Polarimetric Decompositions for Soil Moisture Retrieval from Vegetated Soils in TERENO Observatories

Thomas Jagdhuber[1], Irena Hajnsek[1,2], Konstantinos P. Papathanassiou[1]

[1]Microwaves and Radar Institute, Pol-InSAR Research Group, DLR
[2]Institute of Environmental Engineering, Earth Observation, ETH Zurich

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ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

thomas.jagdhuber@dlr.de

What do We need for a Soil Moisture Retrieval under Vegetation with Polarimetric SAR Remote Sensing?

Algorithm Requirements

- **Physically-based retrieval approach**
- **Analytically solvable inversion algorithm with reasonable computational costs**
- **High transferability to different areas of interest / no use of a priori knowledge**

Goal of Scientific Research

- **Estimate soil moisture under vegetation cover using polarimetric SAR remote sensing techniques @ L-band and validate with in situ measurements.**

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Experimental Campaigns - TERENO 2011 / 2012

DLR's Novel SAR Sensor: F-SAR

- **Frequency: L-band**
- **Fully polarimetric (HH/HV/VH/VV)**
- **Spatial Resolution (r/a): 2mx0.6m**
- **Date: KW 21-22, KW 19-21 (23.5.-7.6.2011, 10-23.5.2012)**

TERENO Observatories

- **Bavarian Alps: Ammer - KIT**
- **Harz: Bode – UFZ/WESS**
- **Eifel: Rur – FZ Jülich**
- **DEMMIN: Peene – DLR/GFZ**

Ground Measurements

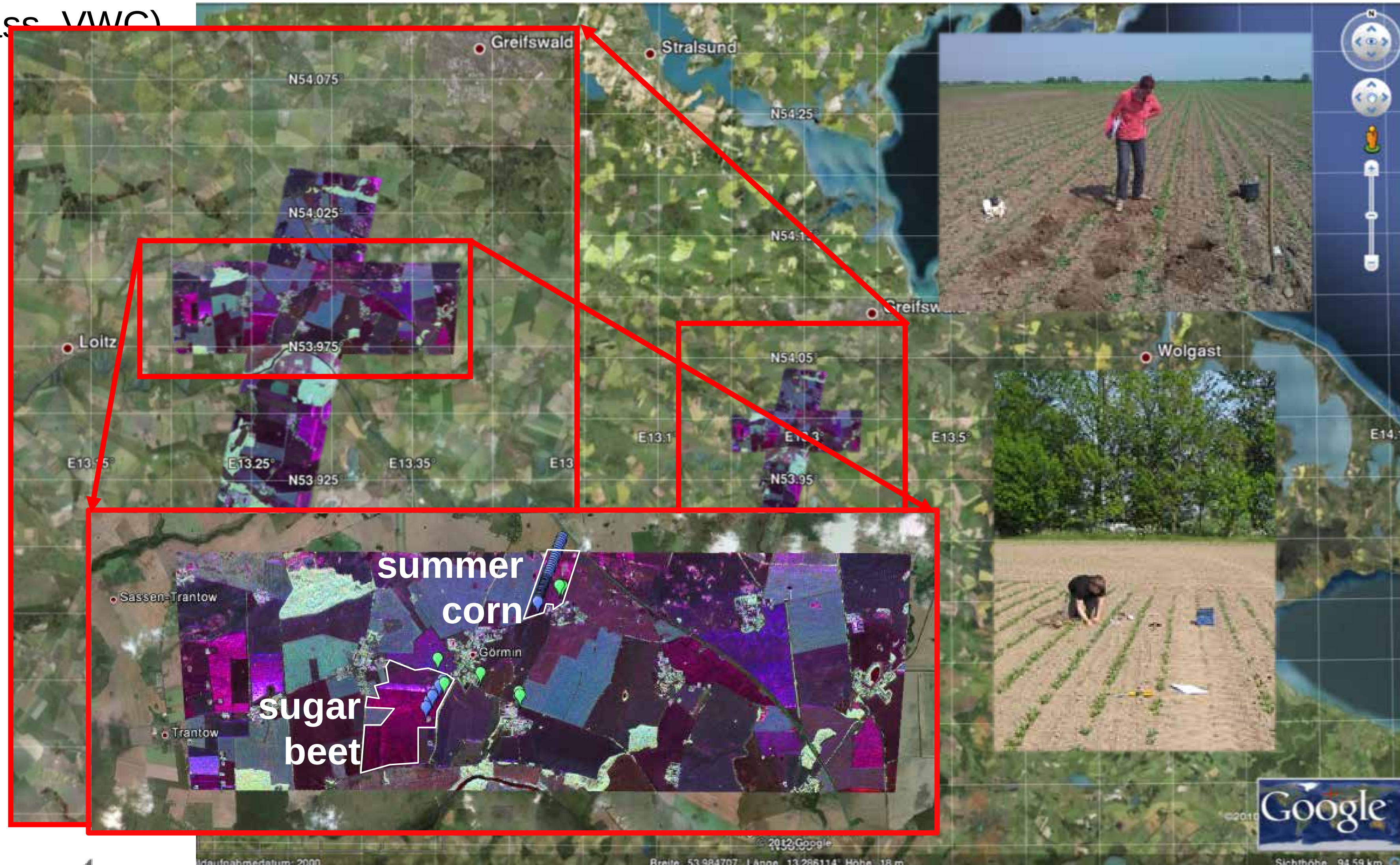
- **Conducted by the research institutes of the observatories.**
- **DLR supported for the Ammer and the Bode catchment in 2011.**

Catchment	Date	Conducted *in situ* measurements
Rur		…oilNet …obes), …ight
Bode		…nobile …oilNet …n height, …s, VWC,
Ammer		…re …es), …ight
DEMMIN	23/05/2012	…SoilNet cluster, mobile probes), **vegetation** height, biomass, VWC

Test site – DEMMIN / Peene Catchment

Flight strips of F-SAR: 11 x 4 km (E-W), 27 x 4 km (N-S)

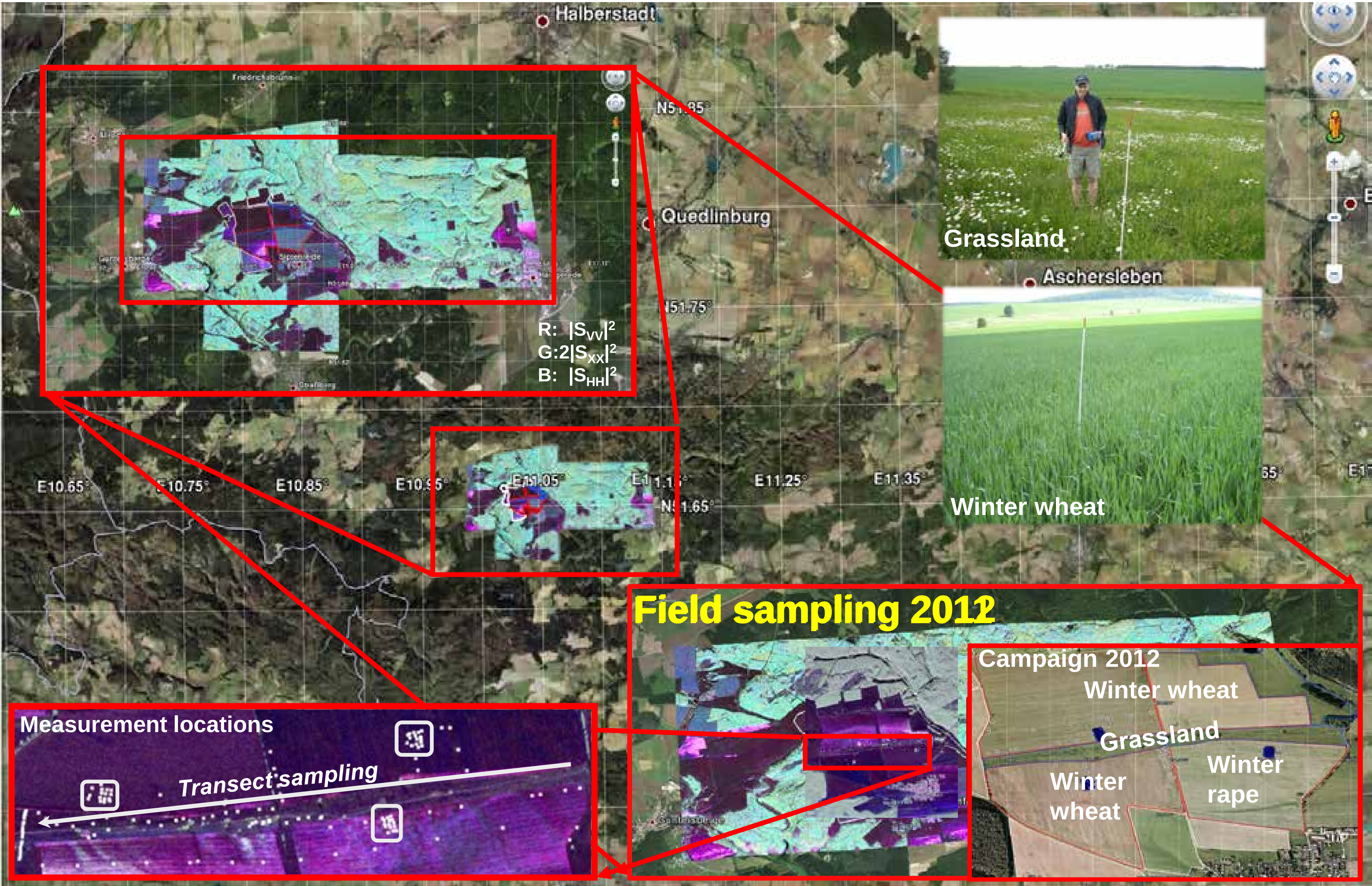
***Field measurements by DLR/GFZ:* Soil moisture ,vegetation** (height, phenology, biomass, VWC)



