Time Series Analysis of Sentinel-1 Backscatter Data on a High Performance Computing Platform

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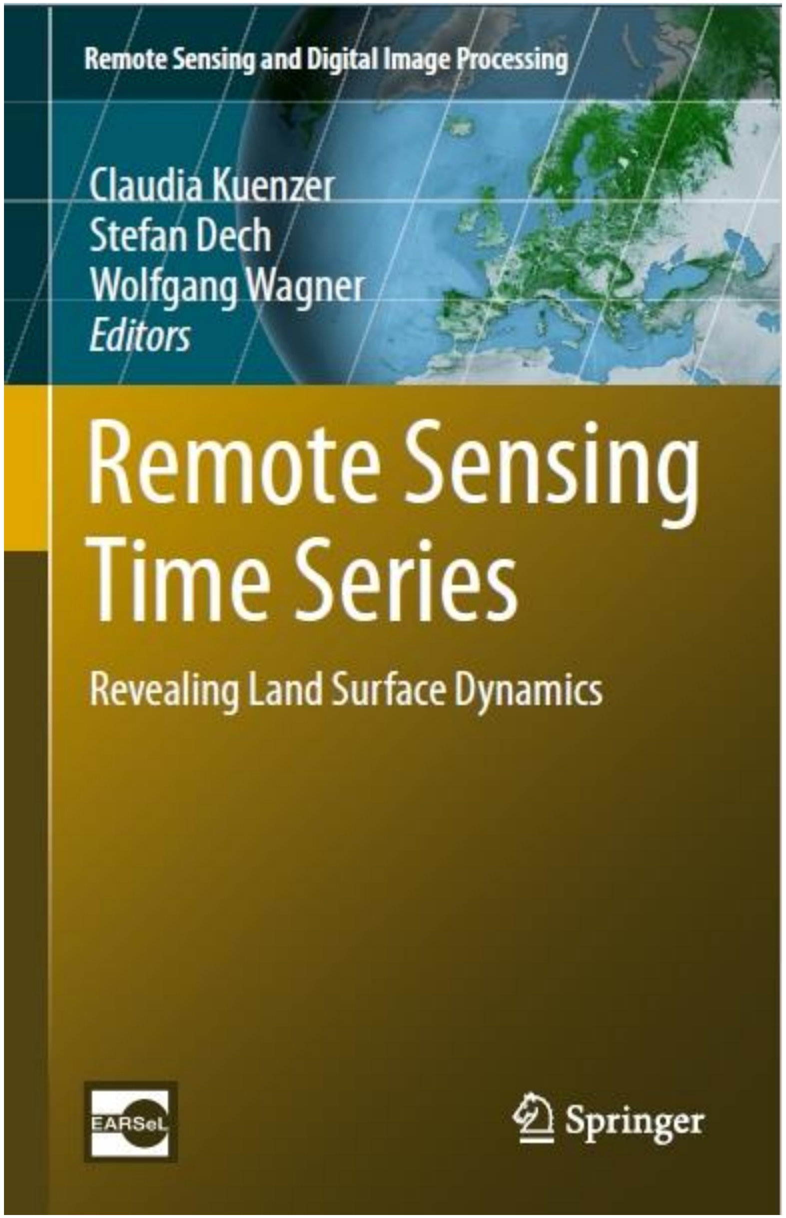


- Time series analysis is an old concept in remote sensing but something has changed …

- Demand for global data sets
- Opening up of satellite data archives
- Free and open data policy
- Open source movement
- Cloud computing
- Computer literacy
- Big Data

- Remote sensing time series analysis is suddenly a hot topic again!

Why are Time Series so Important?

Gain Process Understanding

Calibrate Remote Sensing Models

Remote Sensing Model Formulation, Calibration & Retrieval

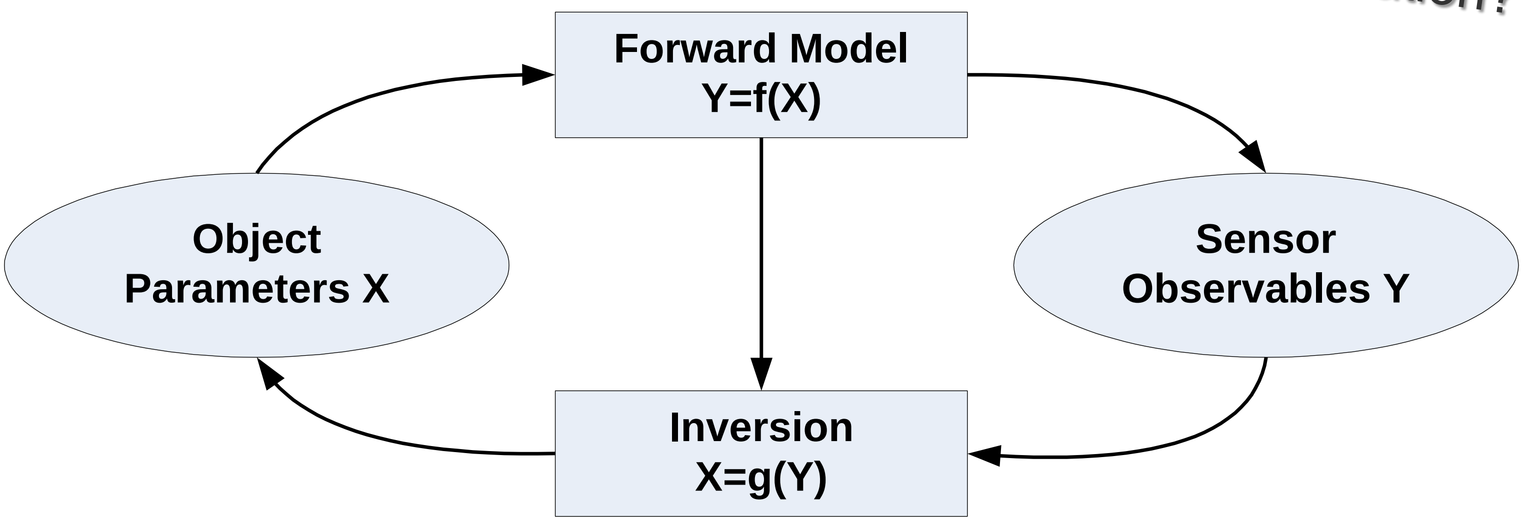
Remote Sensing Models & Retrieval Approaches

Empirical models

Semi-empirical models

Theoretical models

Underdetermination?
Equifinality?
Validation?



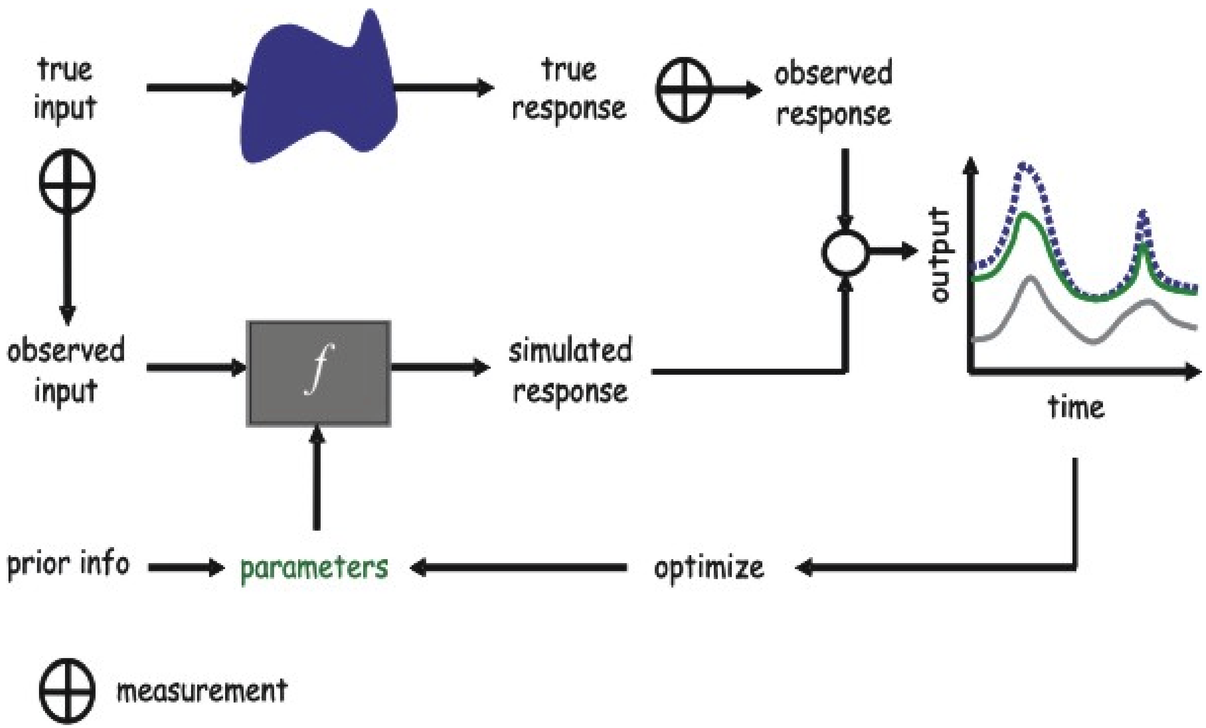
Lookup tables and neural networks

Least-square matching

Direct inversion

Why Model Calibration is Needed

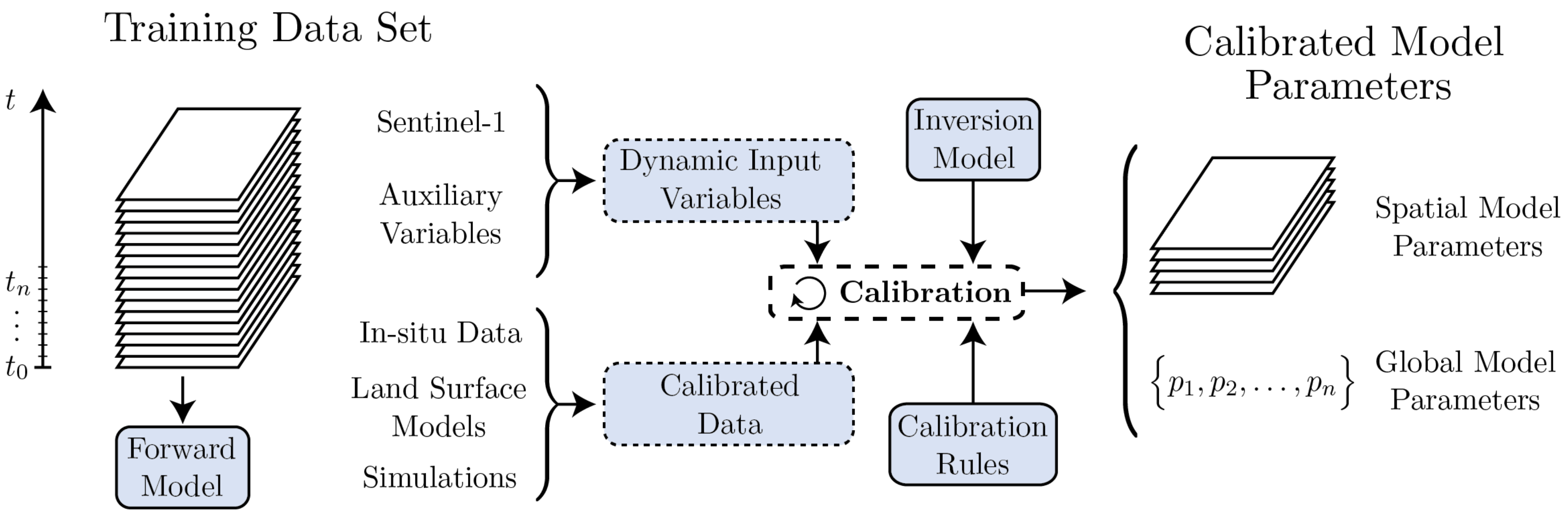
- No model is all-encompassing $\rightarrow$ Calibration is needed



“All natural systems models are to some degree lumped, and use effective parameters to characterize these spatial-temporal processes.”

Jasper Vrugt http://math.lanl.gov/~vrugt/research/

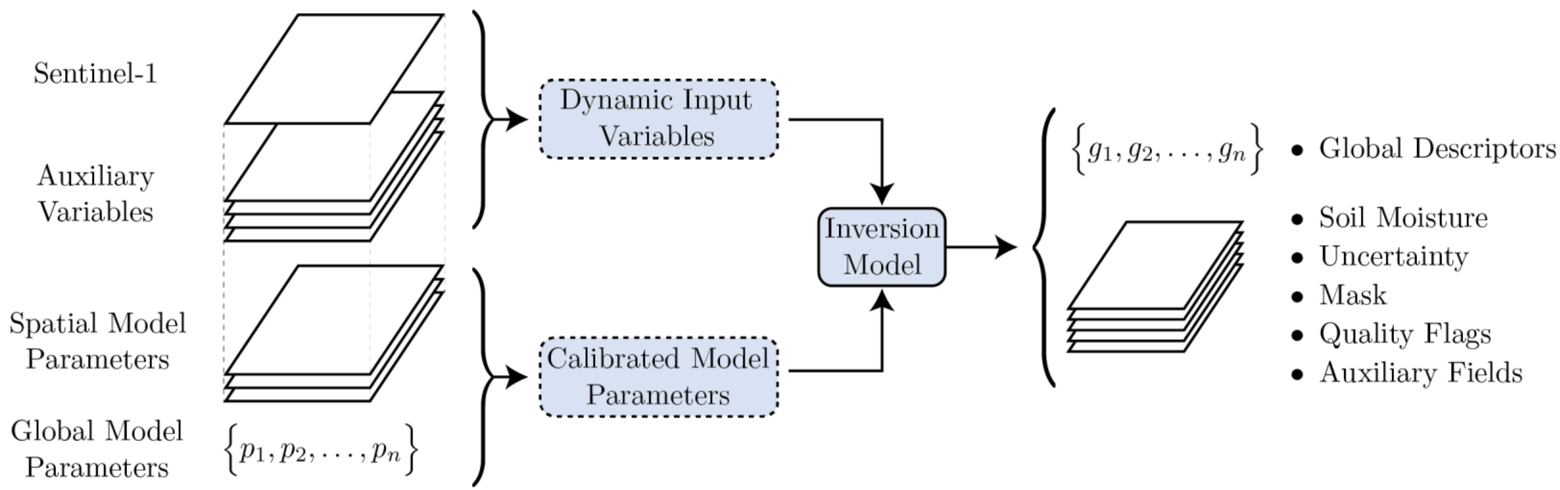
Calibration Procedure



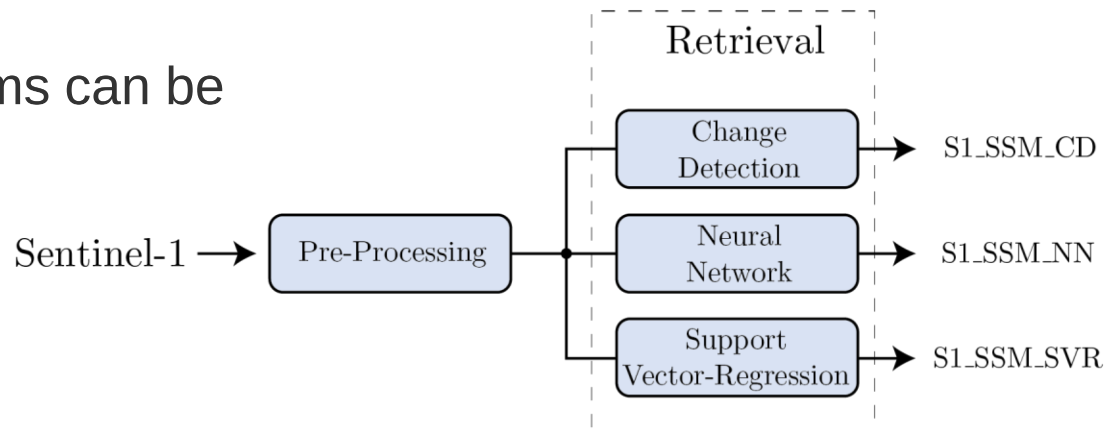
- The TU Wien processing architecture allows for calibration
  - *Per-pixel calibration* is done - as far as possible - just based on historic satellite time series
  - Auxiliary data are used for calibrating *model parameters*

