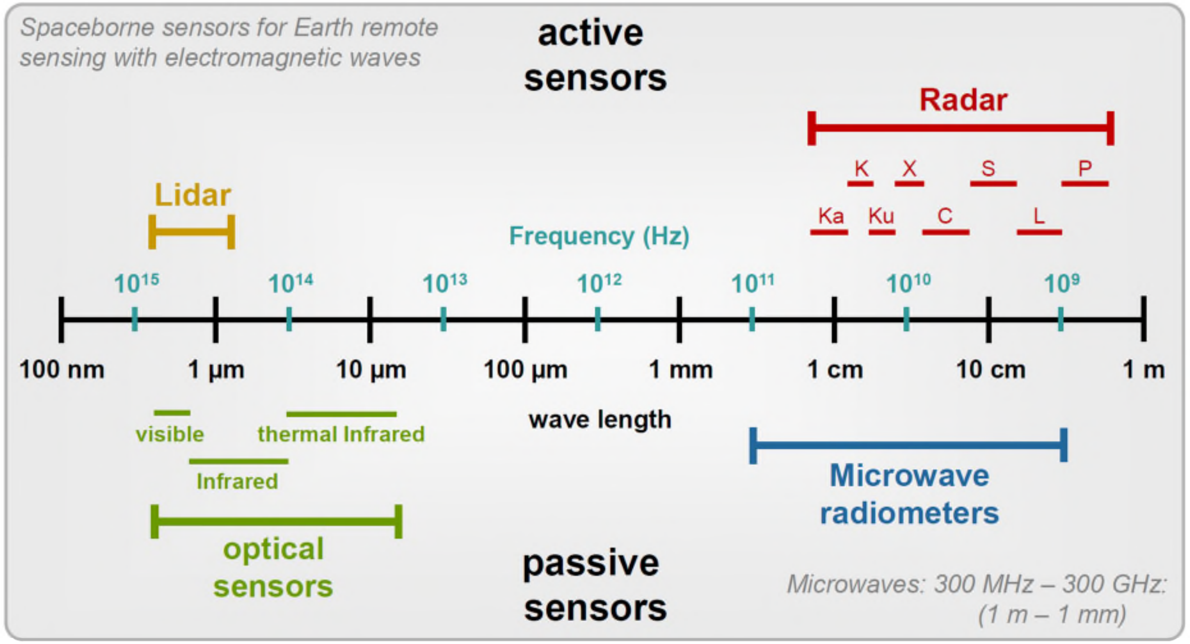
- Overview of Remote Sensing Soil Moisture Data Products Satellites and Sensors
  - Physical Basis
  - Microwave Satellites and Sensors
  - Soil Moisture Retrieval
  - Soil Moisture Data Products
  - Soil Water Index
- Use of CRNS/in situ Data for Validation of Remote Sensing Soil Moisture Products
  - Information Content of Satellite Data
  - Comparison to CRNS/in situ Data
- Applications of Remote Sensing Soil Moisture Data Products
  - Capturing Rainfall
  - Drought Monitoring
  - Other Applications

PHYSICAL BASIS

Approaches to Remote Sensing of Soil Moisture

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

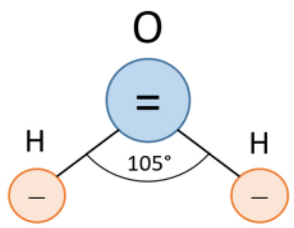
- Optical to Mid-Infrared (0.4 – 3 μm)
  - Change of “colour”
  - Water absorption bands at 1.4, 1.9 and 2.7 μm
- Thermal Infrared (7-15 μm)
  - Indirect assessment of soil moisture through its effect on the surface energy balance (temperature, thermal inertia, etc.)
- Microwaves (1 mm – 1 m)
  - Change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



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

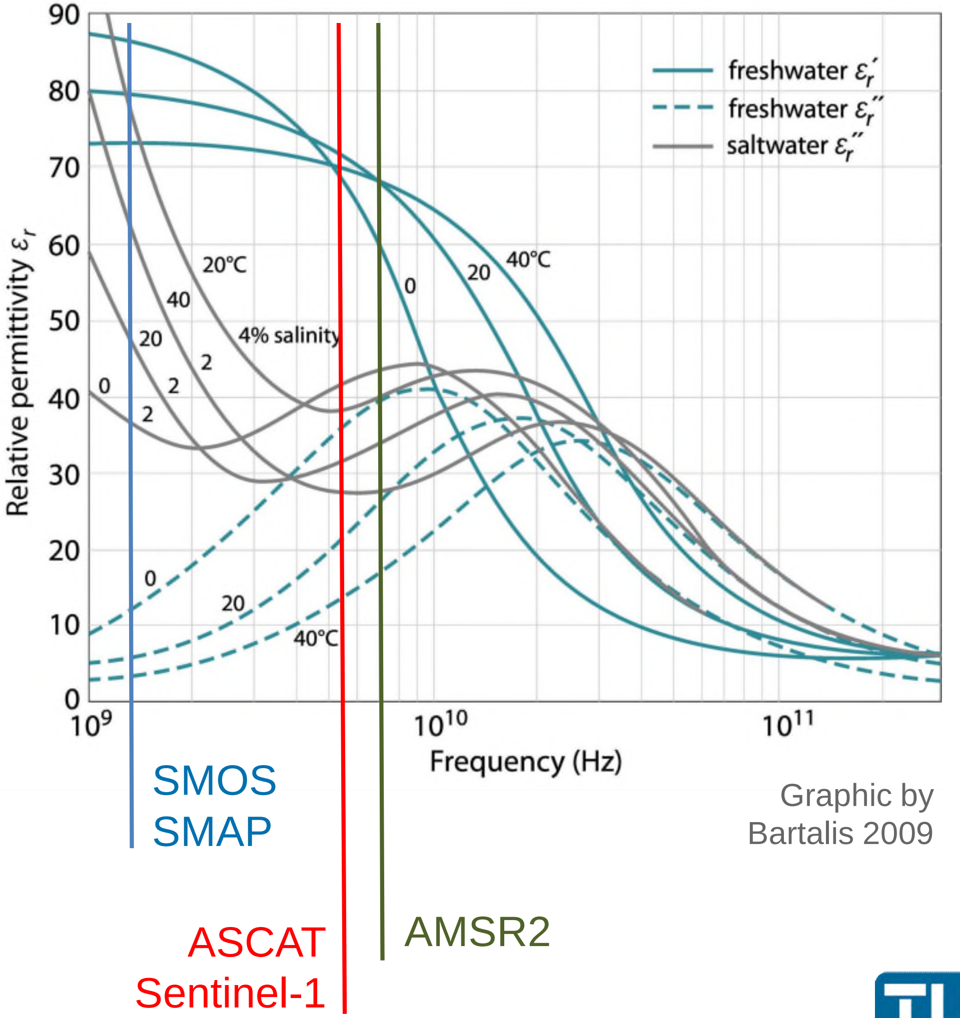
Microwaves

- All-weather, day-round measurement capability
- Microwave measurements are sensitive to
  - Geometric structure
    - Roughness
  - Dielectric properties
    - Water
- High penetration into vegetation and soils
  - Longer wavelengths beneficial
- Target quantities
  - Soil moisture
  - Vegetation water
  - Freeze/thawing
  - Surface water
  - Etc.



The dipole moment of water molecules causes "orientational polarisation", i.e. a high dielectric constant

Dielectric properties of water at microwave frequencies



Graphic by Bartalis 2009

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

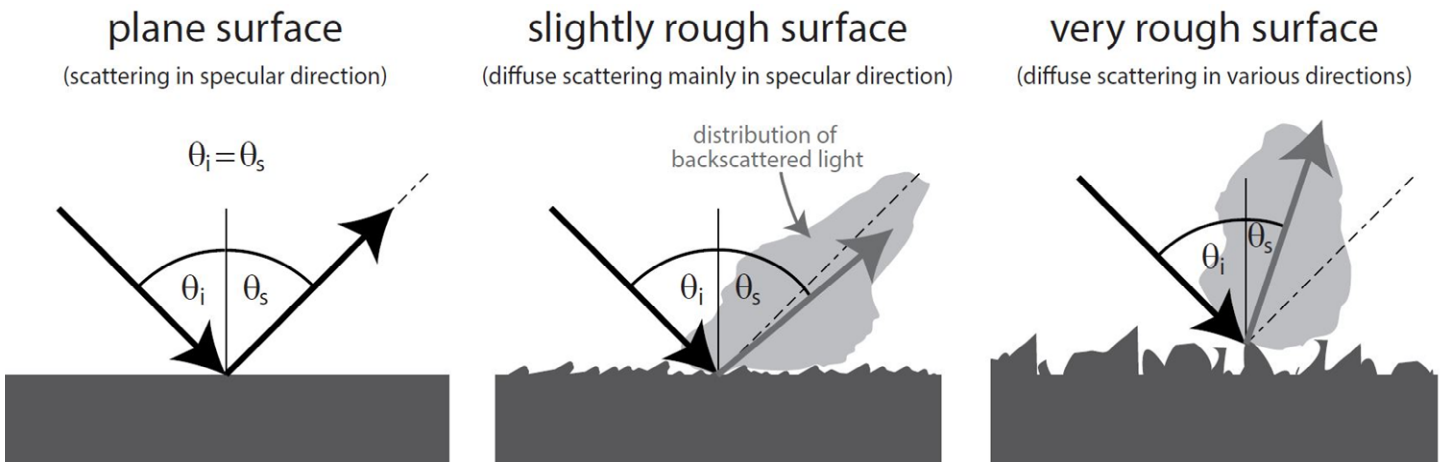
Passive Sensors

- 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 much better spatial resolution
- Despite these differences both active and passive sensors measure essentially the same variables:
  - Passive and active methods are interrelated through Kirchhoff's law: $e = 1 - r$ where r is the reflectivity