Test Site – Harz / Bode Catchment

Flight strips of F-SAR: 11 x 4 km (E-W), 6 x 4km (N-S)

Field measurements *by UFZ/WESS***:** **Soil moisture**, **Vegetation** (height, phenology, biomass)



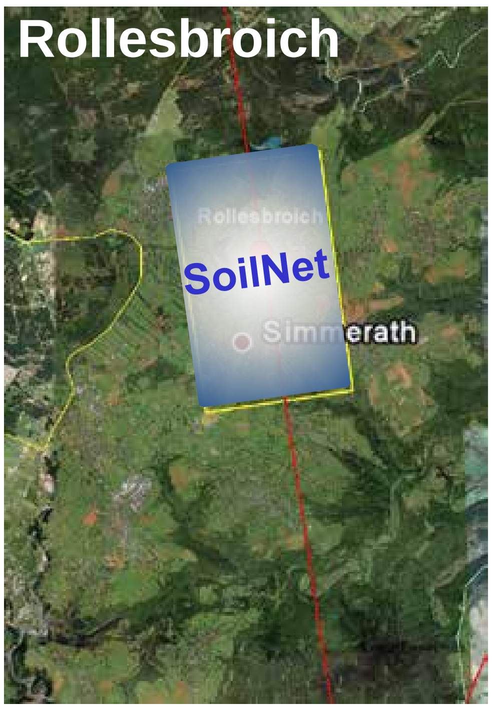
Test Site – Eifel / Rur Catchment

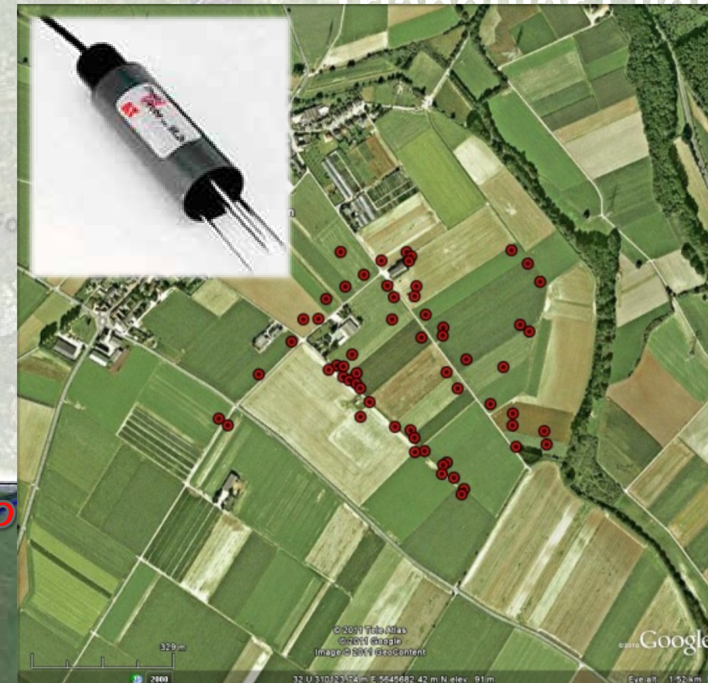
Triangular Flight Configuration

Measurement areas: 5 x 3 km (3) and 10 x3 km

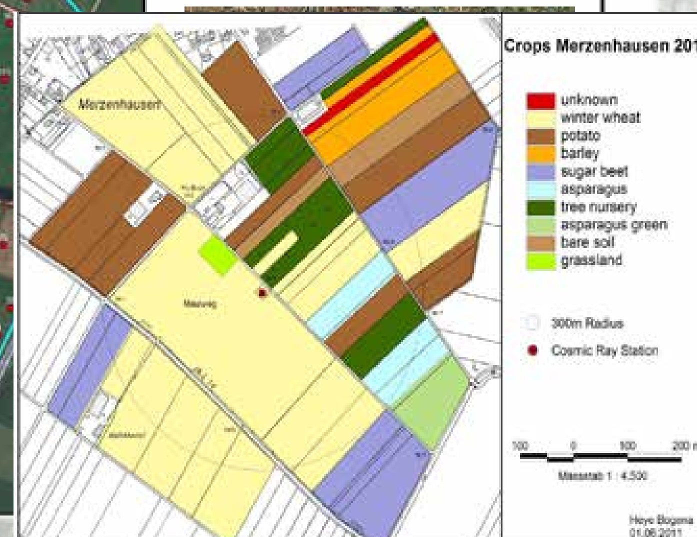
Field Measurements: Soil Moisture, Vegetation

Soil Moisture Network (grassland (Rollesbroich))
Mobile FDR probes (agriculture (Merzenhausen))