Retrieval Procedure

- Retrieval can be performed in near-real-time and off-line

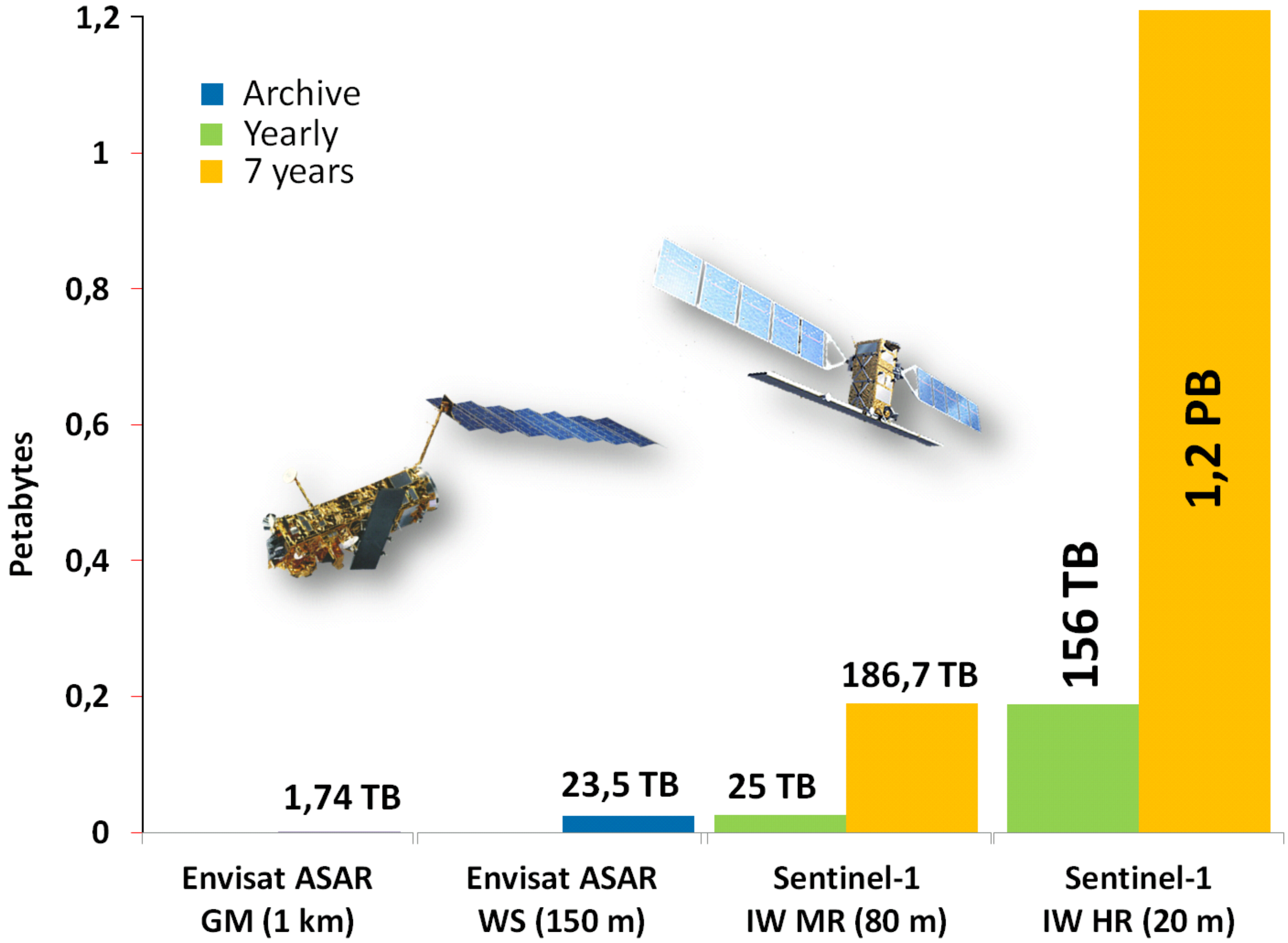


- Several algorithms can be used in parallel



Big Data Infrastructures

Exponentially Growing Data Volumes

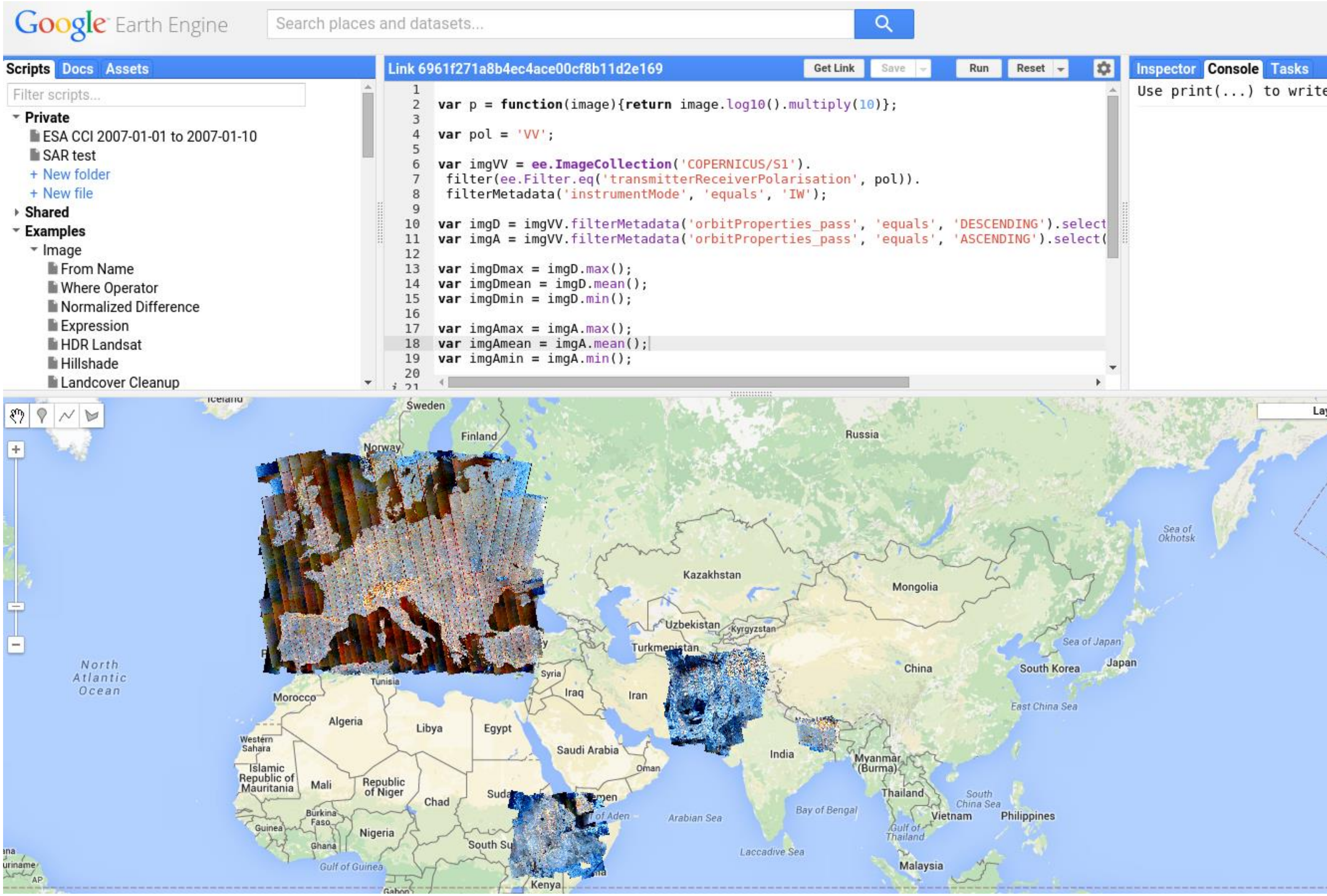


Big Data Infrastructures for the Sentinels

- Private Sector
  - Google Earth Engine
  - Amazon Web Services
    - Offers Landsat data (complete from 2015 onwards) for its cloud user
  - Helix Nebula Science Cloud
    - Consortium of European ICT providers teaming up with ESA, CERN, etc.
  - etc.
- Public Sector
  - Initiatives trigged mainly by national space programmes
    - THEIA Land Data Centre (France)
    - Climate, Environment and Monitoring from Space (CEMS) (UK)
    - OPUS/Copernicus Centre (Germany)
  - European Space Agency
    - Thematic Exploitation Platforms
    - Mission Exploitation Platforms
  - etc.

Google Earth Engine

- Premier platform for the scientific analysis of high-resolution imagery
  - Combines the strength of an ICT giant with expertise in earth observation
  - Rolled out on at least three Google data centres (US, Europe, Asia)
  - Access through Java Script or Python API
  - Programming in “Googlish”, i.e. code can only run on Google Earth Engine
  - Image-oriented data structure, including image pyramids for interactive analysis
  - Commercial usage is possible
  - Data download possible (original and processed data)
    - Landsat: complete archive
    - MODIS: many geophysical variables
    - Sentinel-1
    - Sentinel-2



Snapshot of Google Earth Engine Interface showing Sentinel-1 data holding as of 4/9/2015 (https://ee-api.appspot.com)

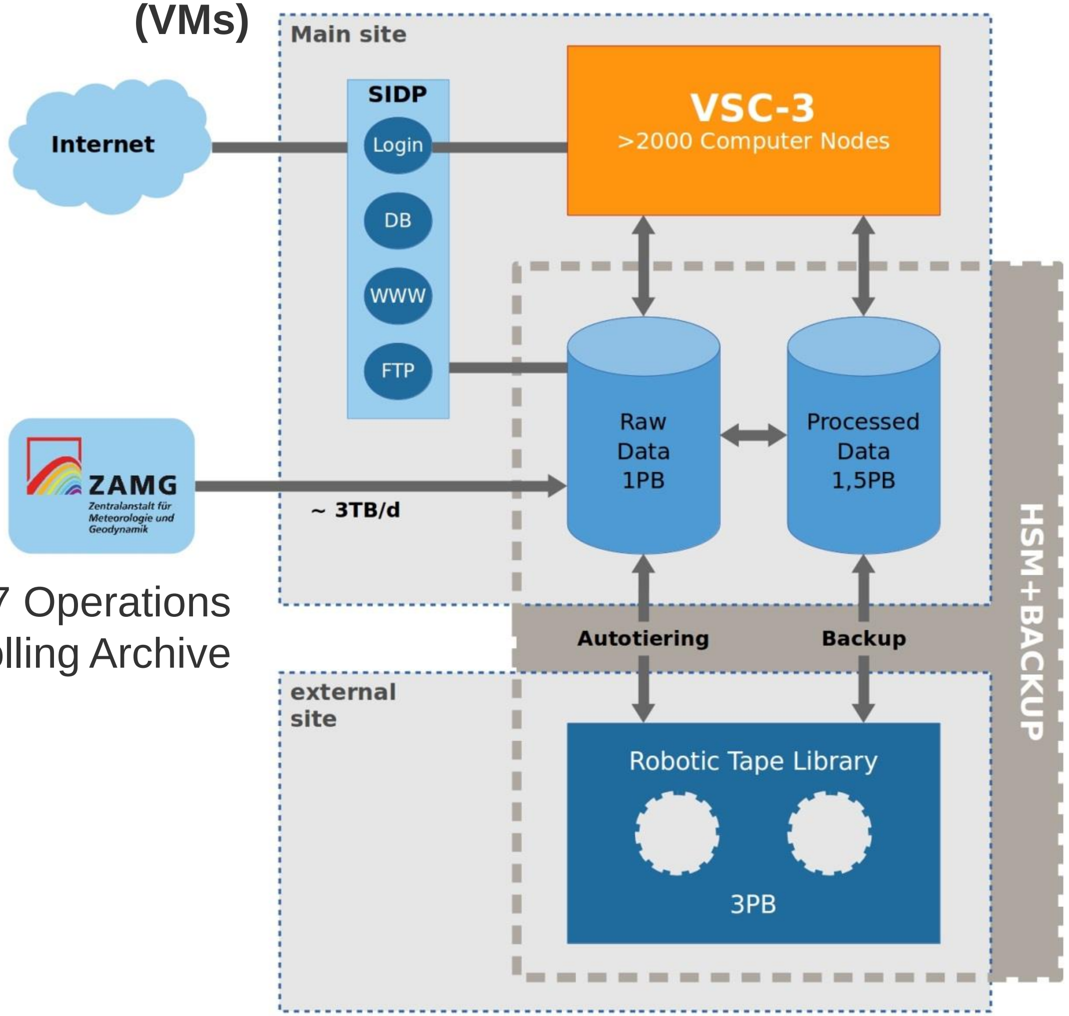
Earth Observation Data Centre

- EODC works together with its partners from science, the public- and the private sectors in order to foster the use of EO data for monitoring of water and land
- Central Goals
  - Bring users and their software to the data
  - Organise cooperation & enable specialisation
- Joint developments
  - Cloud infrastructure
  - Operational data services
  - Software
    - Open Source
- Processing of Big Data
  - From satellite raw data over EO data products up to model forecasts
  - Focus on European Satellites with high temporal coverage
    - Sentinel-1, Sentinel-2, etc.

EODC Infrastructure in Vienna

Virtual Machines (VMs)

Supercomputer



24/7 Operations
& Rolling Archive

VSC-3 Rank 85 of the World‘s most powerful computers (11/2014)

Petabyte-Scale Disk Storage
2-3 Petabyte (mid-2016)

