Ministry of Science and Higher Education
Republic of Poland

JAGIELLONIAN UNIVERSITY IN KRAKÓW

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15 - 19 June 2026 | Auditorium Maximum of the Jagiellonian University, Kraków, Poland

FRINGE 2026

Estimating Soil Moisture Anomalies via Temporal-SKP Decomposition: AKQUA-SMA

Giovanni Costa, Stefano Tebaldini, Andrea Virgilio Monti Guarnieri

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RIDE RADAR IMAGING & DIGITAL EARTH

OUTLINE

- **INTRODUCTION**

- **AKQUA-SMA** :
  - Algorithm philosophy and scheme;
  - SKP decomposition in the Temporal-Polarimetric framework (T-SKP);
  - T-SKP solution selection;
  - Stitching.

- **AKQUA-SMA on real data**:
  - HydroSoil Campaign introduction;
  - Barley Campaign.

- **CONCLUSIONS & OUTLOOKS**

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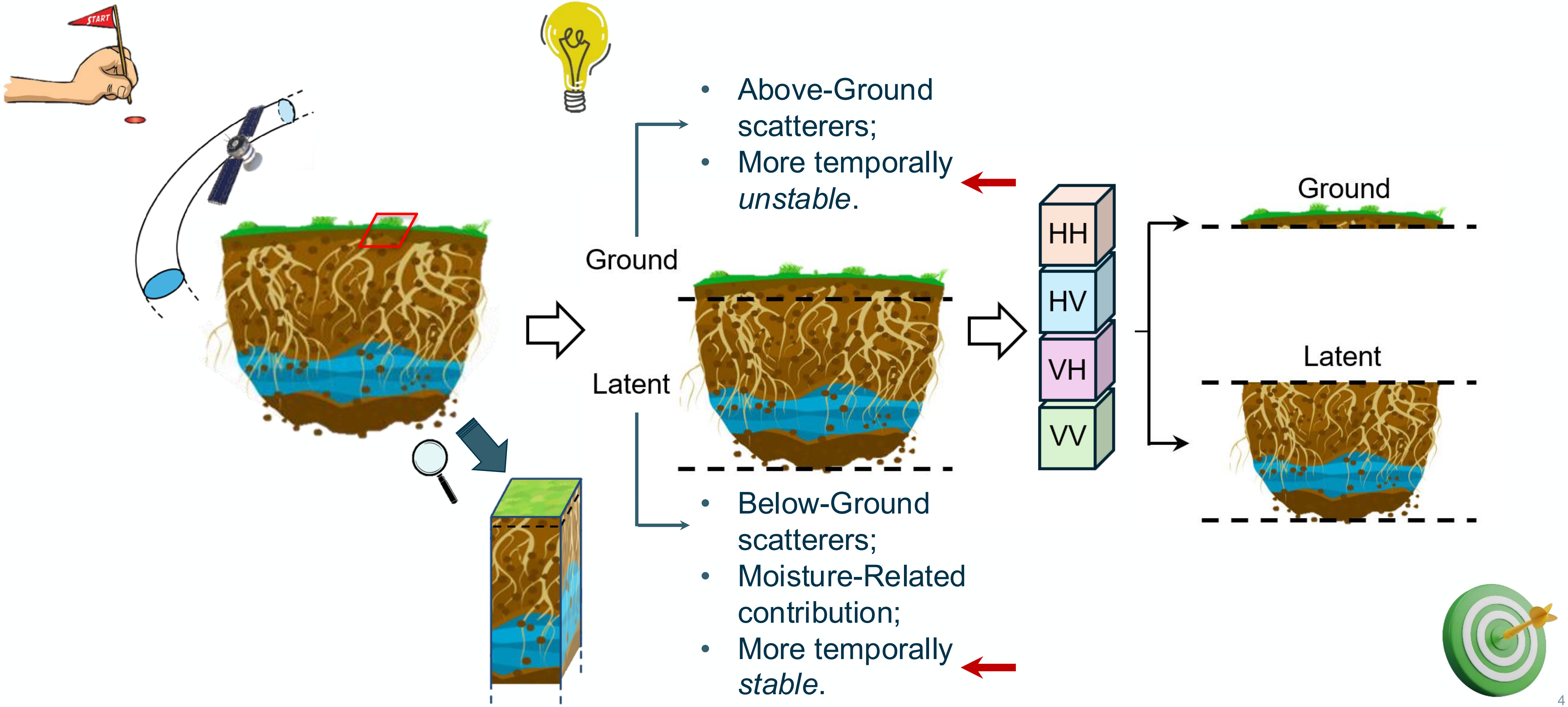
START
Ground
Latent
• Above-Ground scatterers;
• More temporally *unstable*.
• Below-Ground scatterers;
• Moisture-Related contribution;
• More temporally *stable*.
HH
HV
VH
VV
Ground
Latent

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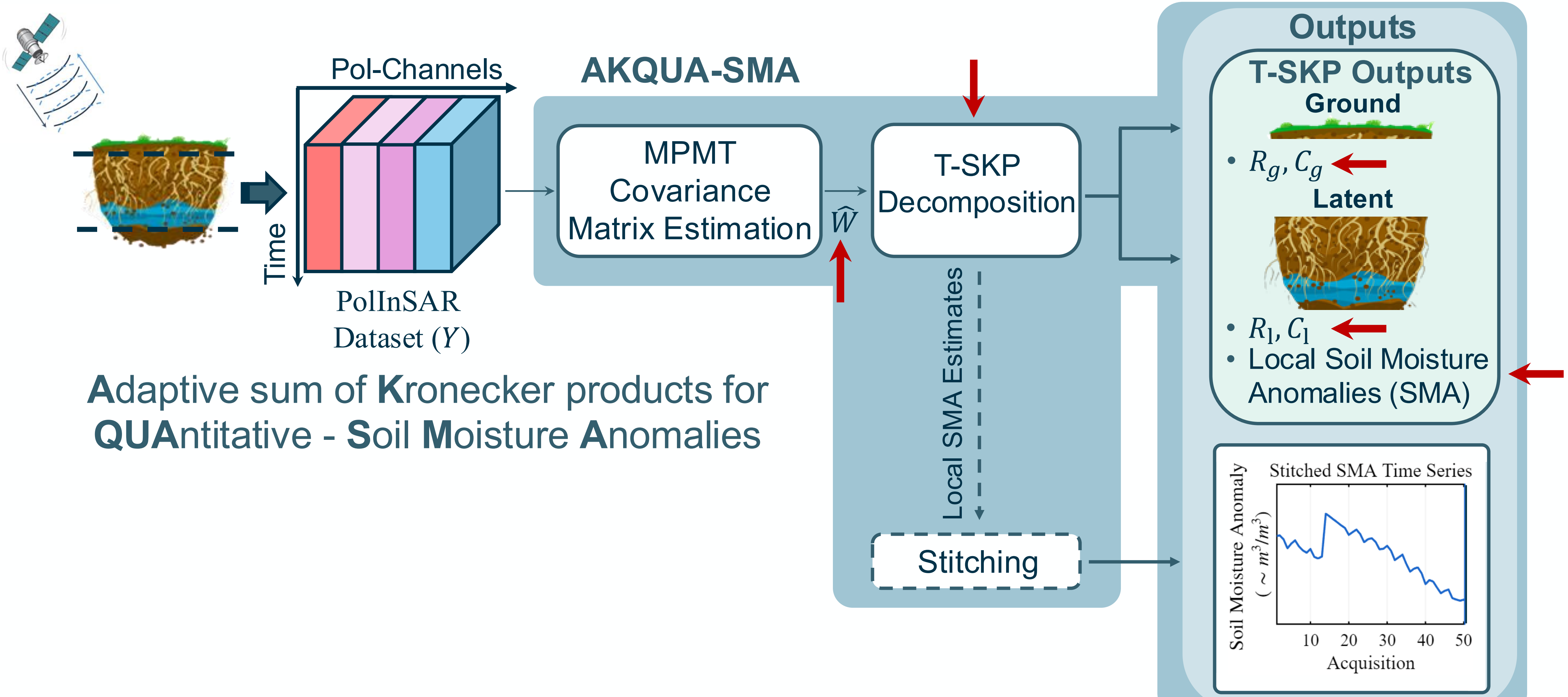
AKQUA-SMA