Location of measurements



Field crops

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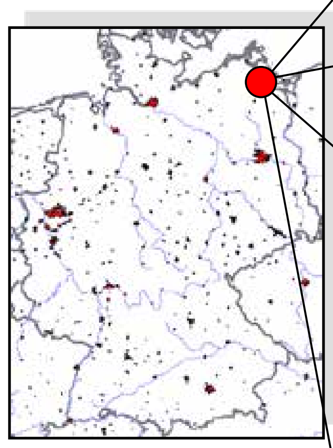
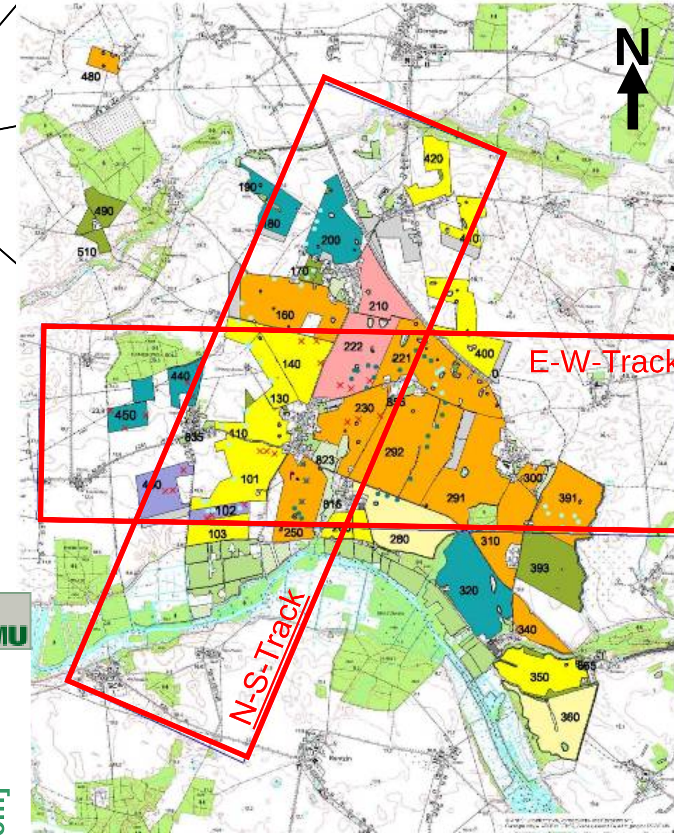
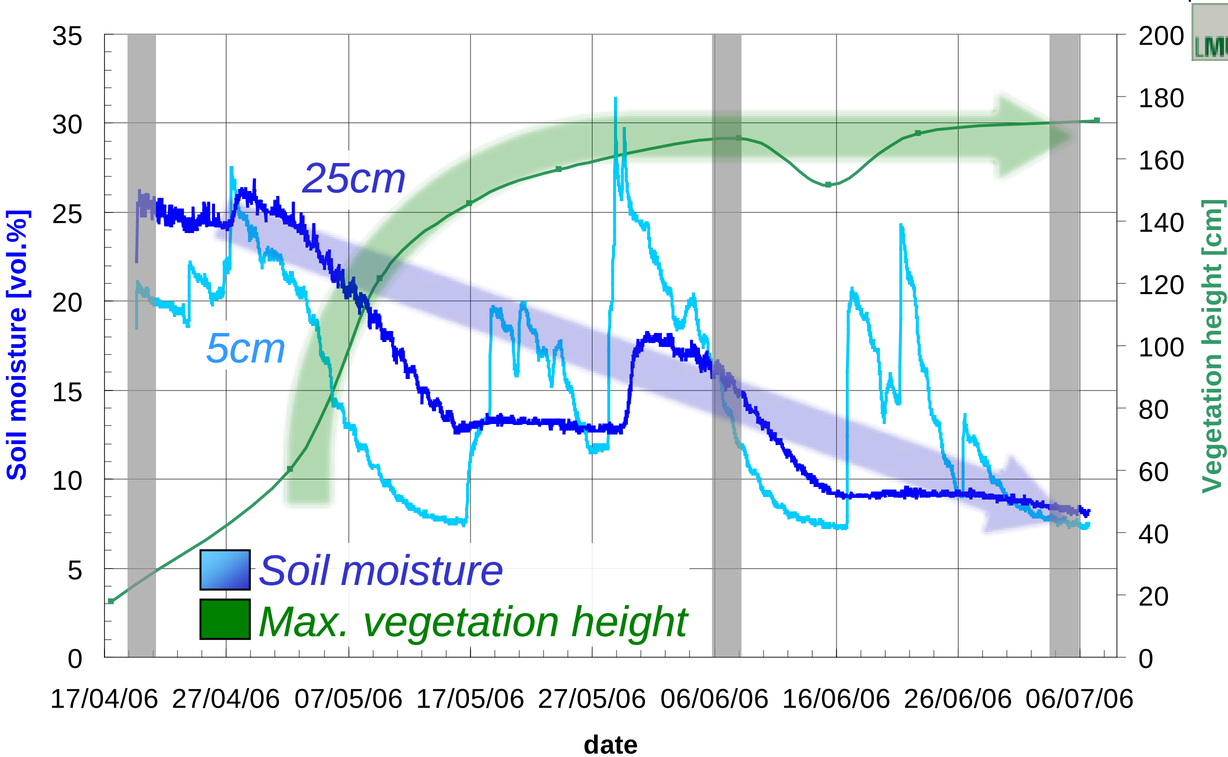
Experimental Campaign – AgriSAR 2006

Agricultural parameter estimation over an entire vegetation growth period (April-August)

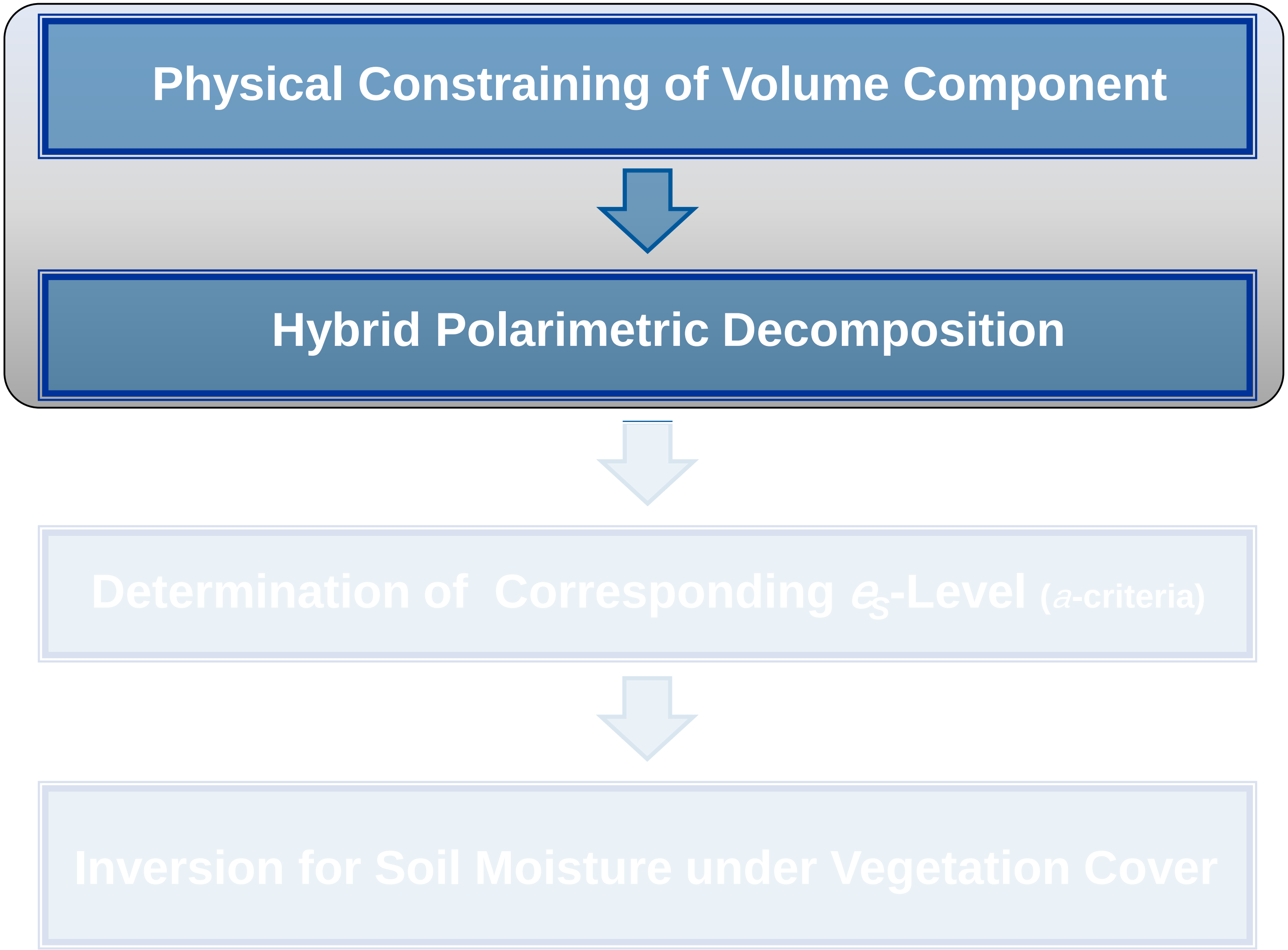
16 fully polarimetric Radar data acquisition flights with the **E-SAR** system at L-band for two flight headings (**E-W-track, N-S-track**) and **in situ measurements** on test fields for soil moisture, soil roughness, vegetation height, phenology, biomass,…