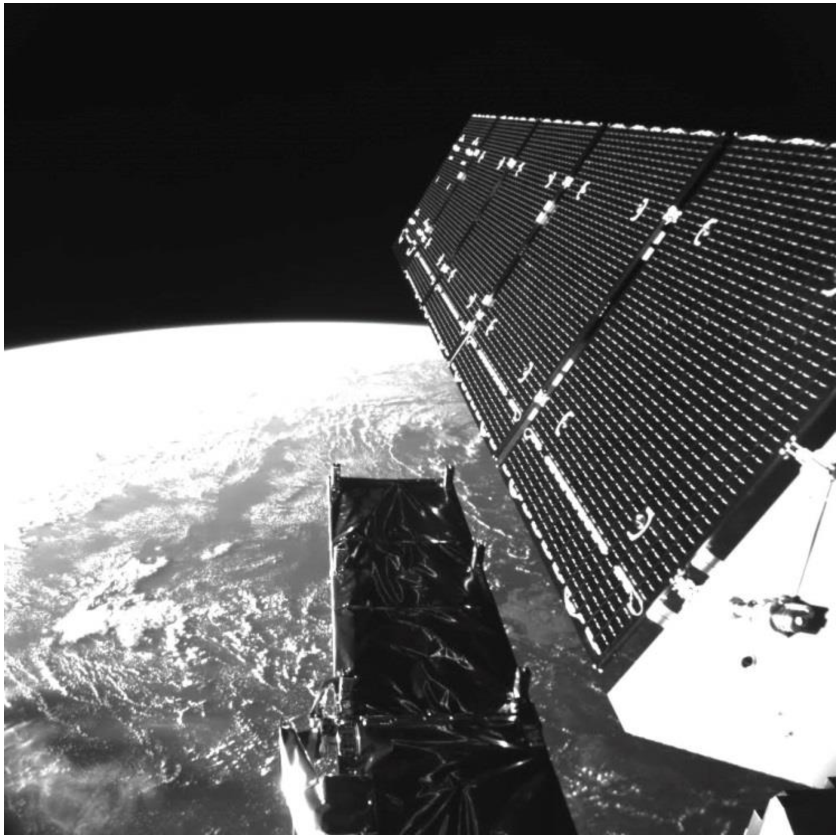
Tape Storage

Sentinel-1

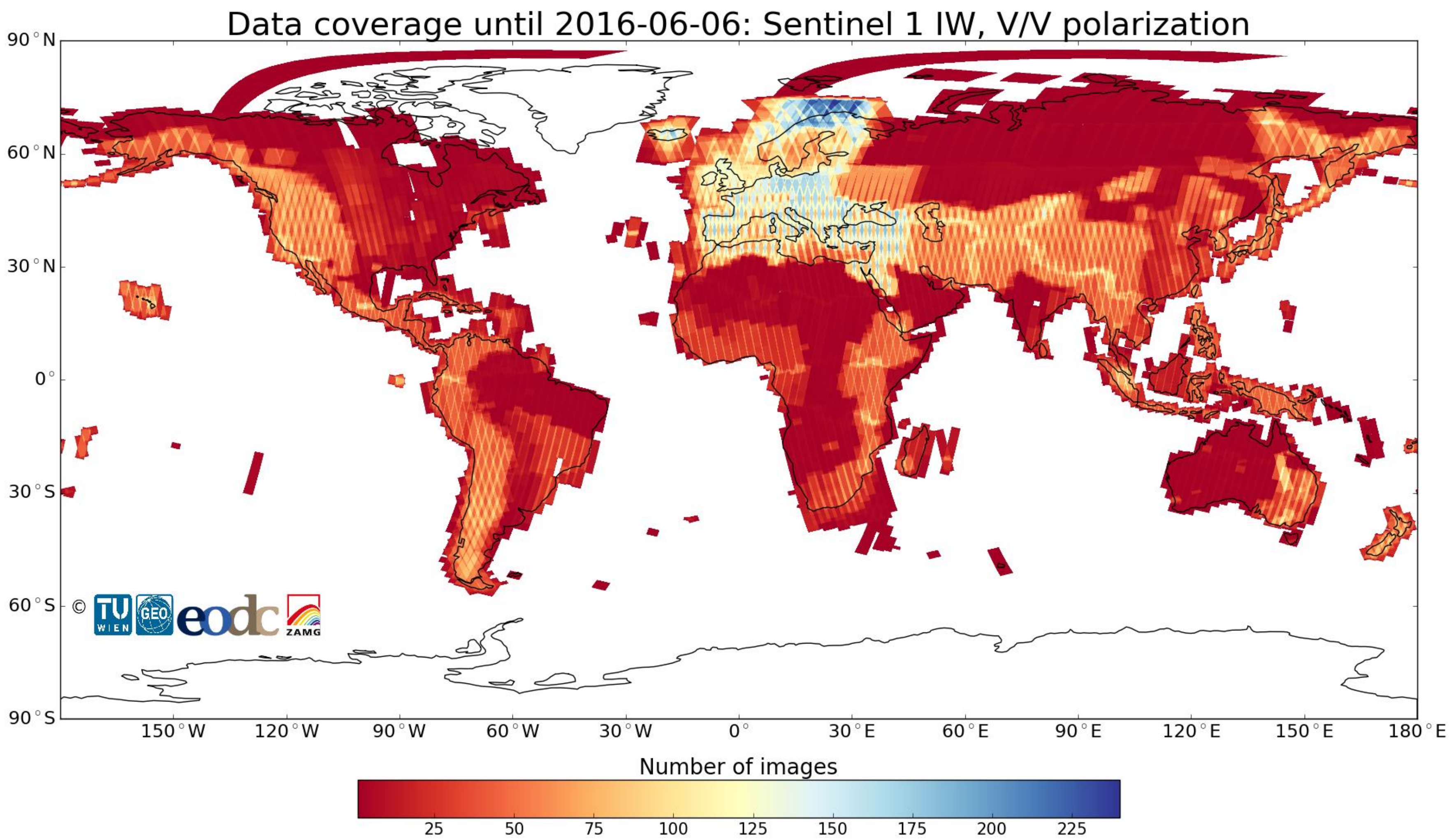
Sentinel-1 – A Game Changer

- C-band SAR satellite in continuation of ERS-1/2 and ENVISAT
- High spatio-temporal coverage
  - Spatial resolution 20-80 m
  - Temporal resolution < 3 days over Europe and Canada
    - with 2 satellites
- Excellent data quality
- Highly dynamic land surface processes can be captured
  - Impact on water management, health and other applications could be high if the challenges in the ground segment can be overcome

Solar panel and SAR antenna of Sentinel-1 launched 3 April 2014. Image was acquired by the satellite's onboard camera. © ESA



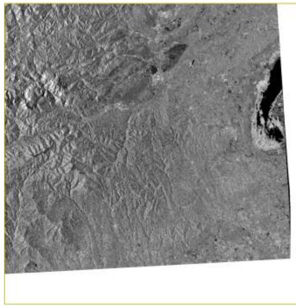
Sentinel-1 Data Availability @ EODC

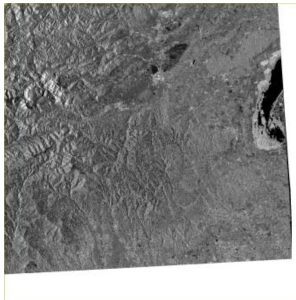


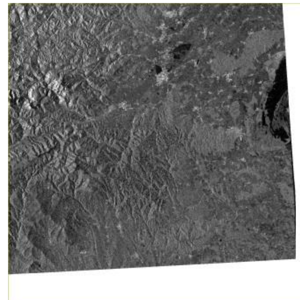
Up-to-date coverage maps available from https://www.eodc.eu/sentinel-1a-coverage-maps/


Sentinel-1 Image of Upper
Austria taken on 13/04/2015

Sentinel-1 Time Series


2014-11-08


2014-12-14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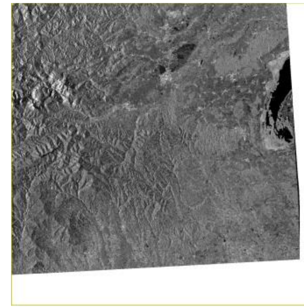
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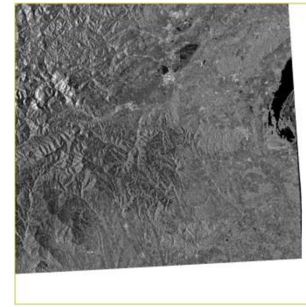
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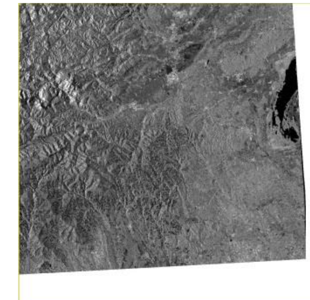
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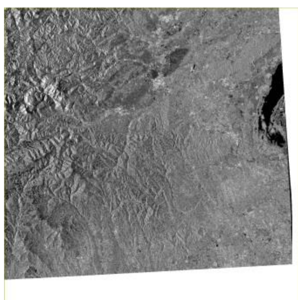
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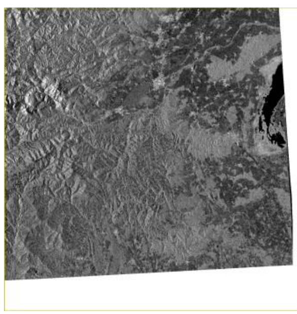
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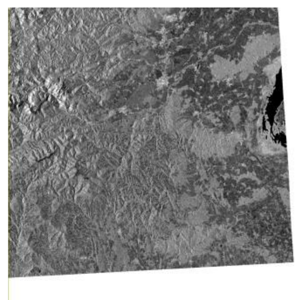
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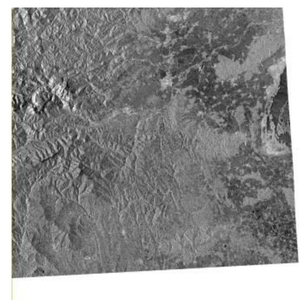
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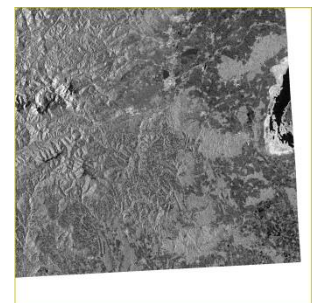
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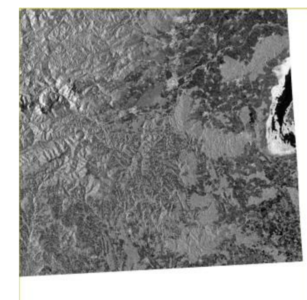
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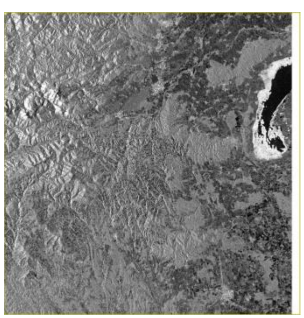
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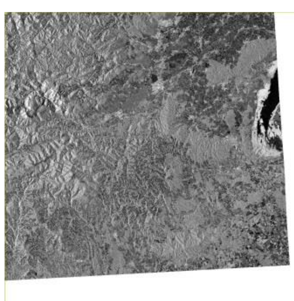
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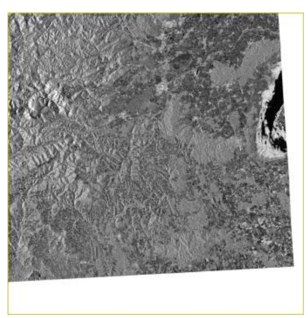
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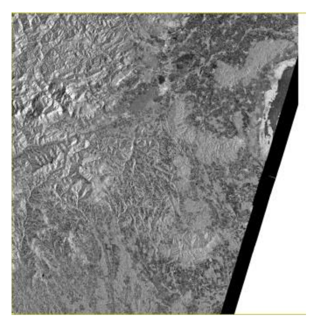
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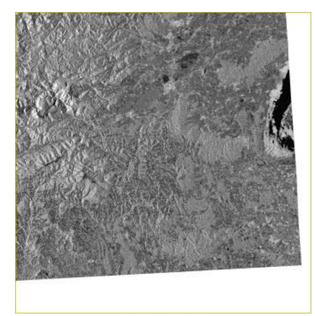
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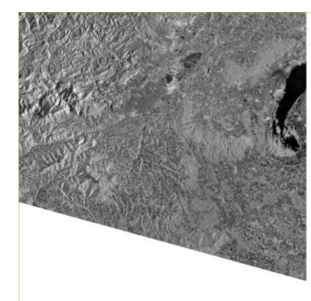
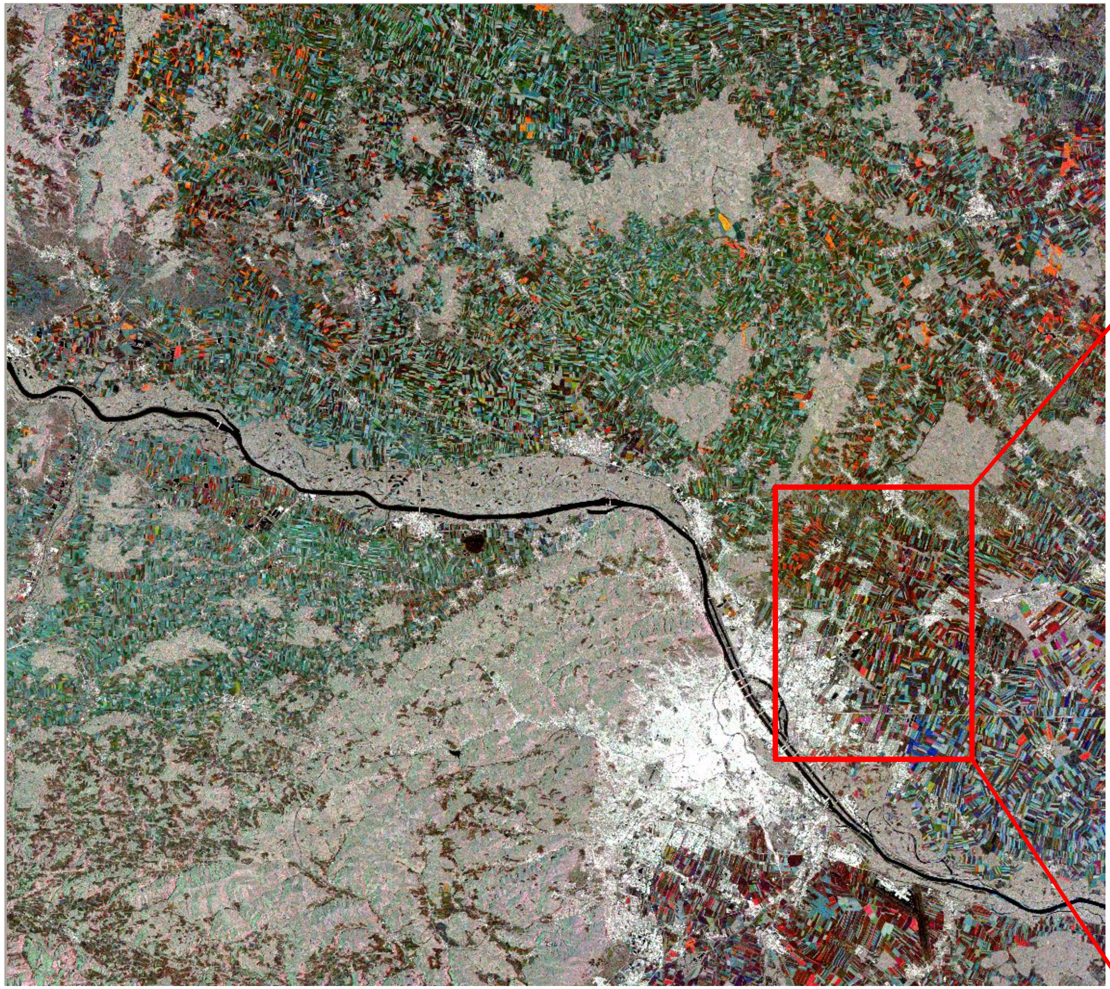
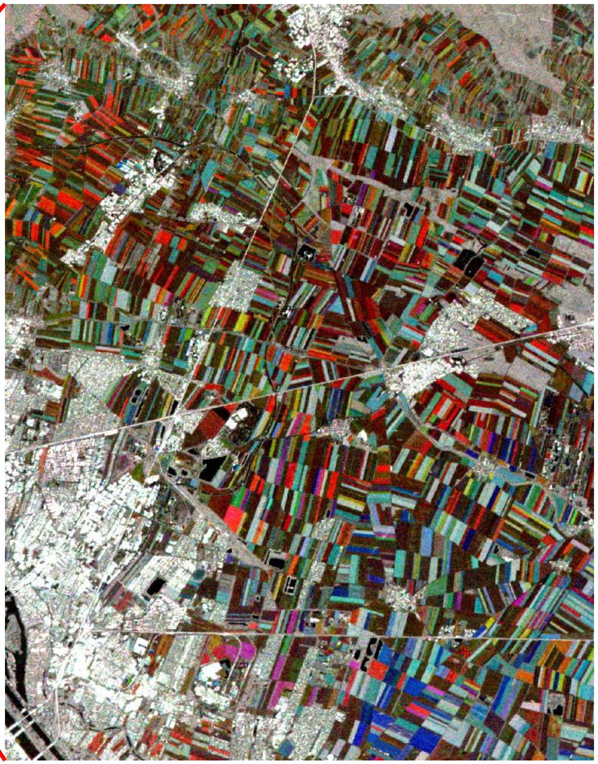

2015-06-23

Sentinel-1 Cross-Pol (VH) Images

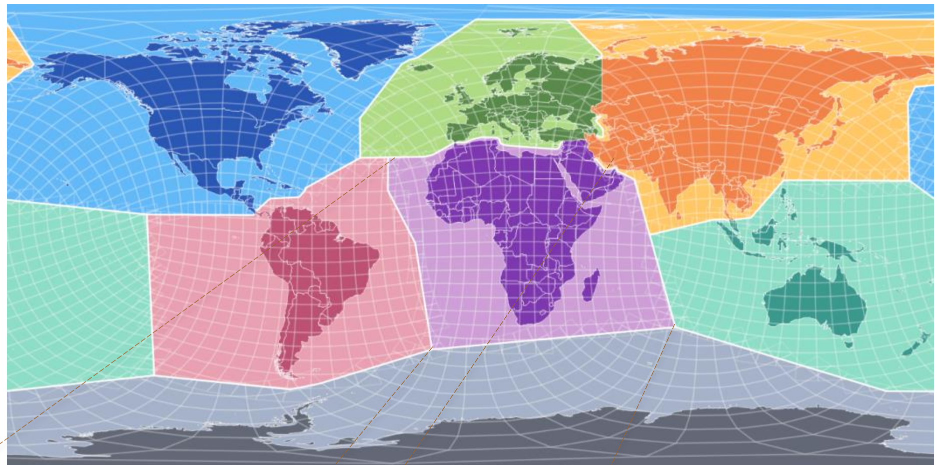


False-colour image of Sentinel-1
VH monthly image mosaics

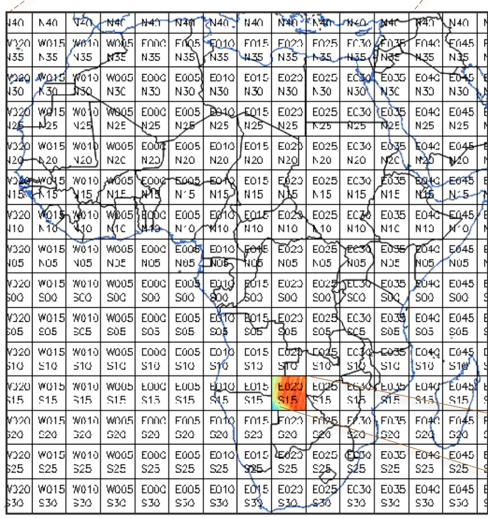
Red – June
Green – July
Blue – August

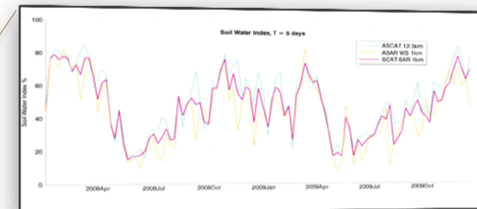


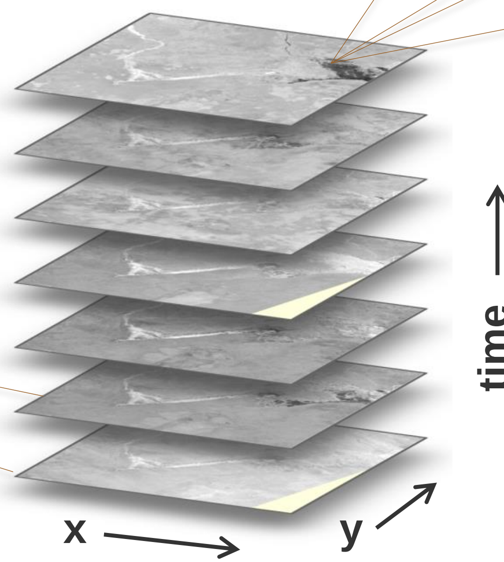
Global Grid System for Time Series Processing



Equi7 Grid
Bauer-Marschallinger et al (2014) Optimisation of global grids for high-resolution remote sensing data, Computers & Geosciences, 72, 84-93.

