Agricultural monitoring with Polarimetric SAR time series

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Synthetic Aperture Radar - Advantages

Synthetic Aperture Radar (SAR) are active & coherent systems providing information about the scene reflectivity at microwave frequencies.

- **High spatial resolution**: The Synthetic Aperture concept allows under 1m resolution
  - ✔ Own illumination source → independent of the day/night cycle
  - ✔ Atmosphere is transparent at microwave frequencies → independent of cloud coverage / atmospheric state

⇩

- **All-weather imaging sensors**: very reliable for the observation of all the Earth surface

- **Sensitive to target structure & deformation**: since SAR are coherent sensors, interferometric & polarimetric information may be fully exploited

  - SAR Interferometry: phase differences between two (or more) acquisitions are exploited.

    ⇩

    Target height / displacement / vertical profile

  - SAR Polarimetry: distinct polarization states are employed for transmitted and received waves.

    ⇩

    Target structure / properties

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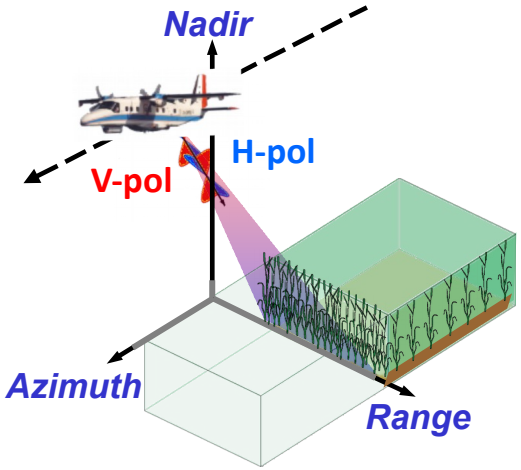
Multidimensional SAR – Polarimetry and time series

Multidimensional SAR systems acquire *m* complex SAR images

Target vector

$$\boldsymbol{k} = [S_1, S_2, \ldots, S_m]^T$$



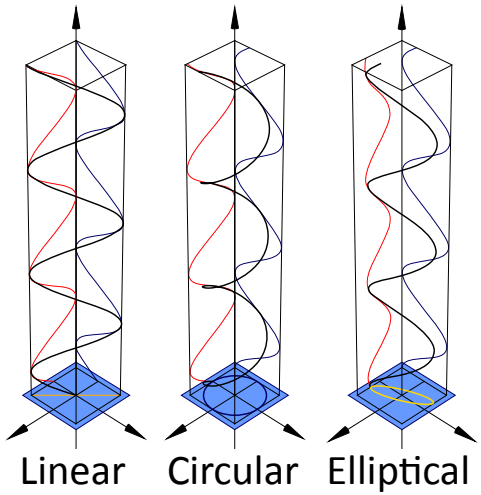
Multidimensional SAR systems provide additional information to improve scene characterization

- SAR Polarimetry: distinct polarization states are employed for transmitted and received waves.

$$\begin{bmatrix} E_h^s \\ E_v^s \end{bmatrix} = \frac{e^{-jkr}}{r} \begin{bmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{bmatrix} \begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix}$$

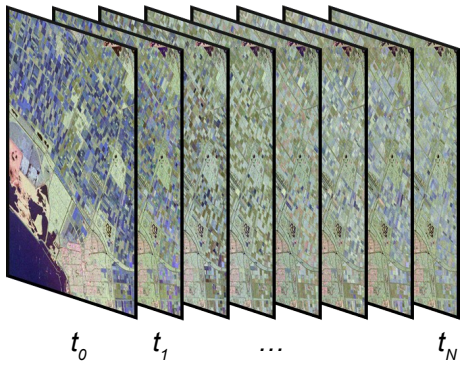
$$\boldsymbol{k} = [S_{hh}, \sqrt{2}S_{hv}, S_{vv}]^T$$

⇨ Information related to target structure and properties



- Temporal series: several acquisitions of the same scene at different times.

⇨ Information related to the scene evolution



Some types of Multidimensional SAR data

Temporal Analysis

- Extended covariance matrix: includes the polarimetric temporal evolution information

$$\boldsymbol{Z}_N = \begin{pmatrix} \boldsymbol{Z}_{11} & \boldsymbol{\Omega}_{12} & \cdots & \boldsymbol{\Omega}_{1N} \\ \boldsymbol{\Omega}_{12}^H & \boldsymbol{Z}_{22} & \cdots & \boldsymbol{\Omega}_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{\Omega}_{1N}^H & \boldsymbol{\Omega}_{2N}^H & \cdots & \boldsymbol{Z}_{NN} \end{pmatrix}$$

The temporal stability is evaluated for each area with a similarity measure

The average similarity measure for all the combinations of $\boldsymbol{Z}_{ii}$ is computed

⇒ For time series BPT the temporal stability may be measured by comparing the different $\boldsymbol{Z}_{ii}$ matrices:

$$t_s = \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} \left\| \log\left(\boldsymbol{Z}_{ii}^{-1/2} \boldsymbol{Z}_{jj} \boldsymbol{Z}_{ii}^{-1/2} \right) \right\|_F$$

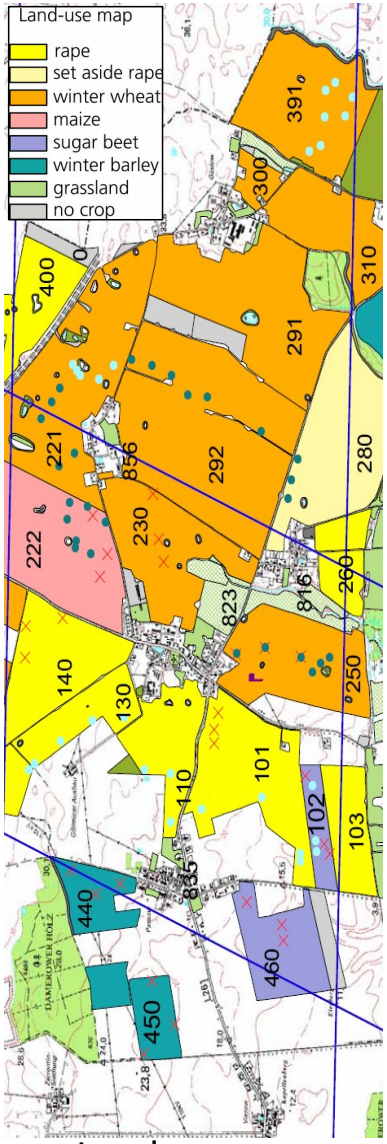
TE BPT measures the amount of polarimetric change among all the acquisitions (temporal stability)

DLR

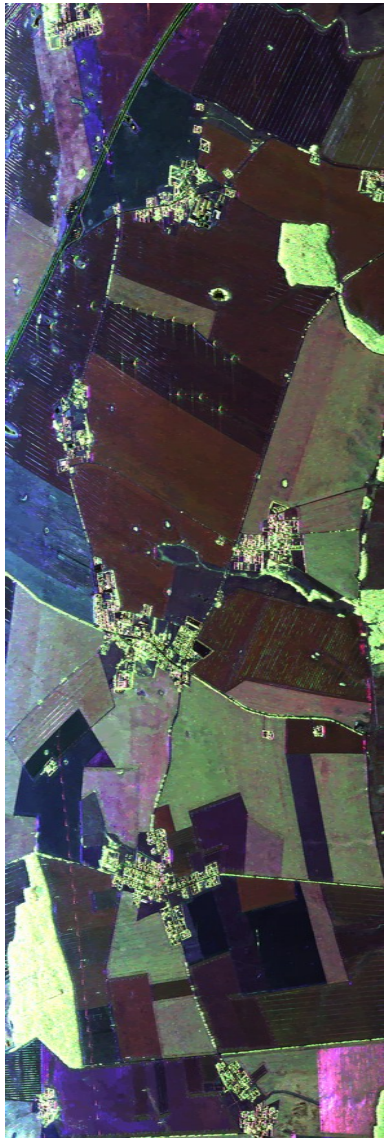
Time series dataset

Demmin test site

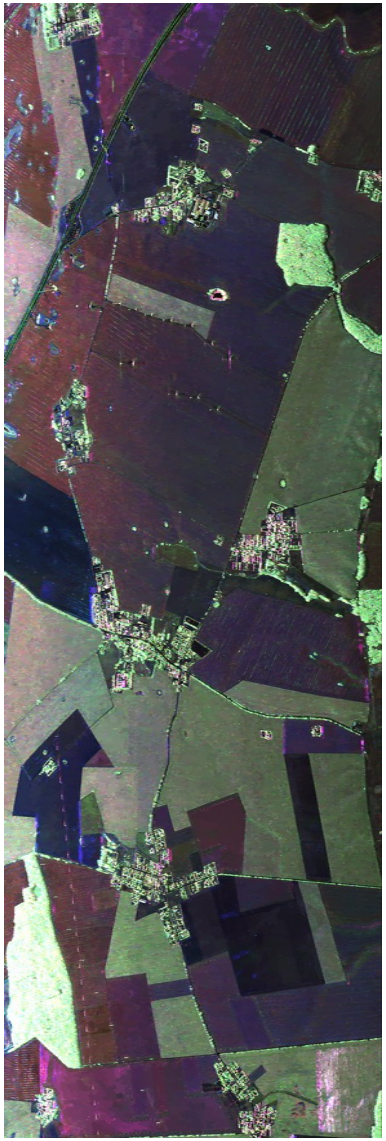
ESAR @ L-band



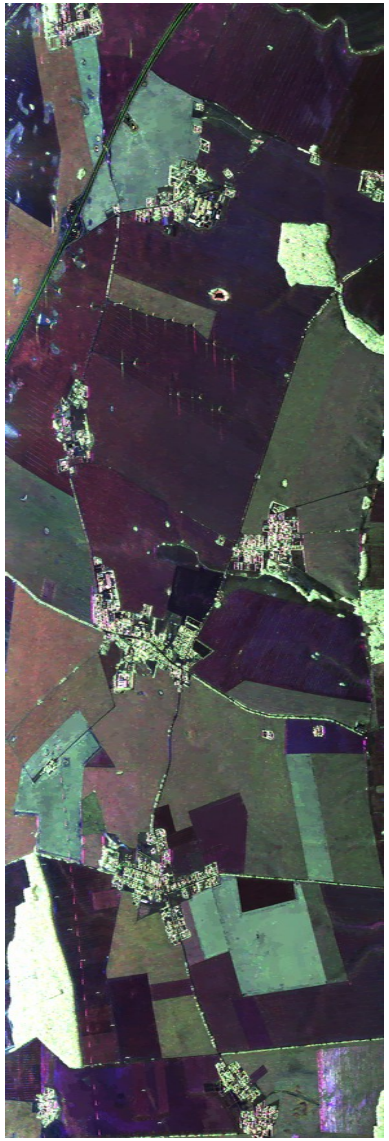
Land-use map



19. April 06

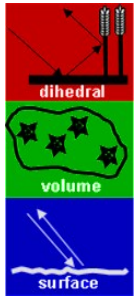


07. June 06



05. July 06

Pauli RGB



$|S_{hh}+S_{vv}|$

$|S_{hv}+S_{vh}|$

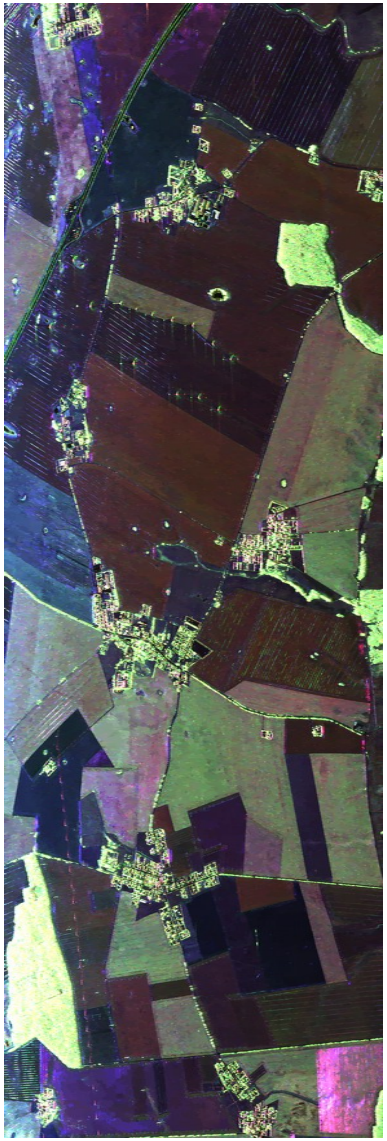
$|S_{hh}-S_{vv}|$

DLR

Temporal stability

Demmin test site

ESAR @ L-band



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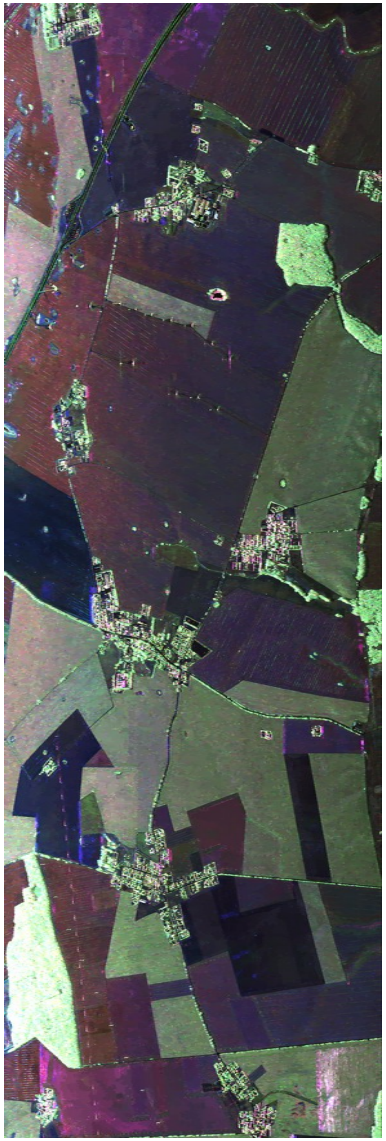