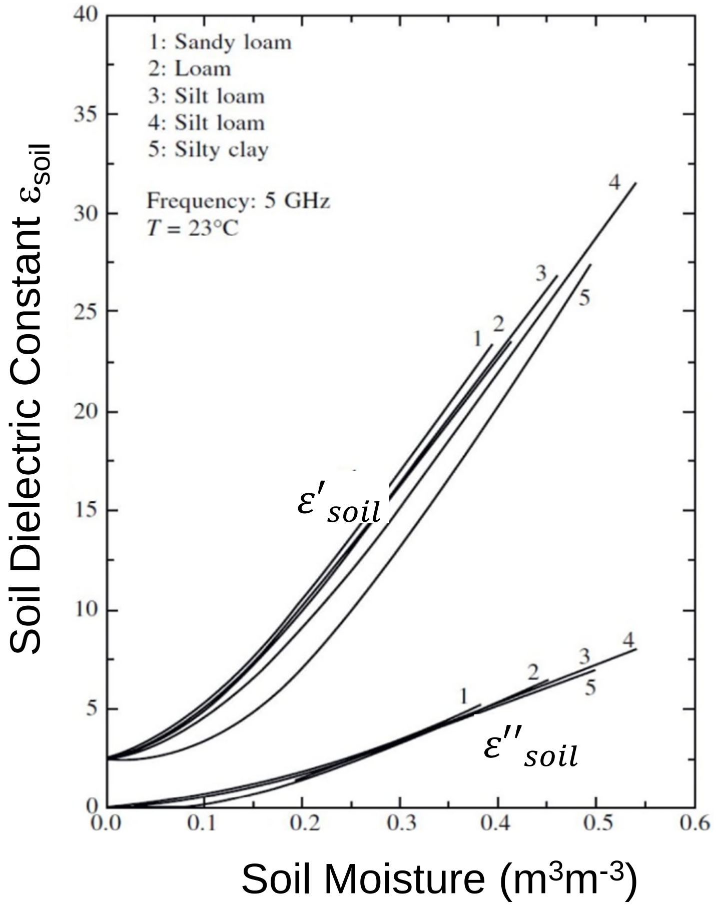
Soil Scattering

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

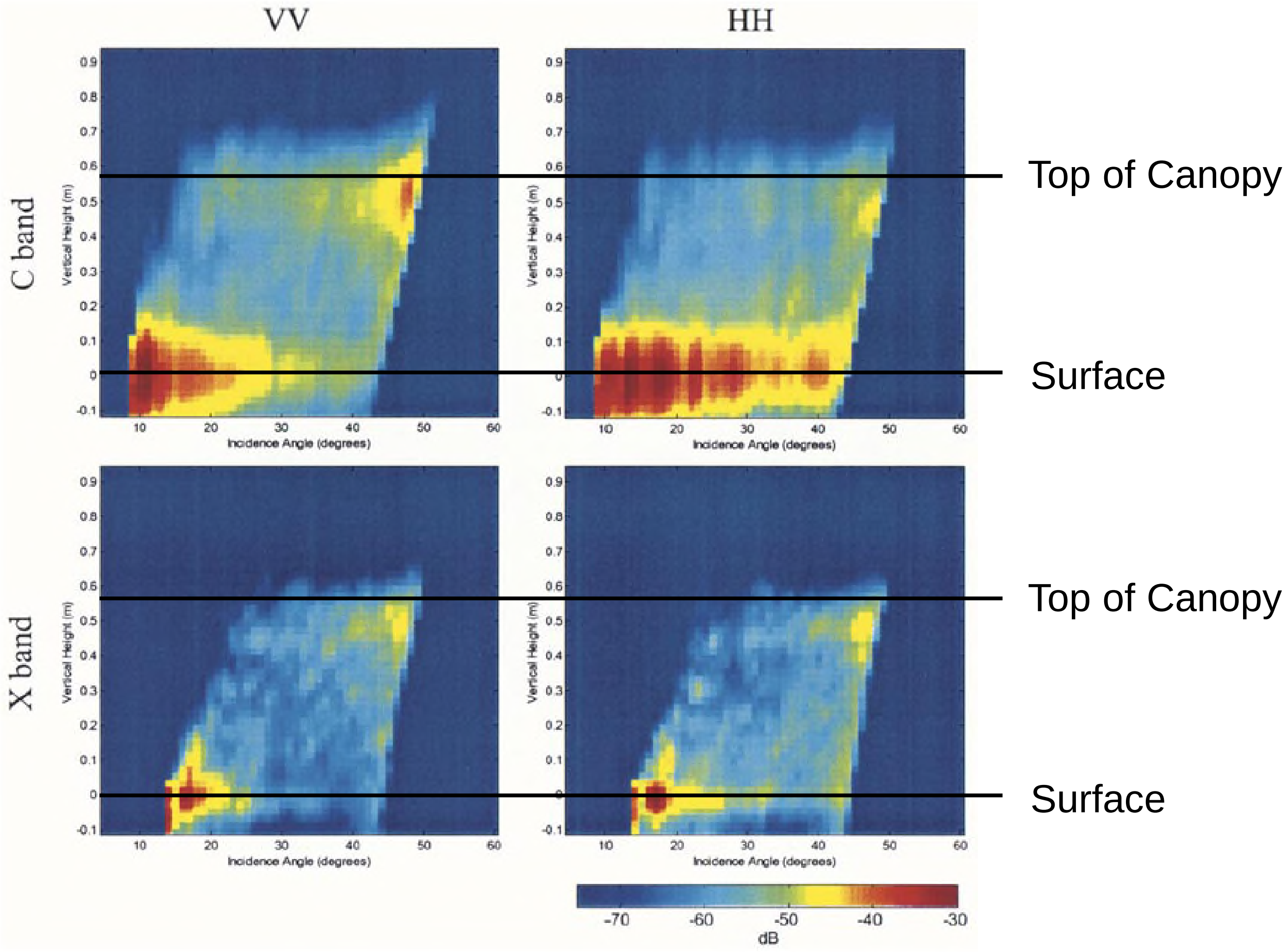


Graphic by R. Quast, TU Wien

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



Vegetation Scattering

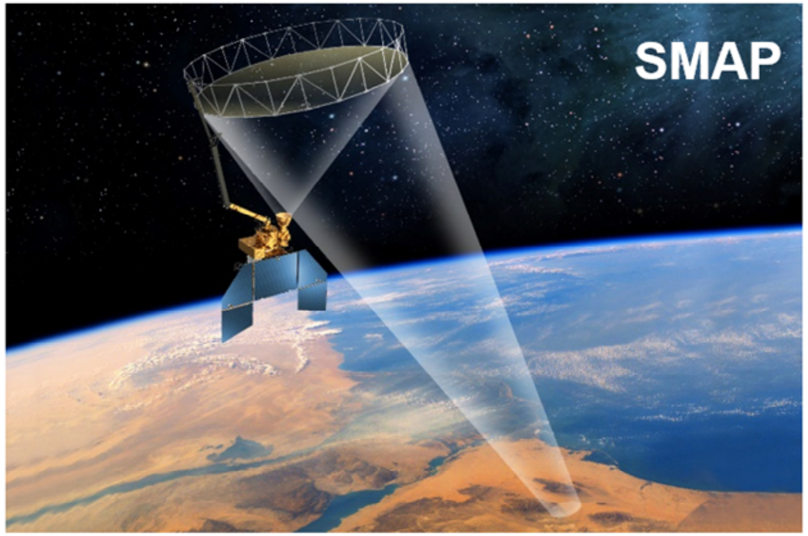


3D radar measurements of a 58 cm high wheat canopy

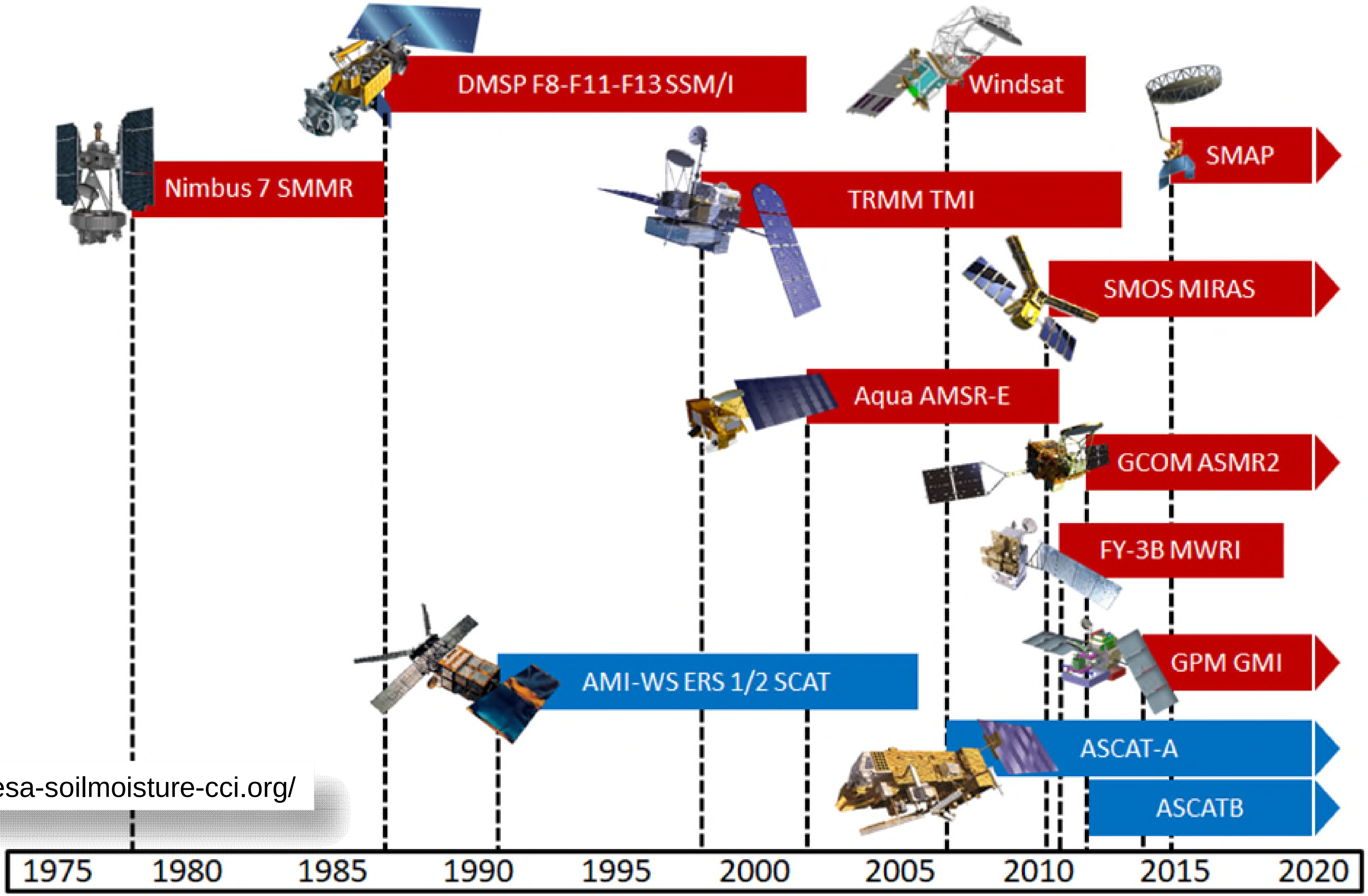
Brown et al. (2003) High-resolution measurements of scattering in wheat canopies - Implications for crop parameter retrieval
IEEE Transactions on Geoscience and Remote Sensing, 41(7), 1602-1610.

MICROWAVE SATELLITES & SENSORS

Satellites and Sensors for Soil Moisture Monitoring



Sensor Timeline



https://www.esa-soilmoisture-cci.org/

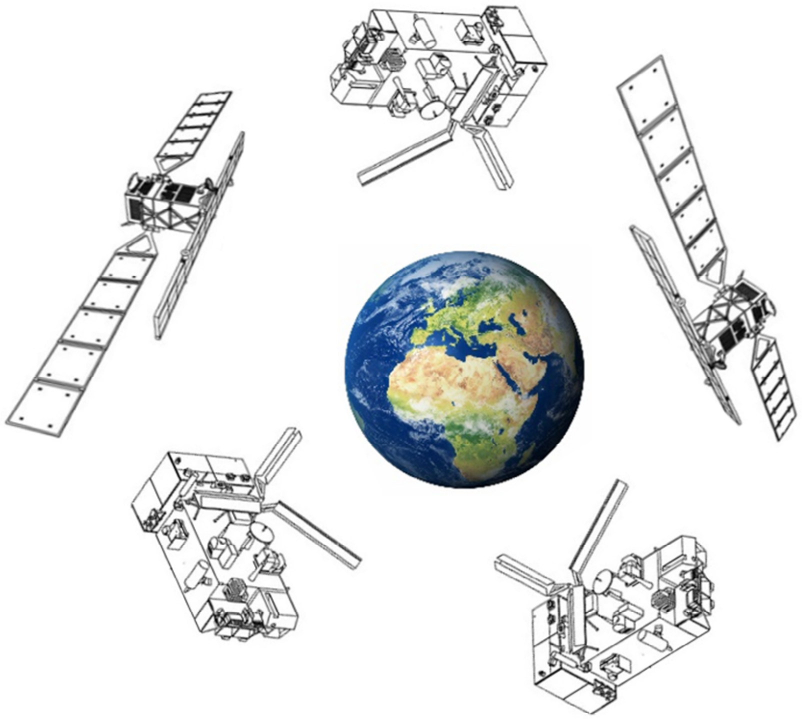
METOP ASCAT and Sentinel-1 SAR Constellations

METOP ASCAT

Frequency: 5.255 GHz
Polarisation: VV

Resolution: 25 km
Daily coverage: 82%

Satellites
METOP-A: 2006 ongoing
METOP-B: 2012 ongoing
METOP-C: 2018 ongoing



Sentinel-1 SAR IW

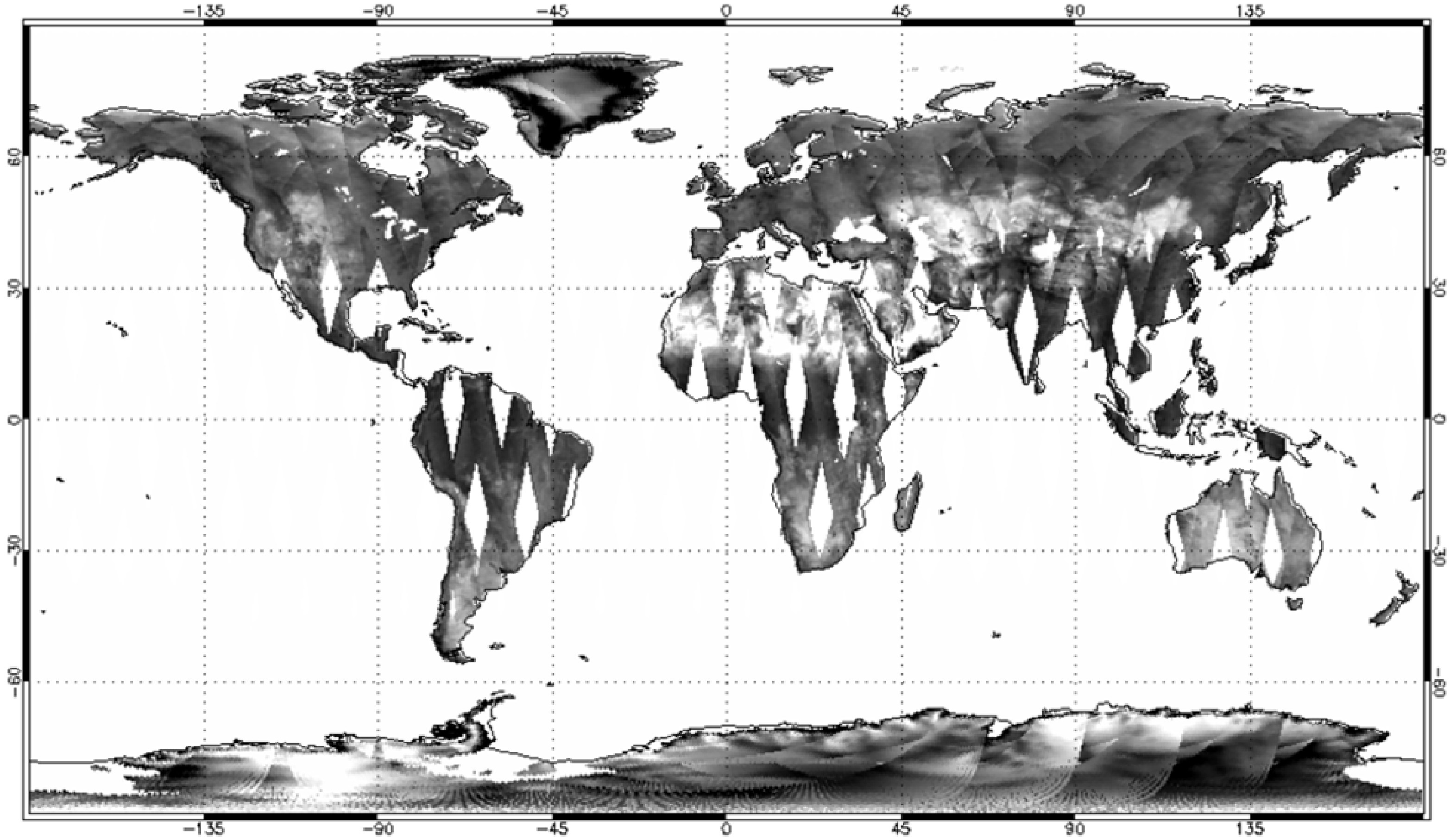
Frequency: 5.405 GHz
Polarisation: VV+VH