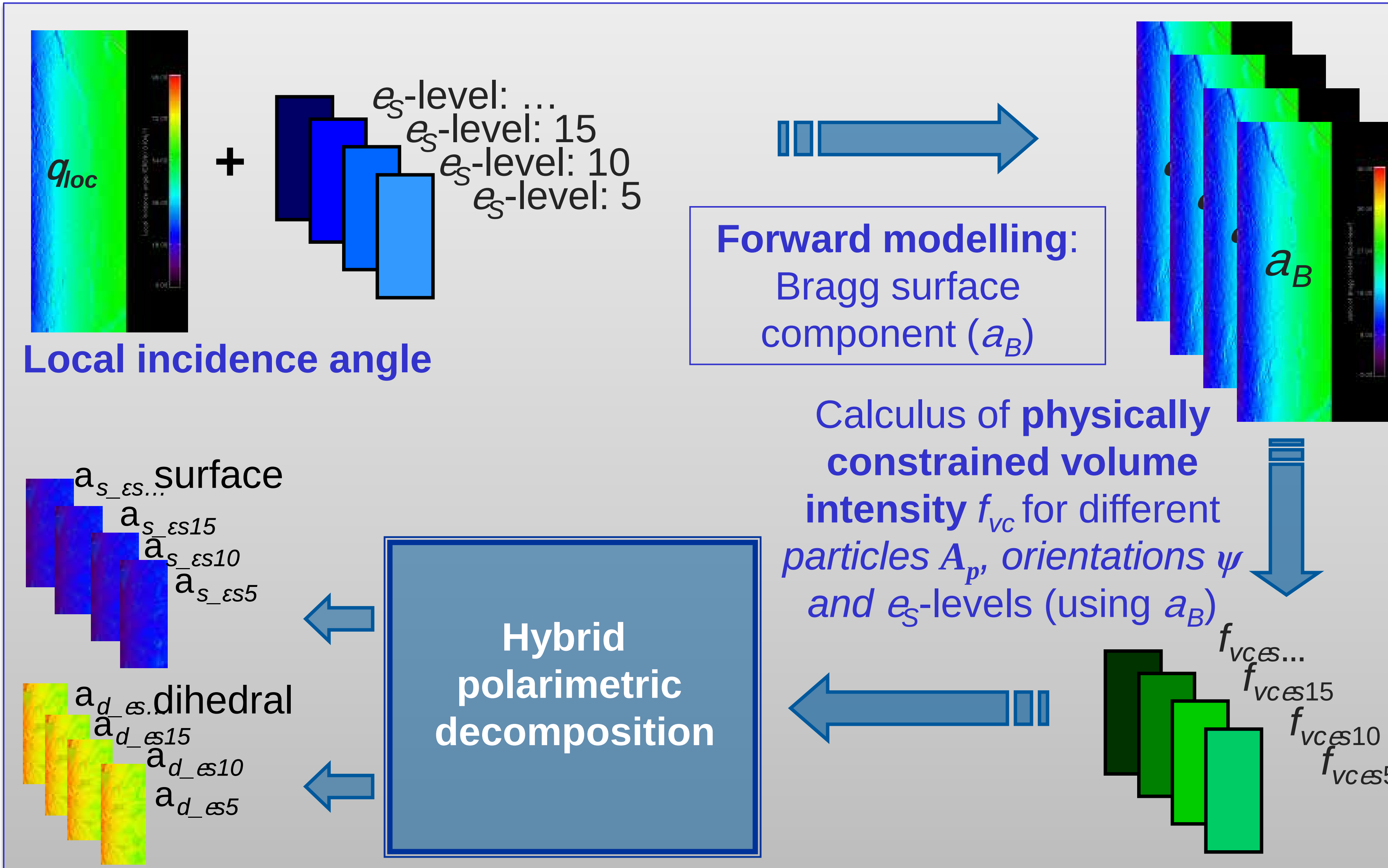




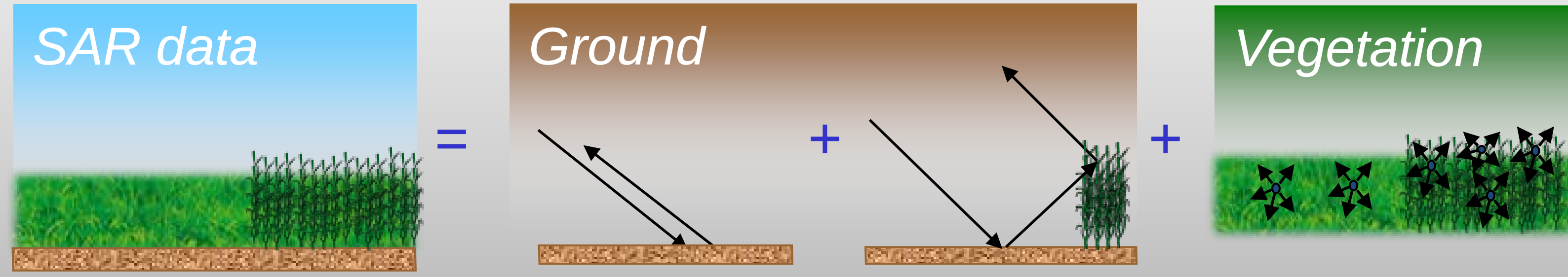
Scheme of Hybrid Decomposition and Inversion for Soil Moisture under Vegetation Cover



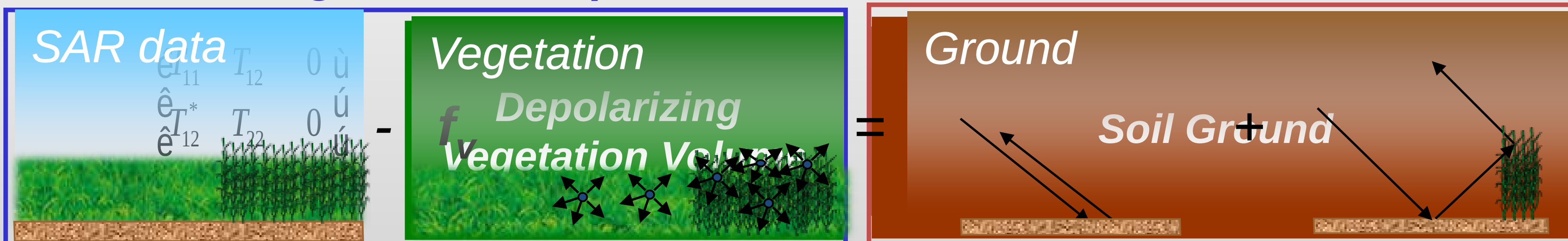
Physically Constrained Hybrid Polarimetric Decomposition



Basic Principle of Hybrid Polarimetric Decomposition



Removal of vegetation component



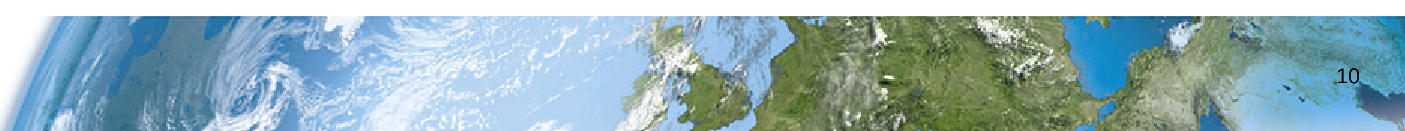
Hybrid Polarimetric Decomposition

Physically constrained volume intensity (f_{vc}) with surface scattering (α_b)

Volume intensity (f_v)

$$f_{vc} = 4T_{33} \quad T_{11} / V \quad T_{33} \; T_{22} + \csc(2a_b)^2 \sqrt{\left| (-T_{12} + T_{12}^*) + (T_{12} + T_{12}^*)\cos(2a_b) \right|^2 \sin(2a_b)^2}$$

Not physically constraint volume intensity!