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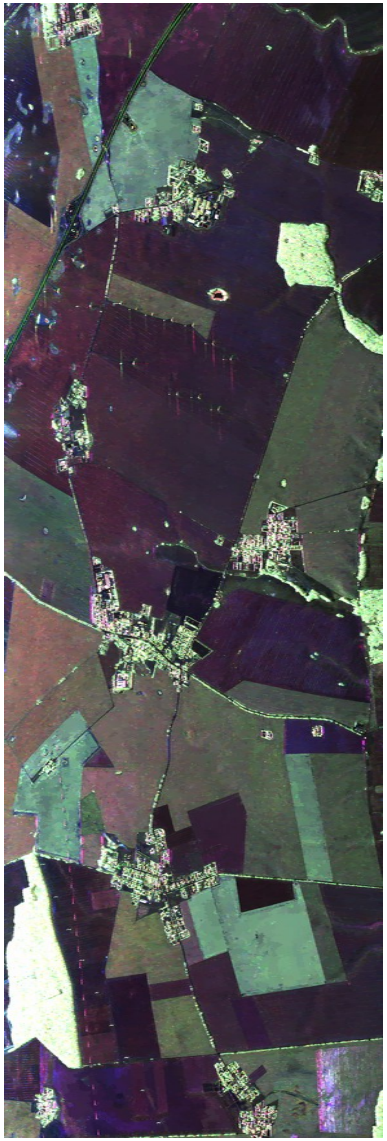

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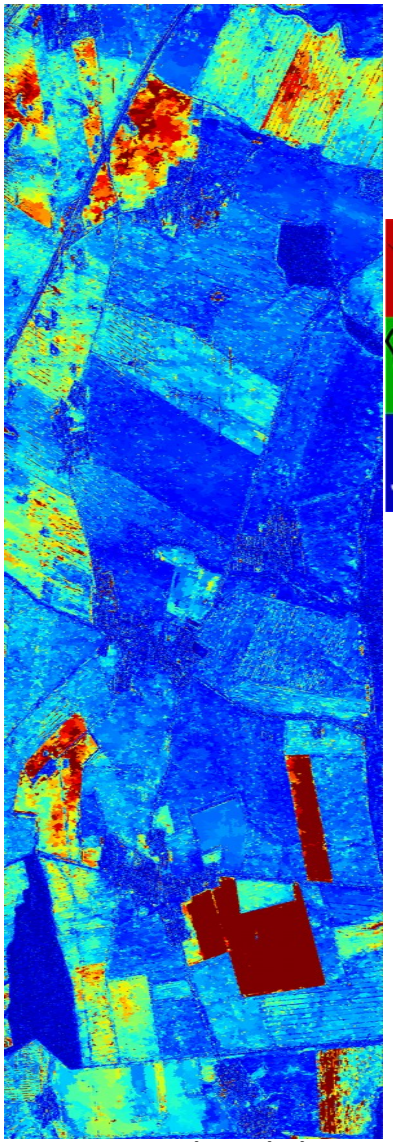