Resolution: 20 m
Repeat coverage: 3 – 12 days

Satellites
Sentinel-1A: 2014 ongoing
Sentinel-1B: 2016 ongoing

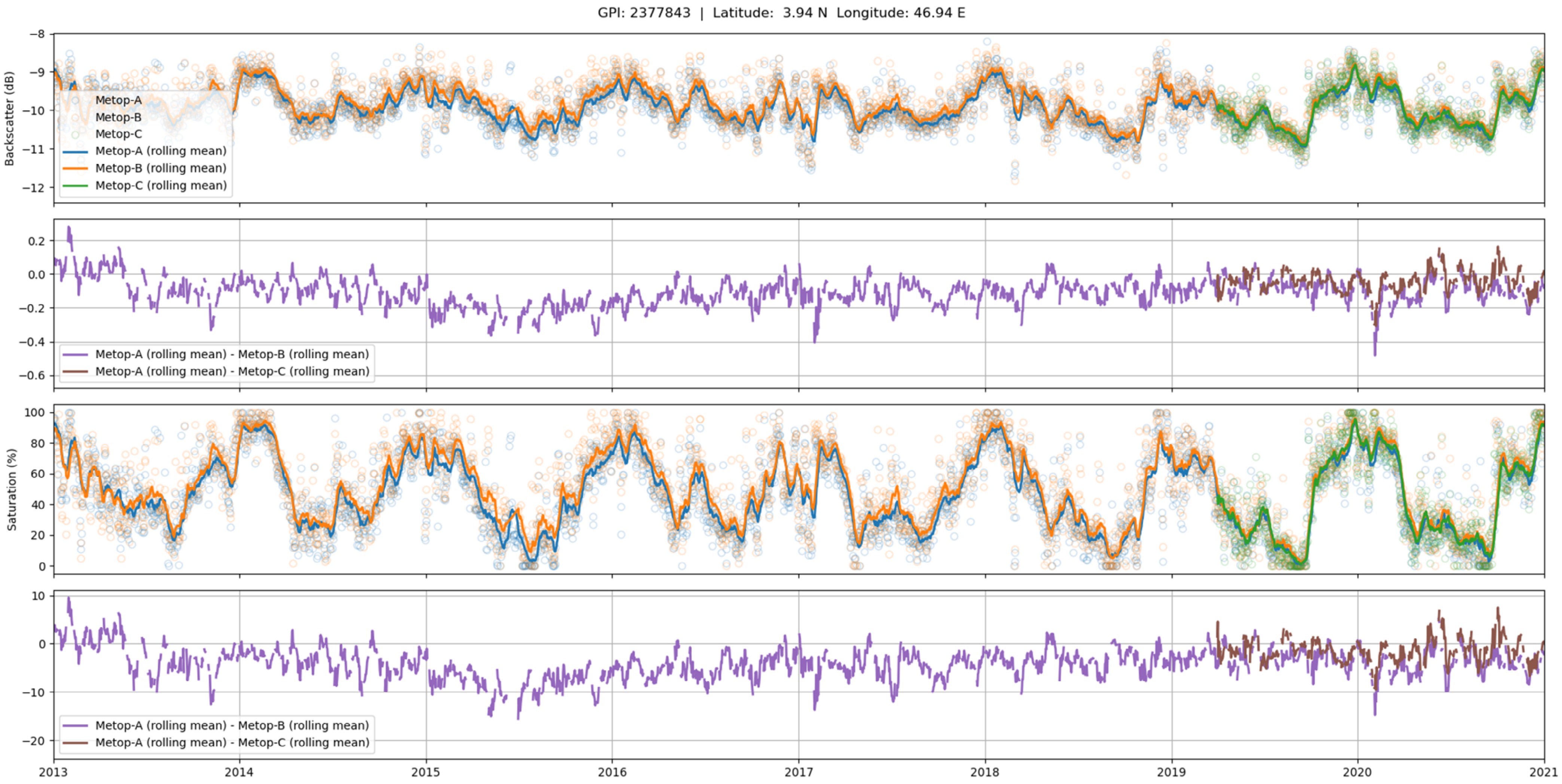
Spatio-Temporal Sampling of ASCAT

Daily global ASCAT coverage achieved by METOP-A and METOP-B constellation



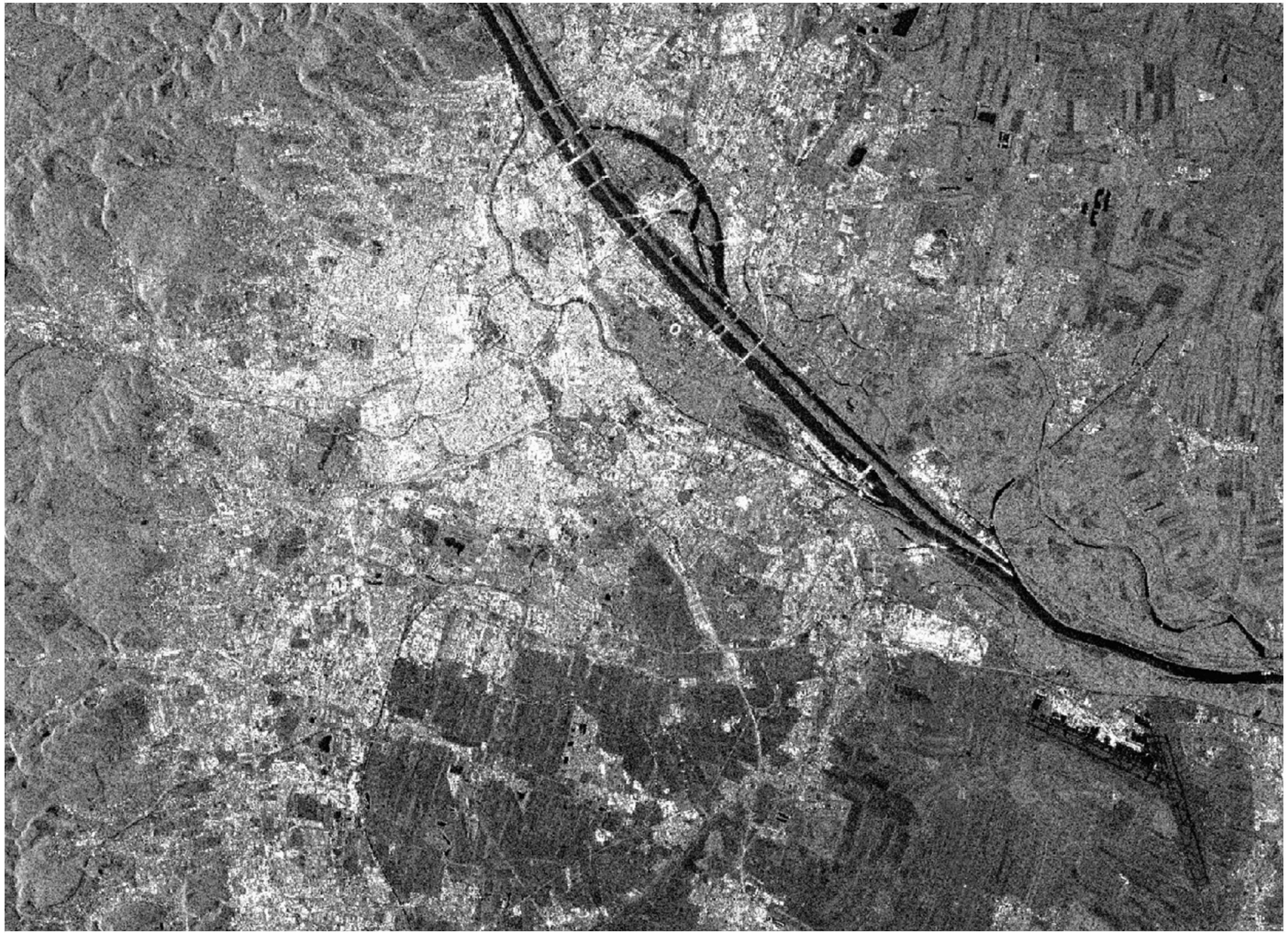
Wagner et al. (2013) The ASCAT soil moisture product: A review of its specifications, validation results, and emerging applications, Meteorologische Zeitschrift, 22(1), 5-33.

METOP-A/B/C Intercalibration



H119 Soil Moisture Data Record

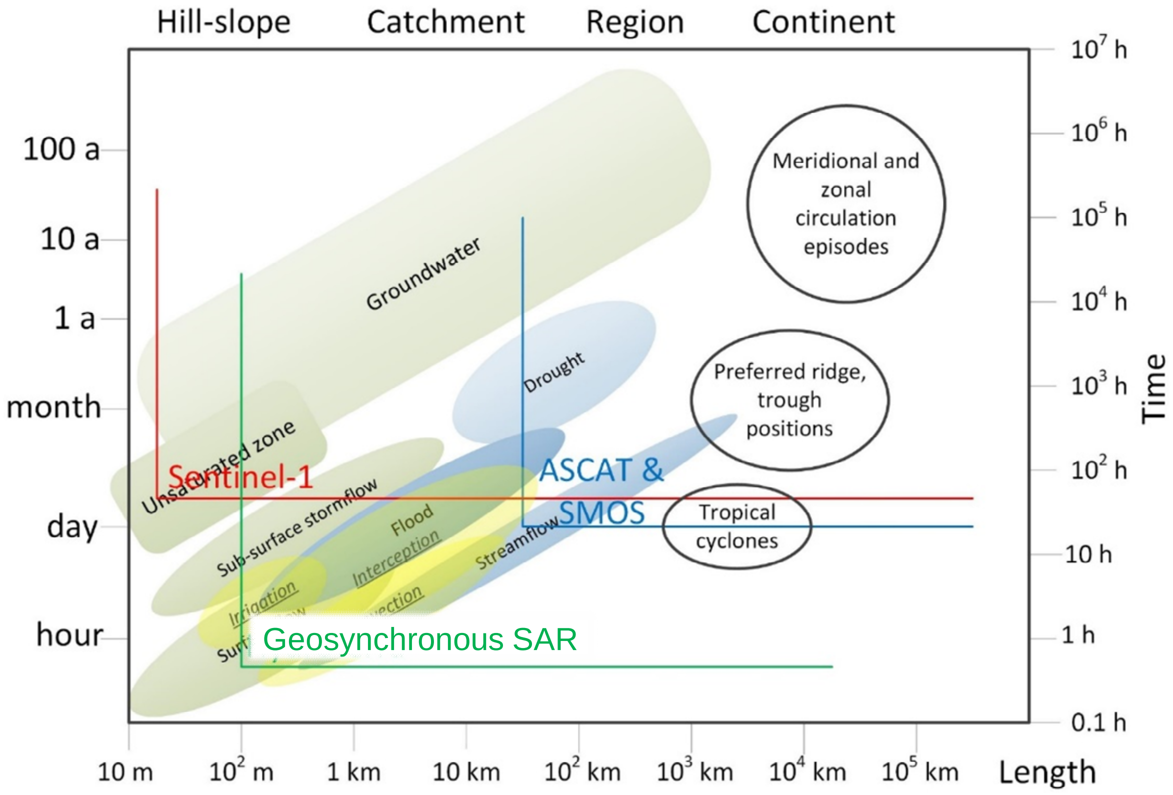
Spatial Resolution Sentinel-1

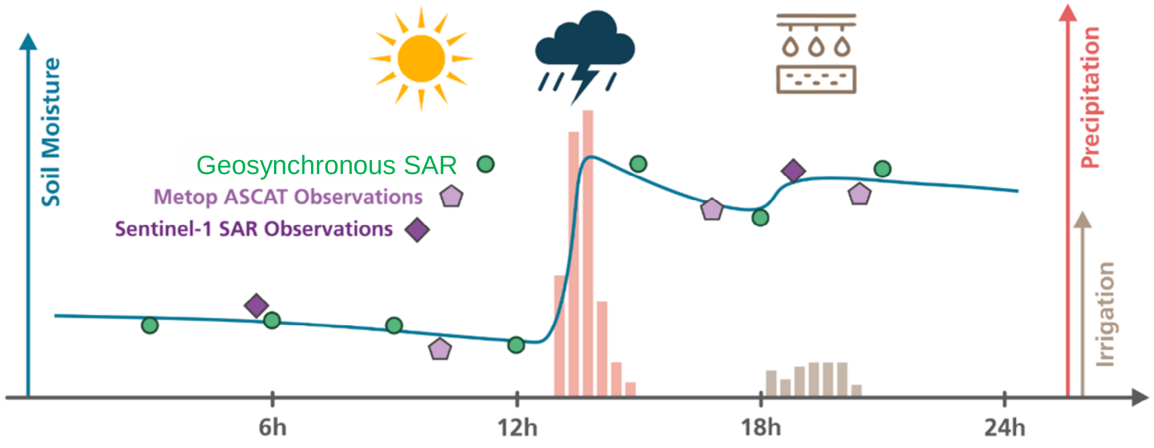


Sentinel-1 Image of Vienna 15/03/2015 Orbit 5045

Towards Improved Spatio-Temporal Monitoring

- By combing ASCAT and Sentinel-1 a much larger range of processes can be captured than using both sensor systems in isolation. Still, there are some “blind spots”