Pol-Channels
Time
PolInSAR Dataset (Y)
AKQUA-SMA
MPMT Covariance Matrix Estimation
$\widehat{W}$
T-SKP Decomposition
Local SMA Estimates
Stitching
Outputs
T-SKP Outputs
Ground
• R_g, C_g
Latent
• R_l, C_l
• Local Soil Moisture Anomalies (SMA)
Stitched SMA Time Series
Soil Moisture Anomaly ($\sim m^3/m^3$)
10
20
30
40
50
Acquisition
Adaptive sum of Kronecker products for QUAntitative - Soil Moisture Anomalies

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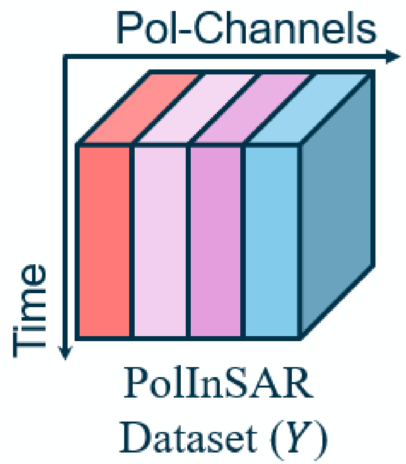
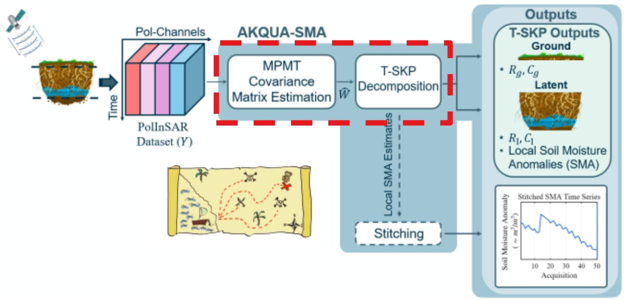




ORGANIZE

$$y_{MPMT} = [y_{HH}^T \ y_{HV}^T \ y_{VV}^T \ ]^T \in \mathbb{C}^{[3N,L]},$$

with N number of acquisitions per channel and

L number of looks

ESTIMATE

Intuitively, the MPMT covariance matrix tells the story of how scattering mechanisms behave over time across co/cross-pol channels.

$$W_K = \mathbb{E}[y_{MPMT} \, y_{MPMT}^H] \in \mathbb{C}^{[3N,3N]}$$

Number of scattering mechanisms

- How many K ? 2 (Ground and Latent);
- The T-SKP solution isn't unique. How do you choose it?

Apply T-SKP Decomposition

$$W_K = \sum_{k=1}^{K} C_k \otimes R_k$$

Structure Matrix

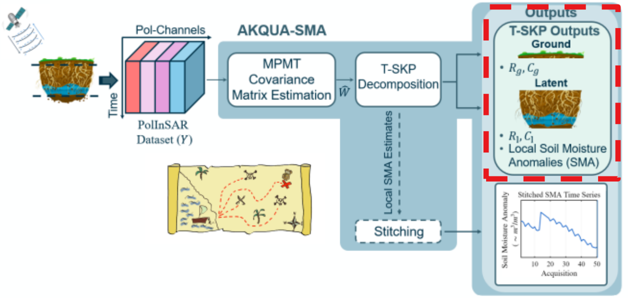
Polarimetric Signature Matrix

Hermitian Semipositive Definite

(for physical admissibility)

- The T-SKP isn't unique. How do you choose it?

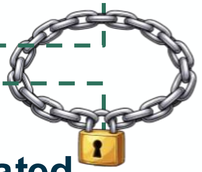
In this case $\boldsymbol{K} = \mathbf{2}$, the result of the decomposition depends on a space of real solutions defined by two parameters (a,b), (*Tebaldini S., 2015*).



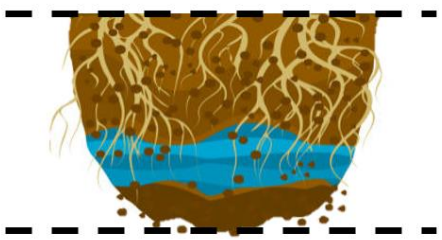
The solution selection among all the possible (a,b) pairs, **must**

Ground

- Act as a phase calibrator;
- The Ground component (R_G, C_G), is chosen as the one that minimizes the phase residues, i.e., the most triangular scattering mechanism.



Latent

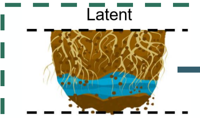


- *Maximize the similarity* between the **estimated Latent contributions** $\boldsymbol{R_2} \in \mathbb{C}^{[N,N]}$ out of T-SKP, and a **theoretical model of moisture related effects** on the Latent's interferometric features.

Model-Based

The Latent Structure Matrix R_l is the covariance matrix of the moisture effects, so…

$$R_l = \begin{bmatrix} & |\cdot|e^{j\varphi_{1,2}} & |\cdot|e^{j\varphi_{1,3}} \\ |\cdot|e^{-j\varphi_{1,2}} & & |\cdot|e^{j\varphi_{2,3}} \\ |\cdot|e^{-j\varphi_{1,3}} & |\cdot|e^{-j\varphi_{2,3}} & \end{bmatrix}$$



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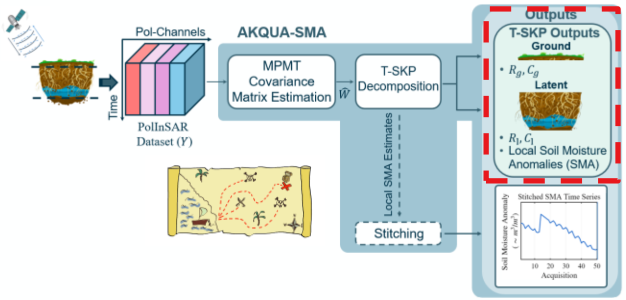
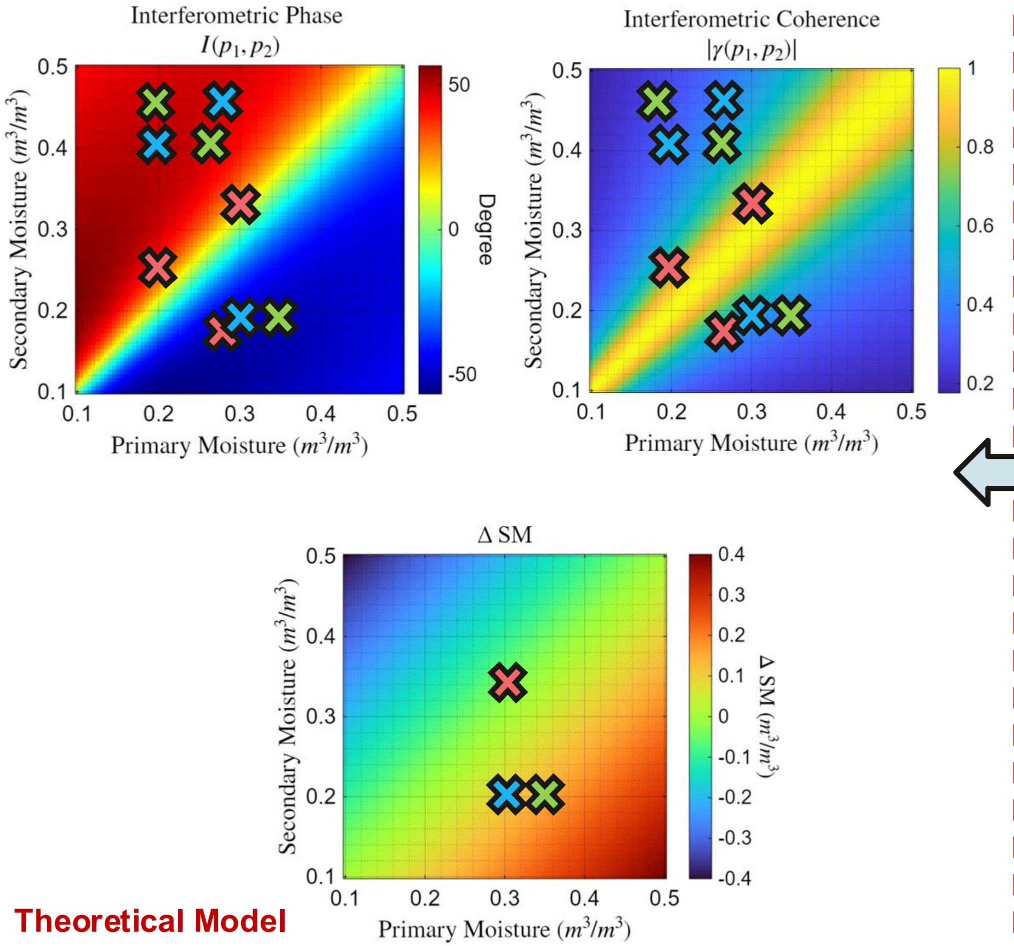
Model-Based