Temporal Stability

Pauli RGB

Large change

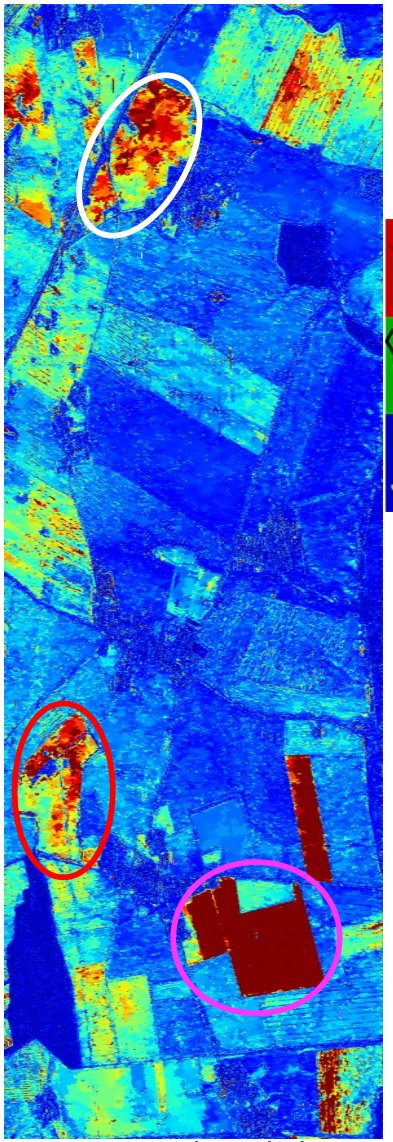
Small change

DLR

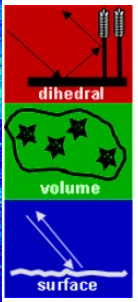
Temporal stability

Demmin test site

ESAR @ L-band



Pauli RGB



Large change

Small change

19. April 06

07. June 06

05. July 06

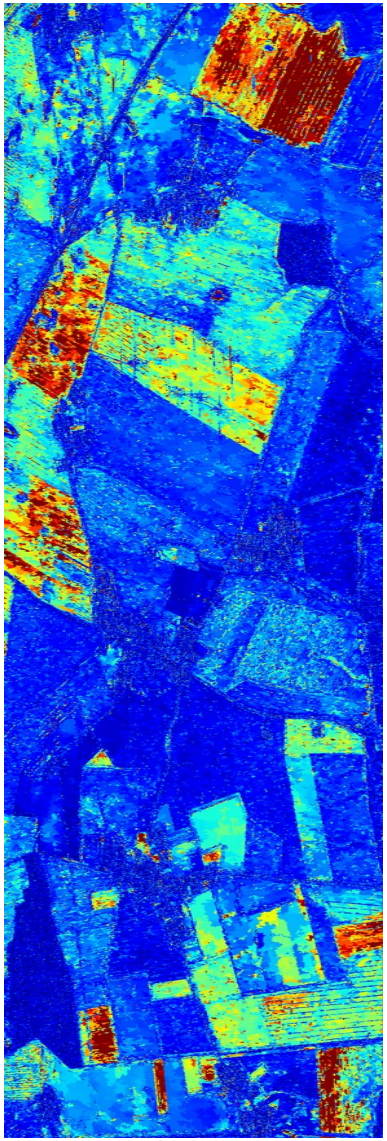
Temporal Stability

DLR

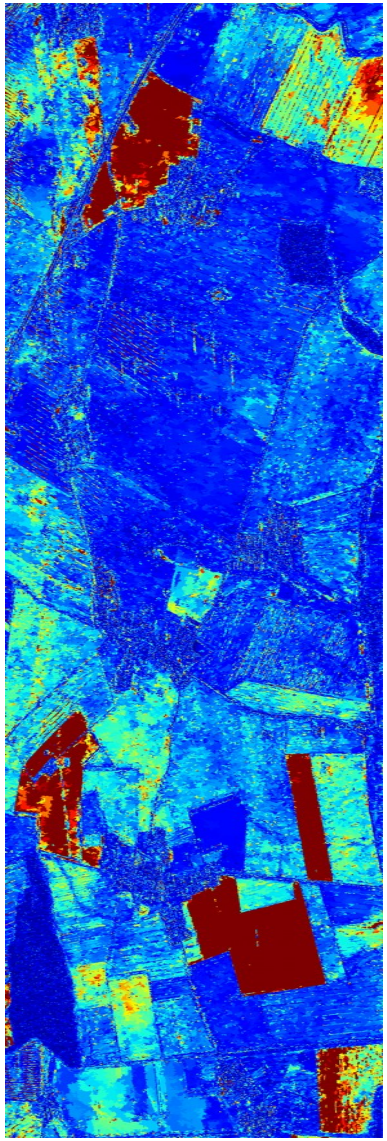
Temporal stability

Demmin test site

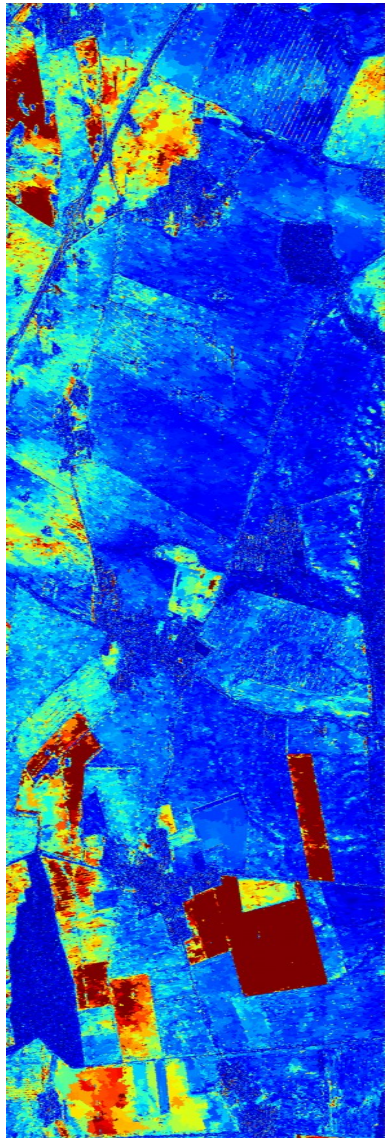
ESAR @ L-band



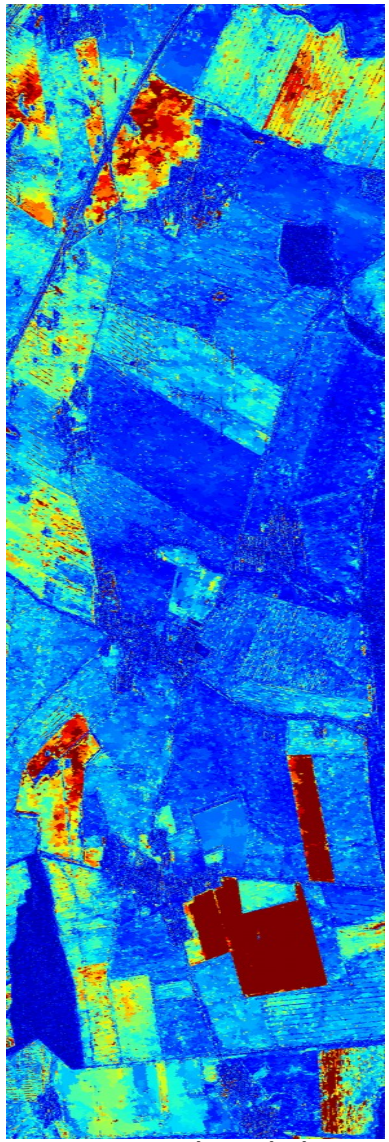
19. April → 07. June



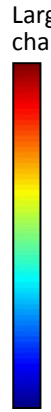
19. April → 05. July



07. June → 05. July



Temporal Stability



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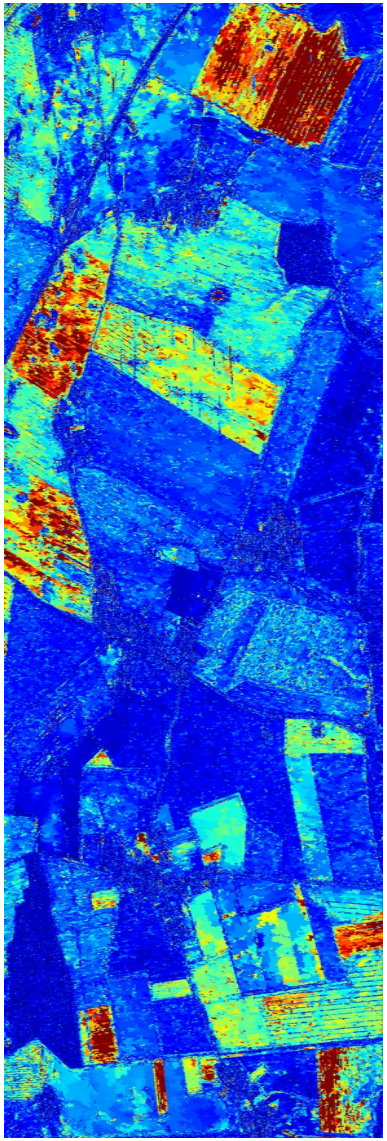
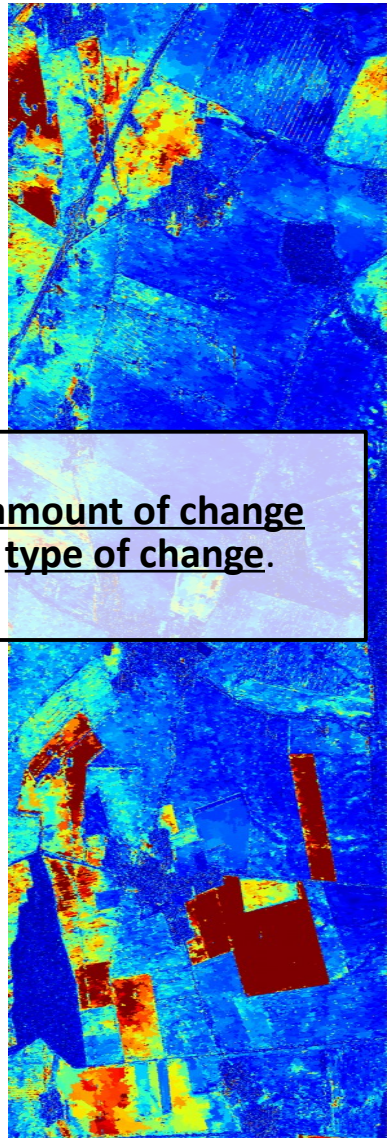
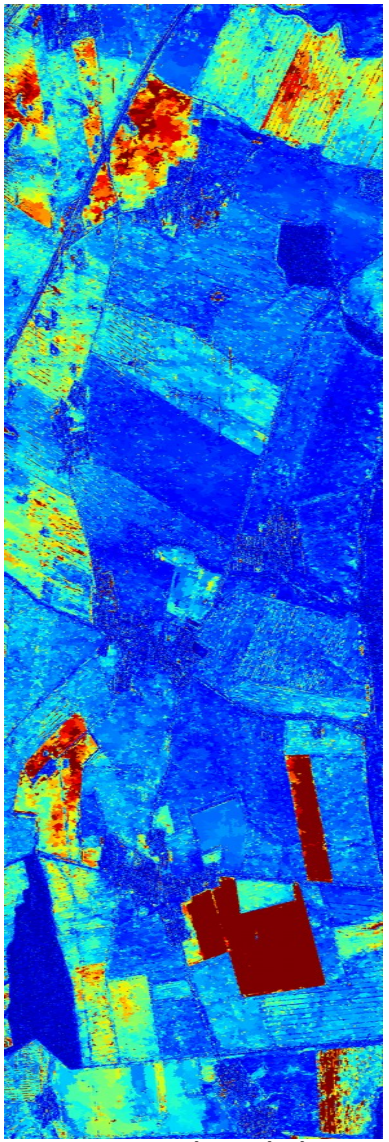
Temporal stability

Demmin test site

ESAR @ L-band







Information of the **amount of change** but not about the **type of change**.

Large change

Small change

19. April → 07. June

19. April → 05. July

07. June → 05. July

Temporal Stability

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Polarimetric change analysis

A method is proposed to analyze the change among two acquisitions in the polarimetric space

$$P_c(\boldsymbol{T}_1, \boldsymbol{T}_2, \boldsymbol{w}) = \frac{\boldsymbol{w}^H \boldsymbol{T}_2 \boldsymbol{w}}{\boldsymbol{w}^H \boldsymbol{T}_1 \boldsymbol{w}}$$

Polarimetric contrast for each polarization state $\boldsymbol{w}$

Only information about the relative change

The range of values for the polarimetric contrast may be obtained from:

$$\boldsymbol{T}_2 \boldsymbol{w} = \lambda \boldsymbol{T}_1 \boldsymbol{w}$$

which may be solved by the equation:

$$det(\boldsymbol{T}_2 - \lambda \boldsymbol{T}_1) = 0$$

Generalized eigendecomposition between $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$

The set of generalized eigenvalues represent the polarimetric contrast

$$\lambda_1 \geqslant \lambda_2 \geqslant \lambda_3$$

Maximum contrast

Minimum contrast

The set of generalized eigenvectors represent the corresponding polarization states

$$\boldsymbol{w}_1, \boldsymbol{w}_2, \boldsymbol{w}_3$$

Fully polarimetric (magnitude and phase information)

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Polarimetric change representation

A change representation is proposed to condense all the information of the polarimetric change analysis and make it more comprehensible

- Extract the information related to the polarization states that have increase & decrease between the 2 acquisitions
- Weight each polarization state by the amount of change it represents

Generalized eigenvalues between $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$:

$$\lambda_1 \geqslant \lambda_2 \geqslant \lambda_3$$

Generalized eigenvectors between $\boldsymbol{T}_1$ and $\boldsymbol{T}_2$:

$$\boldsymbol{w}_1,\ \boldsymbol{w}_2,\ \boldsymbol{w}_3 \xrightarrow[\text{basis}]{\text{Pauli}} \boldsymbol{p}_i = \left(\left|w_i^1\right|, \left|w_i^2\right|, \left|w_i^3\right|\right)^T$$

$$\boldsymbol{p}_{inc} = 10\left[\sum_{i\,|\,\lambda_i>1} \left(\log(\lambda_i)\,\boldsymbol{p}_i\right)^2\right]^{\frac{1}{2}}$$

Increase

$$\boldsymbol{p}_{dec} = 10\left[\sum_{i\,|\,\lambda_i<1} \left(-\log(\lambda_i)\,\boldsymbol{p}_i\right)^2\right]^{\frac{1}{2}}$$

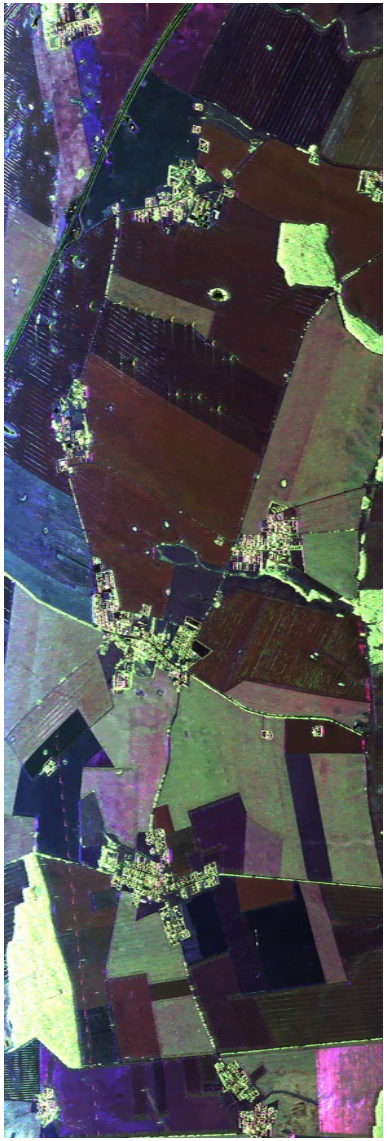
Decrease

Pauli of the increasing and decreasing polarization states

- Intensity → amount of increase/decrease
- Color → type of change (Pauli RGB)

DLR

Polarimetric change analysis representation



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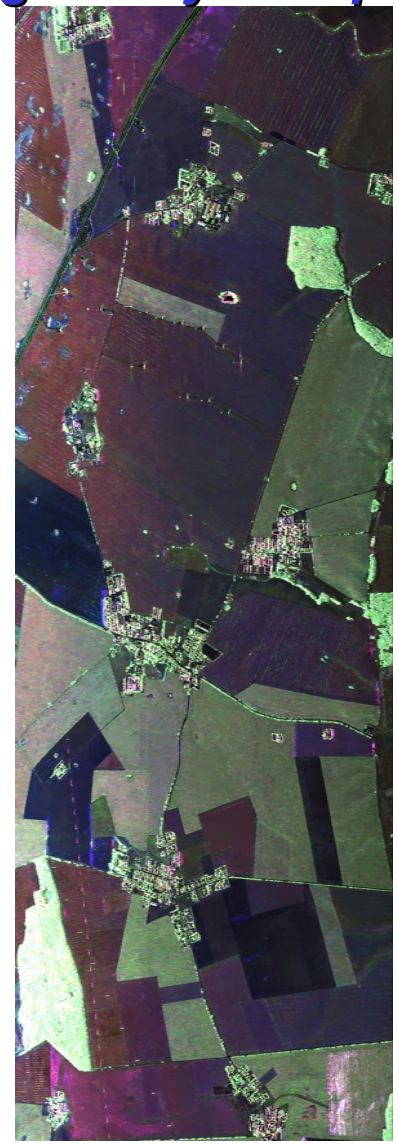
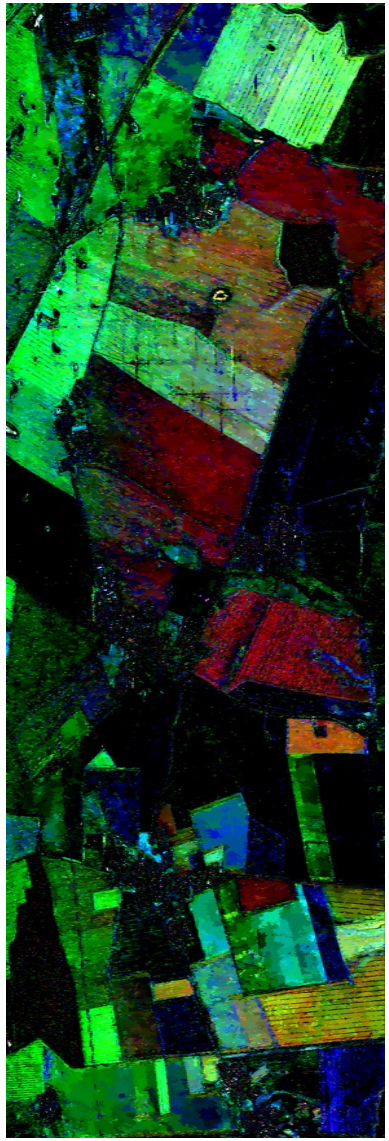
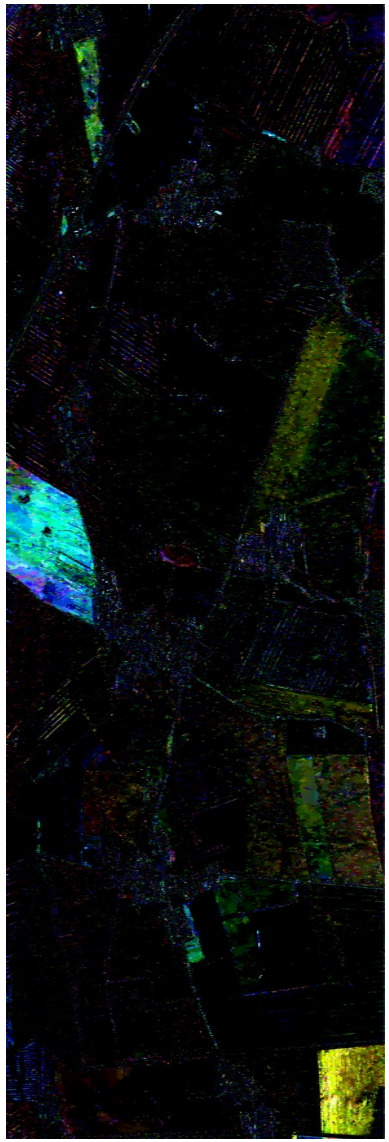