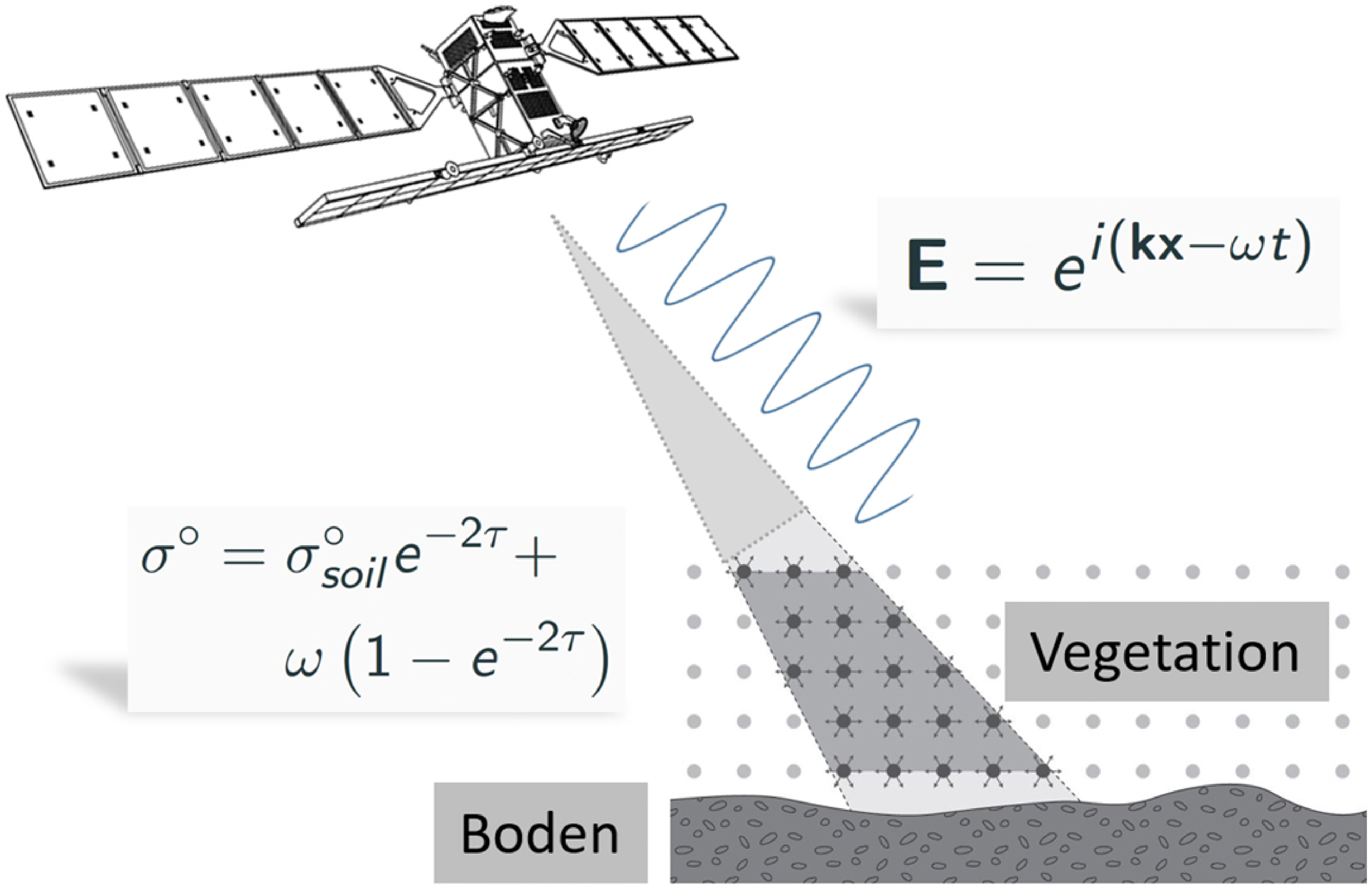




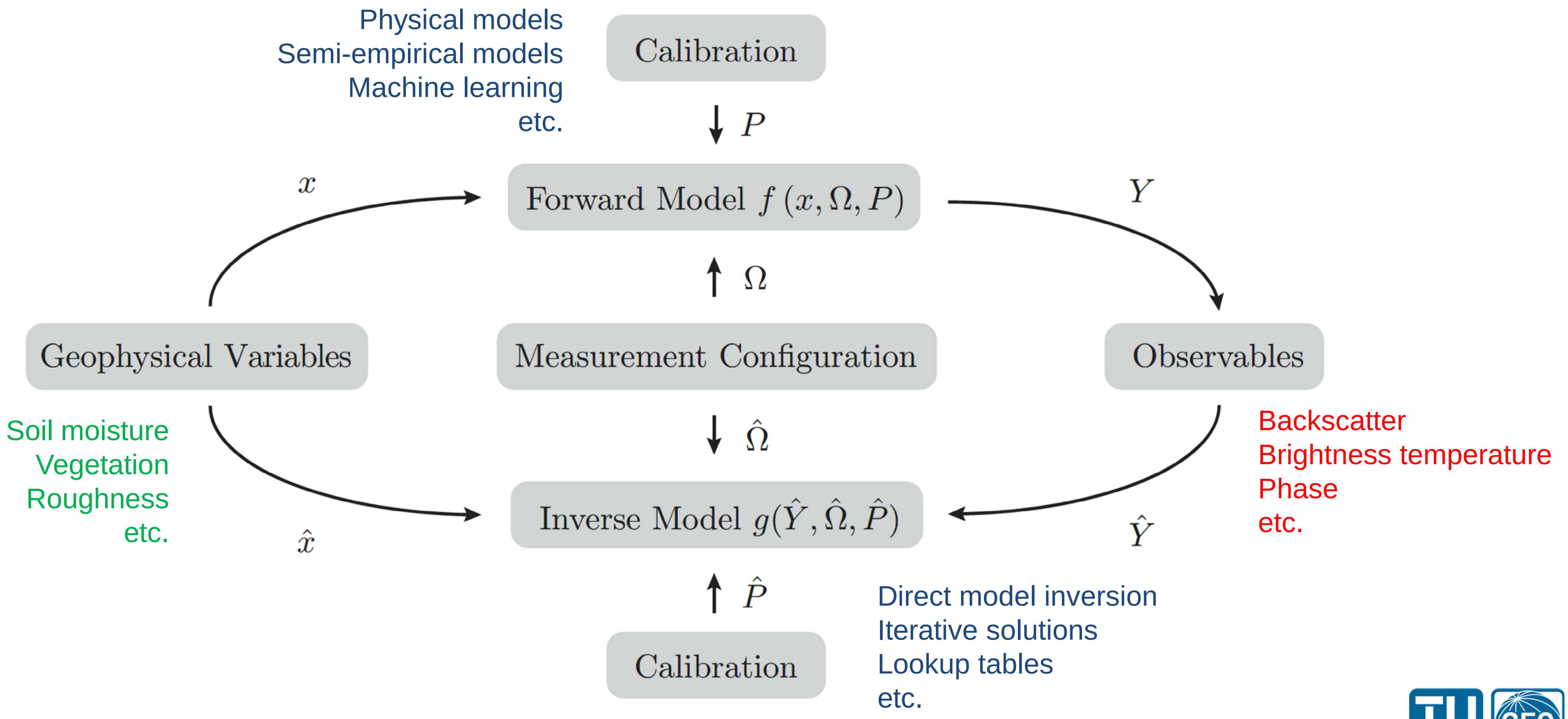
by Hydroterra Science Team
(based upon Stahl and Hisdal 2004)