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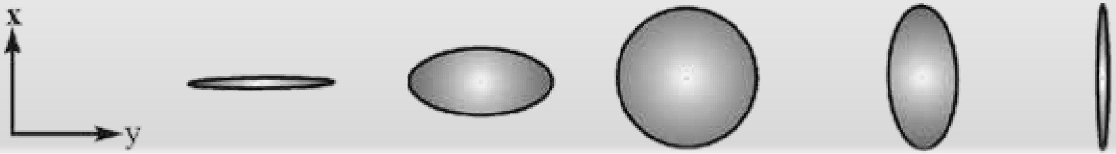
Modification of Hybrid Decompositions – Generalized Volume Scattering of Oriented Spheroids

- *Volume modelling of a cloud of* ***uniformly shaped (A_p) spheroids*** *with a* ***3D-distribution of orientations (ψ,τ,χ)*** *in space*

Particle anisotropy A_P linked to the **shape of spheroids** forming the volume



Generalized Vegetation Scattering Volume

$$T_V = \frac{1}{1+A_p^2}\begin{bmatrix} \frac{1}{2}(A_p+1)^2 & \frac{1}{2}(A_p^2-1)\,\mathrm{sinc}(2\Delta\psi) & 0 \\ \frac{1}{2}(A_p^2-1)\,\mathrm{sinc}(2\Delta\psi) & \frac{1}{4}(A_p-1)^2(1+\mathrm{sinc}(4\Delta\psi)) & 0 \\ 0 & 0 & \frac{1}{4}(A_p-1)^2(1-\mathrm{sinc}(4\Delta\psi)) \end{bmatrix}$$

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Retrieval of the Ground Scattering Components

SAR Data - Depolarizing Vegetation Volume = Soil Ground

Hybrid Polarimetric Decomposition

Intensity of ground components (f_d, f_s)

$$f_{d,s} = \frac{1}{2}\left(T_{11} + T_{22} - f_V V_{11} - f_V V_{22} \pm \sqrt{-4\left(T_{22}\left(T_{11} - f_V V_{11}\right) + \left(T_{12} - f_V V_{12}\right)\left(f_V V_{12}^* - T_{12}^*\right) + f_V\left(f_V V_{11} - T_{11}\right)V_{22}\right) + \left(T_{11} + T_{22} - f_V\left(V_{11} + V_{22}\right)\right)^2}\right)$$

From eigenvalues

Scattering mechanism of ground components (α_d, α_s)

$$\alpha_{d,s} = \arccos\left(\left(1 + \left|\frac{2\left(T_{12}^* - f_V V_{12}^*\right)}{T_{11} - T_{22} - f_V V_{11} + f_V V_{22} \pm \sqrt{T_{11}^2 + \left(T_{22} + f_V V_{11}\right)^2 + 4\left(T_{12} - f_V V_{12}\right)\left(T_{12}^* - f_V V_{12}^*\right) - 2T_{11}\left(T_{22} + f_V\left(V_{11} - V_{22}\right)\right) - 2f_V\left(T_{22} + f_V V_{11}\right)V_{22} + f_V^2 V_{22}^2}}\right|^2\right)^{-\frac{1}{2}}\right)$$

From eigenvectors

Physically meaningful separation into ground components

$\alpha_d + \alpha_s = \pi/2$

Orthogonality condition

- $\alpha \in [0, \pi/4]$ **Surface** scattering ⇒ α_s
- $\alpha \in [\pi/4, \pi/2]$ **Dihedral** scattering ⇒ α_d

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Scheme of Hybrid Decomposition and Inversion for Soil Moisture under Vegetation Cover

Physical Constraining of Volume Component

↓

Hybrid Polarimetric Decomposition

↓

Determination of Corresponding e_s-Level (a-criteria)

Assumption: Random Volume of Dipoles (A_p=0, $\Delta\psi=\pi/2$)

↓

Inversion for Soil Moisture under Vegetation Cover

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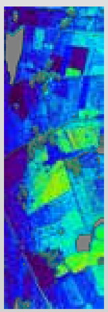
Determination of Mean ε_s-Level of Scene (α_1-criterion)

α_1-criterion : Determination of mean dielectric level (ε_s-*level)* within the scene

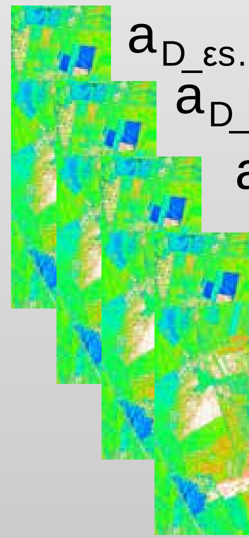
α_1



with forest/urban mask

–

=



Surface dominant scattering

α_1<25°

Find mean-value closest to zero:

$\text{mean}(\{\alpha_{D\_\varepsilon s...}\}_{\alpha 1<25°})$

$\text{mean}(\{\alpha_{D\_\varepsilon s15}\}_{\alpha 1<25°})$

$\text{mean}(\{\alpha_{D\_\varepsilon s10}\}_{\alpha 1<25°})$

$\text{mean}(\{\alpha_{D\_\varepsilon s5}\}_{\alpha 1<25°})$

⇨ **Corresponding Mean α_s**

⇨ **Corresponding Mean ε_s-level**

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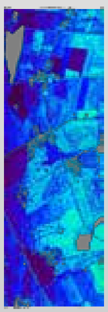
Pixelwise Refinement of ε_s-Level (α_{min}-criterion)

α_{min}-criterion : Refinement of dielectric level for each pixel

$\min_{a_s, \varepsilon_s}$

$a_{min} = \min(a_1, a_2)$



with forest/urban mask

$-$

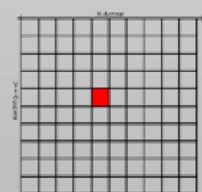
$a_{s\_\varepsilon s...}$

$a_{s\_\varepsilon s15}$

$a_{s\_\varepsilon s10}$

$a_{s\_\varepsilon s5}$

Pixelwise Comparison



Minimum exists

Corresponding a_s and ε_s-level from α_{min}-criterion

soil dominated pixel

No minimum exists

Corresponding a_s and ε_s-level from α_1-criterion

vegetation dominated pixel

Scheme of Hybrid Decomposition and Inversion for Soil Moisture under Vegetation Cover

Physical Constraining of Volume Component

⇩

Hybrid Polarimetric Decomposition

⇩

Determination of Corresponding e_s-Level (*a*-criteria)

⇩

Inversion for Soil Moisture under Vegetation Cover

Soil Moisture Inversion from Surface Scattering Component

Polarimetric SAR data

Surface scattering component *from* ***hybrid polarimetric decomposition***

$$b = -\tan(a_s)$$

Surface scattering model

Bragg scatter modelling *with q_{loc} and a* ***variety of soil dielectric constants e_S***

$$b_m = \frac{R_{HH} - R_{VV}}{R_{HH} + R_{VV}}$$

$$R_{HH}, R_{VV} = f(e_S, q_{loc})$$

Minimization

$$\min_{e_s}\{|b - b_m|\}$$

e_S

Pedo-Transfer Function

of Topp et al.