07. June 06



p_{inc}



p_{dec}

Pauli RGB 3-10 dB

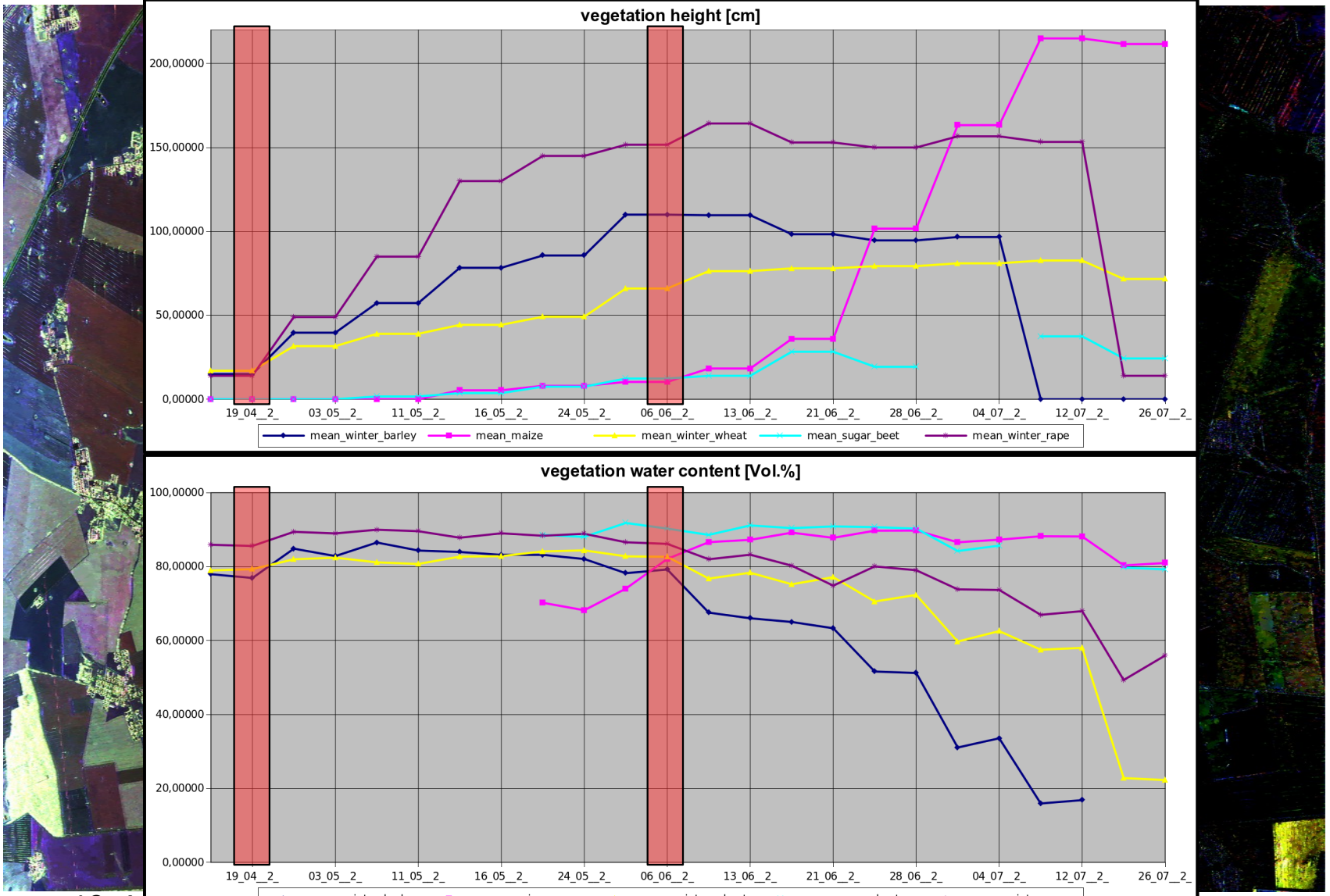
$|S_{hh}+S_{vv}|$

$|S_{hv}+S_{vh}|$

$|S_{hh}-S_{vv}|$

DLR

Polarimetric change analysis representation



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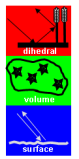
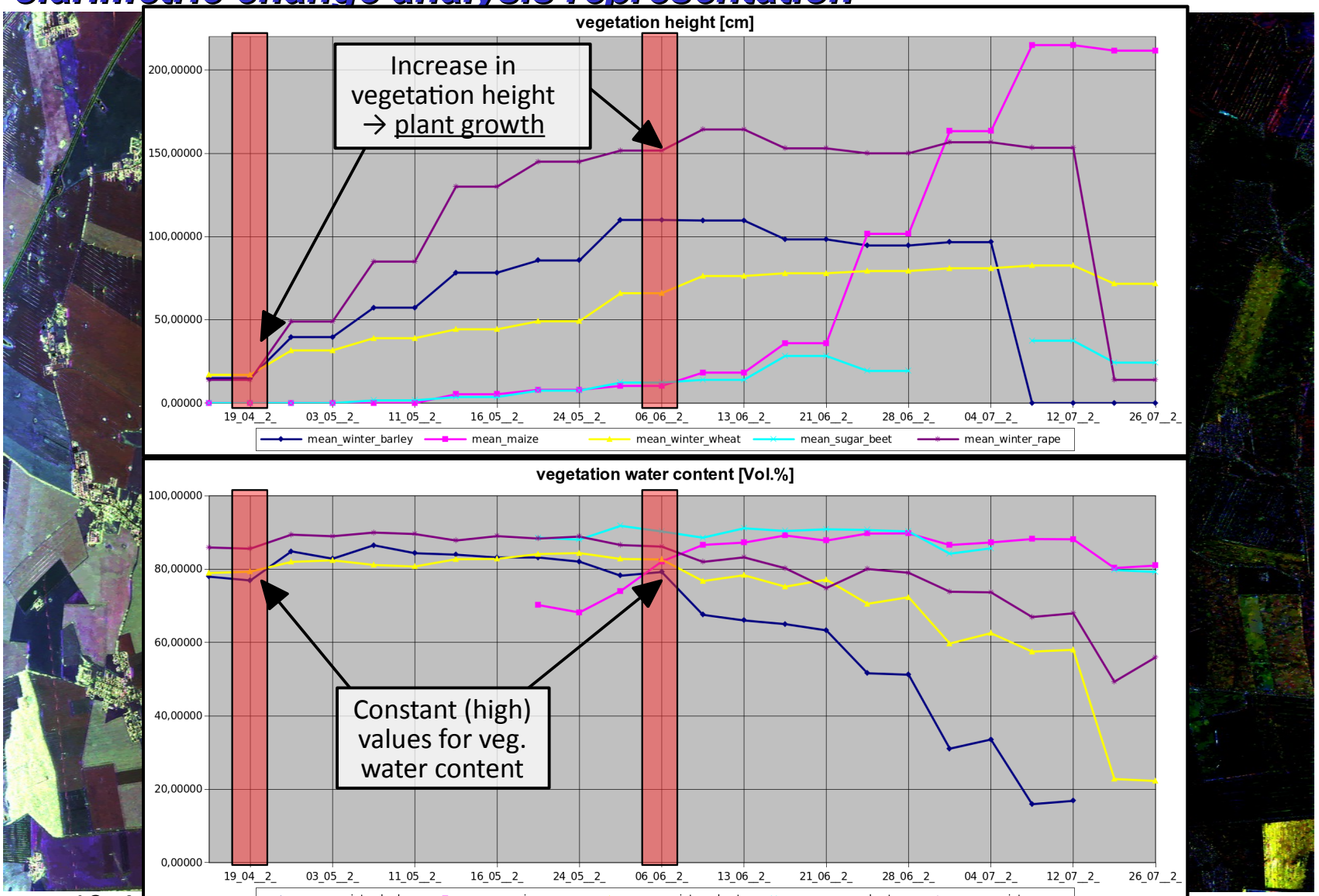


19. A… …ase

DLR

Polarimetric change analysis representation

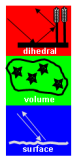


Pauli RGB 3-10 dB

$|S_{hh}+S_{vv}|$

$|S_{hv}+S_{vh}|$

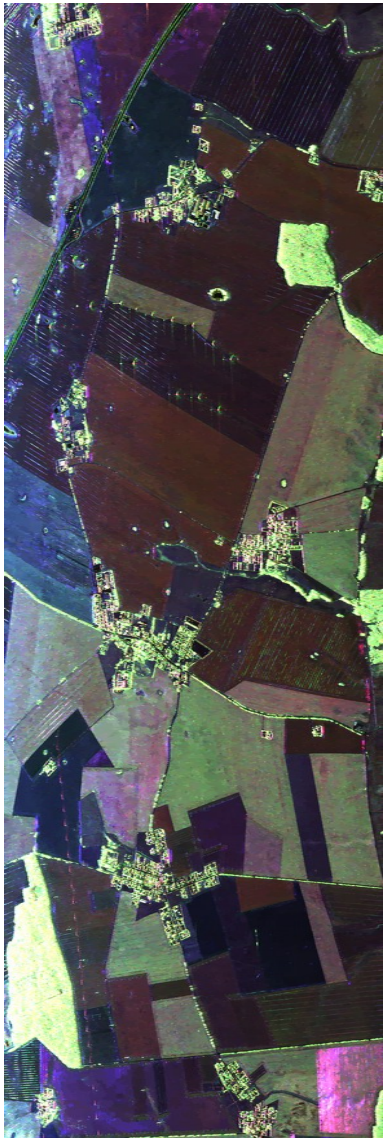
$|S_{hh}-S_{vv}|$



19. A… …ase

DLR

Polarimetric change analysis representation (Winter wheat)



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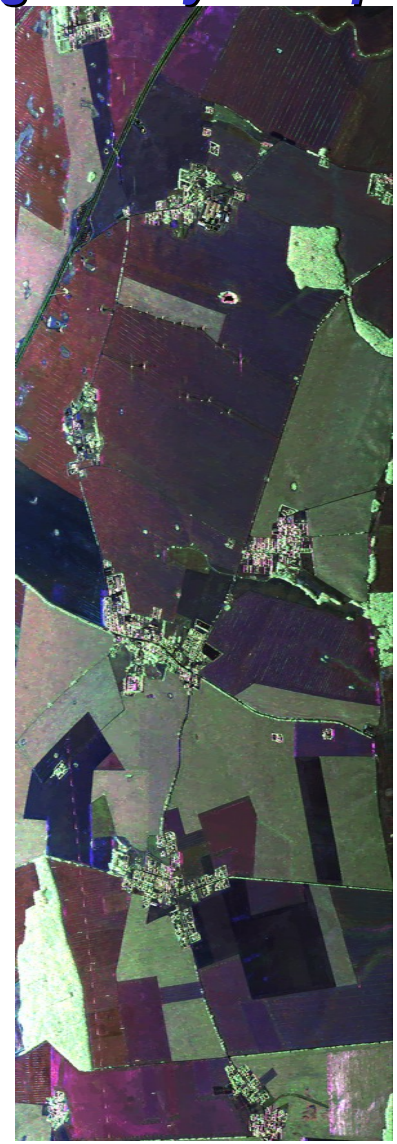