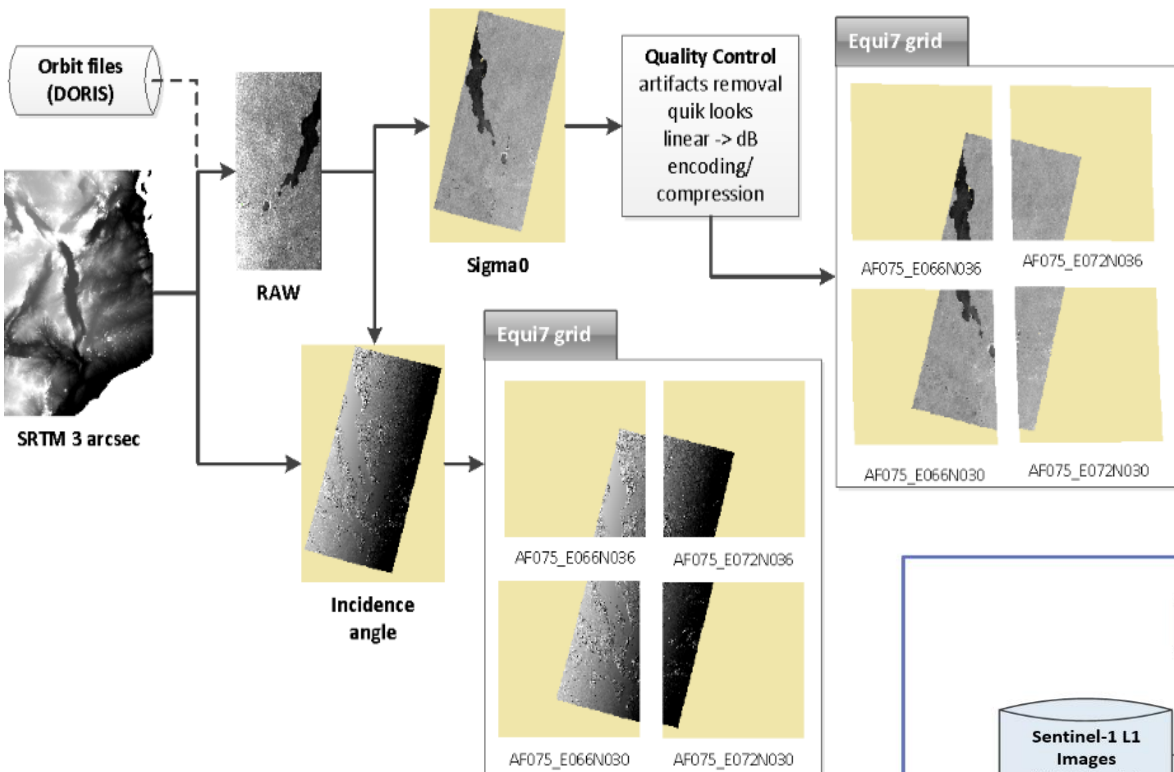




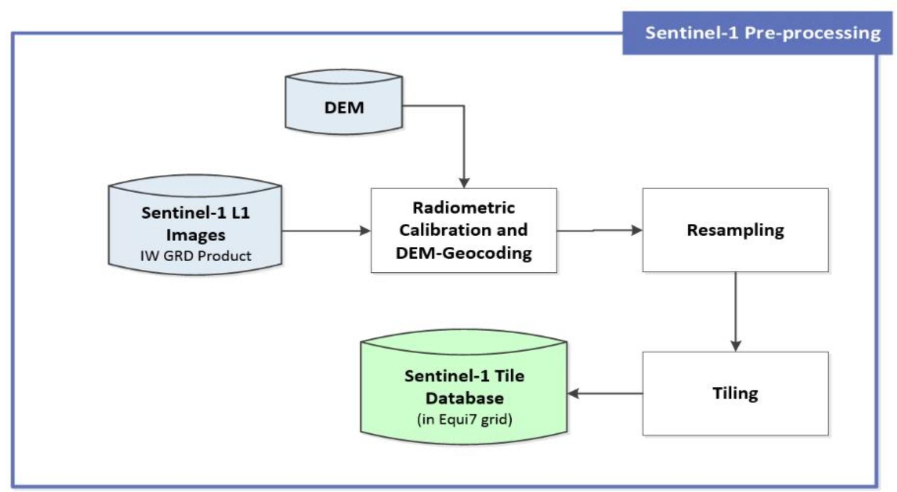


- Equidistant azimuthal projection
- Fast parallel processing
- Optimized data formatting
- Fast access in time and spatial domain
- Efficient data archiving

Sentinel-1 Pre-Processing Chain



Geo-coding is done with ESA's Sentinel-1 Toolbox (S1TBX)



Supercomputing Experiments

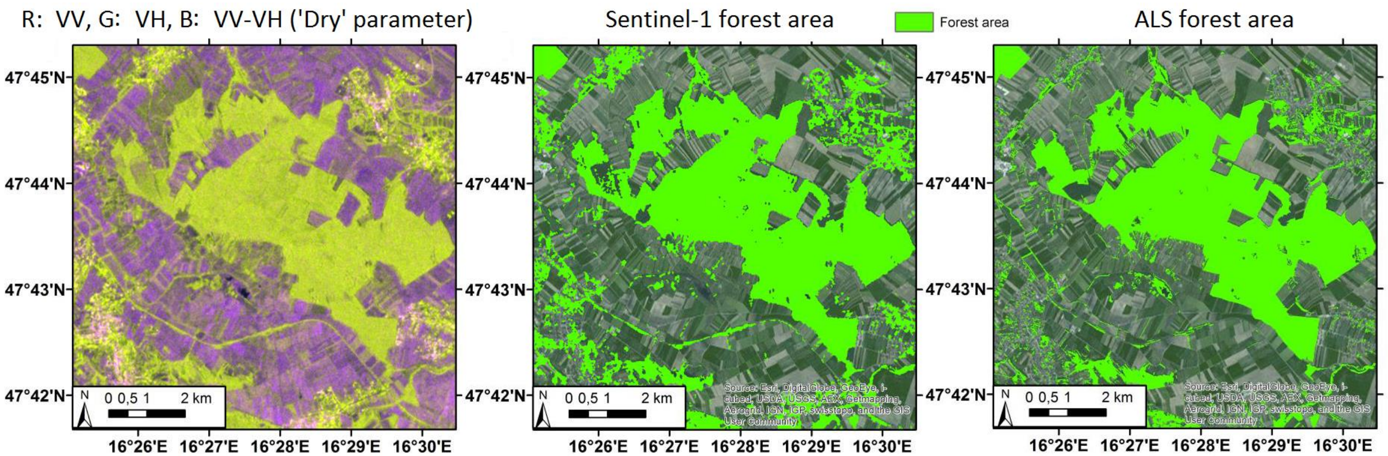
- Vienna Scientific Cluster 3
  - High-performance computing (HPC) system with 2020 nodes
  - Each node has 2 processors Intel Xeon E5-2650v2, 2.6 GHz, and 64 Gbytes of RAM
  - Simple Linux Utility for Resource Management (SLURM)
- First experiment conducted on VSC-3 in 2015
  - Geocoding of 624 Sentinel-1 images from Austria, Sudan and Zambia with Sentinel-1 toolbox
  - Each image is about 1 Gbyte in size
  - Serial processing with one processor would take about two weeks
- Approach
  - Parallel processing on 312 nodes whereas 2 images were simultaneously launched on a single computing node
- Results
  - Processing was completed within 45 min (without queuing)

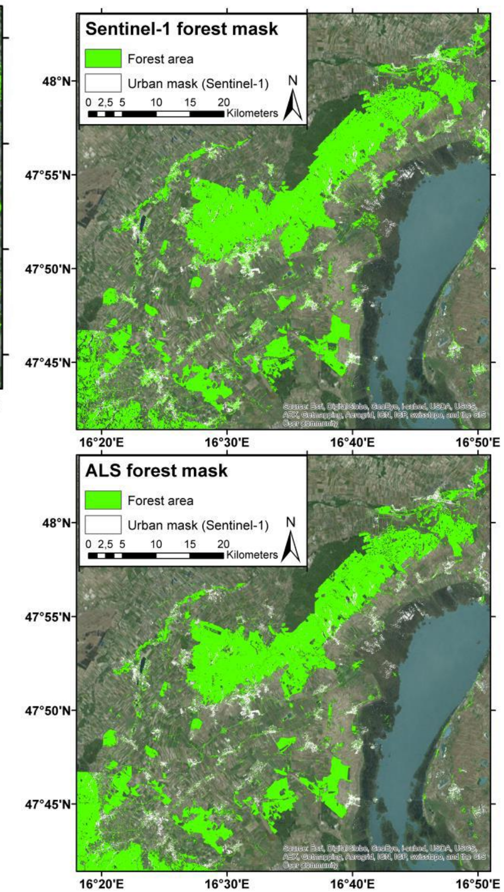
Test	n. 1	n. 2	n. 3	n. 4
SAR product mode	ASAR GM	ASAR WS	ASAR WS	S-1 IW GRDH
Spatial resolution	1 km	150 m	150 m	20 m
Total number of data files	189,621	31,199	31,199	1,075
Number of images for job / Total Number of jobs	8 / 23,703	2 / 15,600	2 / 15,600	1 / 1,075
Input data file size range	1 - 73 MB	12 - 692 MB	12 - 692 MB	0.8 – 1.7 GB
Total input data files size	1.579 TB	5.401 TB	5.401 TB	1.2 TB
Max. number of simultaneous running nodes	417	454	612	396
Number of cores used by Sentinel-1 Toolbox	4	8	8	8
Input data caching on node	False	False	True	True
Output data caching on node	True	True	True	True
Averaged processing time (seconds/MB)	9.18	5.65	2.39	2.69
Elapsed time including SLURM queueing	**≈ 3.5 days**	**≈ 4 days**	**≈ 8 hours**	**≈ 3.5 hours**
Estimated elapsed time using only 1 node	**≈ 167 days**	**≈ 353 days**	**≈ 353 days**	**≈ 37 days**

Elefante et al. (2016) High-performance computing for soil moisture estimation, BiDS’2016, EUR 27775 EN, 95-98.

Forest Mapping

Forest Area from Sentinel-1 Time Series

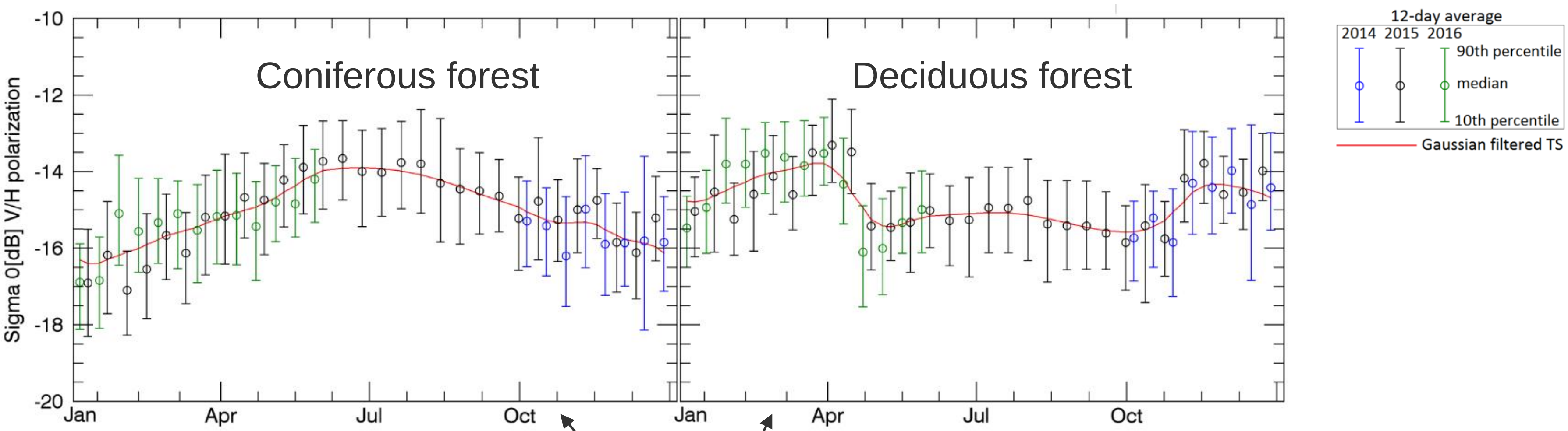


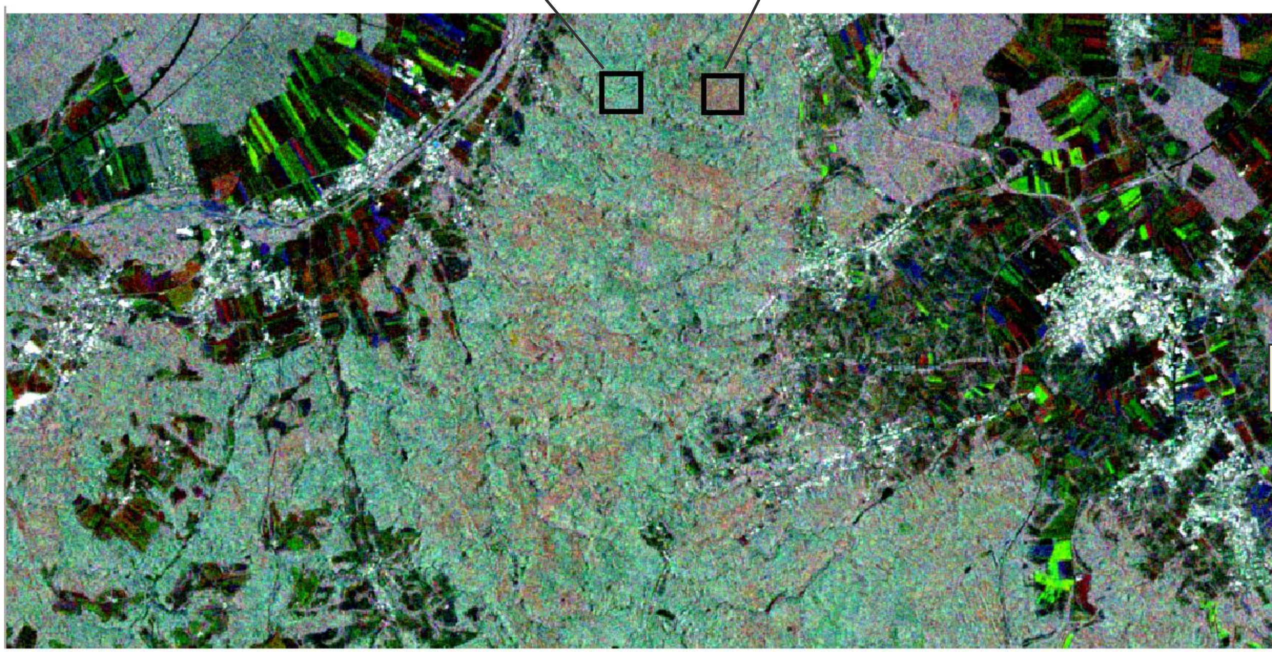


- 10m forest area map of Eastern Burgenland, Austria
- Statistical parameters from the multi-temporal VV and VH data (1-12-2014 to 31-03-2015)
- Thresholding approach (Otsu algorithm) and K-means clustering
- Validation with forest area map from ALS data: Overall accuracy 92%, kappa statistic 0.81

Dostalova et al. (2016) Forest Area Derivation from Sentinel-1 Data, ISPRS Annals, 227-233.