Soil moisture [vol.%]

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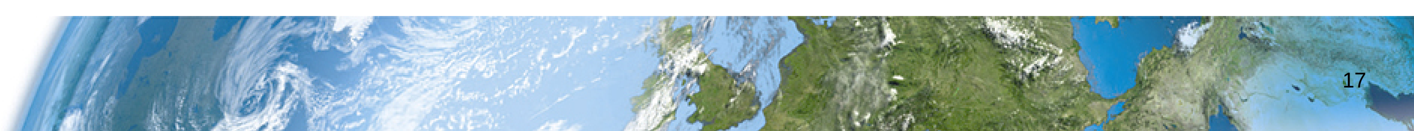
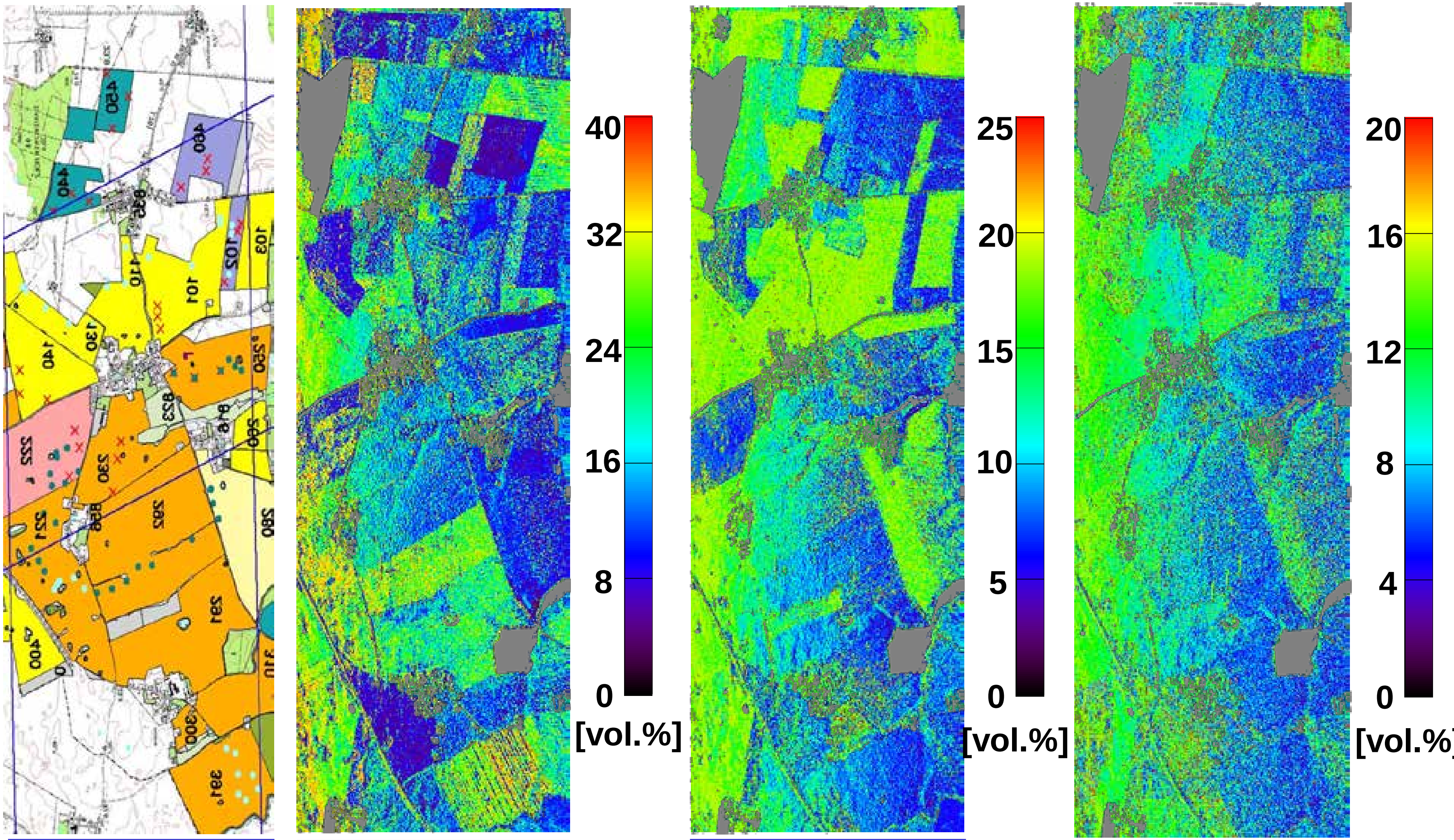


Moisture Monitoring along an Entire Agricultural Growth Cycle for AgriSAR 2006

=Mask for forested + urban areas



Land use | 19. APRIL | 7. JUNE | 5. JULY

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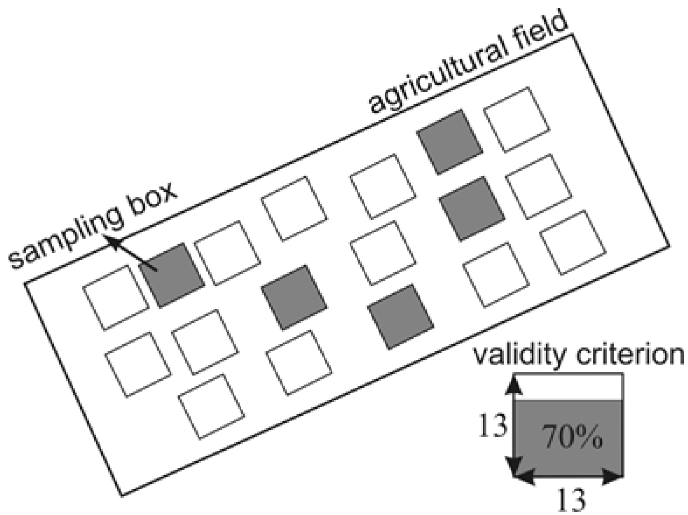
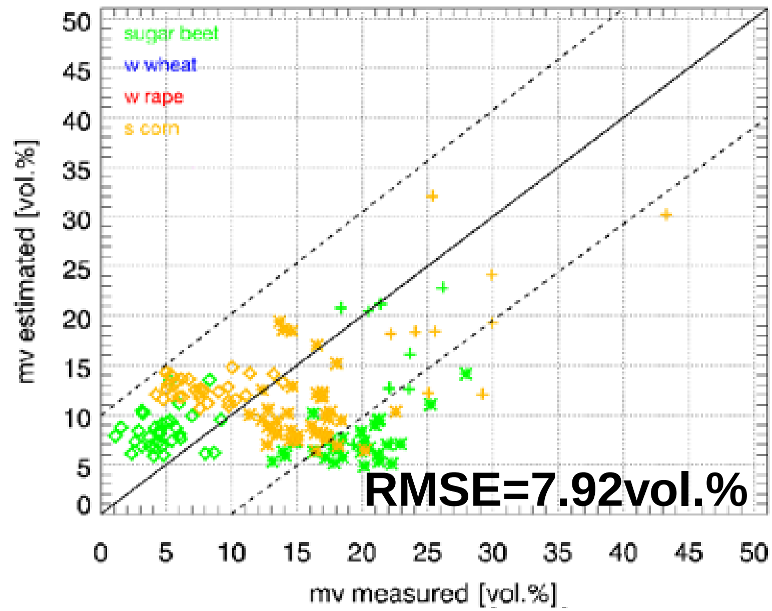
Validation of Soil Moisture Inversion under Vegetation Cover