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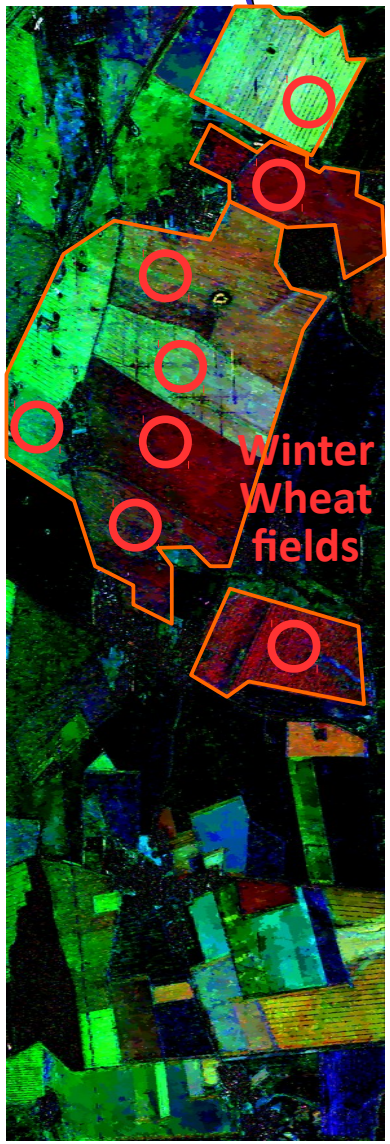
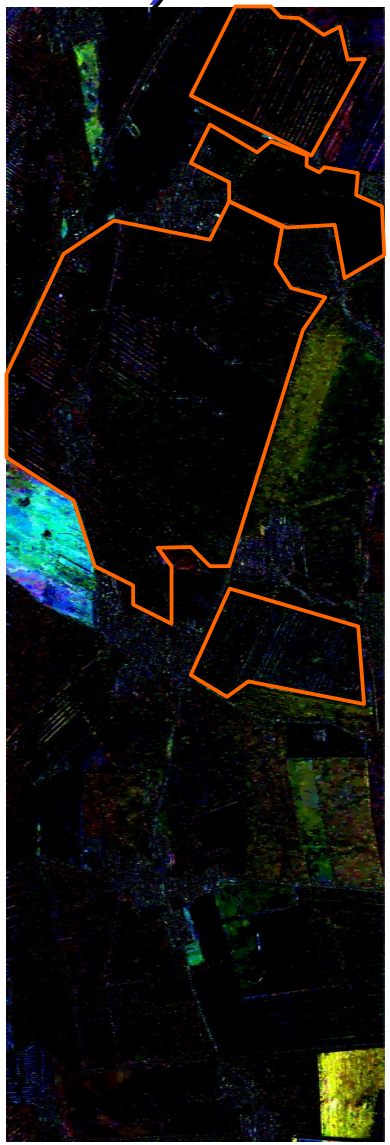


p_{inc}



p_{dec}

Pauli RGB 3-10 dB

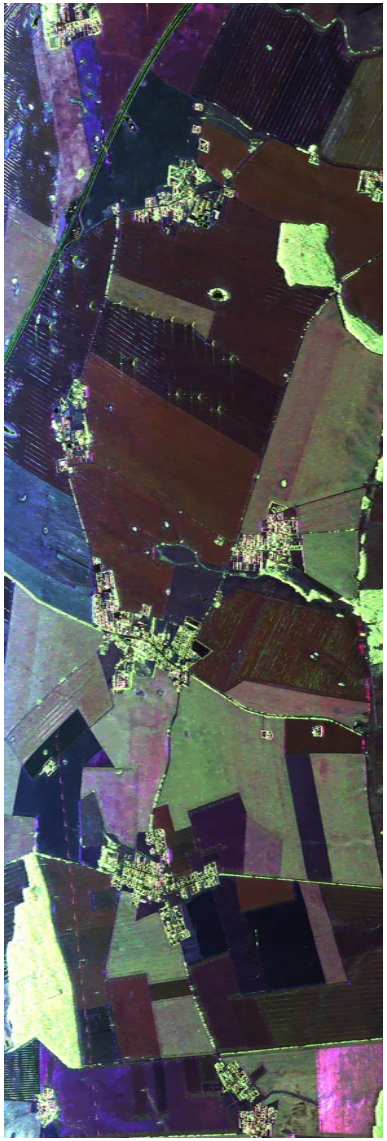
$|S_{hh}+S_{vv}|$

$|S_{hv}+S_{vh}|$

$|S_{hh}-S_{vv}|$

DLR

Polarimetric change analysis representation (Winter wheat)



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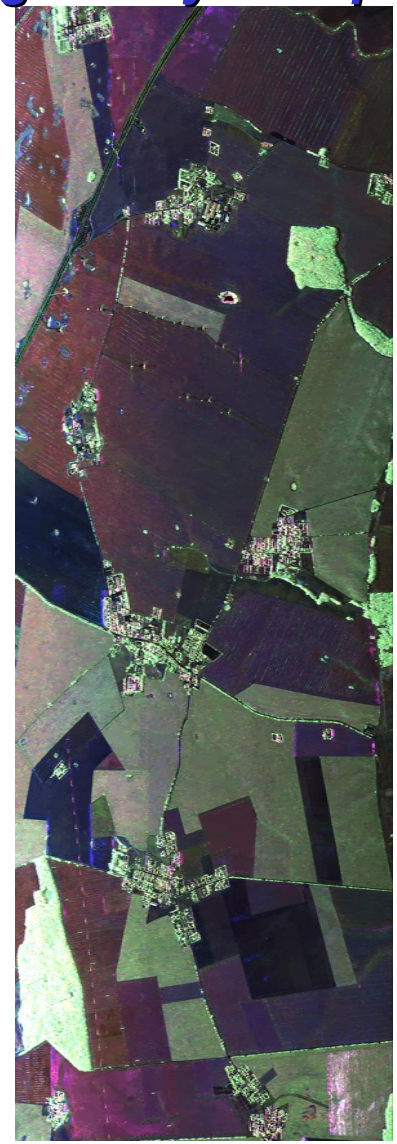

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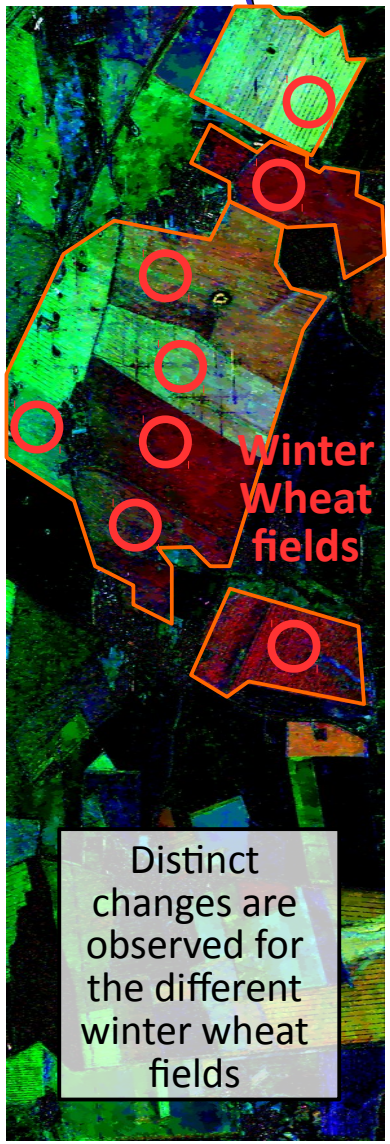
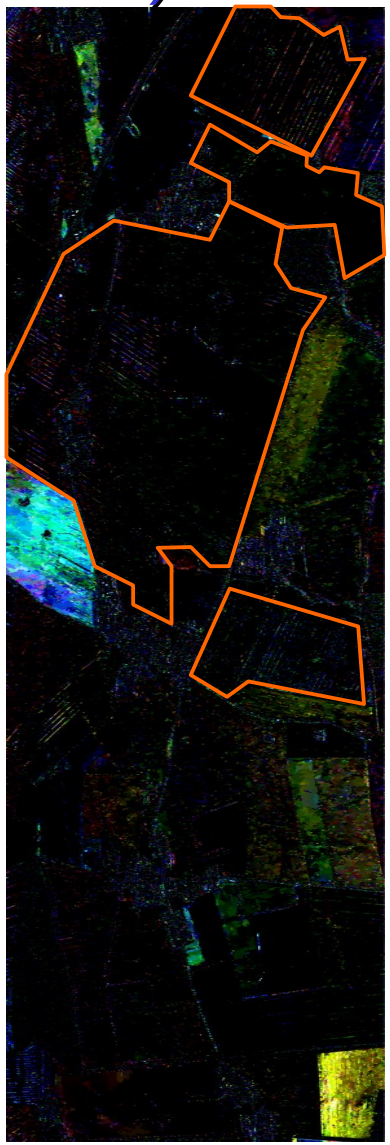


p_{inc}



p_{dec}

Pauli RGB 3-10 dB

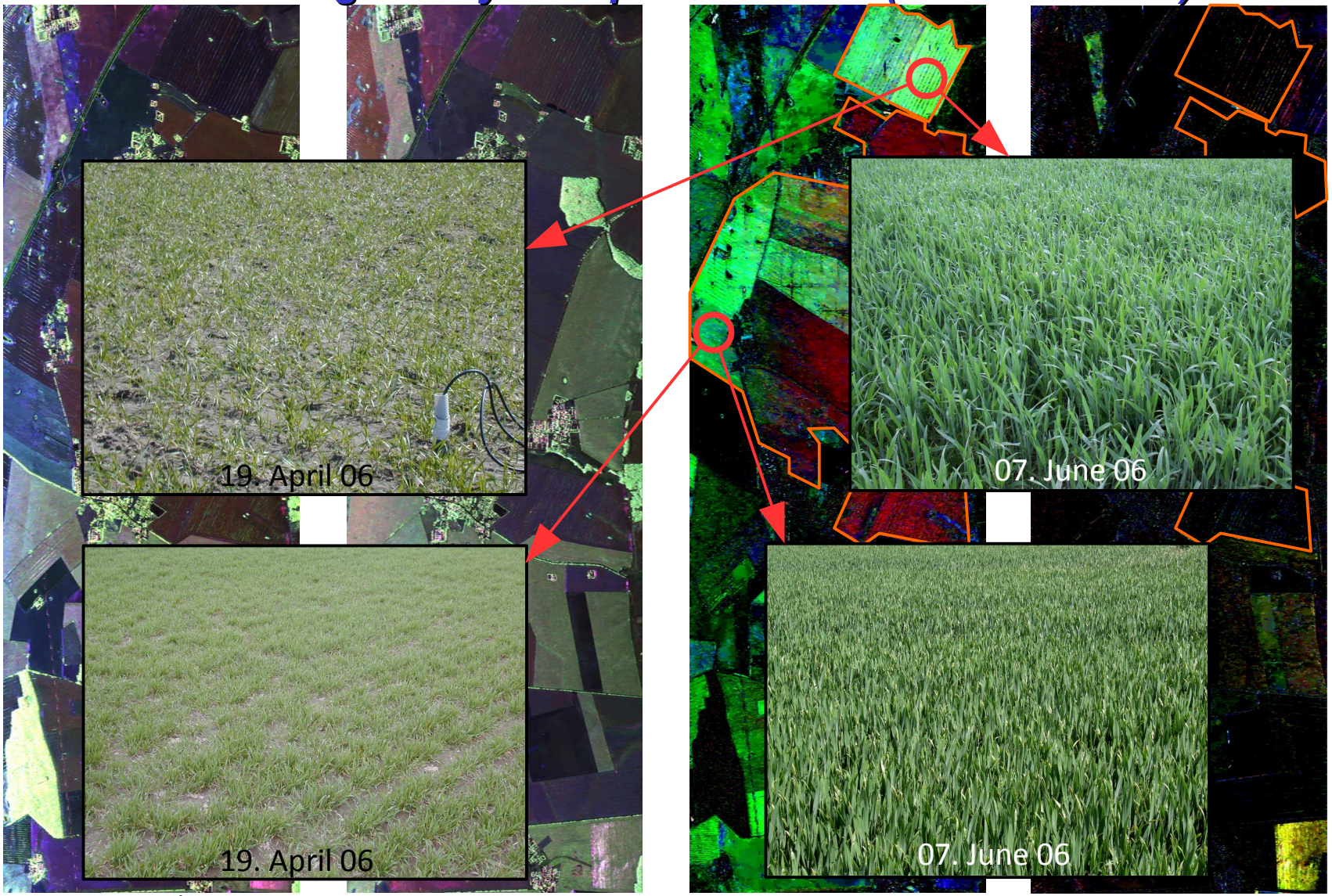
$|S_{hh}+S_{vv}|$

$|S_{hv}+S_{vh}|$

$|S_{hh}-S_{vv}|$

DLR

Polarimetric change analysis representation (Winter wheat I)