Seasonal Backscatter Signal over Forest





False-colour composite of Sentinel-1 VH 12-day image mosaics:

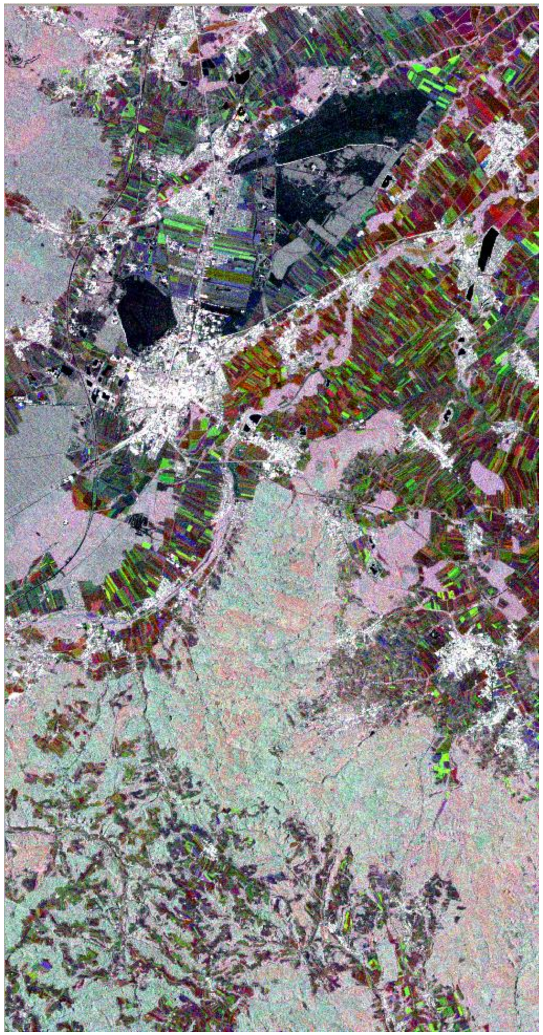
Red: 10th-21st January 2015
Green: 3rd-14th June 2015
Blue: 4th-15th May 2016

Potential for forest type classification

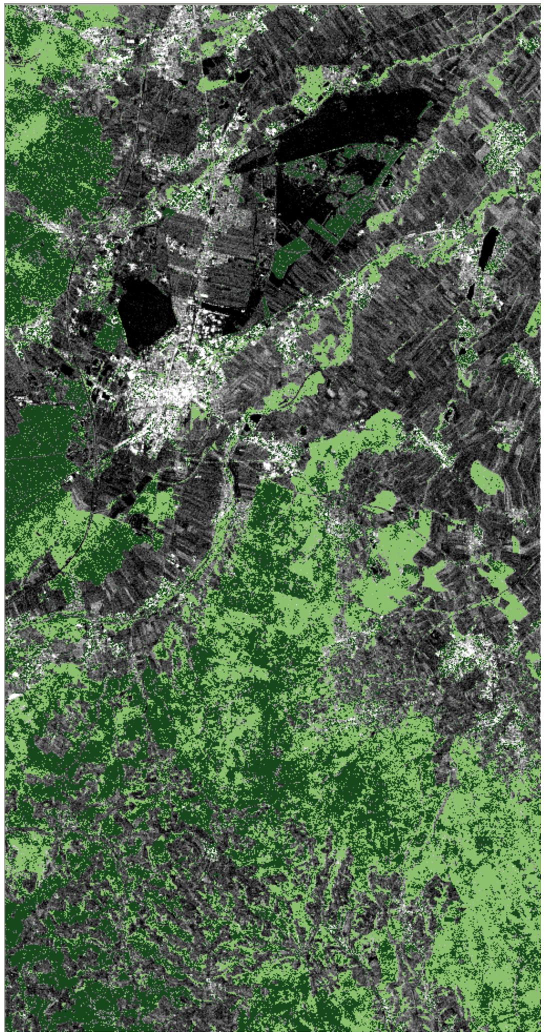
Dostalova et al. (2016) Influence of Forest Structure on the Sentinel-1 Backscatter Variation – Analysis with Full-waveform LiDAR Data, LPS 2016, Prague.

Forest Type Classification

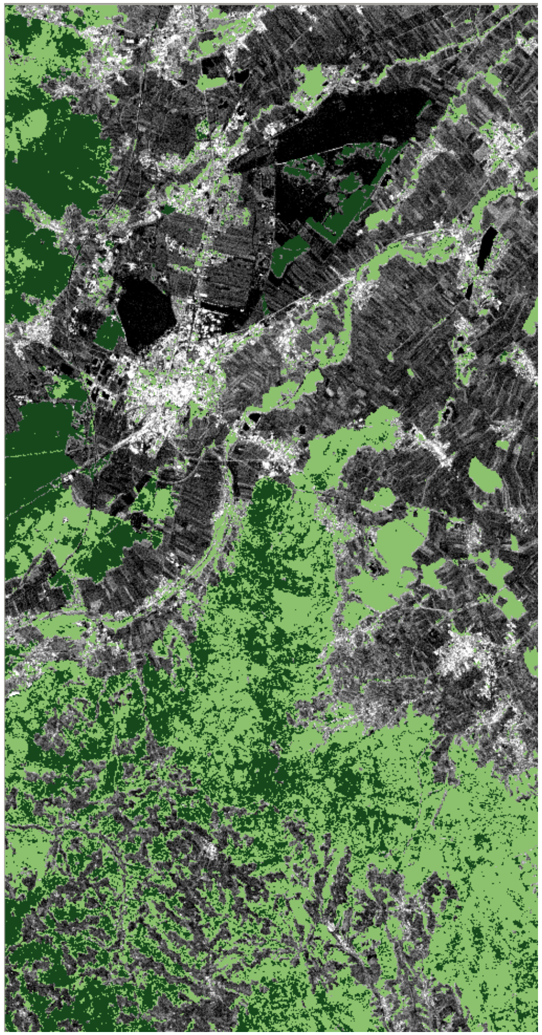
False-colour composite of Sentinel-1 VH 12-days averages



20m forest type map based on yearly seasonality of Sentinel-1 time series



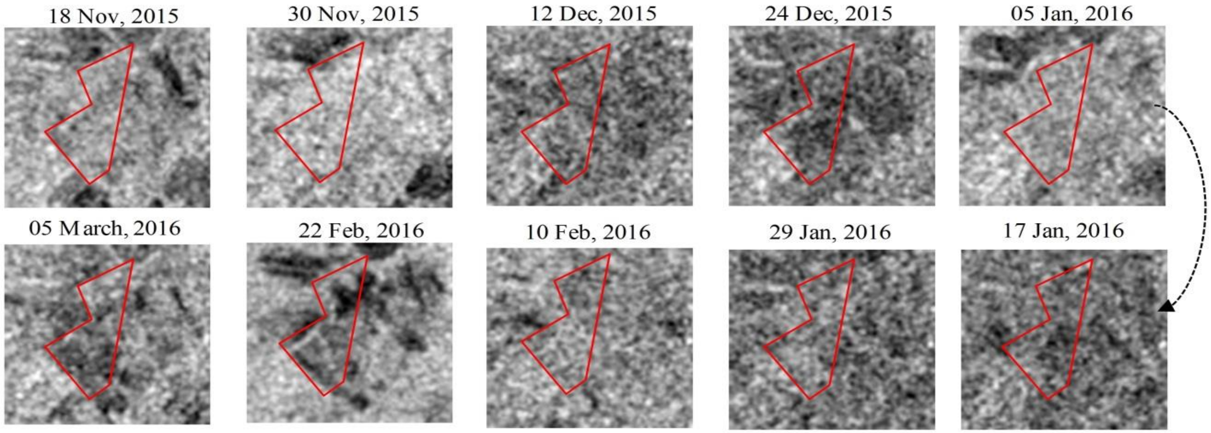
Copernicus HRL 20m Forest type (2012)



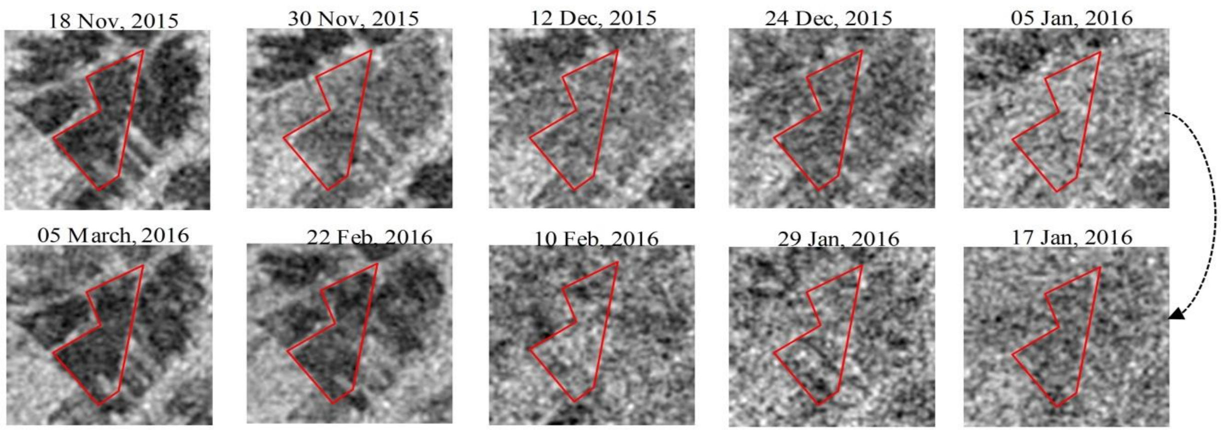
Copernicus HRL Forest type map source:
http://land.copernicus.eu/pan-european/high-resolution-layers/forests

Rice Mapping

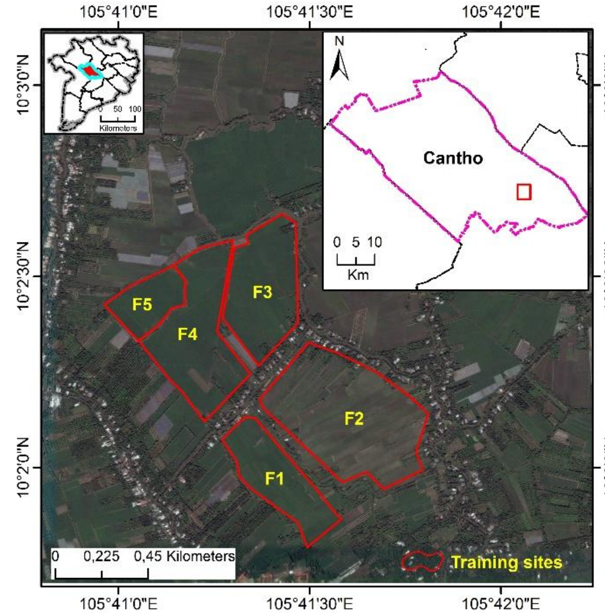
a) Time series backscatter coefficient images at VV polarization



b) Time series backscatter coefficient images at VH polarization

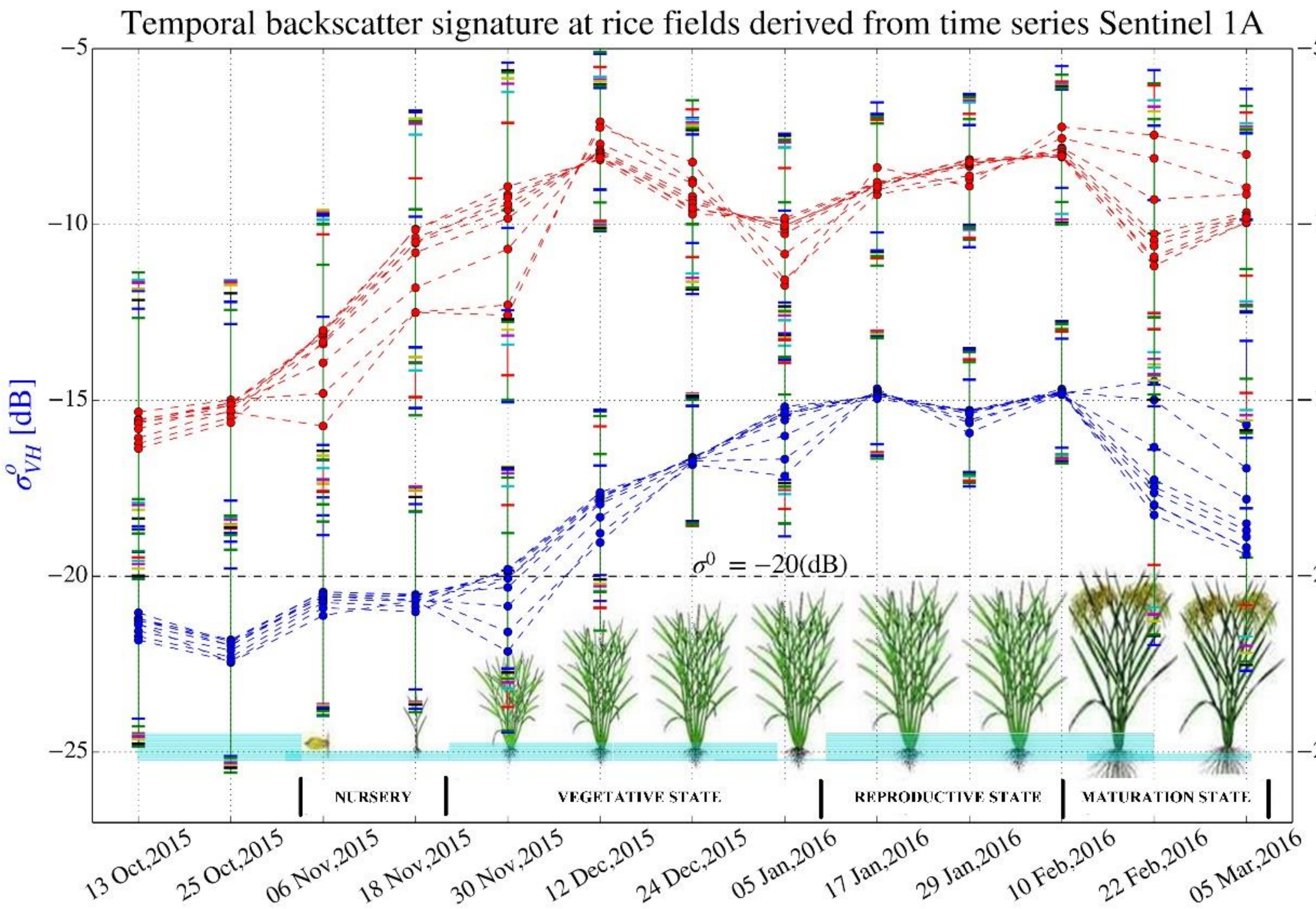


c) Ground survey photos



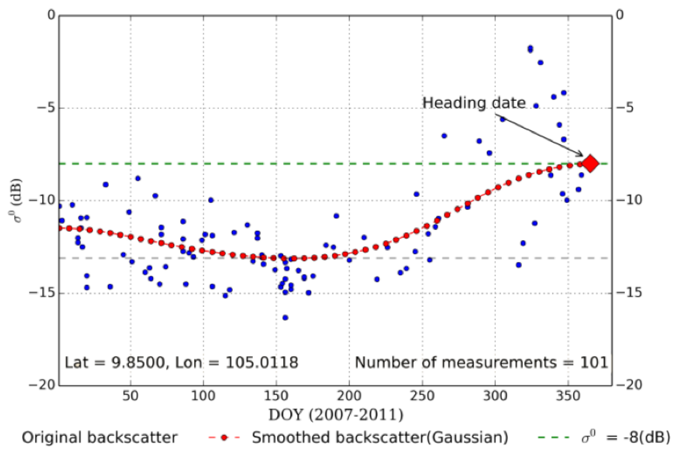
Nguyen, D.B., A. Gruber, W. Wagner (2016) Mapping rice extent and cropping scheme in the Mekong Delta using Sentinel-1A data, Remote Sensing Letters, in revision.