SOIL MOISTURE RETRIEVAL

Problem Formulation

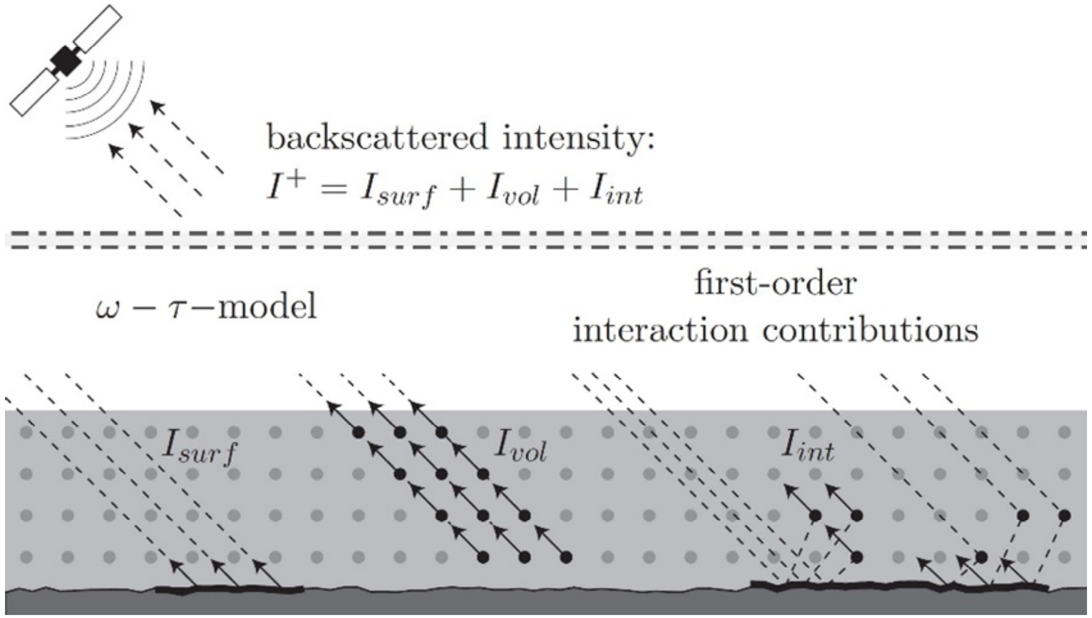


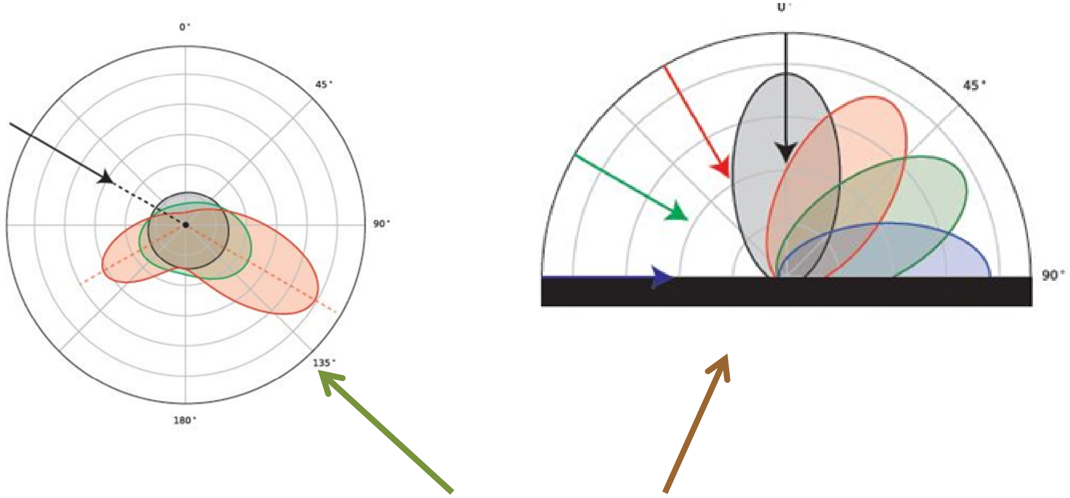
Geophysical Data Retrieval



Scattering of Microwaves by Vegetation and Soil

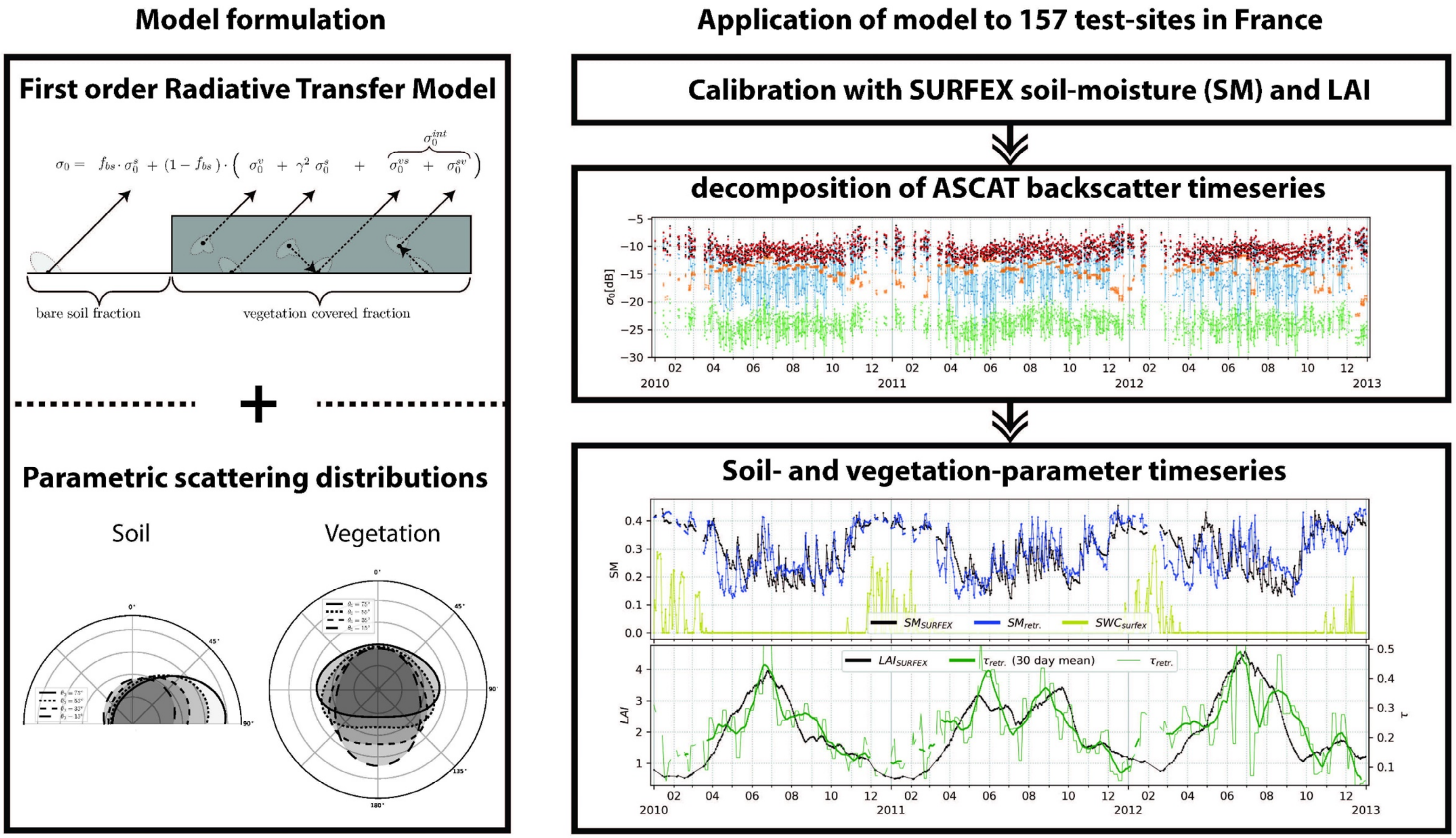
- Radiative transfer model for bi- and monostatic scattering
- Generalised phase functions for modelling surface-volume interactions
- Available on GitHub: https://github.com/TUW-GEO/rt1





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

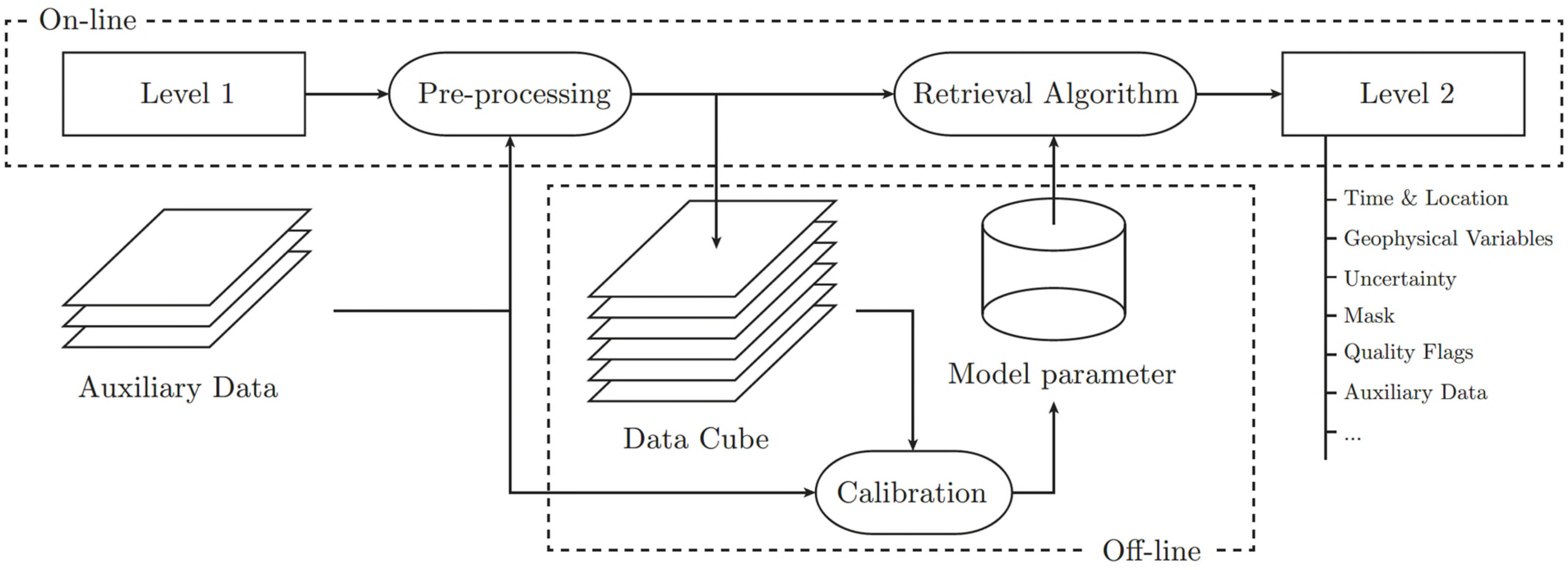
Quast et al. (2019) A generic first-order Radiative Transfer modelling approach for the inversion of soil- and vegetation parameters from scatterometer observations, Remote Sensing, 11, 285, 24p.



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.

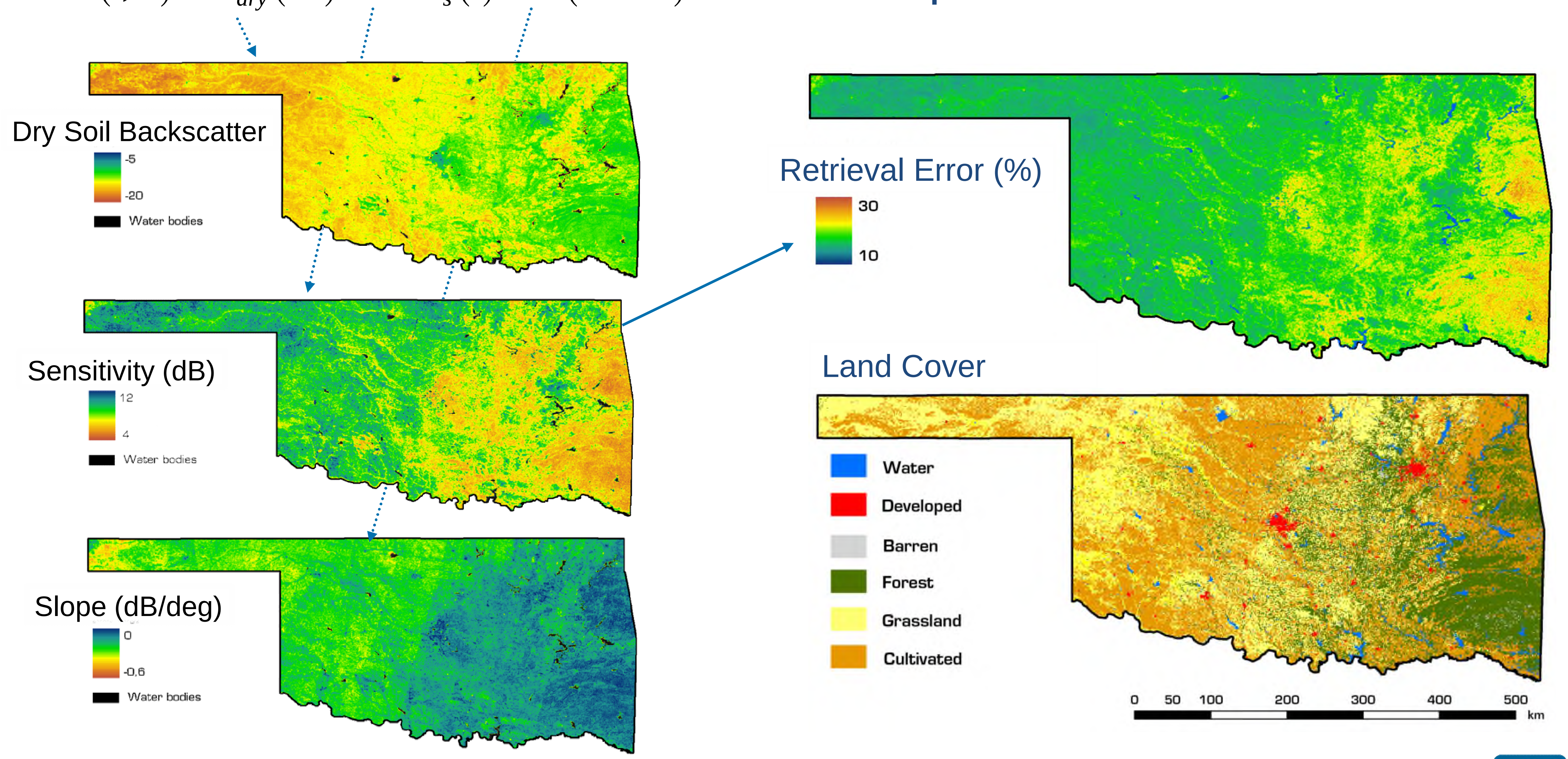
Need to Calibrate EO Data Models

- No EO data model used for retrieving higher-level data is perfect
  - Physical, semi-empirical, empirical/statistical models, machine learning/AI
- Calibration is needed
  - Model calibration is a difficult process requiring historic EO data, ancillary data and procedures for model parameter selection



Simplified Backscatter Model

$$\sigma^0(t,\theta) = \sigma^0_{dry}(30) + S \cdot m_s(t) + \sigma'(\theta - 30)$$