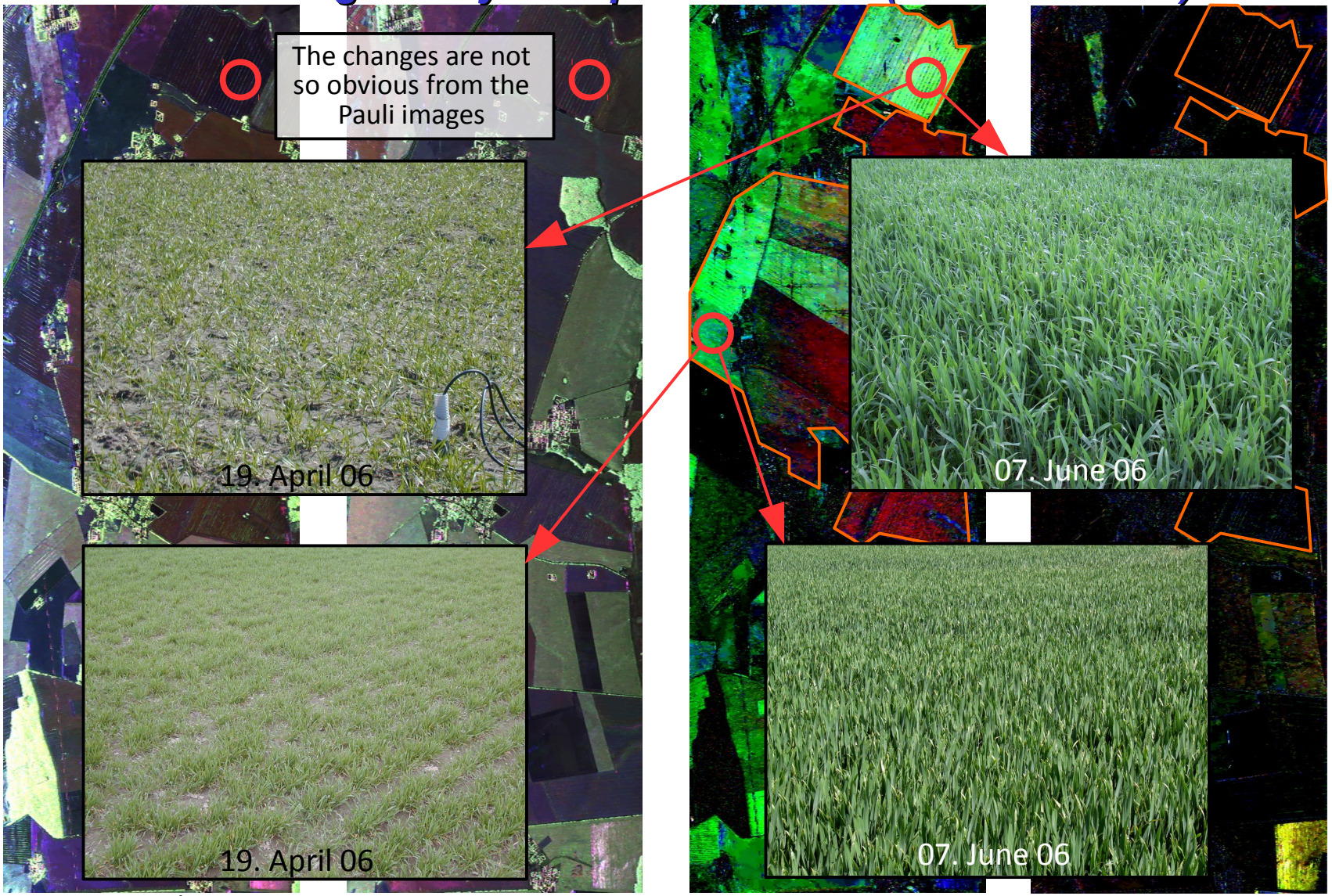


19. April 06 07. June 06

p_{inc} p_{dec}

DLR

Polarimetric change analysis representation (Winter wheat I)

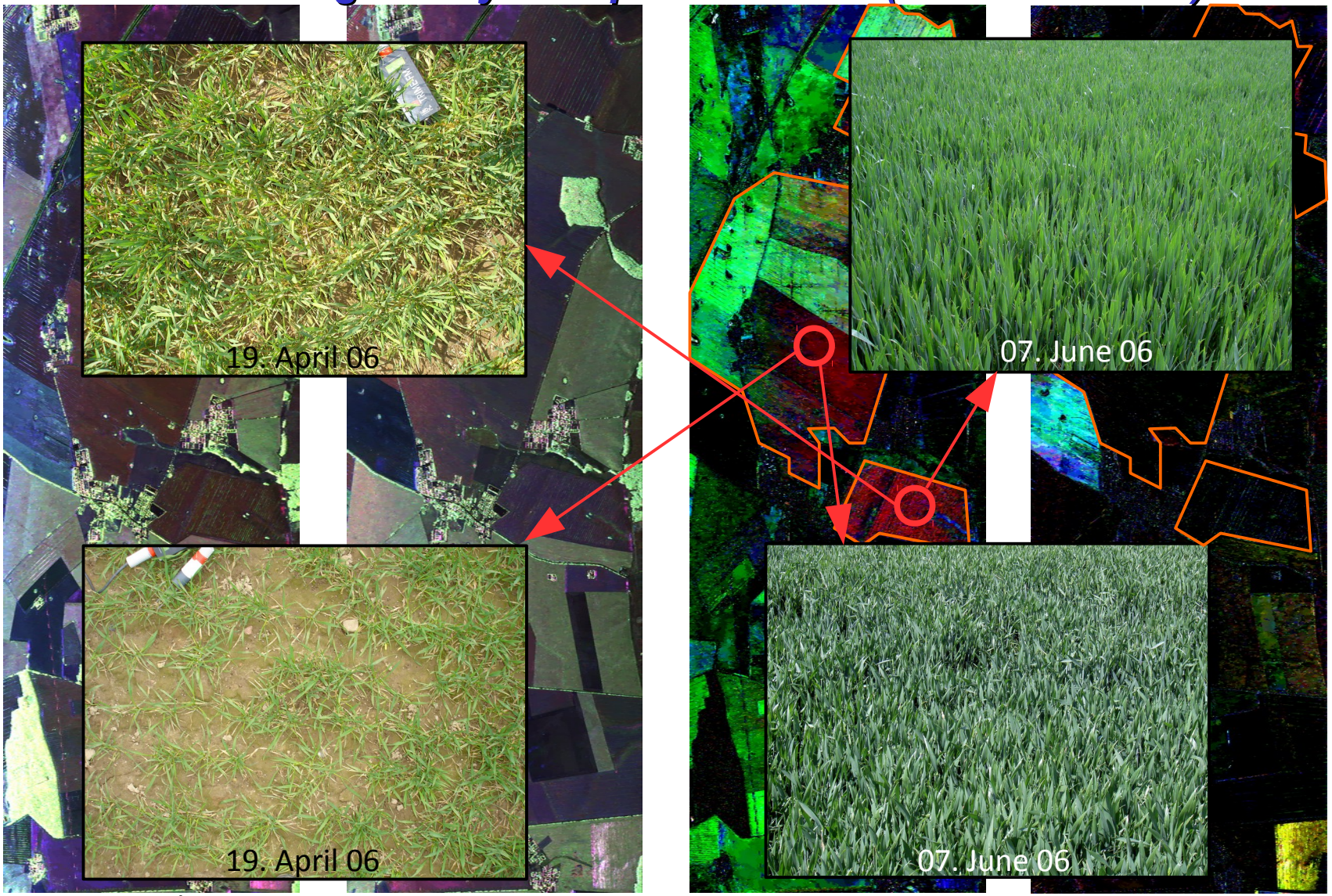


19. April 06 07. June 06

p_{inc} p_{dec}

DLR

Polarimetric change analysis representation (Winter wheat II)

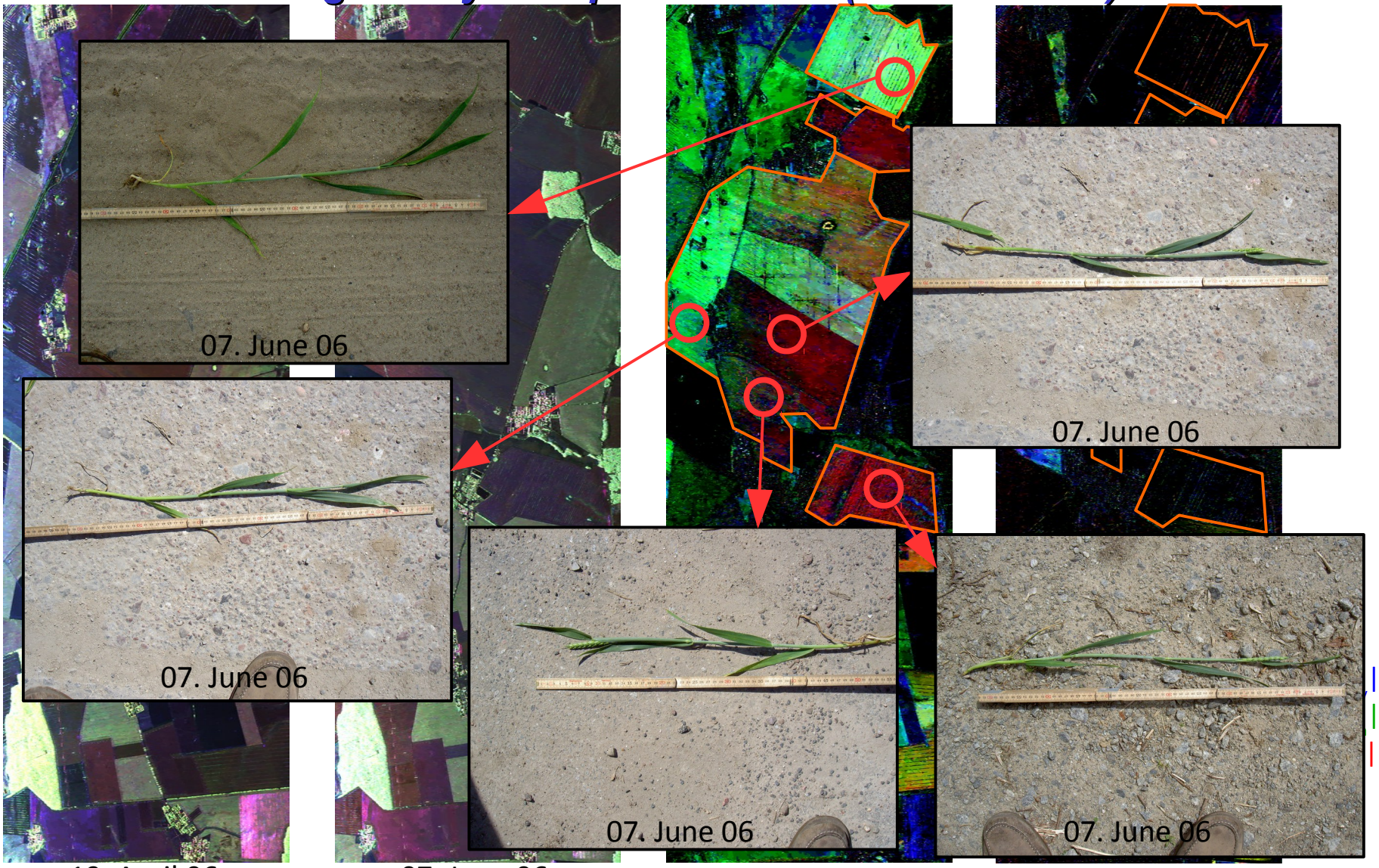


19. April 06 07. June 06

p_{inc} p_{dec}

DLR

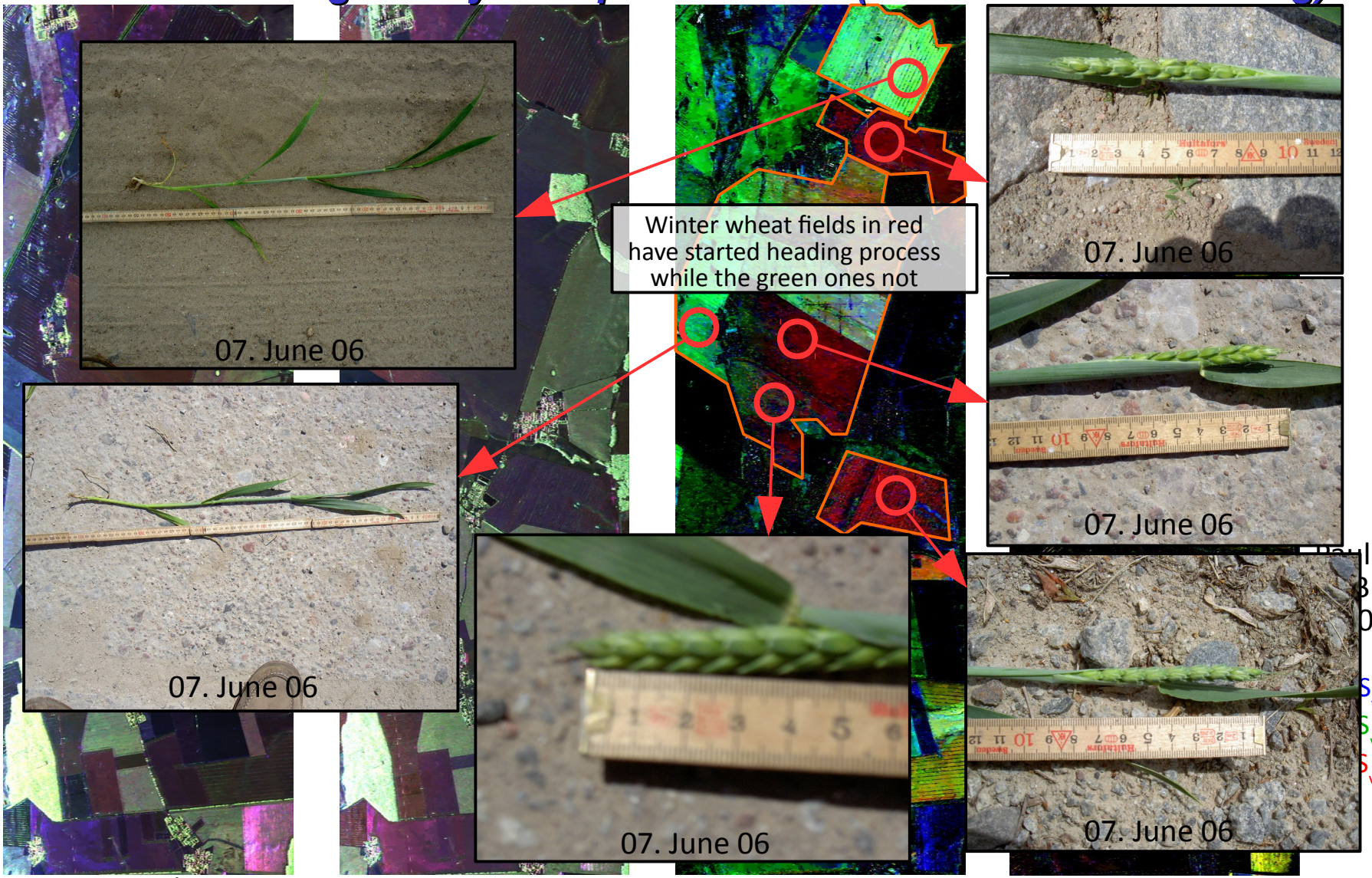
Polarimetric change analysis representation (Winter wheat)