Backscatter Signature of Rice Fields

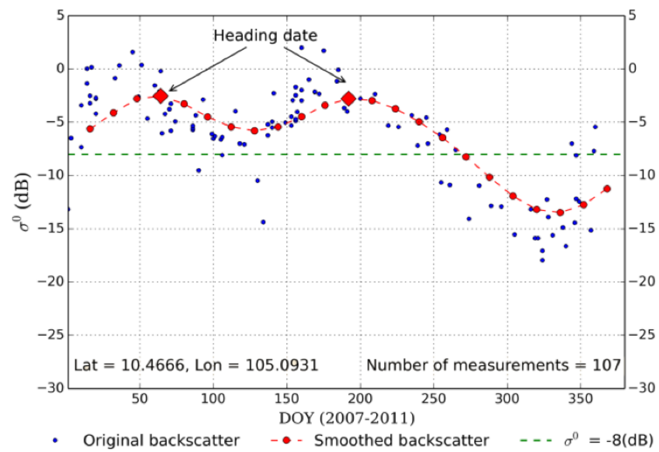


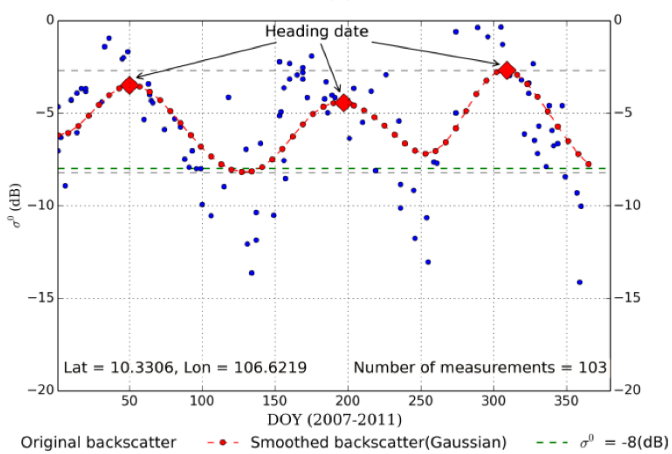
Nguyen, D.B., A. Gruber, W. Wagner (2016) Mapping rice extent and cropping scheme in the Mekong Delta using Sentinel-1A data, Remote Sensing Letters, in revision.

Single-, Double- and Triple-Cropped Rice Areas



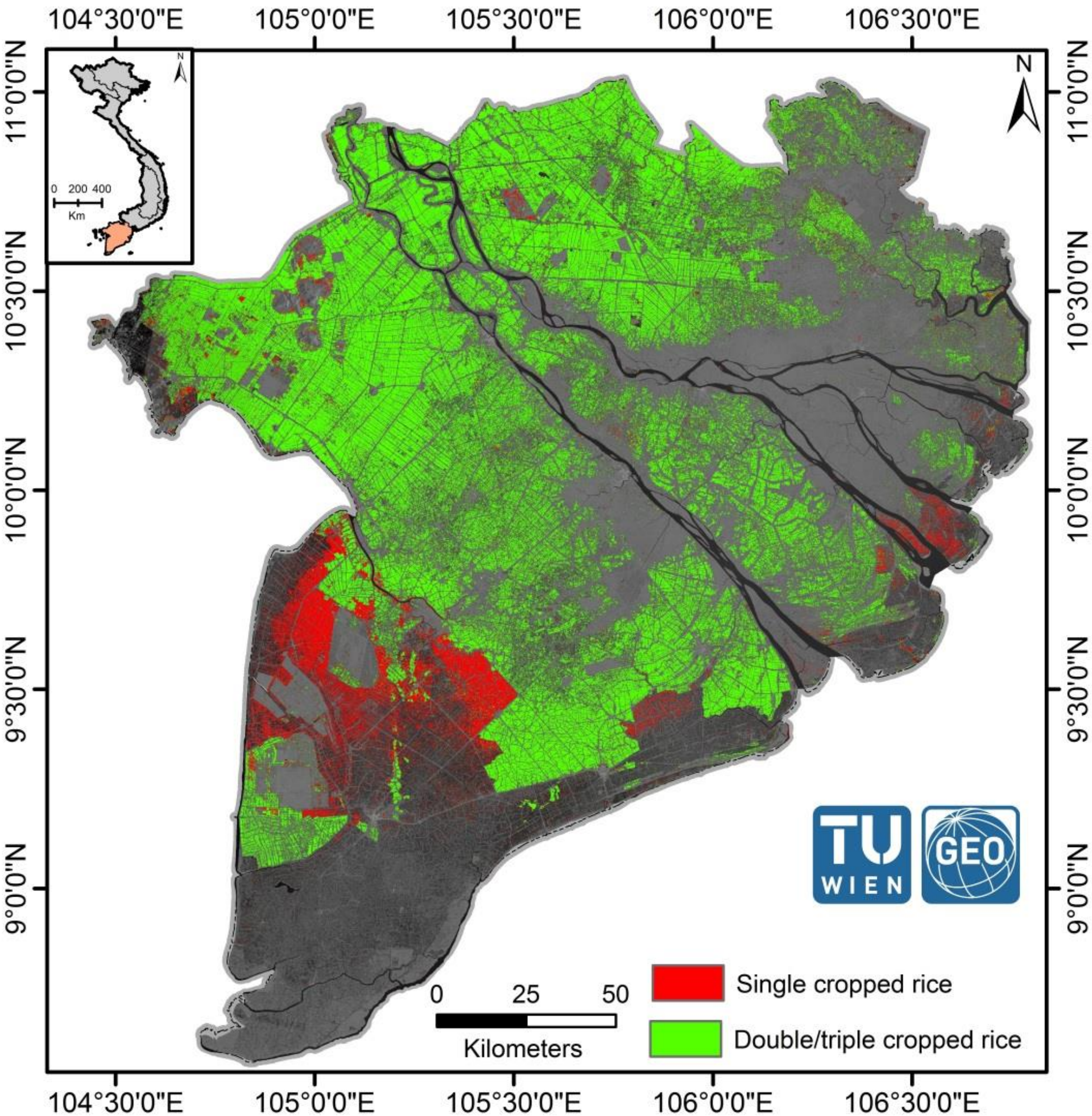
(a)





Nguyen, D., K. Clauss, S. Cao, V. Naeimi, C. Kuenzer, W. Wagner (2015). Mapping Rice Seasonality in the Mekong Delta with Multi-Year Envisat ASAR WSM Data, Remote Sensing, 7, 15808-15893.

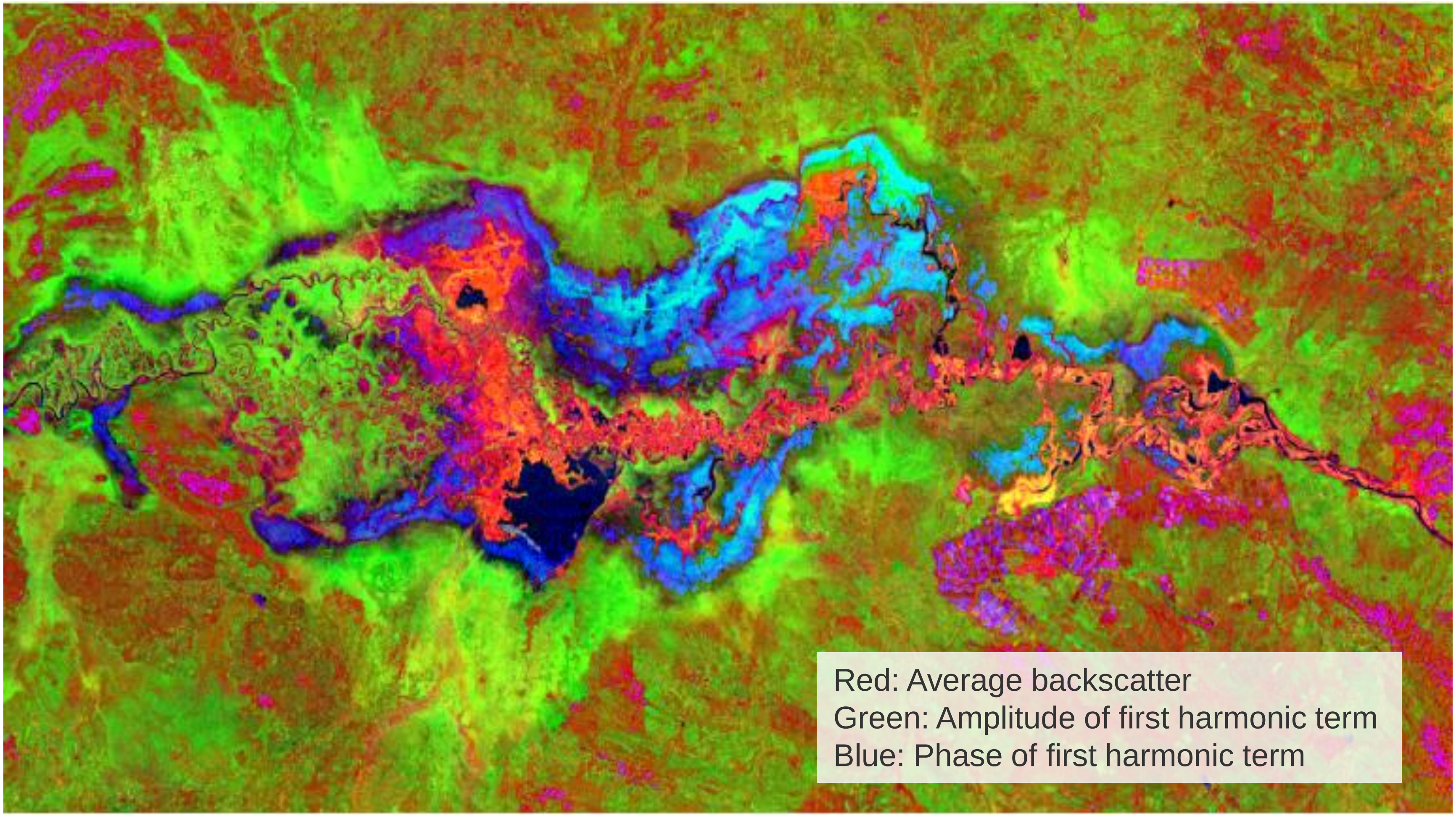
Rice Areas in Mekong River Delta



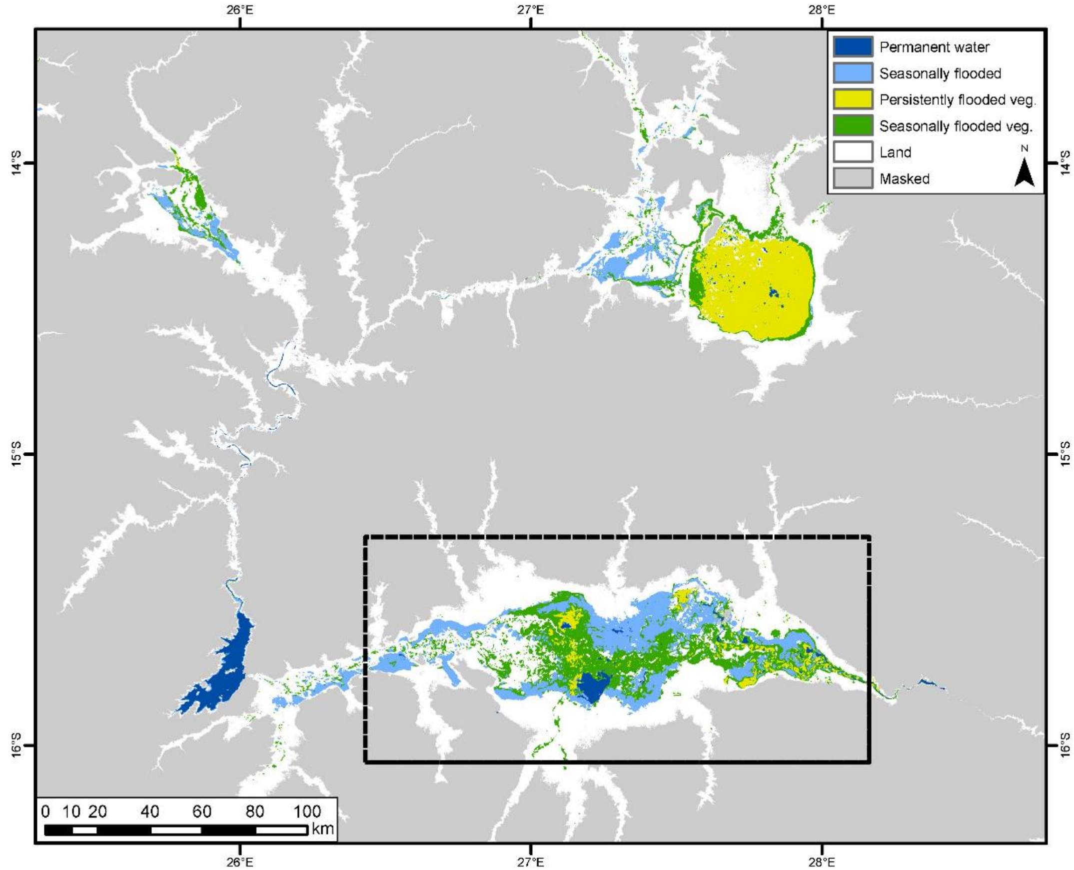
http://www.esa.int/spaceinimages/

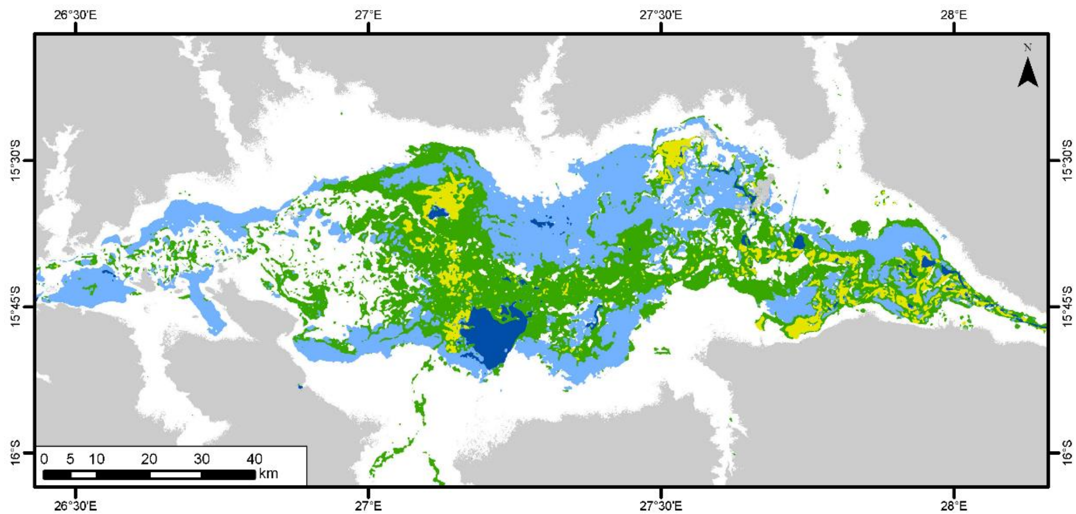
Wetland Mapping

Harmonic Analysis of SAR Time Series



Schlaffer, S., M. Chini, D. Dettmering, W. Wagner (2016) Mapping Wetlands in Zambia Using Seasonal Backscatter Signatures Derived from ENVISAT ASAR Time Series, Remote Sensing, 8(5), 402, 24 p.