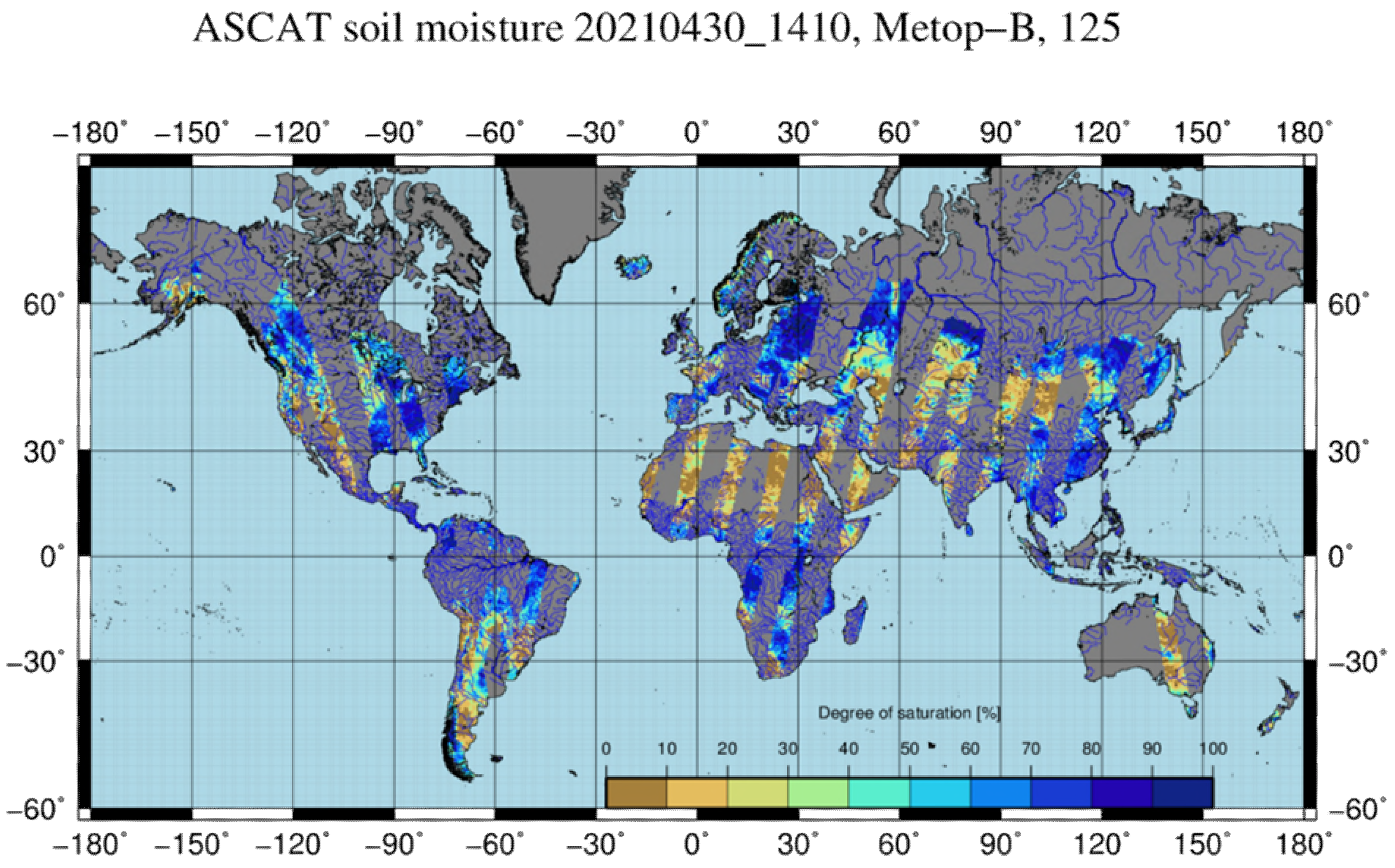


Pathe et al. (2009) Using ENVISAT ASAR Global Mode data for surface soil moisture retrieval over Oklahoma, USA, IEEE Trans. Geoscience and Remote Sensing, 47(2), 468-480.

SOIL MOISTURE DATA PRODUCTS

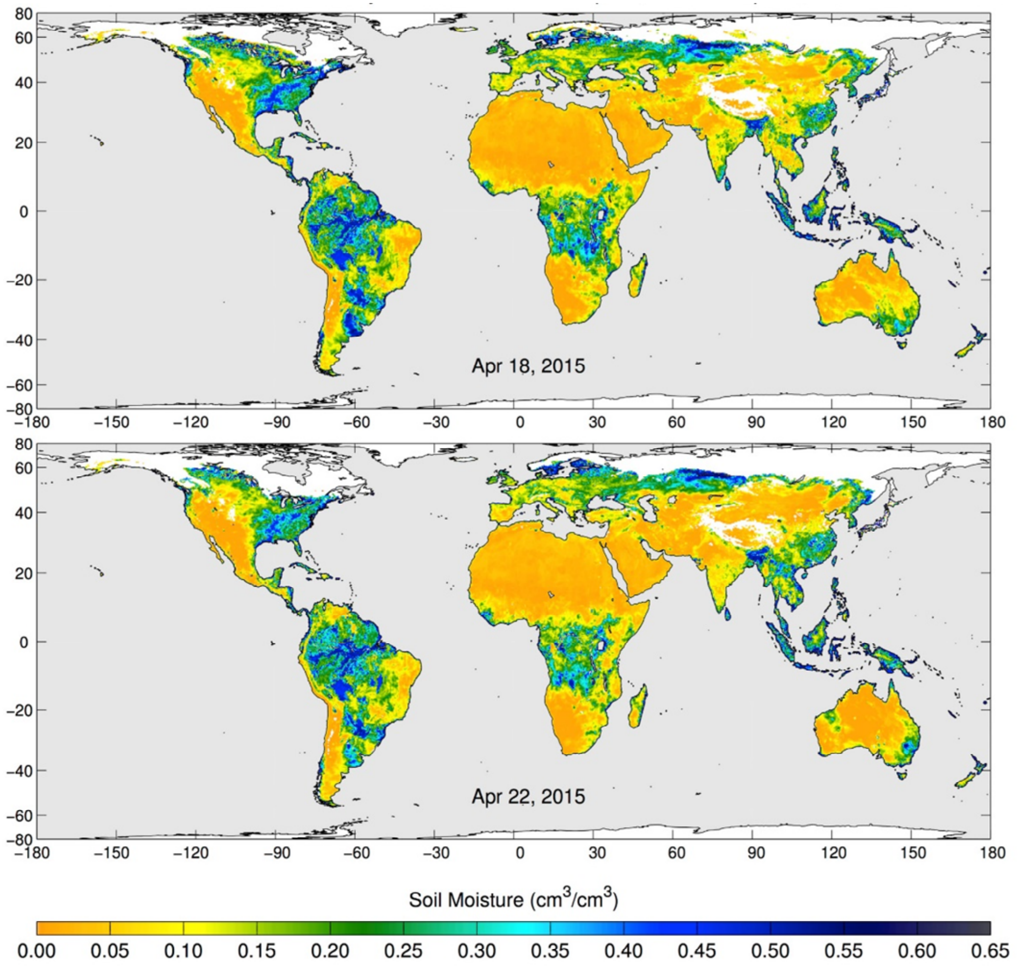
Satellite / Product	Temp. Cov.	Temp. res.	Latency	Spatial sampling	Spatial coverage	Organisation	Access
ESA CCI SSM	1978-	1-2 d	Year	0.25°	Global	ESA	Free
C3S SSM	1978	10 d	10d	0.25°	Global	Copernicus	Free
H SAF ASCAT SSM CDR	2007-	1-2 d	Year	12.5 km	Global	EUMETSAT H SAF	Free
H SAF ASCAT SSM NRT	2007-	1-2 d	1 d	12.5 km	Global	EUMETSAT H SAF	Free
CGLS ASCAT SWI	2007-	Daily	3 d	0.1°	Global	CGLS	Free
SMOS L2 SSM	2010-	1-2 d	1 d	36 km	Global	ESA	Free
SMAP L3 SSM	2015-	1-2 d	1 d	36 km	Global	NASA	Free
SMAP L4 RZSM	2015-	Daily	7 d	9 km	Global	NASA	Free
CGLS S-1 SSM	2015-	3-24 d	1 d	0.5 km	Europe	CGLS	Free
CGLS SCATSAR SWI	2015-	1-2 d	3 d	0.5 km	Europe	CGLS	Free
VanderSat	2002-	Daily		100m	request	VanderSat	Paid

25 km ASCAT Surface Soil Moisture



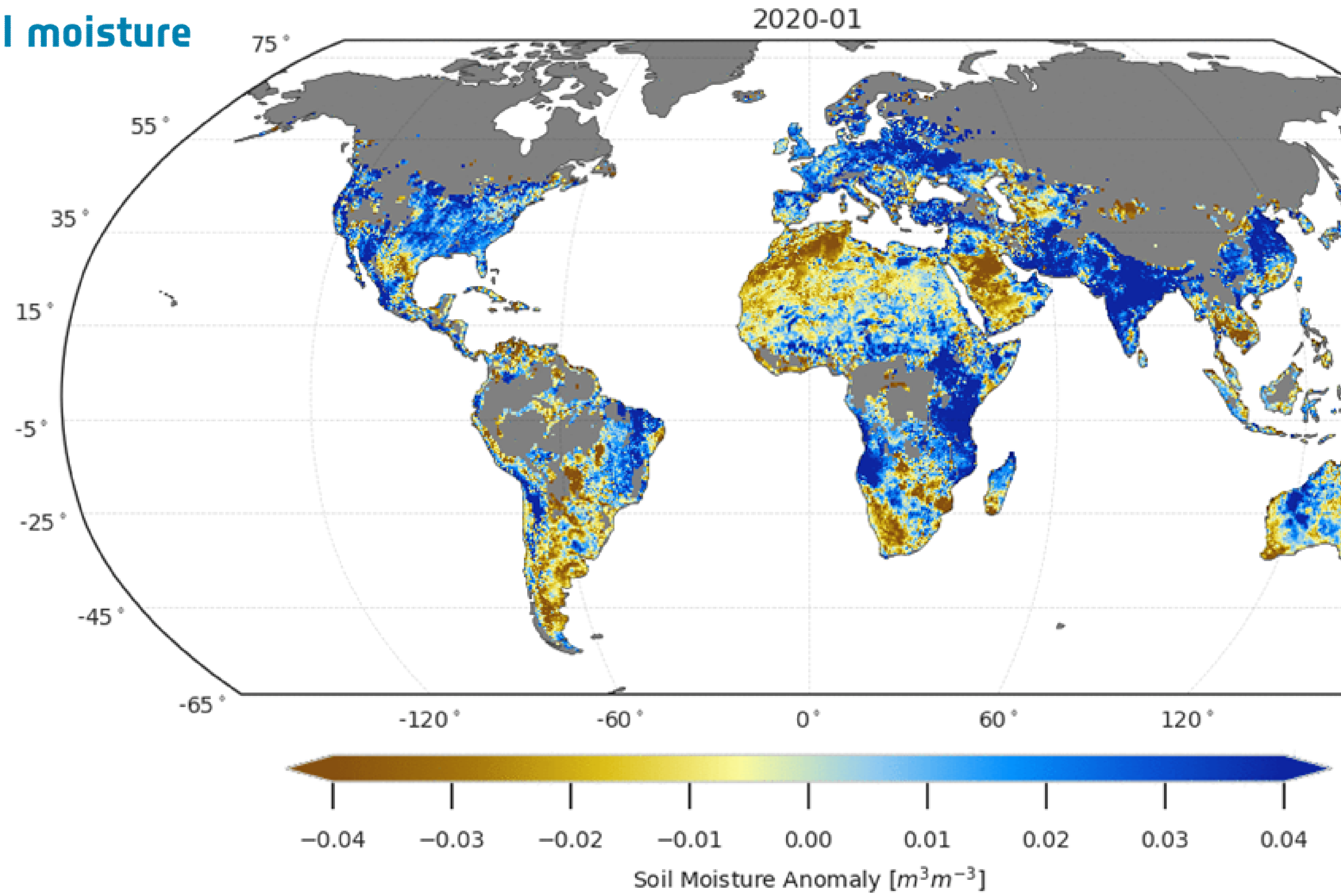
SMAP Data Products

Product Type	Product description	Gridding (resolution)	Granule Extent
L1A_Radar	Parsed SMAP Radar Telemetry (start-July 7, 2015)		Half Orbit
L1B_S0_LoRes	Low resolution radar sigma0 in time order (start-July 7, 2015)	5x30 km	Half Orbit
L1C_S0_HiRes	High resolution radar sigma0 on Swath Grid (start-July 7, 2015)	1 km	Half Orbit
L1A_Radiometer	Parsed Radiometer Telemetry		Half Orbit
L1B_TB	Geolocated, calibrated brightness temperature in time order	36 km	Half Orbit
L1B_TB_E	Backus-Gilbert interpolated, calibrated brightness temperature in time order	9 km	Half Orbit
L1C_TB	Geolocated, calibrated brightness temperature on EASE2 grid	36 km	Half Orbit
L1C_TB_E	Backus-Gilbert interpolated, calibrated brightness temperature on EASE2 grid	9 km	Half Orbit
L2_SM_A	Radar soil moisture (start-July 7, 2015)	3 km	Half Orbit
L2_SM_P	Radiometer soil moisture	36 km	Half Orbit
L2_SM_P_E	Radiometer soil moisture	9 km	Half Orbit
L2_SM_AP	SMAP active-passive soil moisture	9 km	Half Orbit
L2_SM_SP	SMAP radiometer/Copernicus Sentinel-1 soil moisture	3 km	Sentinel-1
L3_SM_P	Daily global composite radiometer soil moisture	36 km	Daily - Global
L3_SM_P_E	Daily global composite radiometer soil moisture	9 km	Daily - Global
L3_FT_A	Daily global composite radar freeze/thaw state (start-July 7, 2015)	3 km	Daily – North of 45 deg N
L3_SM_A	Daily global composite radar soil moisture (start-July 7, 2015)	3 km	Daily - Global
L3_SM_AP	Daily global composite active passive soil moisture (start-July 7, 2015)	9 km	Daily - Global
L3_FT_P	Daily composite freeze/thaw state	36 km	Daily - Global
L3_FT_P_E	Daily composite freeze/thaw state	9 km	Daily - Global
L4_SM	Surface and Root Zone soil moisture	9 km	3 hours - Global
L4_C	Carbon Net Ecosystem Exchange	9 km	Daily – North of 45 N
L1B_TB_NRT	Near Real Time Geolocated, calibrated brightness temperature in time order	36 km	Half Orbit
L2_SM_P_NRT	Near Real Time Radiometer soil moisture	36 km	Half Orbit