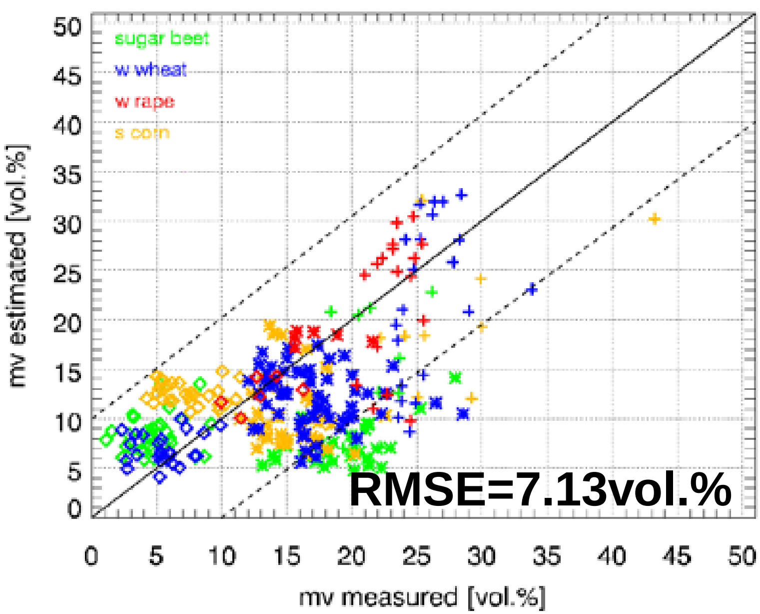
Validation criteria



Summer crops

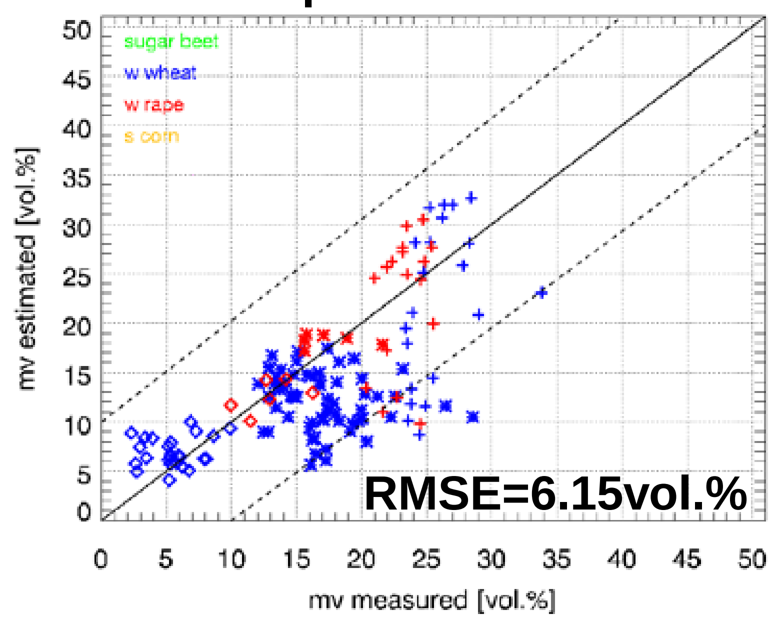


All crops

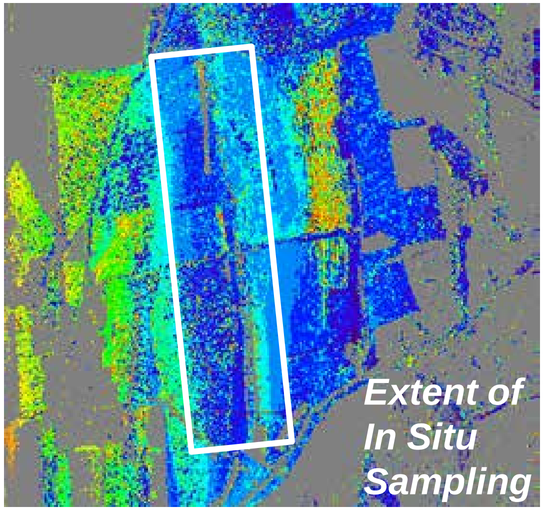


+ AgriSAR April / sugar beet
✱ AgriSAR June / summer corn
◇ AgriSAR July / winter barley
∗ winter wheat
△ winter rape

Winter crops

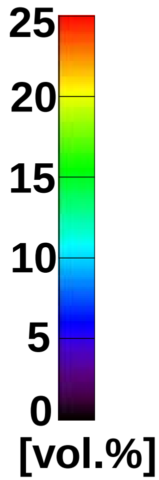


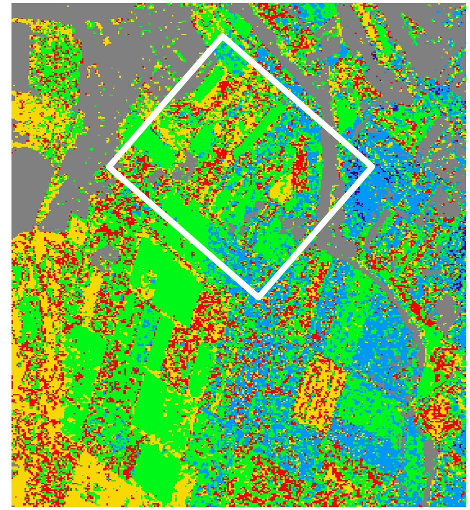
Moisture Monitoring within TERENO Observatories for 2011