Theoretical Model

$$R_1 = \begin{bmatrix} & |\cdot|e^{j\varphi_{1,2}} & |\cdot|e^{j\varphi_{1,3}} \\ |\cdot|e^{-j\varphi_{1,2}} & & |\cdot|e^{j\varphi_{2,3}} \\ |\cdot|e^{-j\varphi_{1,3}} & |\cdot|e^{-j\varphi_{2,3}} & \end{bmatrix}$$

$$\widehat{\Delta SM} = \begin{bmatrix} & \Delta SM_{1,2} & \Delta SM_{1,3} \\ -\Delta SM_{1,2} & & \Delta SM_{2,3} \\ -\Delta SM_{1,3} & -\Delta SM_{2,3} & \end{bmatrix}$$

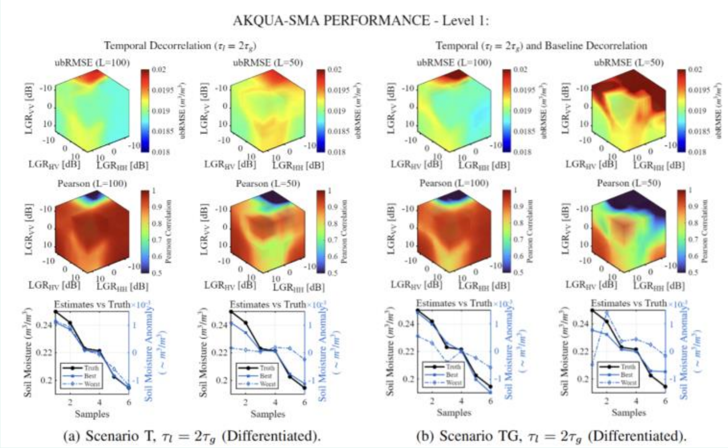
Among **all admissible** Latent structure **matrices** R_2, R_L **is defined by exhaustive search as the one** that **minimizes** the **$l1$-norm of the errors** between **all the elements** in R_2 and the theoretically expected moisture-related complex coherences (De Zan F., et al. 2013).

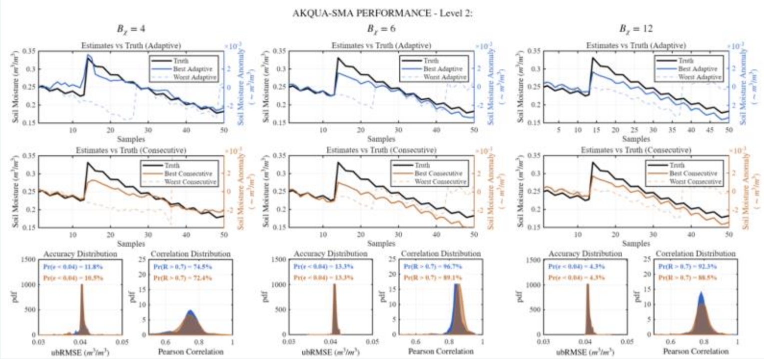
- **Inversion via IRLS:** Once R_L and the associated $\widehat{\Delta SM}$ are selected, the latter is inverted using Iteratively Reweighted Least Squares (IRLS);
- **Rank-Deficient System:** Due to rank deficiency, a zero-mean condition is imposed on the moisture term. Consequently, the inversion yields **Soil Moisture Anomalies (SMA)**, meaning the estimates are defined up to an additive constant;
- **Value of the Anomaly Domain:** The **SMA domain is inherently informative for analytical and trend purposes**. While adding the constant allows switching to the absolute domain, it is not strictly necessary for signal interpretation and monitoring.

AKQUA-SMA

Don't panic!

No deep dive into these ("painful") performance graphs intended; they are included only as mathematical proof for our takeaways. 😉





- **AKQUA-SMA effectiveness:** The effectiveness depends on
  - Temporal and Polarimetric diversity of the scattering mechanisms;
  - Number of Looks (L ≥100), *rather than the number of temporal acquisitions*.

What happens when dealing with large datasets?

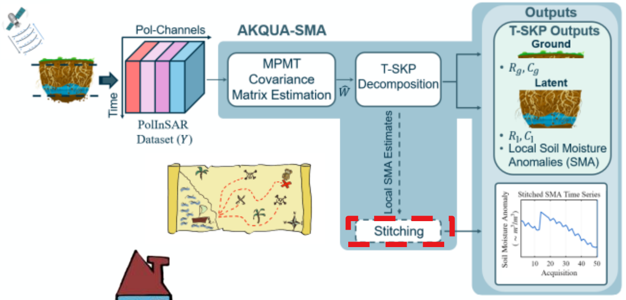
1. **Scan** the dataset through overlapping windows (of size B_w acquisitions);
2. **Apply** T-SKP and store the local SMA estimates;
3. **Stitch** all the estimates in a single SMA time series (i.e., estimate the set of offsets needed to align the local estimates).

What about B_w ?

- **Optimal** B_w **:** ranges from 4 to a maximum of 12 acquisitions (the smaller the better).

What happens when dealing with "extremely" large datasets (N>10B_w)?

- **Apply** AKQUA-SMA **on the entire dataset**;
- **Apply** AKQUA-SMA **on a subsampled version** of the dataset;
- **Combine** the estimates (**Multi-Temporal Synthesis**): this helps recover long-term trends that might otherwise be lost (and counteracts divergences driven by vegetation growth)



TAKE HOME MESSAGE

1) **AKQUA-SMA** simply **consists** of:
- **T-SKP** Decomposition;
- **Exhaustive Search** for solution selection;
- **Two linear system inversions** (local SMA estimates and Stitching);

2) **AKQUA-SMA** does not use phase triplets, **processing** the decomposed **Latent complex coherences directly**;

3) **AKQUA-SMA estimates are defined up to an additive constant.** The anomaly domain alone is sufficient for trend analysis and monitoring, without needing absolute values.

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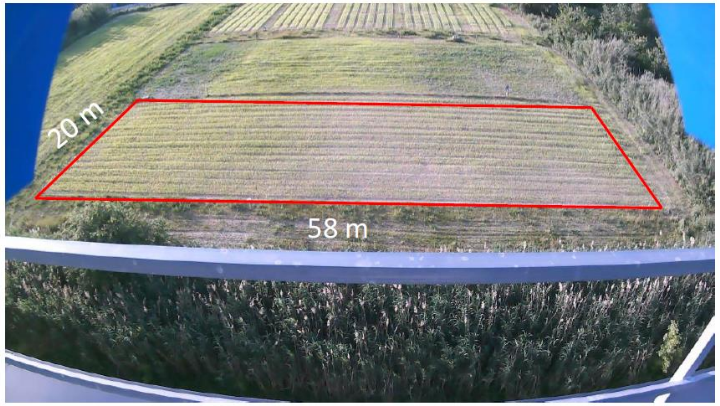
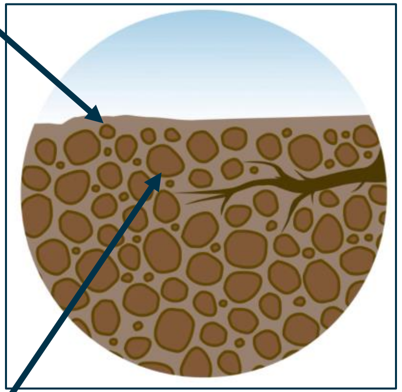
AKQUA-SMA on real data: HydroSoil Campaign



Test area from the radar installation point.