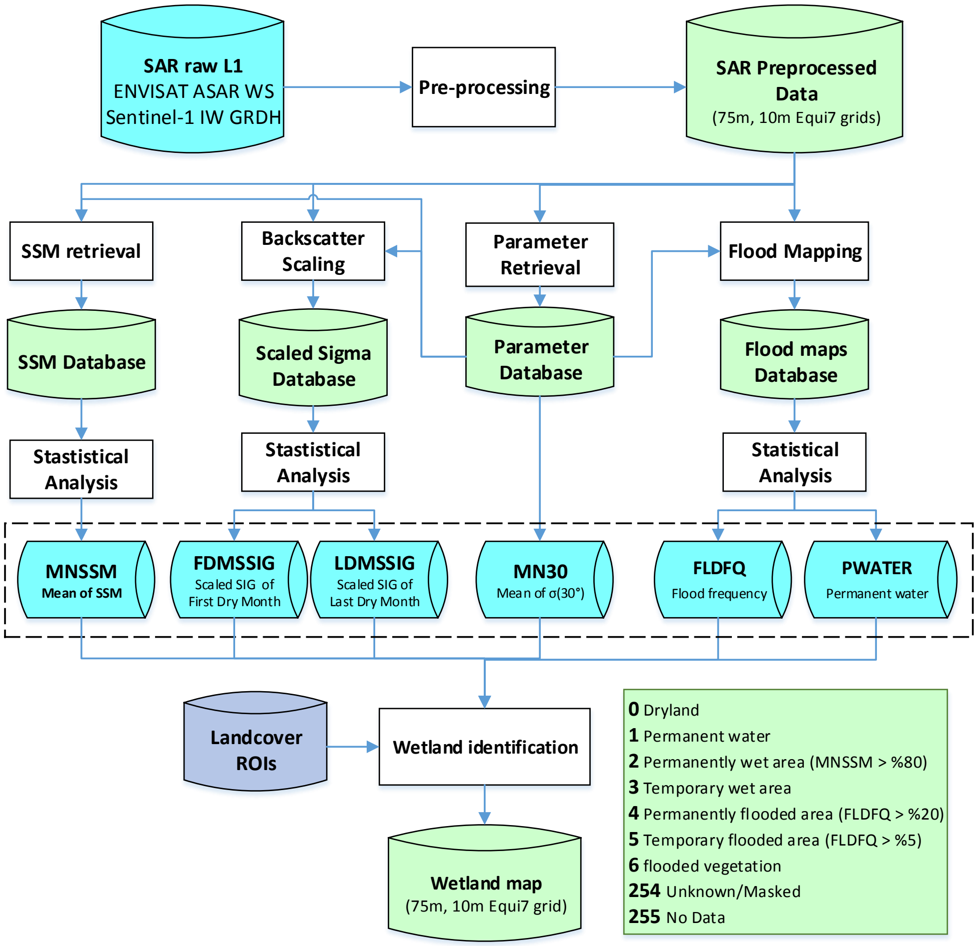
Schlaffer, S., M. Chini, D. Dettmering, W. Wagner (2016) Mapping Wetlands in Zambia Using Seasonal Backscatter Signatures Derived from ENVISAT ASAR Time Series, Remote Sensing, 8(5), 402, 24 p.

Sentinel-1 Wetland Mapping Algorithm

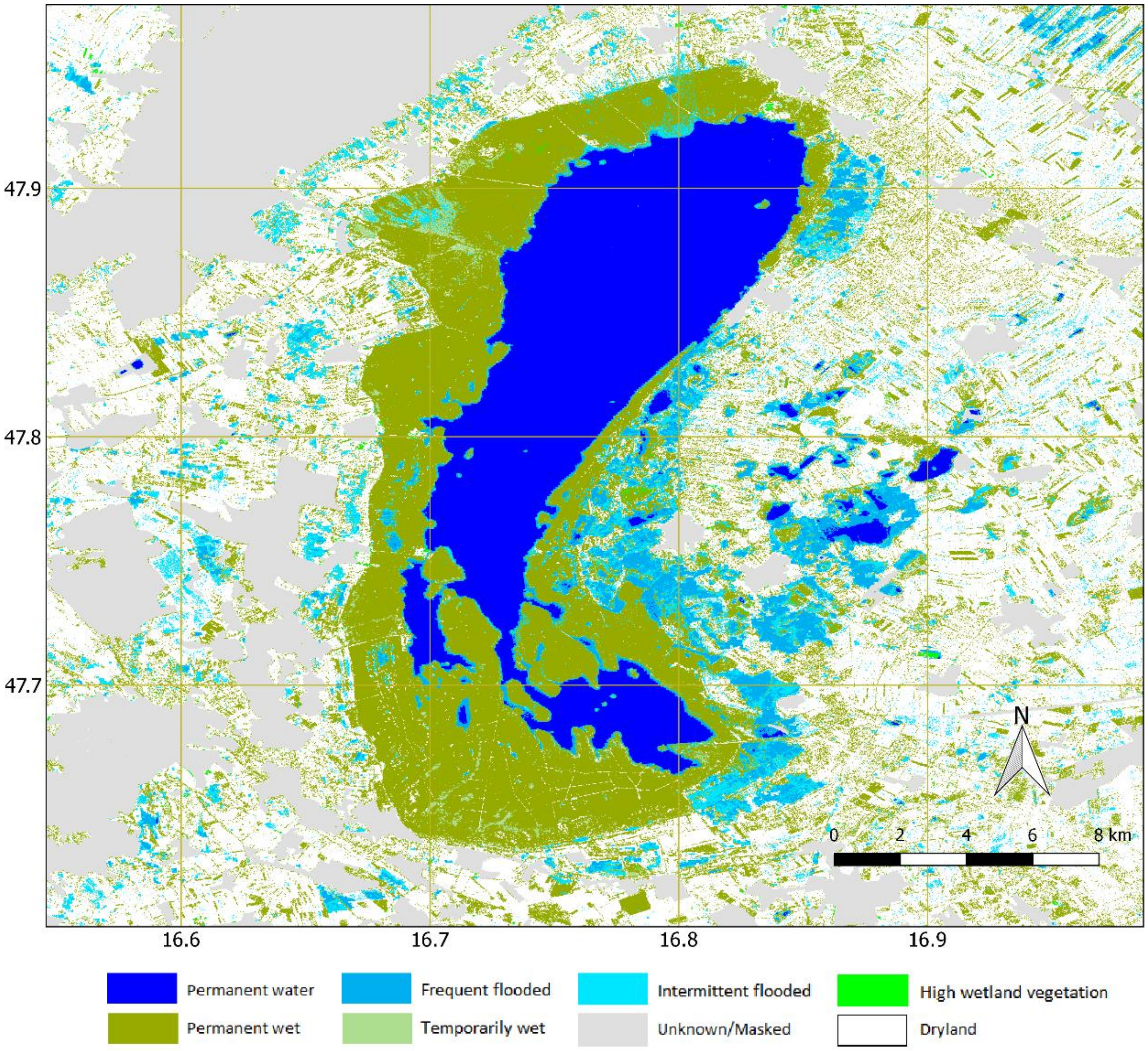
The Wetland mapping processor relies on 6 workflows

- Pre-processing of Level-1 SAR data
- TU Wien model parameters calculations
- Surface Soil Moisture retrieval
- Inundation/water mapping
- Statistical parameters calculation
- Wetland identification

Classification results:
Dryland
Permanent water
Permanent wet
Temporarily wet
Frequent flooding
Intermittent flooding
High wetland vegetation
Unknown/Masked
No data



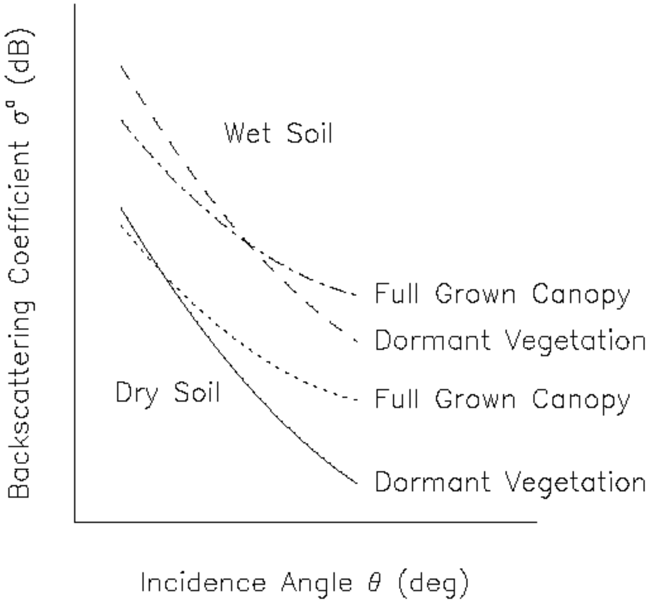
Lake Neusiedl (Sentinel-1 2014-2016)



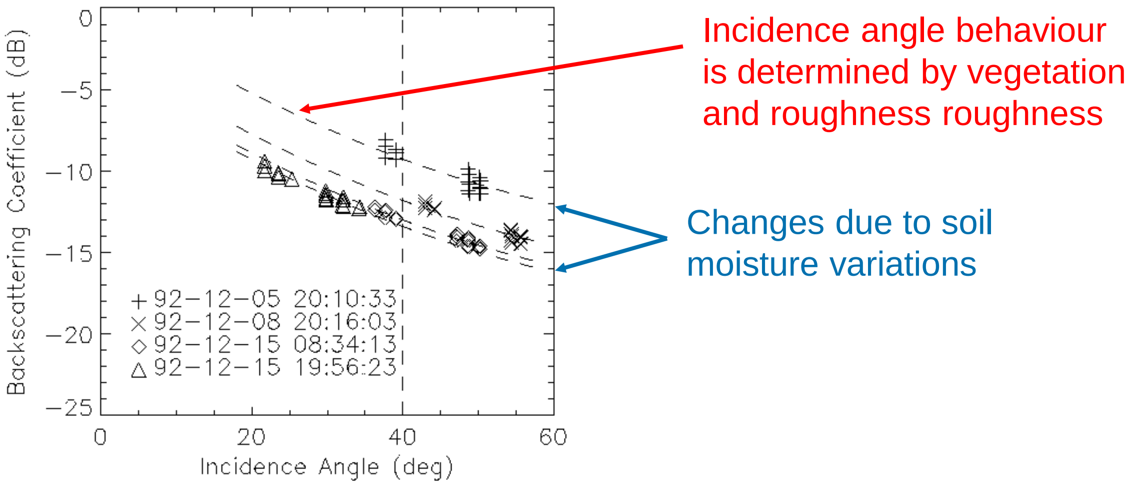
Soil Moisture Monitoring

Backscatter Model for Vegetated Soil Surfaces

- TU Wien model motivated by physical models and empirical evidence
  - Formulated in decibels (dB) domain
  - Linear relationship between backscatter (in dB) and soil moisture
  - Empirical description of incidence angle behaviour
  - Seasonal vegetation effects cancel each other out at the "cross-over angles"
    - dependent on soil moisture



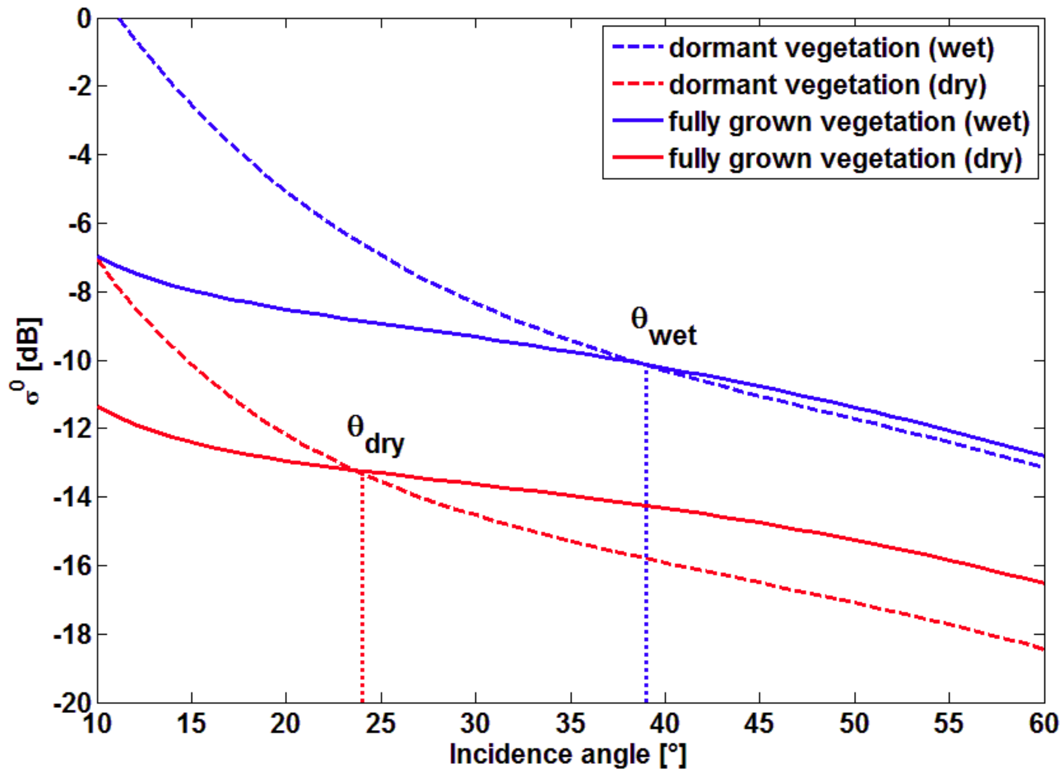
ERS Scatterometer measurements



Functional Behaviour

- The TU Wien backscatter model mimics a semi-empirical backscatter model with a strong surface-volume interaction term

$$\sigma^0 = (1 - f_{nt})\left[\frac{\omega_{tr}\cos\theta}{2}\left(1 - e^{-\frac{2\tau_{tr}}{\cos\theta}}\right) + \sigma_s^0(\theta)e^{-\frac{2\tau_{tr}}{\cos\theta}} + 2\chi R_0\,\omega_{tr}\,\tau_{tr}\,e^{-\frac{2\tau_{tr}}{\cos\theta}}\right] + f_{nt}\,\frac{\omega_{nt}\cos\theta}{2}$$



Mixing model with fraction of non-transparent (*nt*) and transparent (*tr*) vegetation

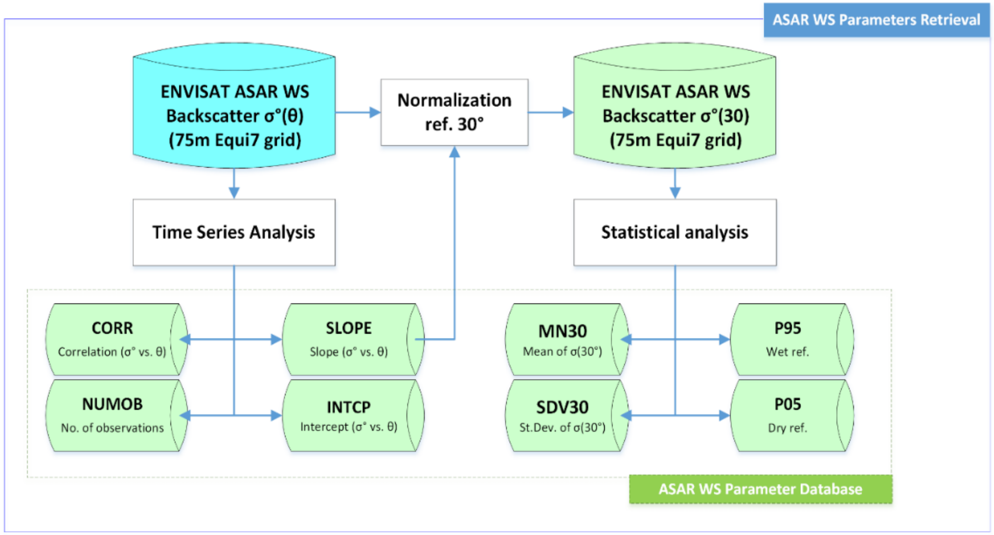
Bare soil scattering $\sigma_s^0(\theta)$ modelled with Improved Integral Equation Method I^2EM