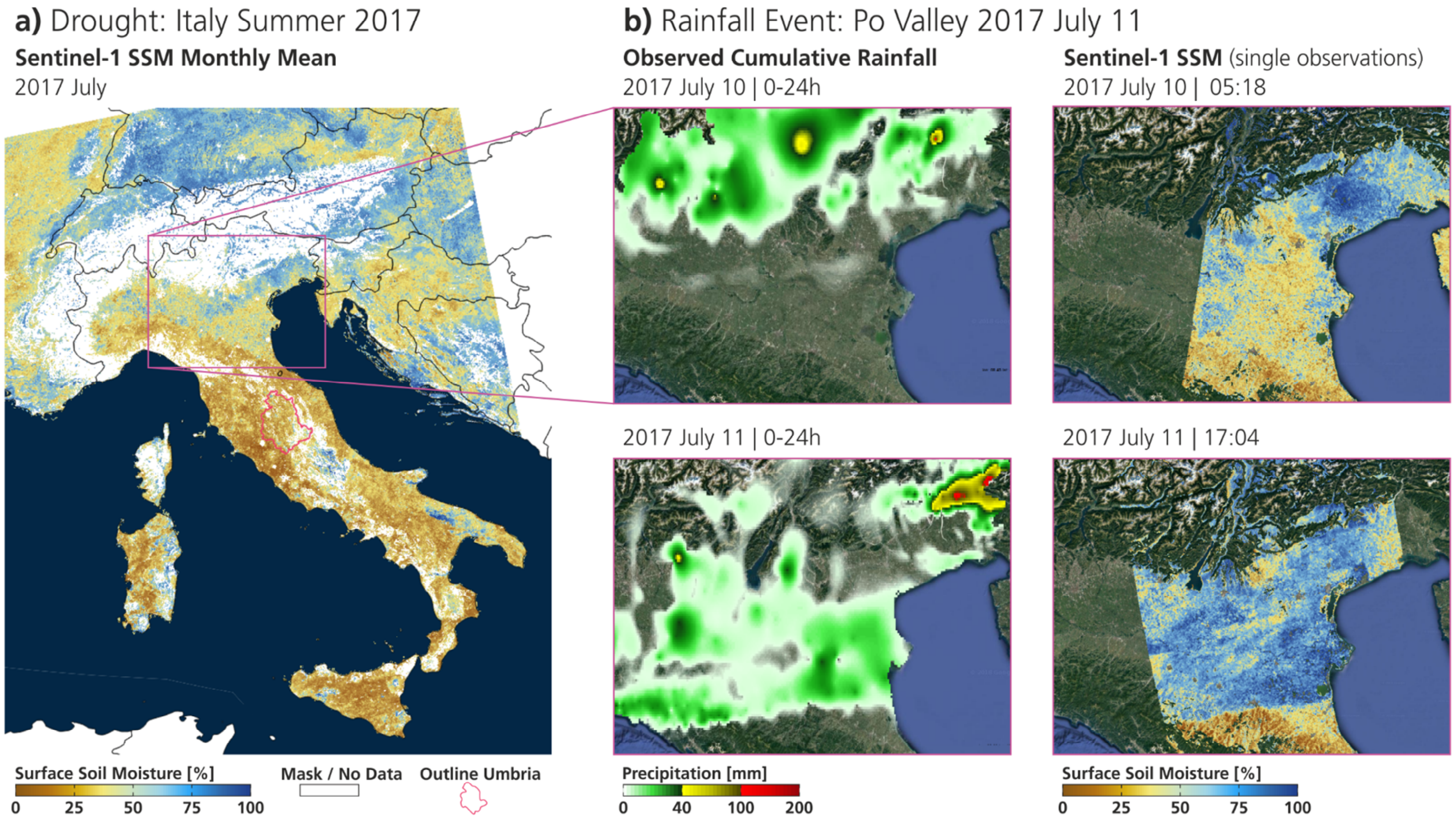
https://smap.jpl.nasa.gov/

ESA CCI Merged Active-Passive Soil Moisture Data Set

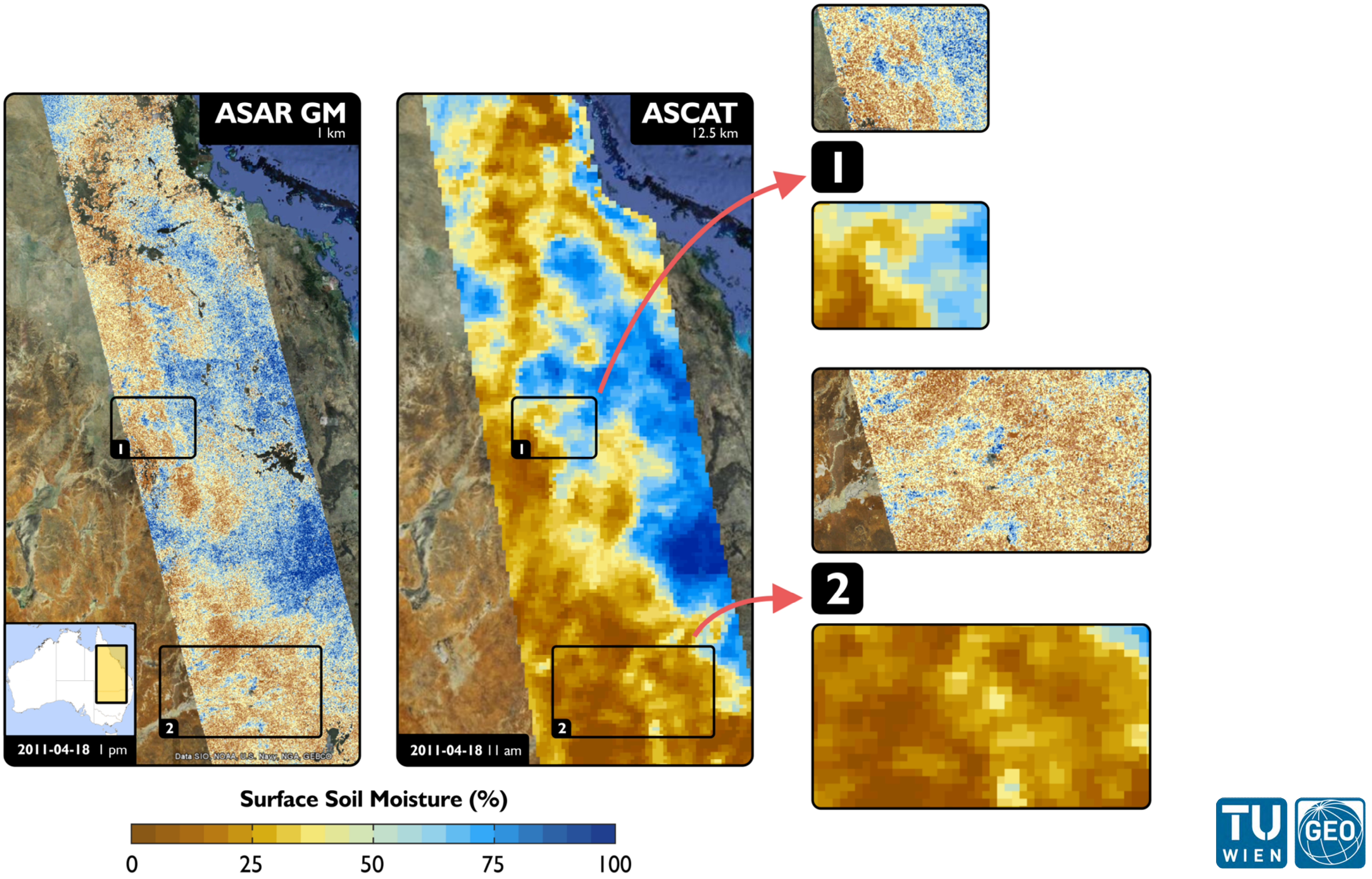


https://www.esa-soilmoisture-cci.org/

1 km Sentinel-1 Surface Soil Moisture



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.


ASAR GM
1 km
ASCAT
12.5 km
1
2
2011-04-18 1 pm
2011-04-18 11 am
Surface Soil Moisture (%)
0
25
50
75
100
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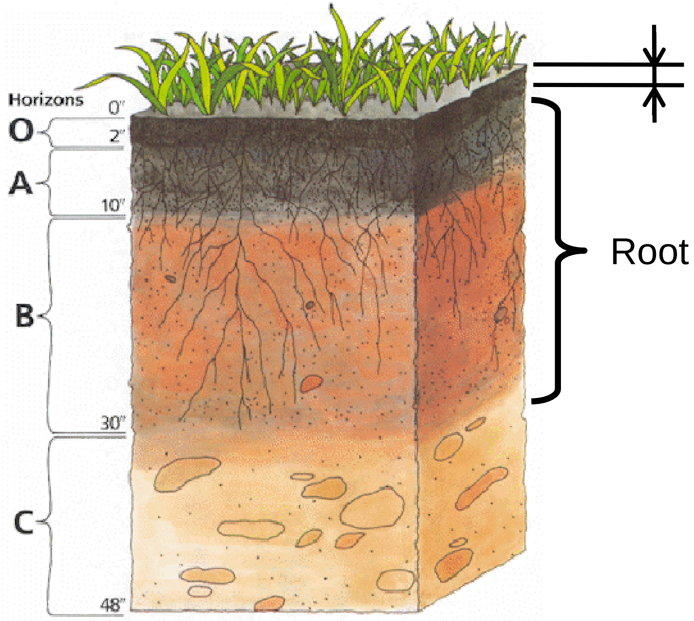
SOIL WATER INDEX

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

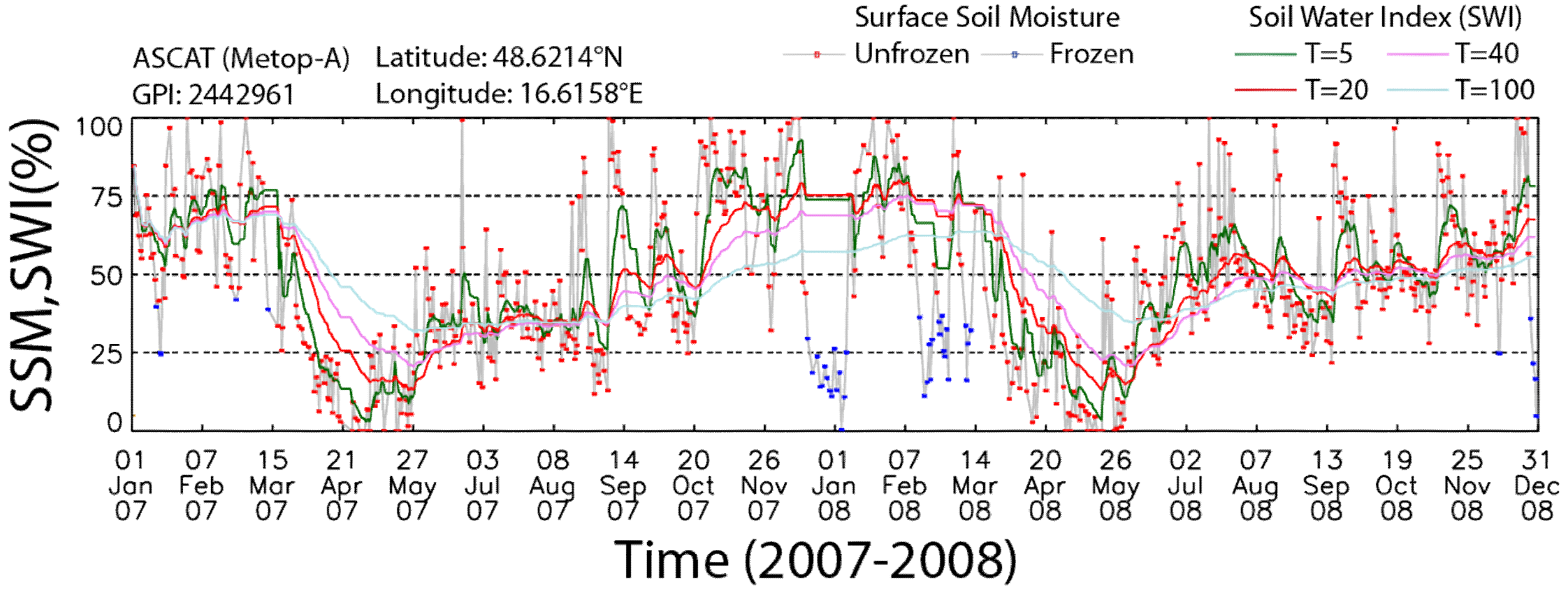
Wagner, W., G. Lemoine, H. Rott (1999) A Method for Estimating Soil Moisture from ERS Scatterometer and Soil Data, Remote Sensing of Environment, 70, 191-207.