Radar Measurements (practically superficial)



Probe Measurements (15-20cm deep)

Depth of the probes **Vs** **SAR Sensing Depth**

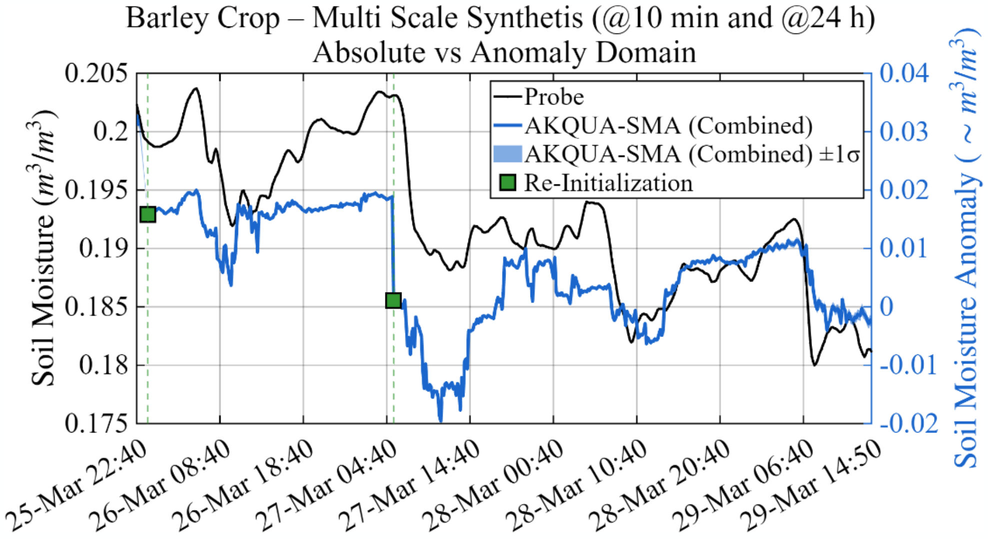
- The HYDROSOIL campaign uses a C-Band ground-based polarimetric SAR (GB-PolSAR) to continuously monitor **barley** and **corn** in an agricultural field (simulating the frequent acquisitions of the HYDROTERRA mission);
- Two measurements campaigns were conducted:
  - **March 2020 - June 2020**: Barley crop, *Poacecae* family (*Hordeum vulgare L. variety*) ~ 20-120 cm height.

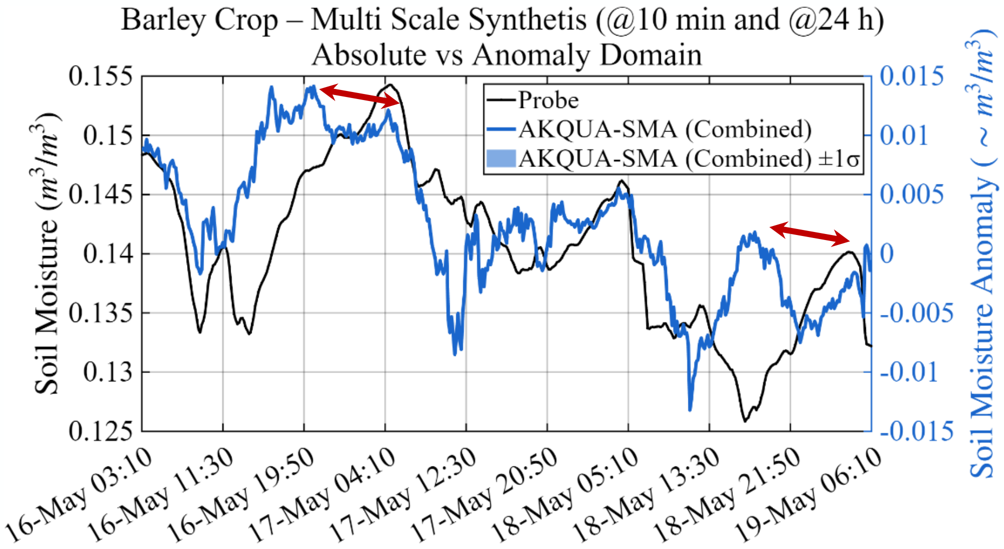
    - **Dataset**: Dual-Pol, ~ 18055 acq. (t_r = 10 min).
    - **Ancillary Data** (e.g., probes measurements, Soil Roughness, Vegetation Sampling, Meteorological Parameters).
  - **July 2020 - November 2020**: Corn crop, *Asparagaceae* family (*Zea Mays L. Konfites variety*) ~ 200-370 cm height.

    - **Dataset**: Quad-Pol, ~ 12945 acq. (t_r = 10 min).
    - **Ancillary Data** (e.g., probes measurements, Soil Roughness, Vegetation Sampling, Meteorological Parameters, Irrigation information).
- AKQUA-SMA was applied following a maximally overlapped window approach, with window size of $B_w = 6$ (1 hour), treating the entire field as a unique resolution cell.

AKQUA-SMA on real data: HydroSoil Campaign (Barley)

Site Phenology: 26 March 2020.





…Let's see some estimated SMA time series…

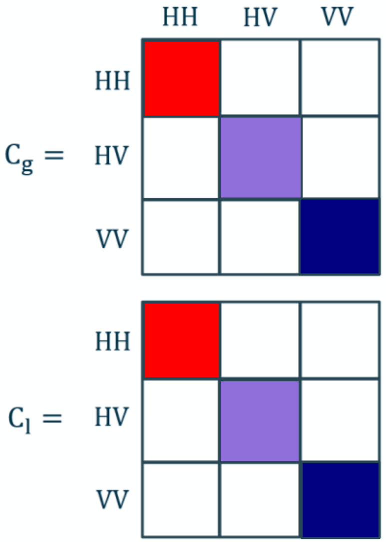
- **Two re-initialization events** (green markers) are **triggered** exclusively **by rainfall** (~2 mm and ~6 mm), which cause a reduction to a single dominant scattering mechanism and a localized coherence drop;
- These **re-initialization events are handled completely independently**, without using any external probe measurements;
- The retrieval successfully captures the dynamics (effective range $\sim 0.02\ m^3/m^3$), maintaining a good match with in-situ data (*without any probe calibration or training*).

Site Phenology: 16 May 2020.

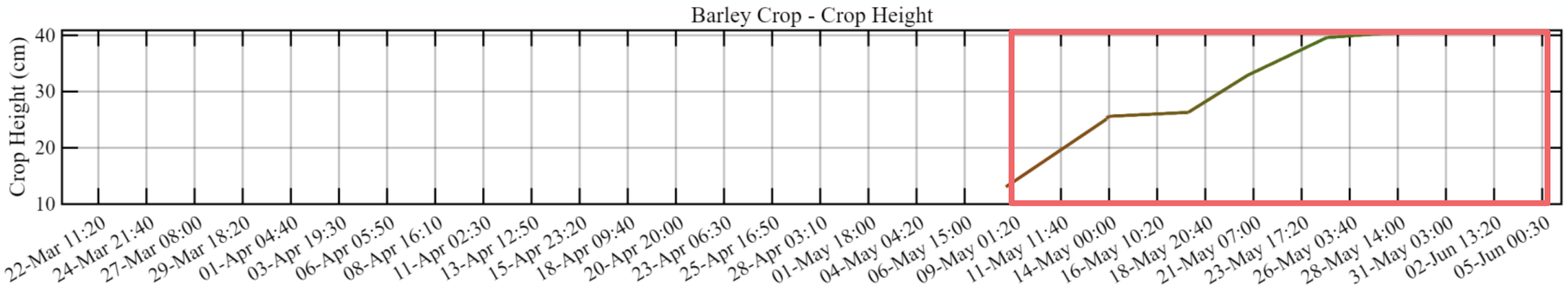
AKQUA-SMA on real data: HydroSoil Campaign (Barley)

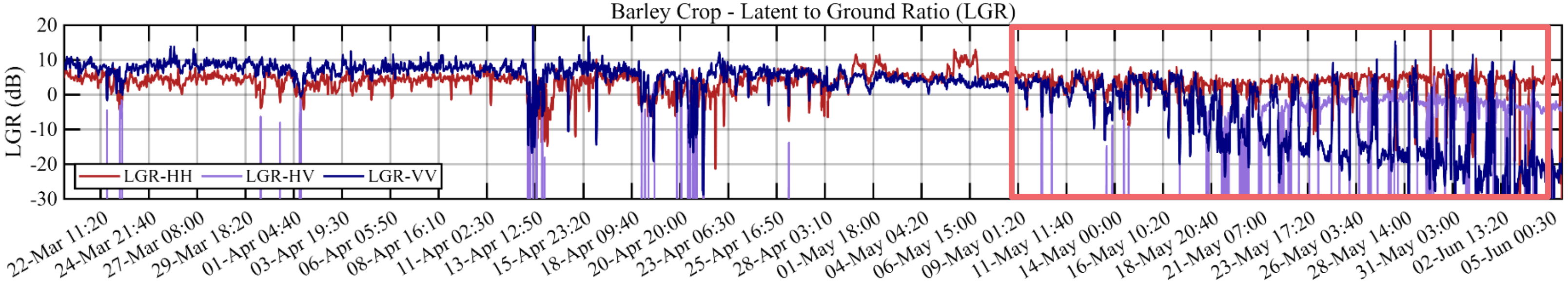
What about the information content in each channel?