19. April 06 | 07. June 06 | p_{inc} | p_{dec}

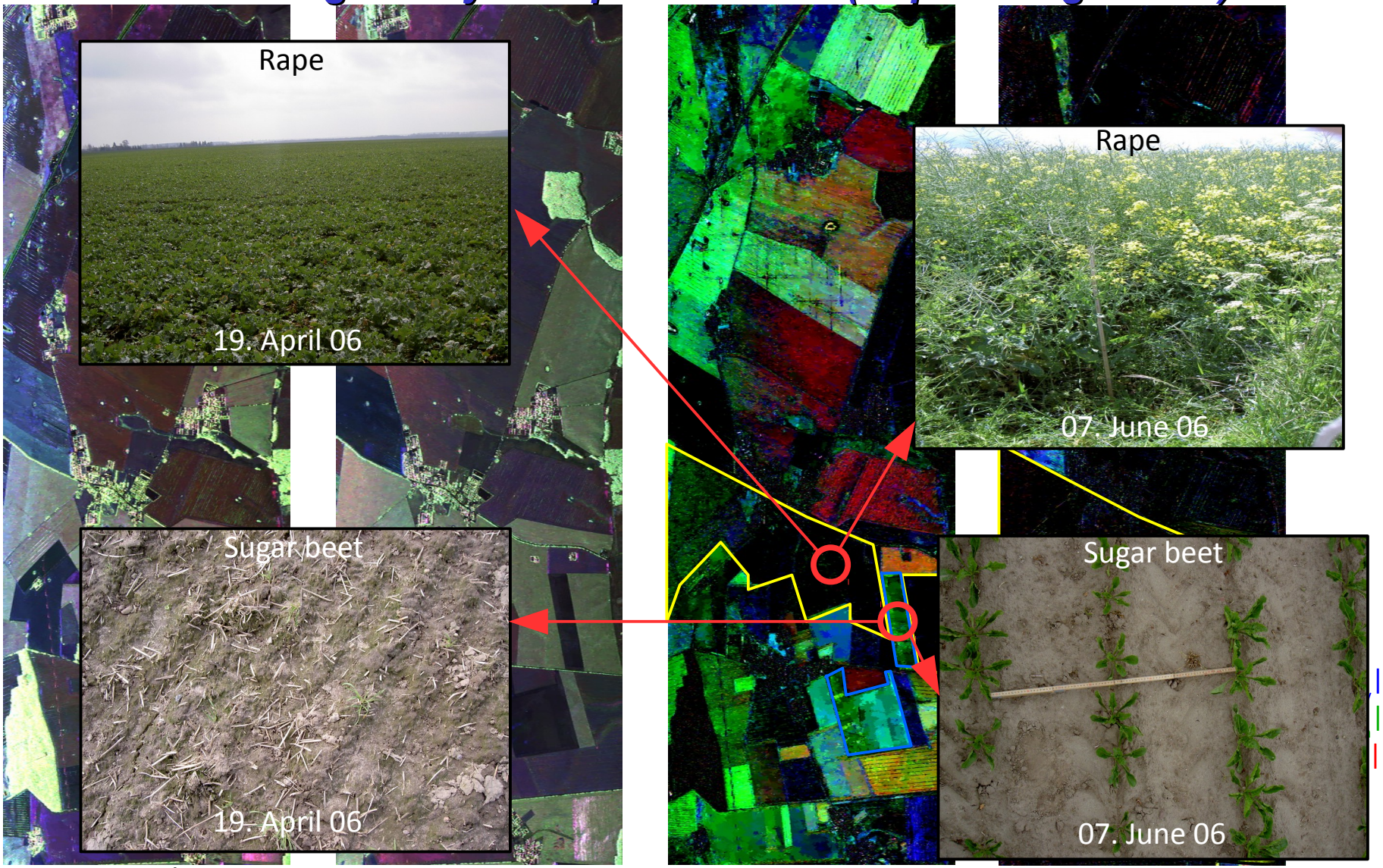
DLR

Polarimetric change analysis representation (Winter wheat flowering)



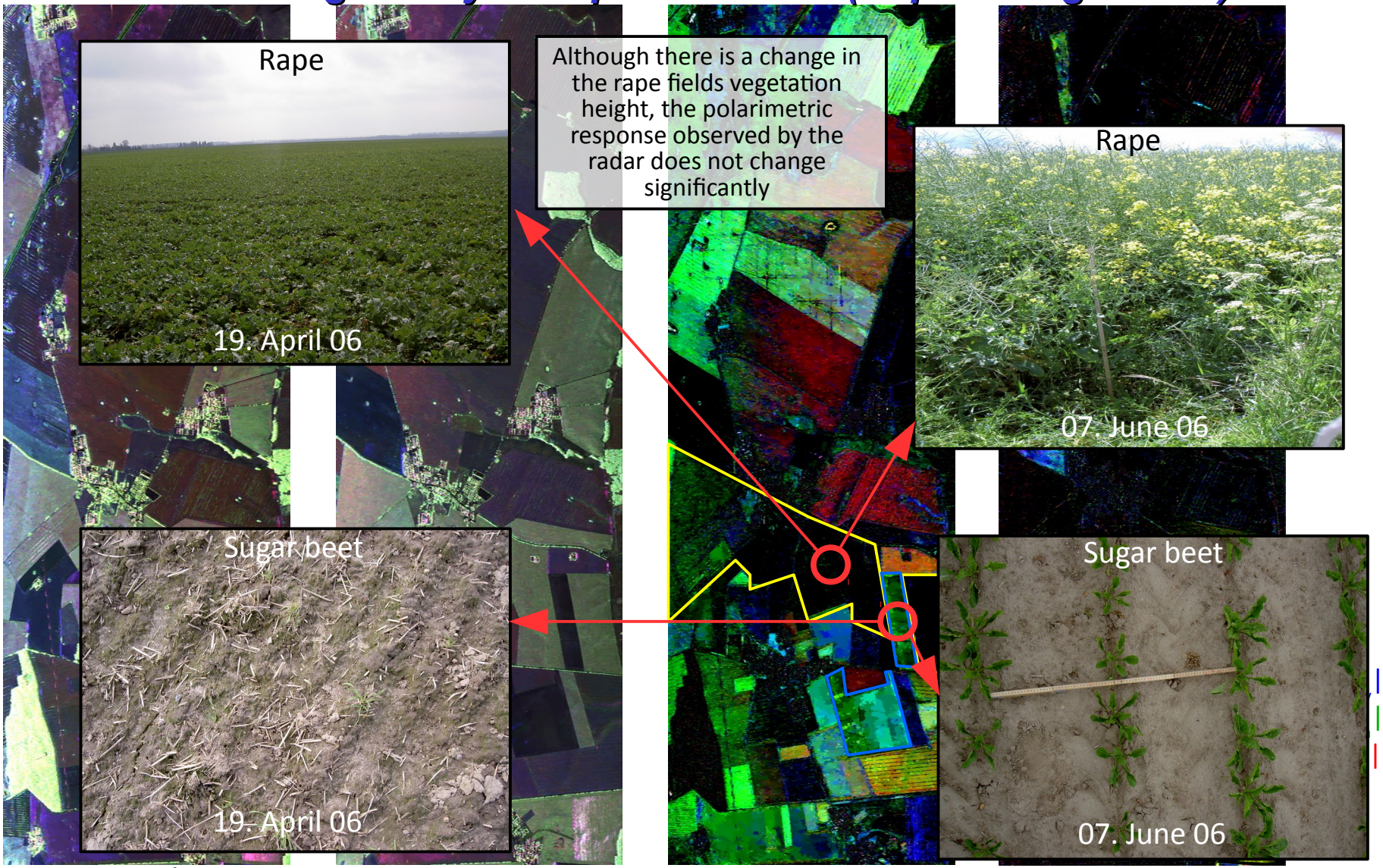
DLR

Polarimetric change analysis representation (Rape & Sugar beet)



DLR

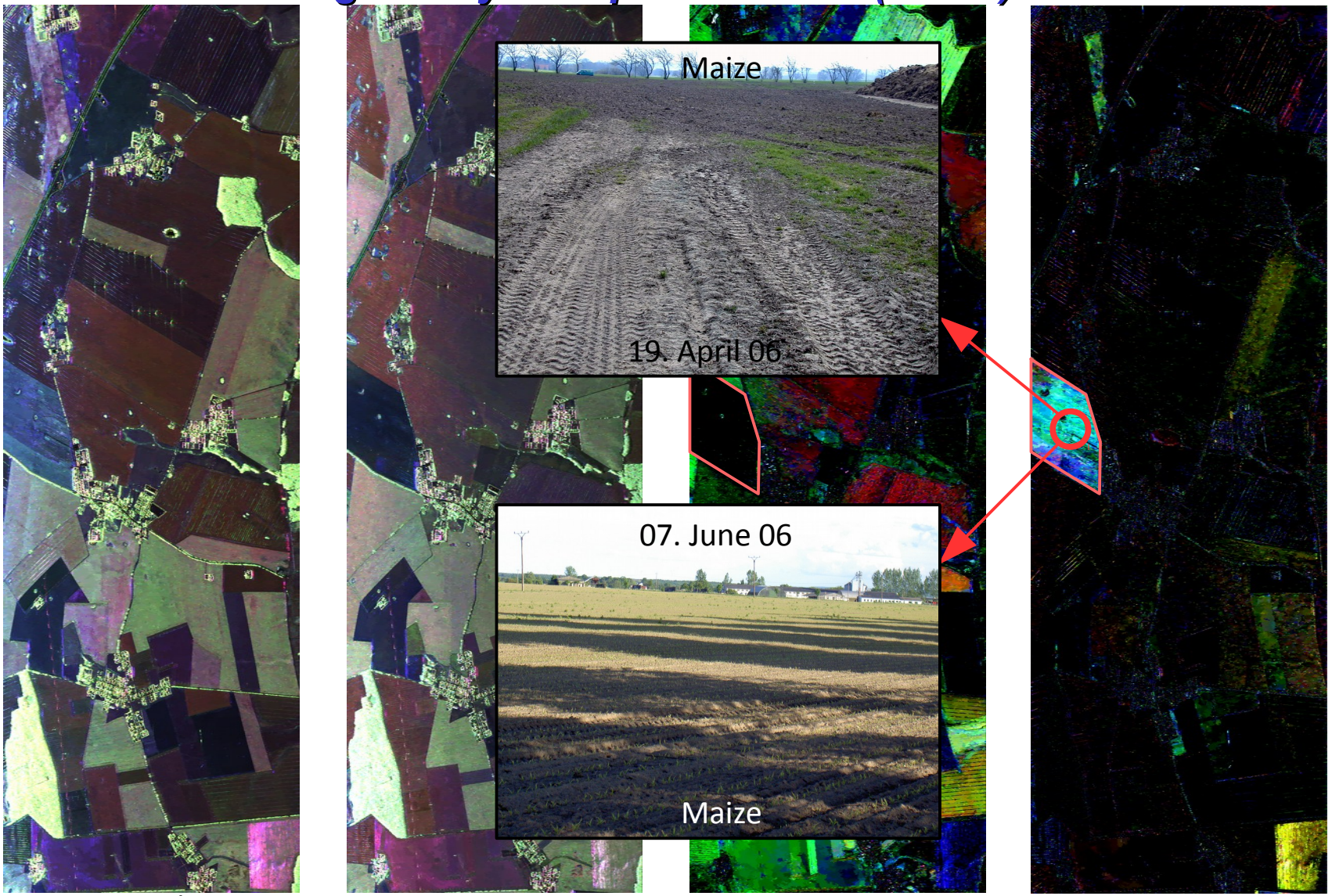
Polarimetric change analysis representation (Rape & Sugar beet)