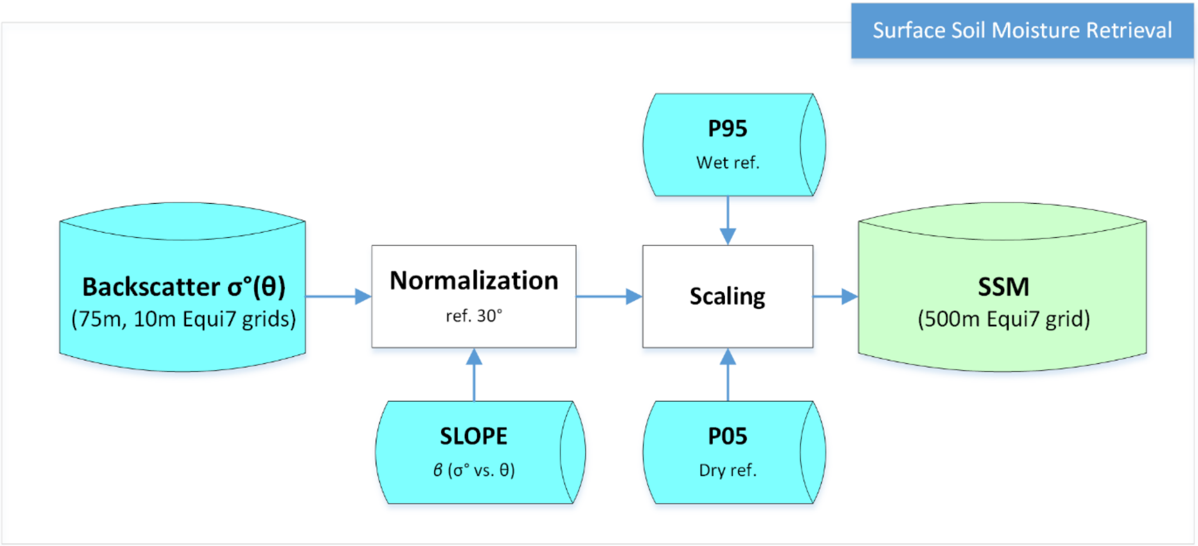
Interaction term enhances soil moisture contributions

Surface Soil Moisture Change Detection

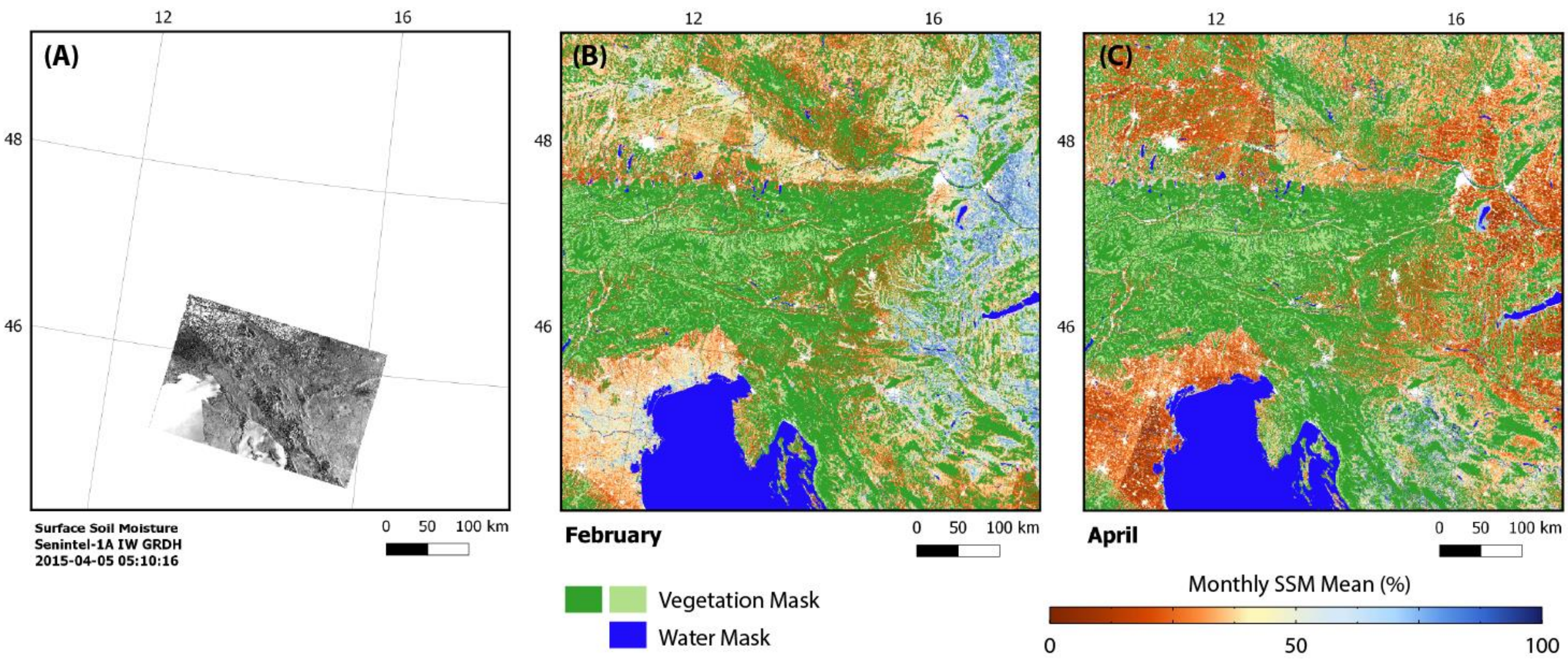
$$\sigma^0(30,t) = \sigma^0(\theta,t) - \beta(\theta - 30)$$

$$\Theta_s(t) = \frac{\sigma^0(30,t) - \sigma^0_{dry}(30)}{\sigma^0_{wet}(30) - \sigma^0_{dry}(30)} \times 100$$



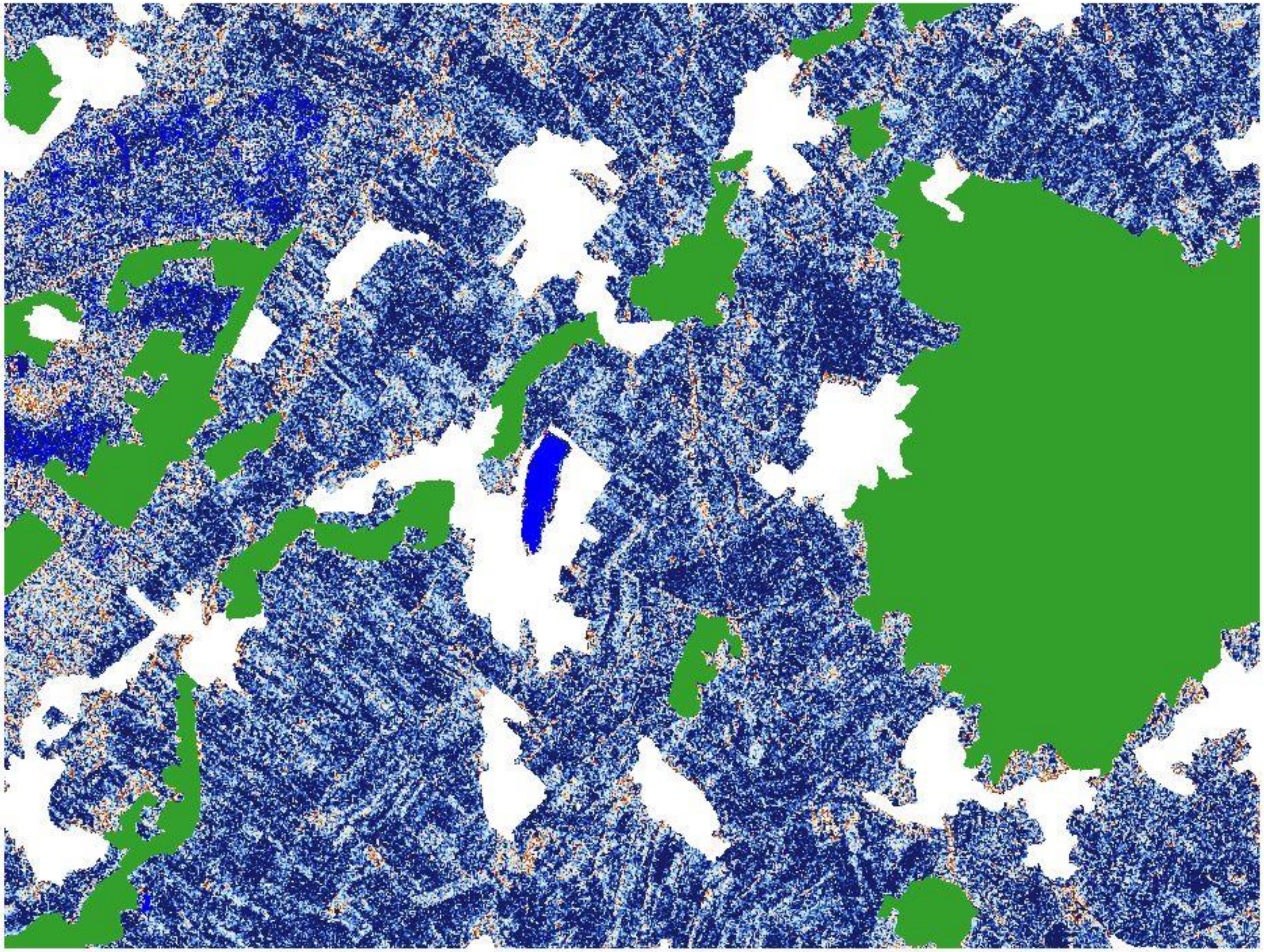


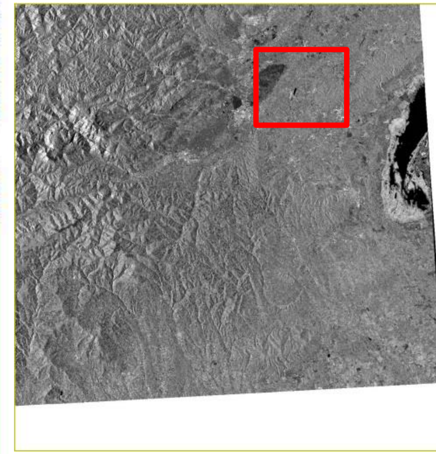
Sentinel-1 Surface Soil Moisture

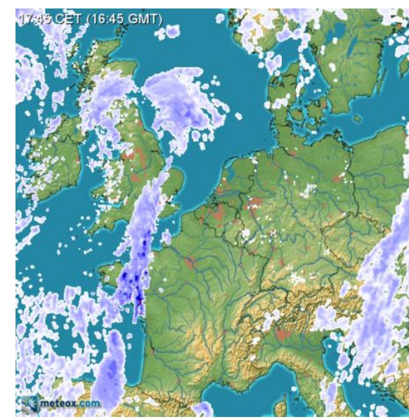


A) Sentinel-1 SSM product, 2015-04-05 05:1:15
B) Monthly average of SSM, February
C) Monthly average of SSM, April.

20 m Sentinel-1 Soil Moisture Index on 2014-11-08

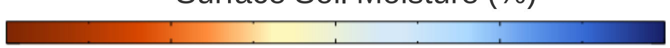






Precipitation map 16:45 UTC
http://www.meteox.com

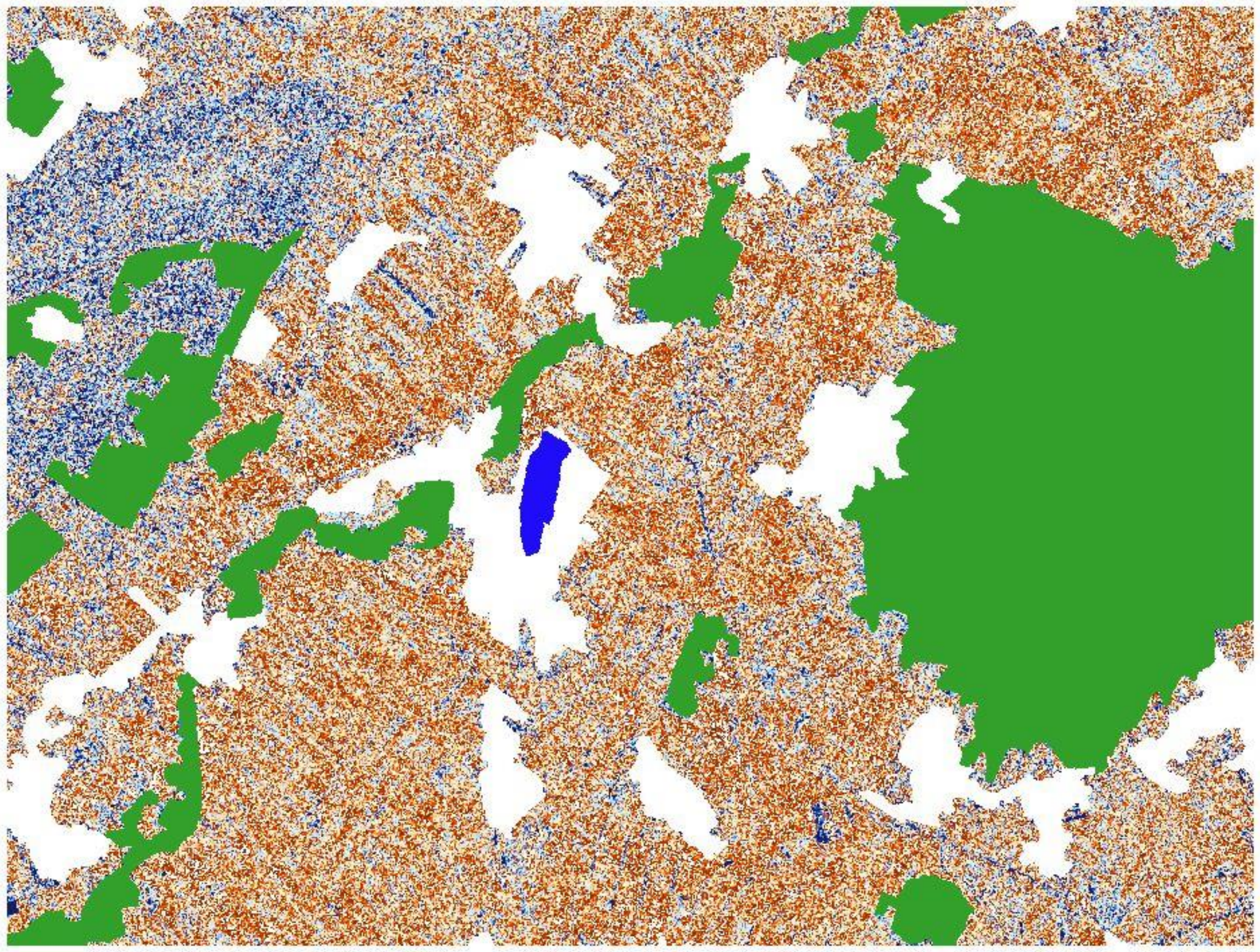
Surface Soil Moisture (%)



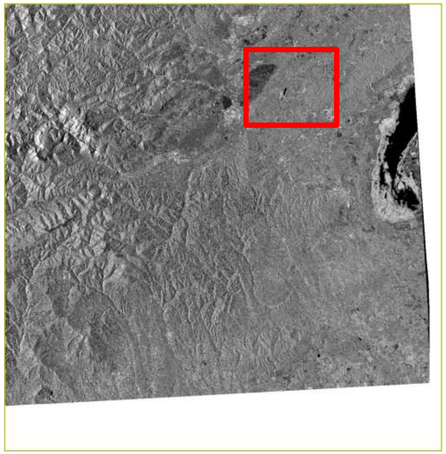
Water bodies

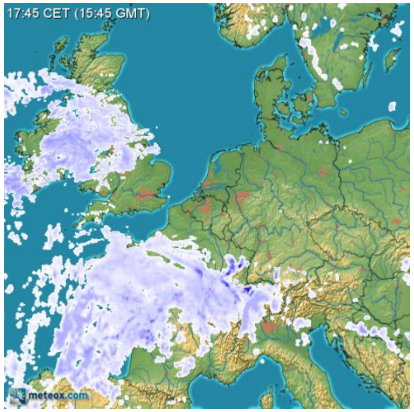
Dense vegetation

20 m Sentinel-1 Soil Moisture Index on 2015-05-02



Surface Soil Moisture (%)





Precipitation map 16:45 UTC
http://www.meteox.com

Water bodies

Dense vegetation

Conclusions

- Sentinel-1 data are of excellent quality
  - Global coverage variable
- Data cubes for supporting time series processing and analysis
  - Model calibration
  - Process understanding
- Sentinel-1 will serve operational monitoring of
  - Soil moisture, water bodies, wetlands, forest area, etc.
- But working with Sentinel-1 data is not easy
  - Big data volume
  - Complex algorithms

eodc

A platform for scientific collaboration, joint software developments and supercomputing

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European Space Agency: Contract No. 4000105732/12/I-NB “TIGER NET”

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