<u>Quick step back</u>: the **polarimetric signature matrices** (i.e., $C_{g,l}$) **collect the backscatter power at which** each the co- and cross- pol **channel sees the decomposed scattering mechanisms.**

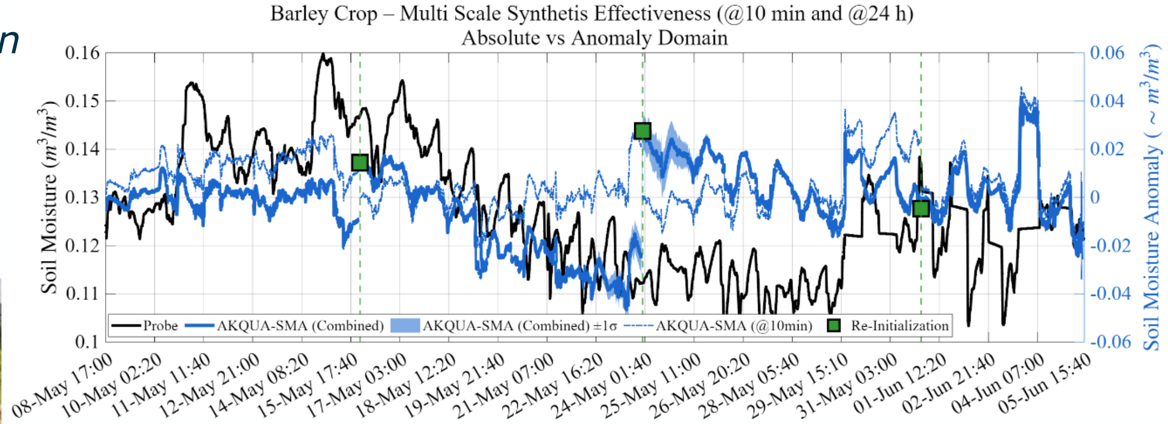


By looking at the **Latent-to-Ground Ratio (LGR)**, each polarization **tells us a different story** about how the decomposed scattering mechanisms behave in that specific channel.



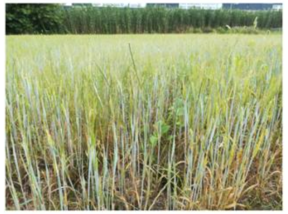


What is the impact on the estimates?



Site Phenology: 8 May 2020.

Multi-Temporal synthesis helps mitigate vegetation-induced divergences



Site Phenology: 5 June 2020.

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CONCLUSIONS & OUTLOOKS

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CONCLUSION

- **AKQUA-SMA** is a novel polarimetric framework for soil moisture anomaly estimation;
- **Core engine:** The Temporal-SKP algebraic decomposition successfully separates moisture-induced scattering (**Latent** contribution) from above-surface reflections (**Ground**);
- **Key Insights & Performance:**
  - *Anomaly Domain:* Estimates are defined up to an additive constant. This anomaly domain is inherently sufficient for trend analysis and monitoring without needing absolute values;
  - *Multi-temporal synthesis* (combining 10-min and 24-h estimates) captures both high- and low-frequency trends, overcoming single-configuration limits (reliable retrieval up to 40-45 cm crop height);
  - Estimated time series show good match with available probe measurements;
  - The Latent to Ground Ratio (LGR) analysis provides useful physical insights into vegetation effects on SMA retrieval.
- **Limitations:** Heavy rain/irrigation events (where a single dominant scattering mechanism is recognized).

OUTLOOKS

- Test AKQUA-SMA on other datasets featuring different frequencies (e.g., L-, P-band) and a wider variety of vegetation/crop types;
- Investigate a Dual-Pol adaptation of the AKQUA-SMA framework to extend its applicability to dual-polarimetric SAR constellations;
- Journal paper is in the final preparation stages and almost ready for submission.

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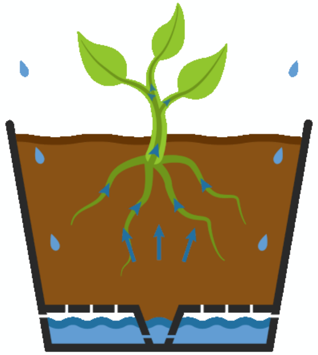
I hope you enjoyed it! =)



Thank You!

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BACKGROUND SLIDES

Temporal Diversity – BG Slide

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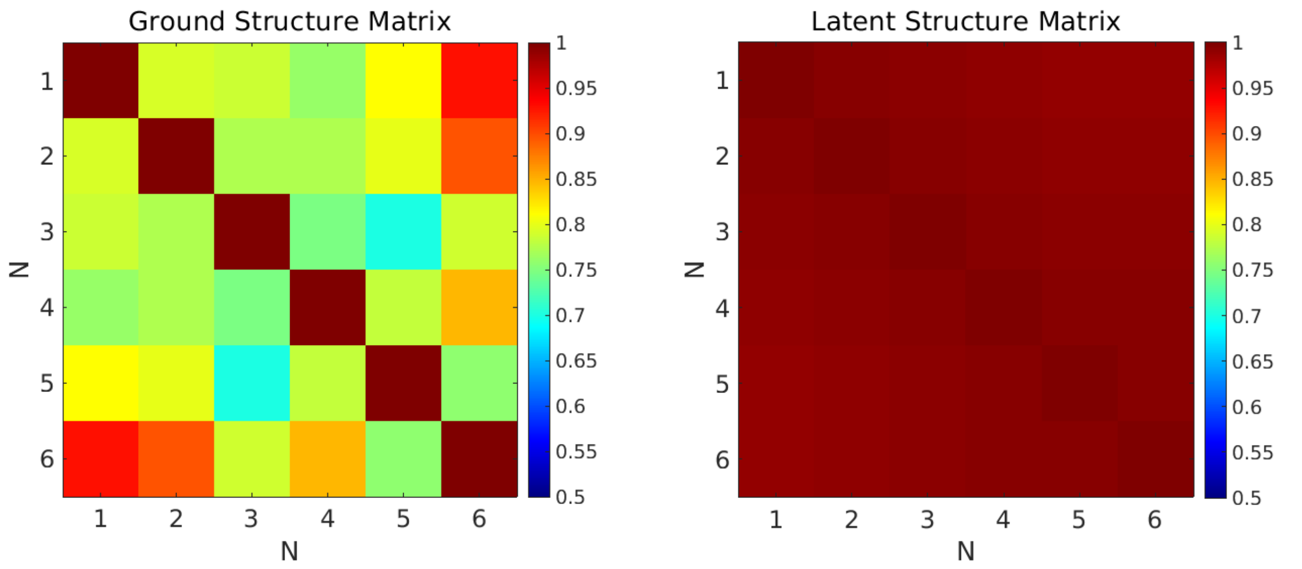

BG - AKQUA-SMA on real data: HydroSoil Campaign (Corn)