TU WIEN GEO

Soil Water Index

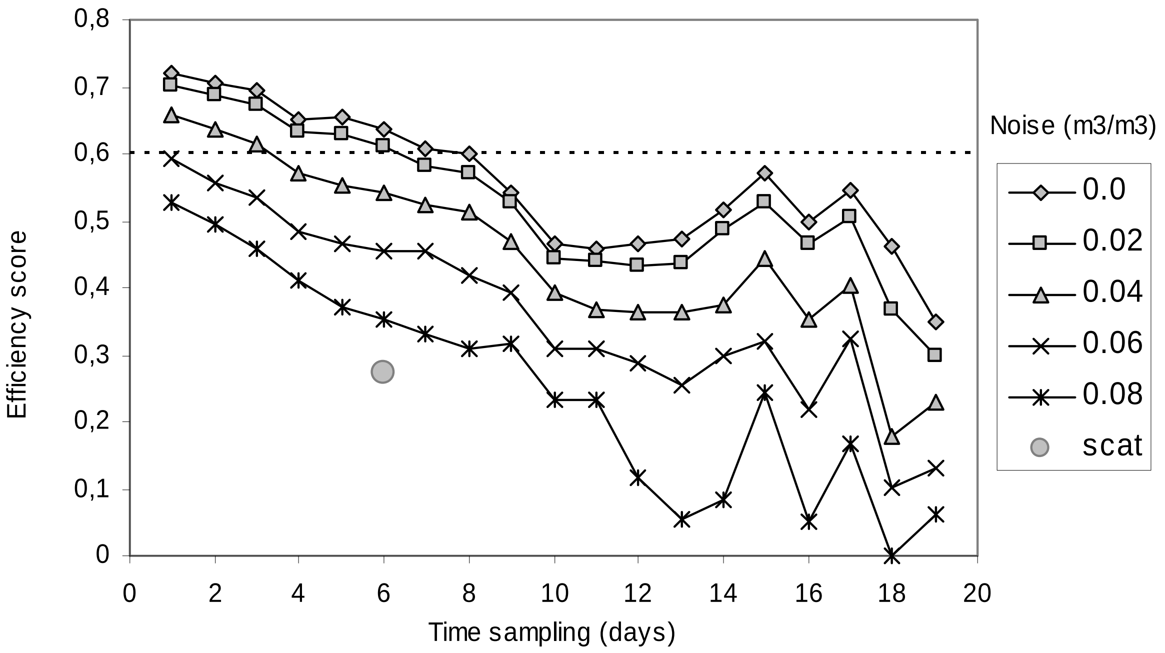
- Discrete version of convolution integral

$$SWI(t) = \frac{\sum_i \Theta_s(t_i) e^{-\frac{t-t_i}{T}}}{\sum_i e^{-\frac{t-t_i}{T}}}$$



Quality of SWI

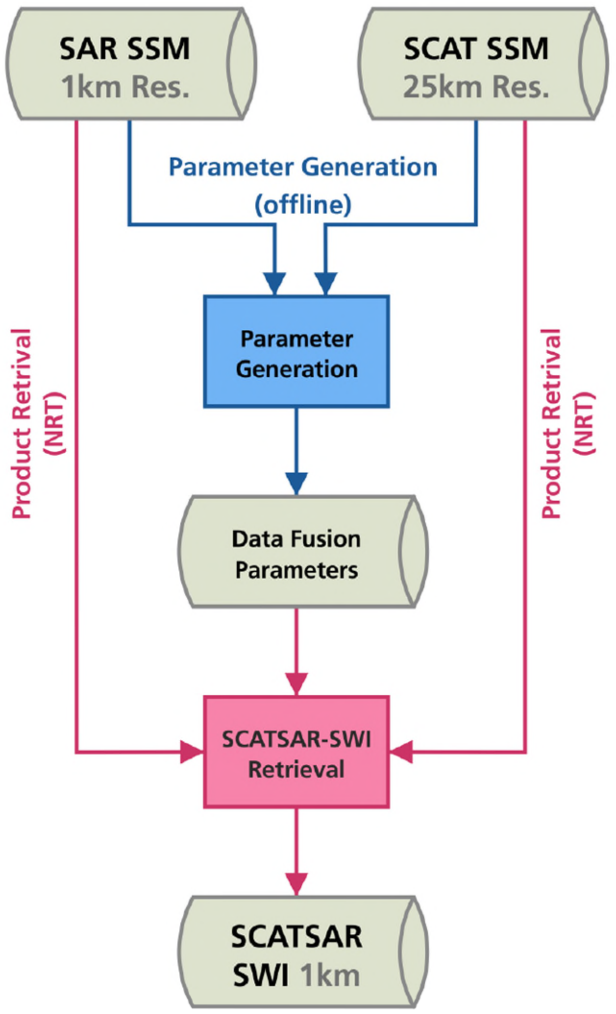
- The quality of SWI depends critically upon
  - Density of time series
  - Regular sampling
  - Removal of erroneous data (frozen and snow covered soil)

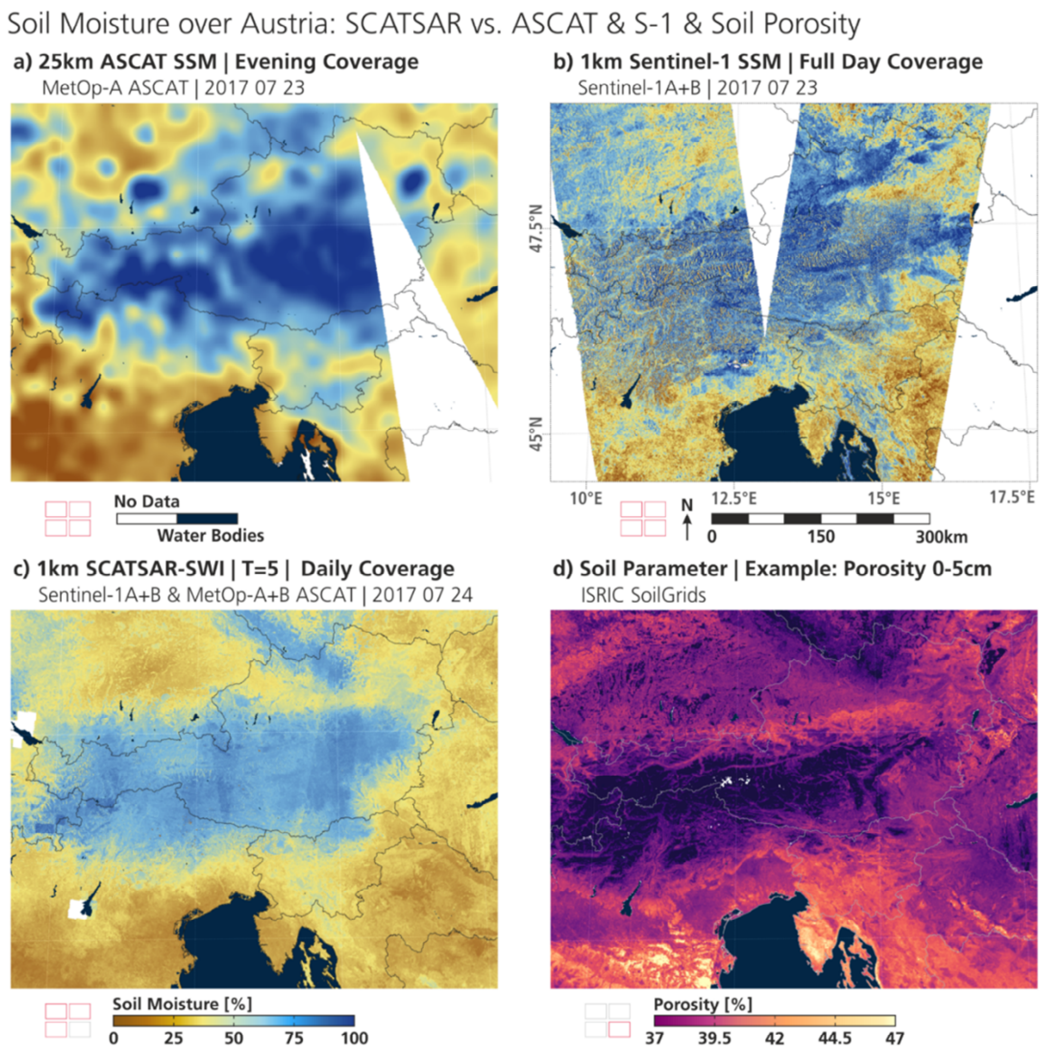


Efficiency based
on Model Simulations

Pellarin, T., J.-C. Calvet, W. Wagner (2006) Evaluation of ERS Scatterometer soil moisture products over a half-degree region in Southwestern France, Geophysical Research Letters, 33(17), L17401.

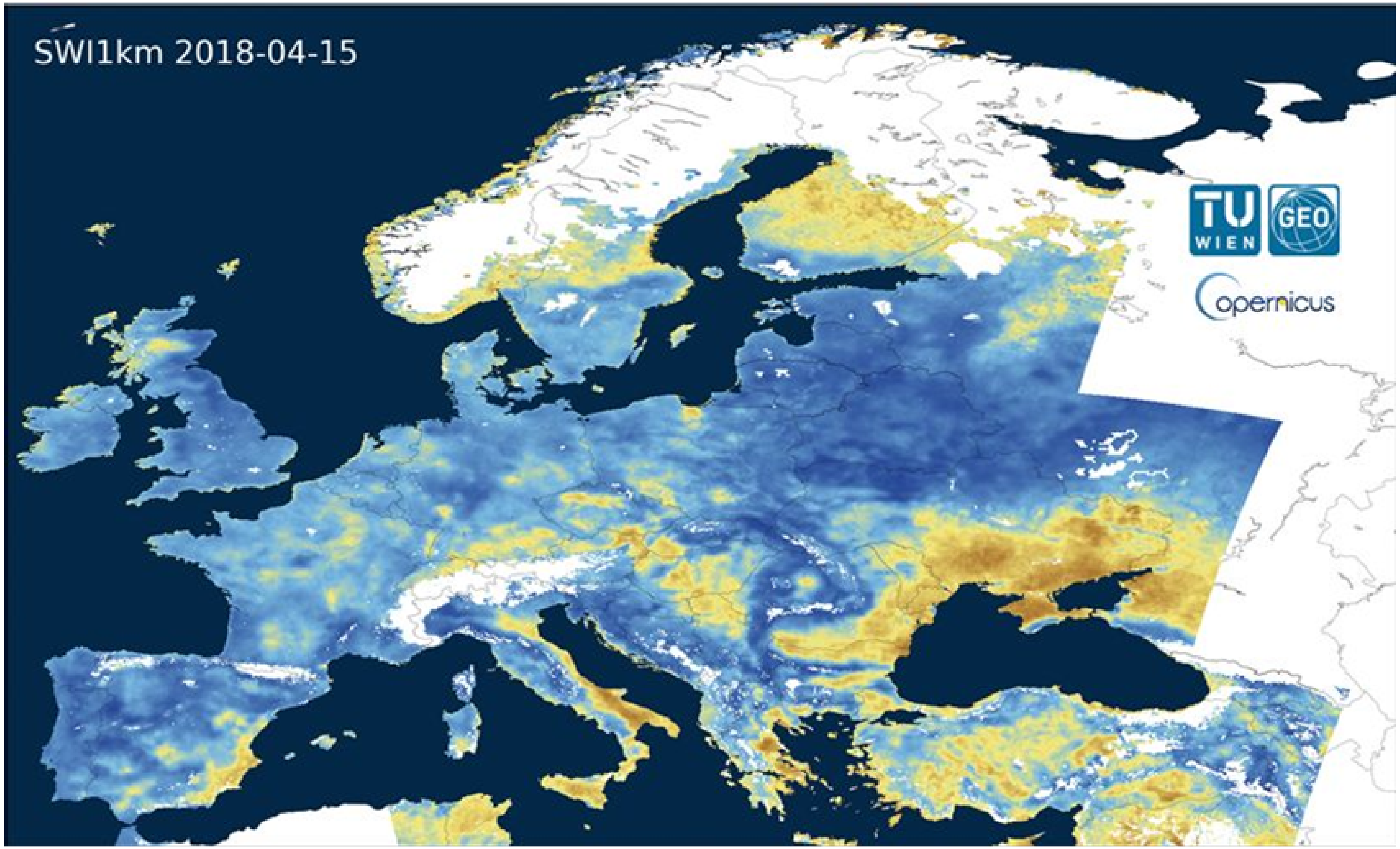
SWI Method for Fusion of Soil Moisture Data





Bauer-Marschallinger et al. (2018) Soil moisture from fusion of scatterometer and SAR: Closing the scale gap with temporal filtering, Remote Sensing, 10(7), 1030, 26 p.

ASCAT and Sentinel-1 based SWI



- Surface soil moisture from Sentinel-1
- ASCAT surface soil moisture from EUMETSAT H SAF

Bauer-Marschallinger et al. (2018) Soil moisture from fusion of scatterometer and SAR: Closing the scale gap with temporal filtering, Remote Sensing, 10(7), 1030.