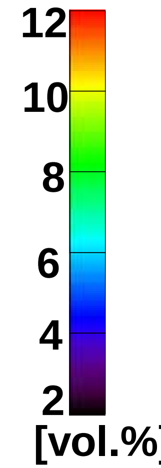
=Mask for forested + urban areas

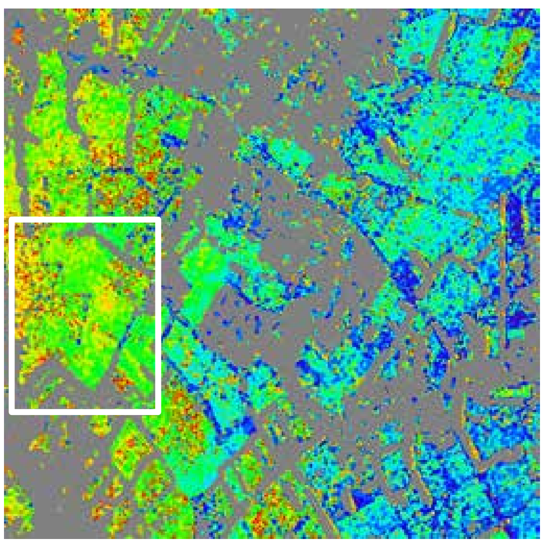
Bode



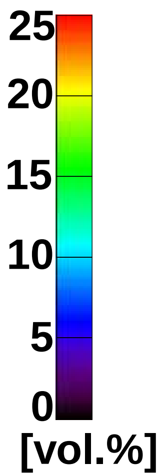


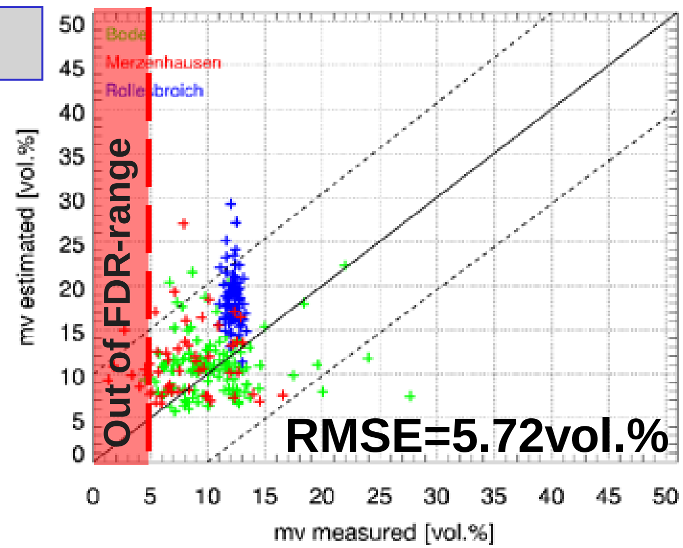
Merzenhausen





Rollesbroich





Validation

Validation box: 13x13

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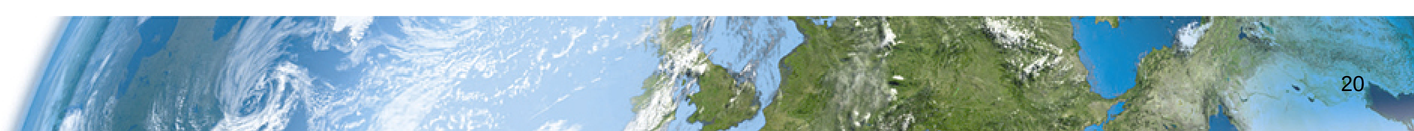
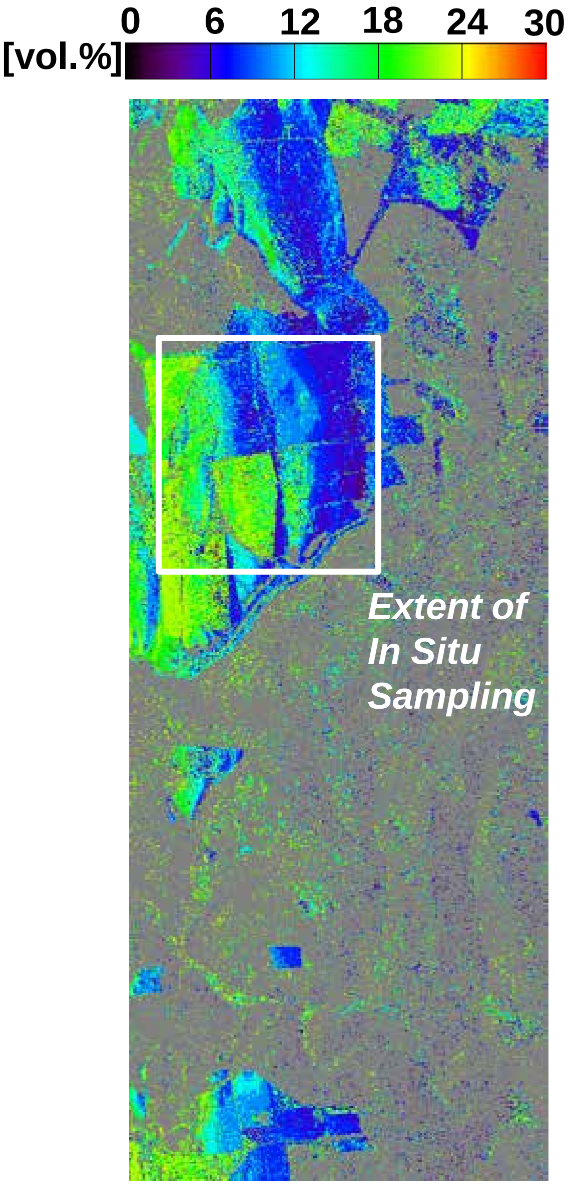
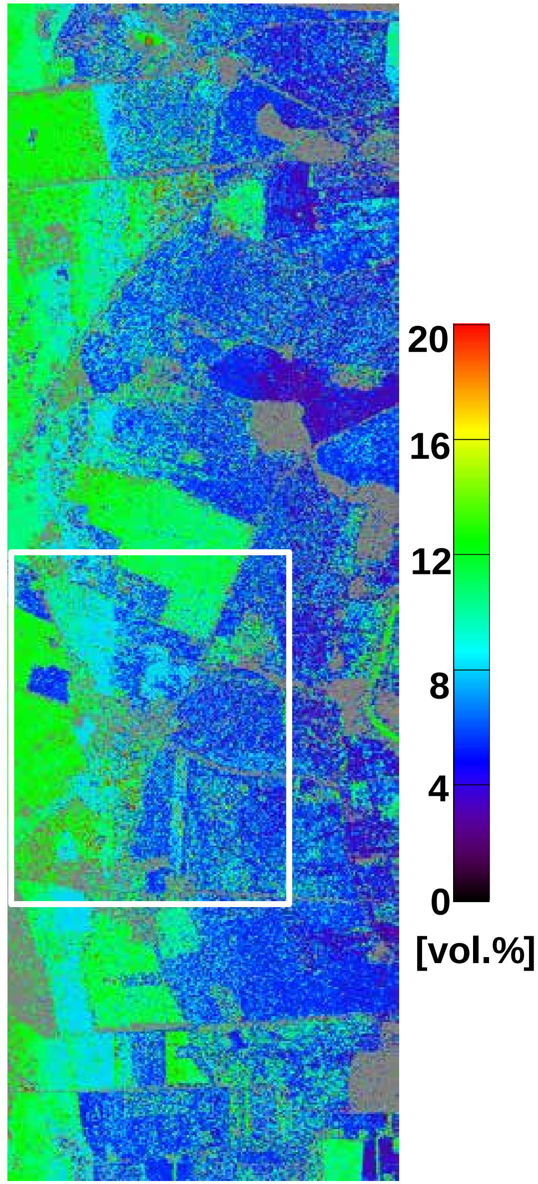


Moisture Monitoring within TERENO Observatories for 2012



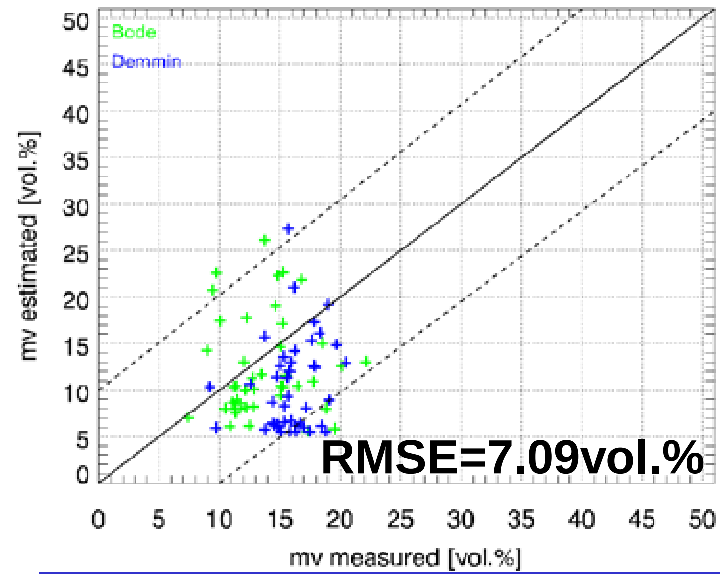
Bode



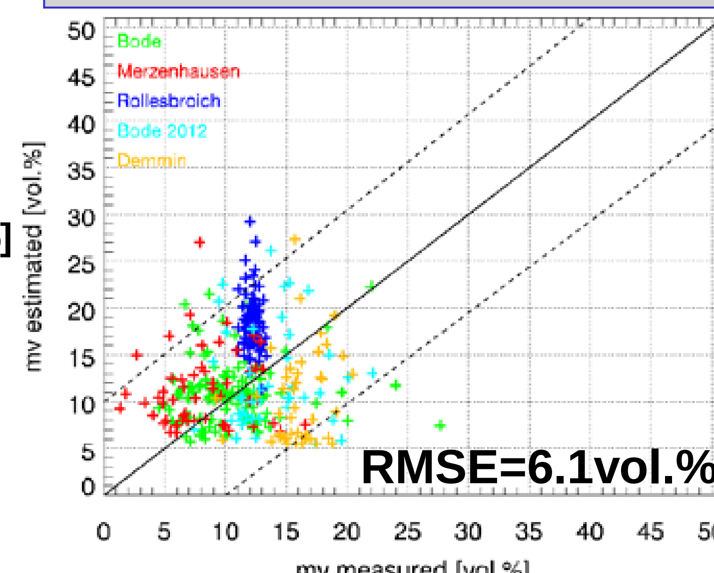
Demmin

=*Mask for forested + urban areas*

Validation of TERENO 2012



Validation of TERENO 2011+2012

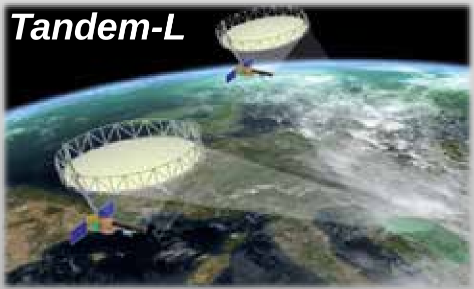


Validation box: 13x13

Summary and Outlook

- Inversion of soil moisture under various agricultural vegetation is feasible with very high inversion rates (>98%) using hybrid decomposition and inversion techniques on fully polarimetric SAR data @ L-band.
    - High-resolution (compared to passive sensors) and wide area (compared to field-based techniques) mapping is possible.
    - Monitoring period covers the entire growing season.
- Validation with ground-based sensors (FDR, TDR, Wireless SoilNets) revealed a well agreement with the SAR-based moisture estimates resulting in an RMSE from 5.7vol.% to 7.9vol.% including the growth season and a variety of crop types in different phenological stages.

- Further investigations on the retrieval algorithm towards operationality.
    - Oriented vegetation volume scattering (variable A_p and $\Delta\psi$),
    - Robust volume type selection,
    - Residual incidence effects (multi-angular data).
- Application adaption to forested areas for a spatially continuous monitoring strategy.
- Algorithm implementation for upcoming, space-borne, long-wavelength SAR missions (ALOS-2, Tandem-L) heading towards a global monitoring strategy.



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Thank you very much for your attention!
Acknowledgement to all the TERENO and AgriSAR campaign members!