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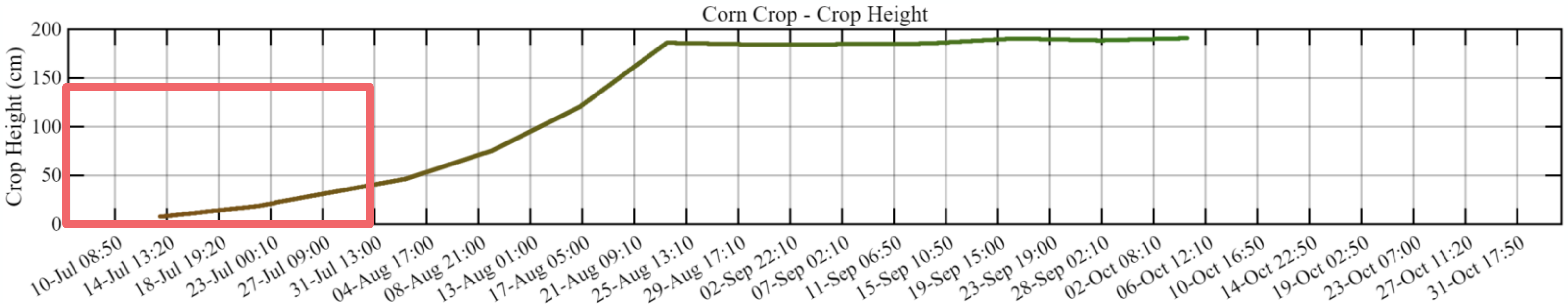
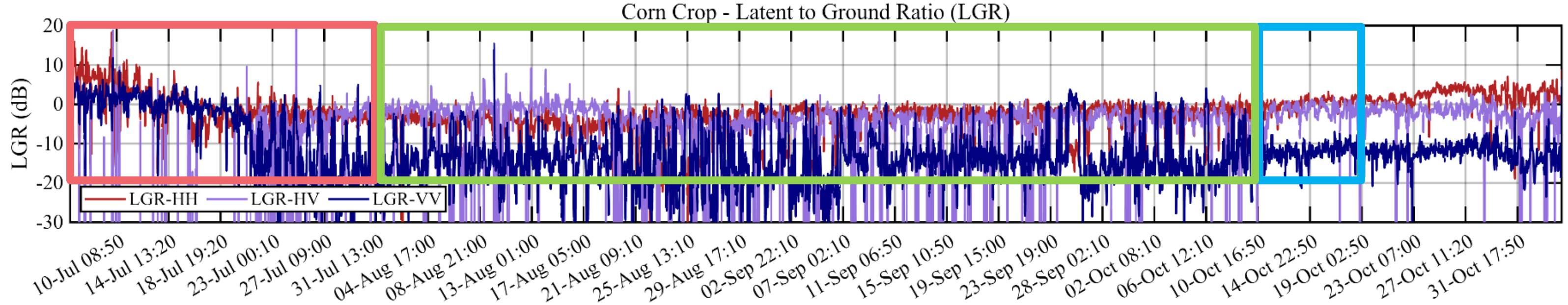
Site Phenology: 10 July 2020.

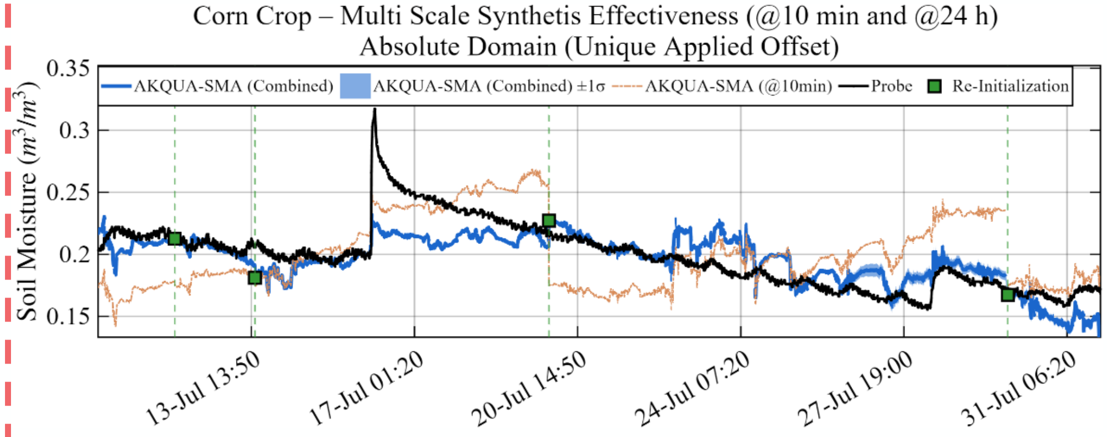
Site Phenology: 31 July 2020.

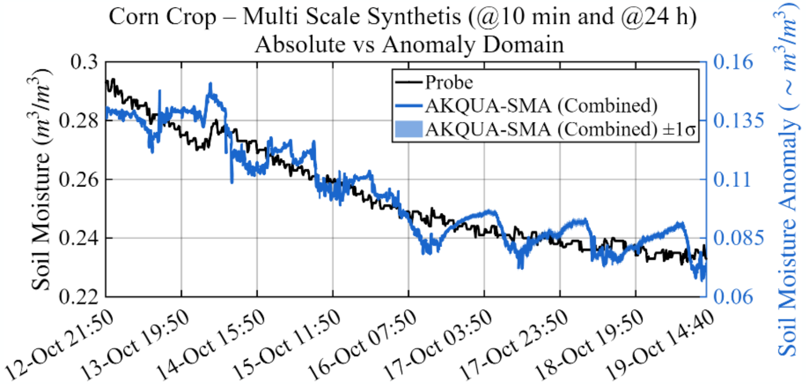




Site Phenology: 12 Oct 2020.

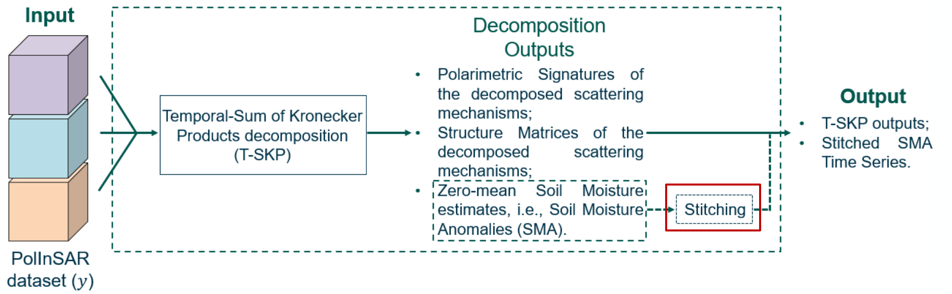
Site Phenology: 19 Oct 2020.

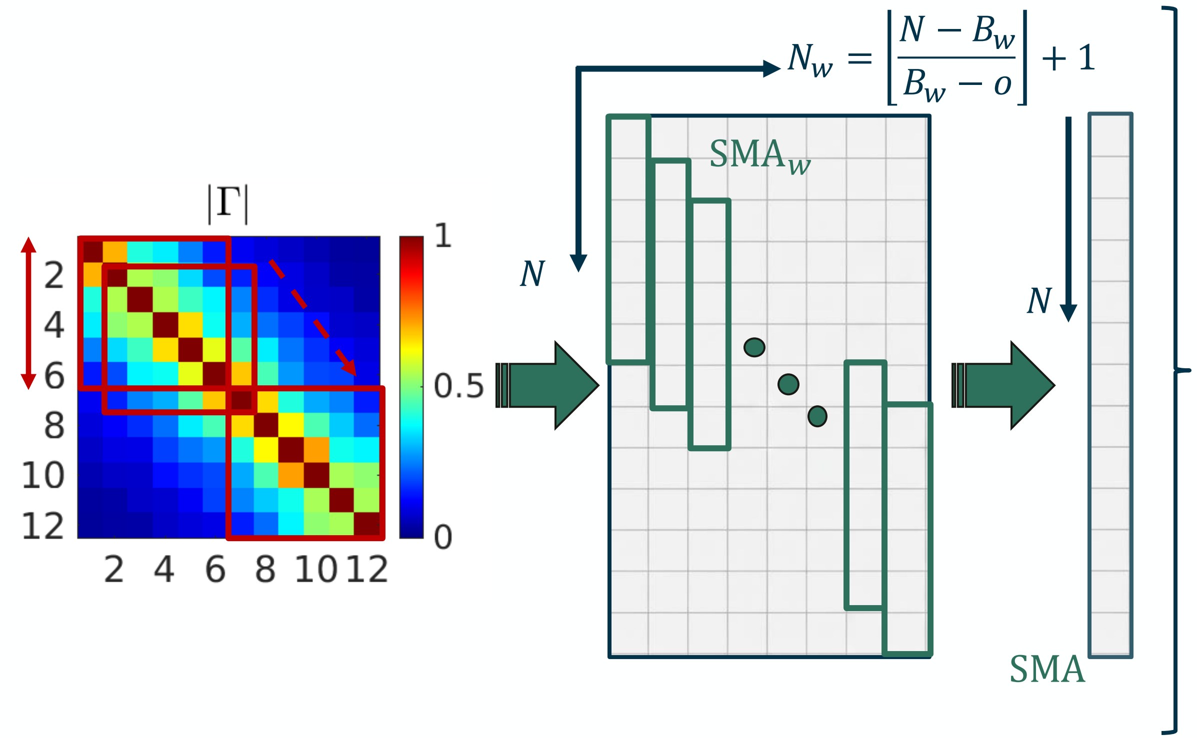




Stitching – BG Slide

- The effectiveness of the proposed decomposition, depends more on the number of Looks (L) than the number of temporal acquisitions (the less, the better);
- The idea is:
  - Scan the entire dataset of N acquisitions through temporal overlapping windows of B_w acquisitions;
  - Store the regressed $\mathrm{SMA}_w \in \mathbb{R}^{[B_w,1]}$;
  - Stitch all the SMA_w in a unique $\mathrm{SMA} \in \mathbb{R}^{[N,1]}$.





- The stitching aims to provide with a set of offsets to align all the N_w estimates;

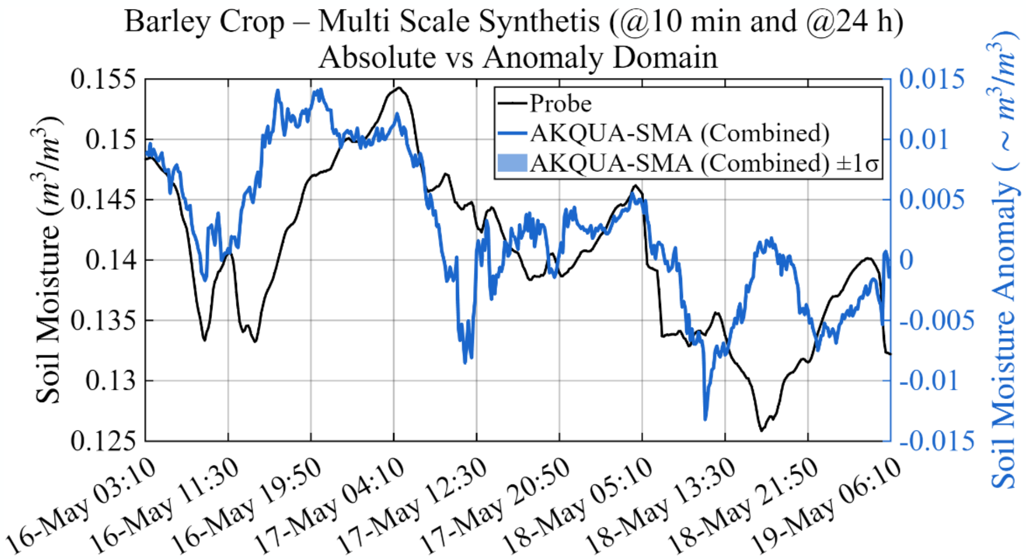
$$\boxed{SMA_w|_{\text{overlap}} = SMA_{w+n}|_{\text{overlap}} + \delta W_{w,w+n}}$$

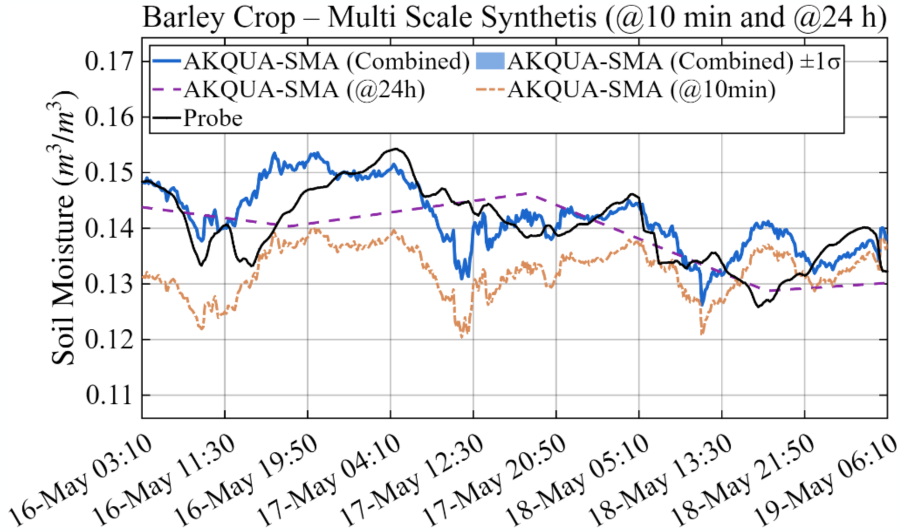
- Collect all median differences M between temporal windows sharing at least one overlapping acquisition, in a vector $O \in \mathbb{R}^{[M,1]}$;
- Invert the system (through IRLS)

$$O = Z\Delta W,$$

where $\Delta W \in \mathbb{R}^{[N_w,1]}$ is the vector of the window-wise offsets, $Z \in \mathbb{R}^{[M,N_w]}$, is the sparse matrix filled with ± 1 in dependence on the considered median difference.

Barley – BG Slide





Barley – BG Slide

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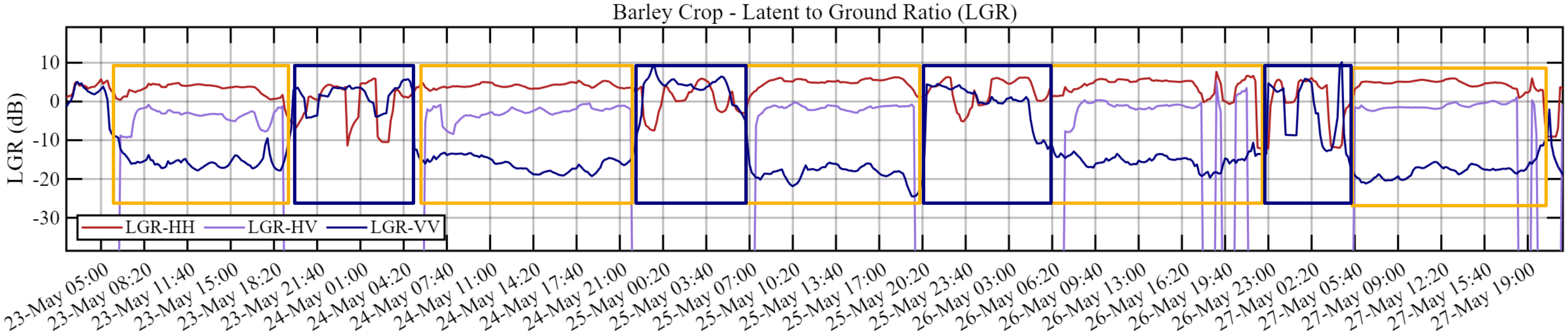


- **Day cycle**, crops activities are:
  - Photosynthesis;
  - Respiration;
  - Starch Accumulation;
  - Water Loss (Transpiration);
  - Growth Direction.

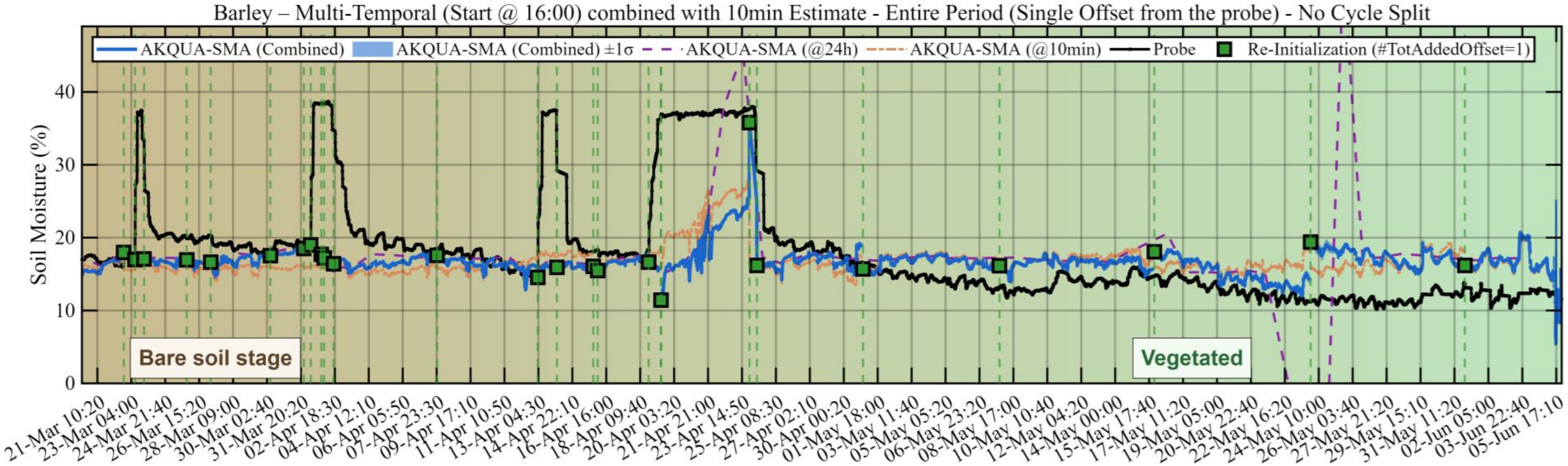
Photosynthesis and Energy Storage

- **Night cycle**, crops activities are:
  - Respiration;
  - Starch Degradation;
  - Reduced Water Uptake;
  - Growth (vertical).

Respiration and Resource Management

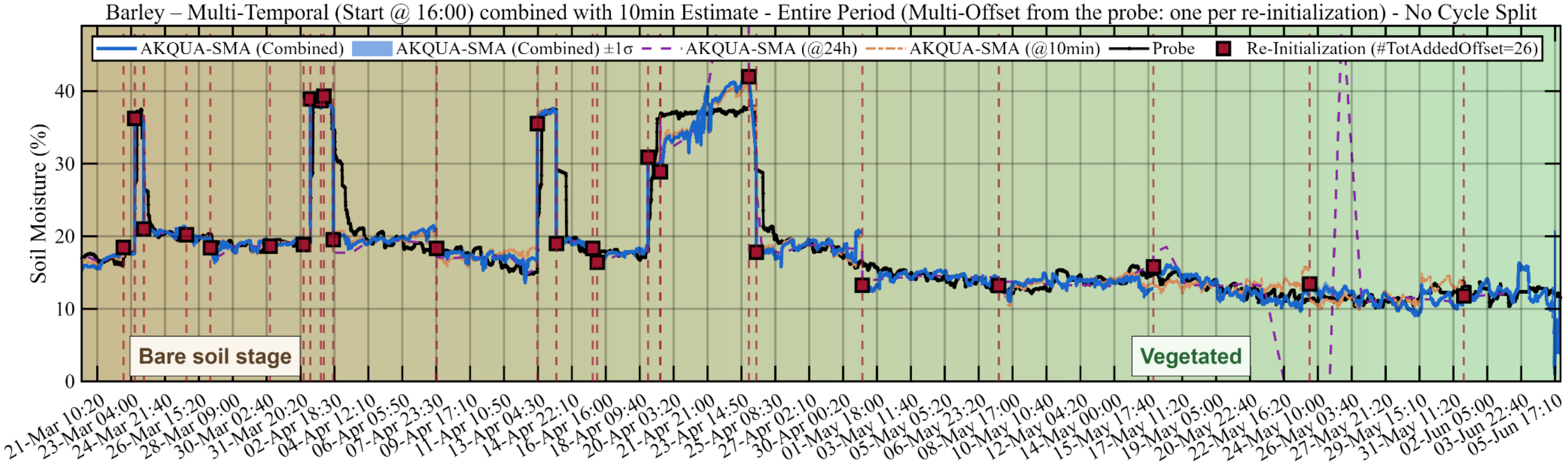
Barley – BG Slide

“Default” Raw Result (<u>only one offset</u> available from the probe)



If a new offset can be injected every time the algorithm reinitializes, then…

Best case scenario (26 offsets added, one per Re-Initialization)



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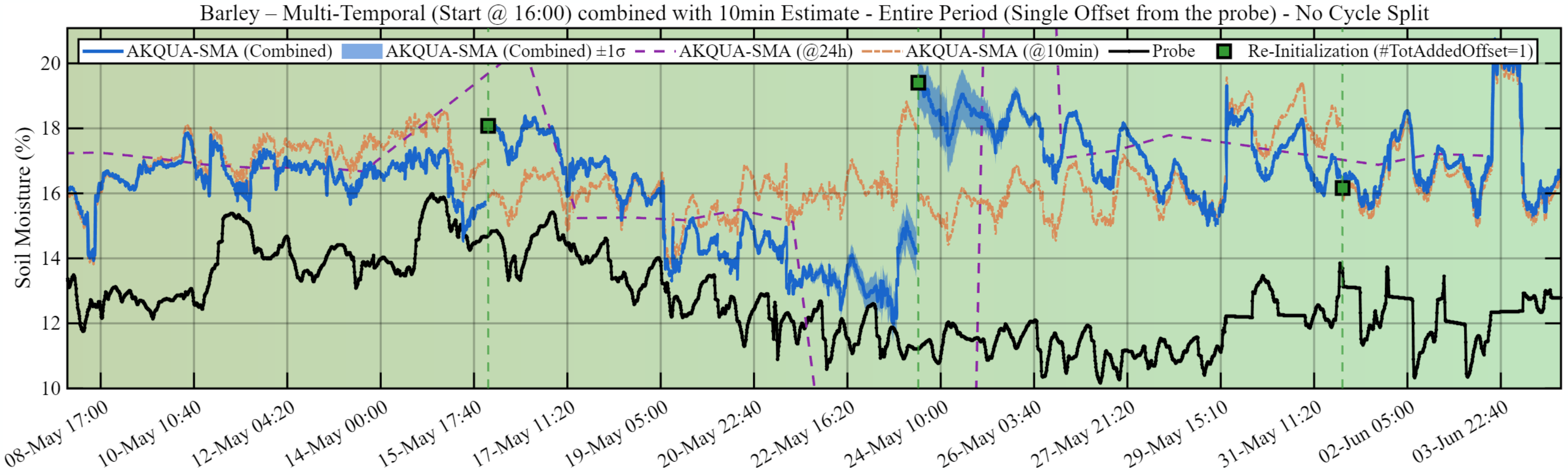

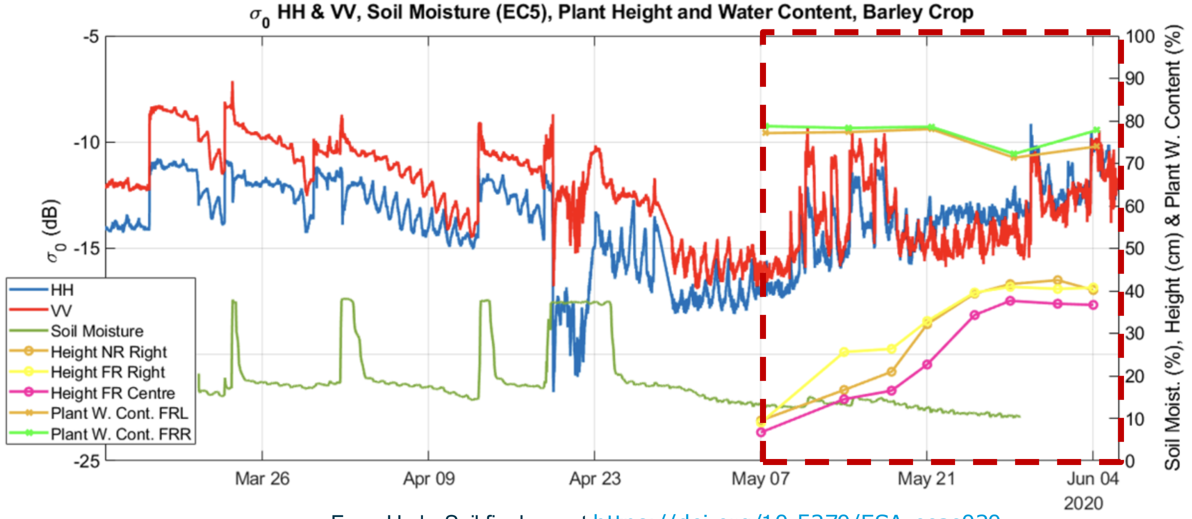

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