19. April 06 | 07. June 06 | p_{inc} | p_{dec}

DLR

Polarimetric change analysis representation (Maize)



19. April 06

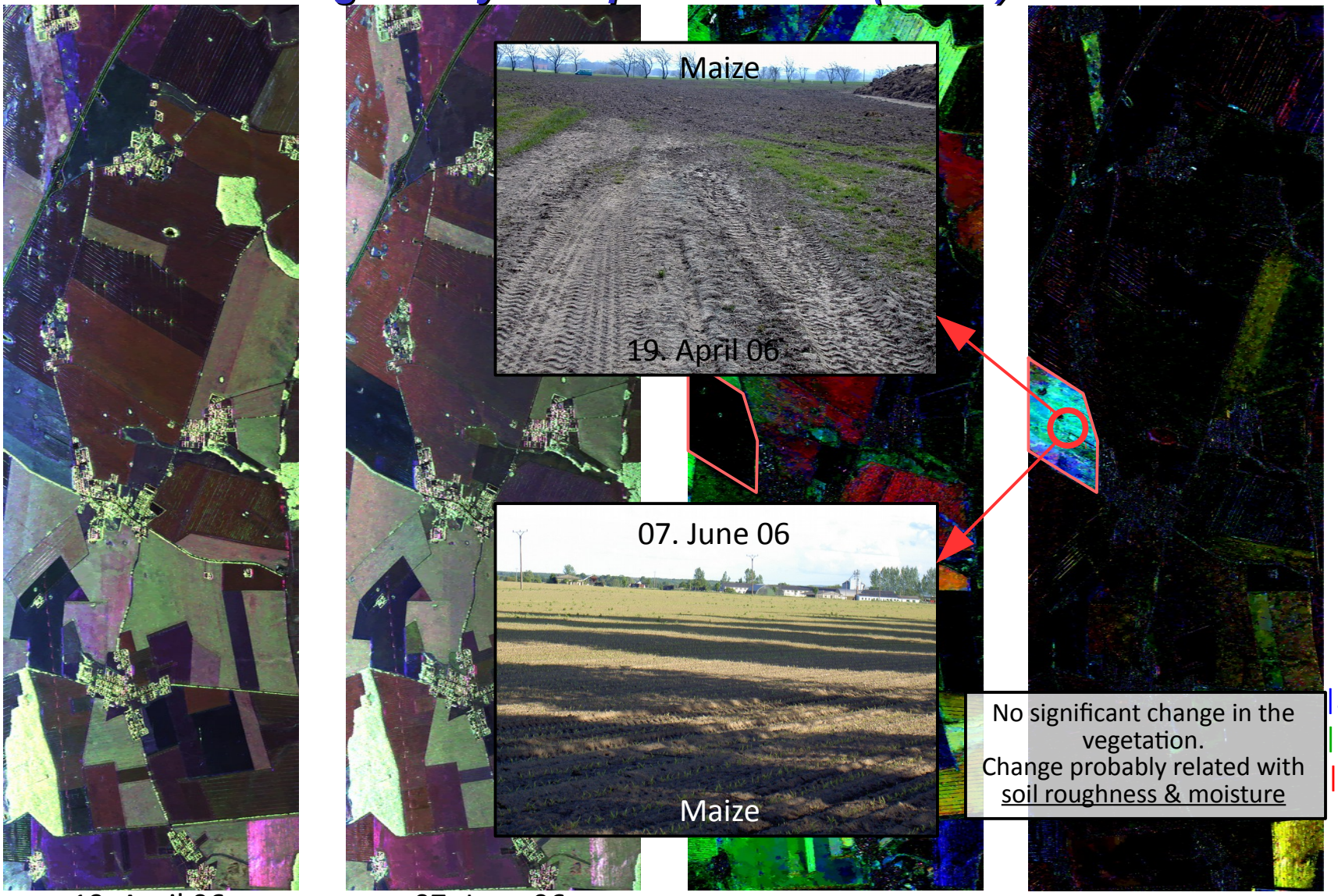
07. June 06

p_{inc}

p_{dec}

DLR

Polarimetric change analysis representation (Maize)



19. April 06

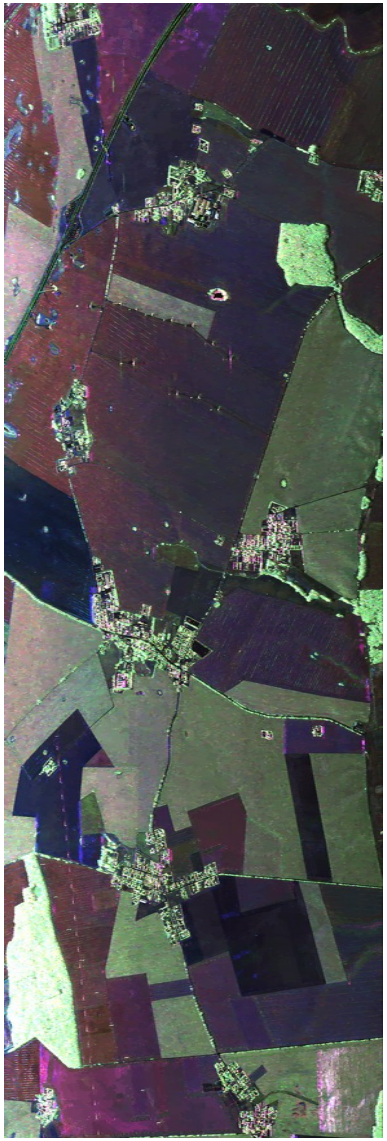
07. June 06

$\boldsymbol{p}_{inc}$

$\boldsymbol{p}_{dec}$

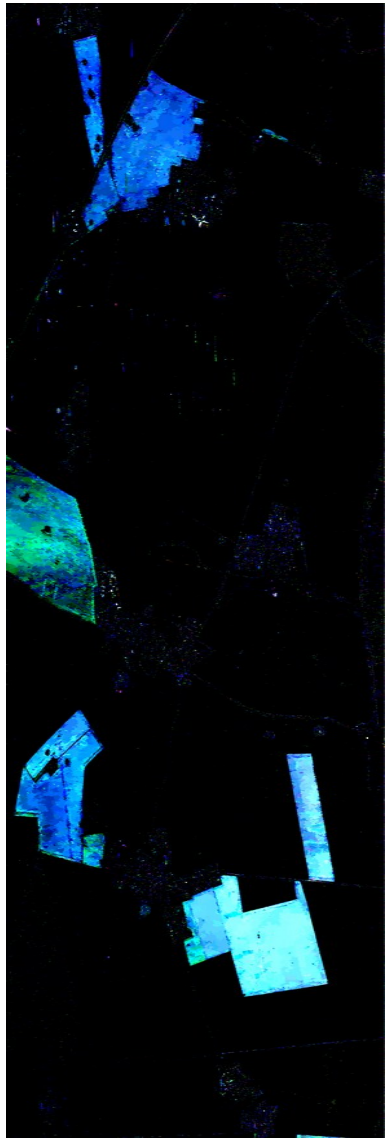
DLR

Polarimetric change analysis representation

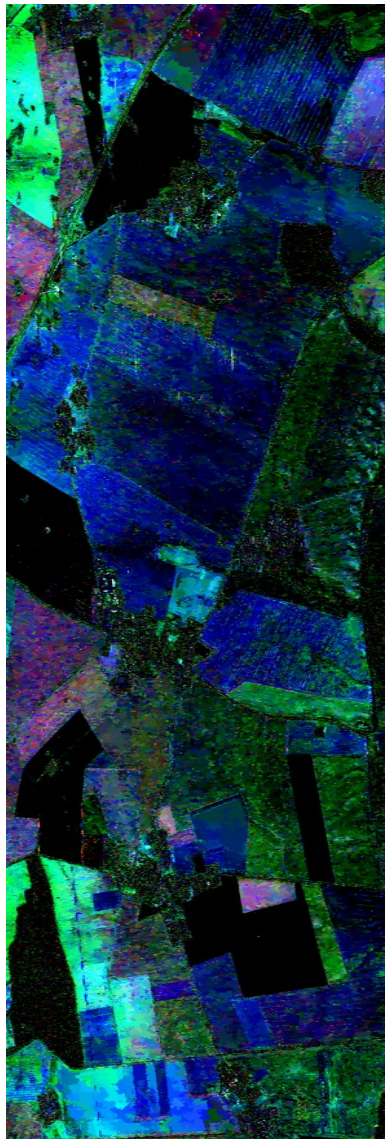


07. June 06

05. July 06



p_{inc}



p_{dec}

Pauli RGB 3-10 dB

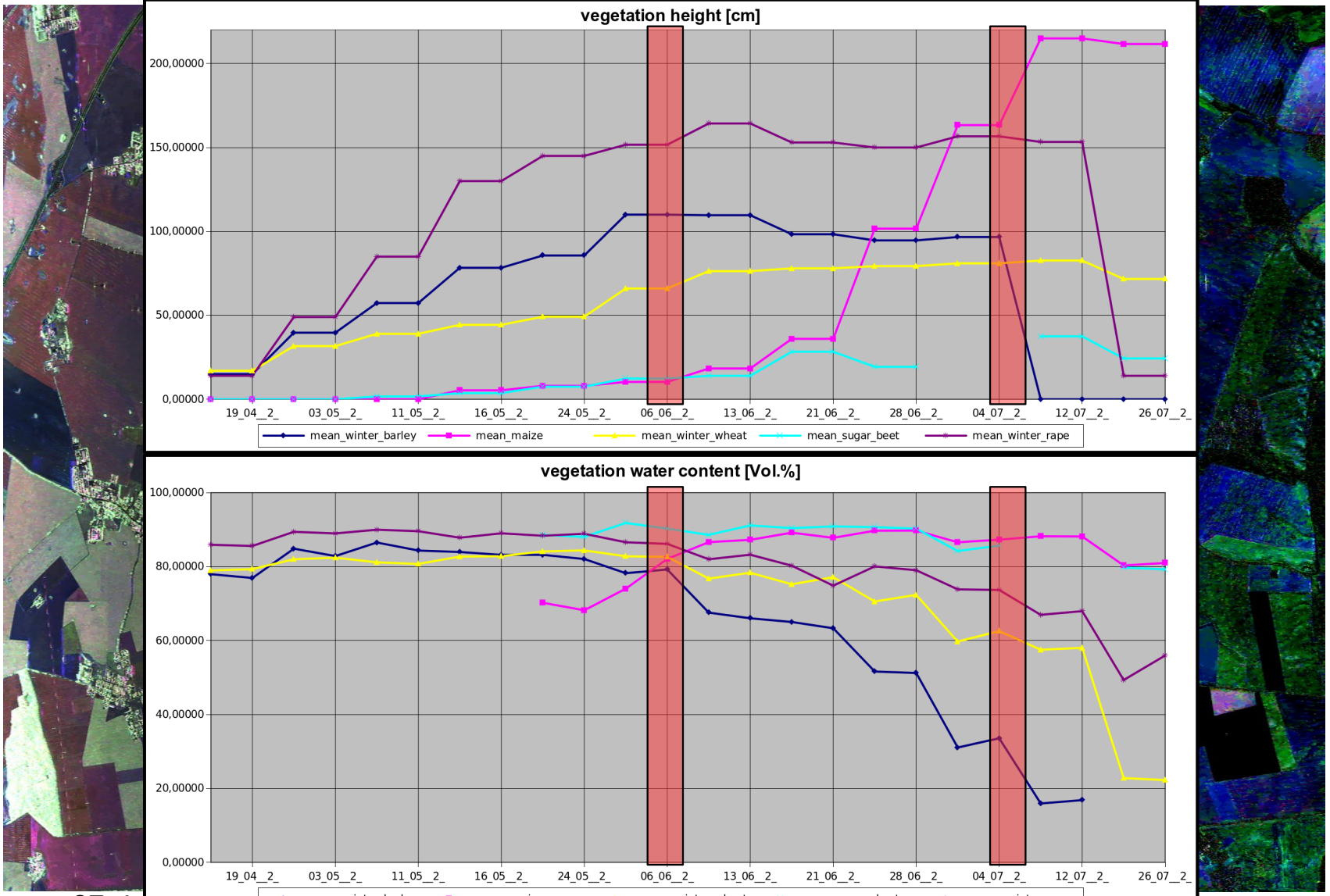
$|S_{hh}+S_{vv}|$

$|S_{hv}+S_{vh}|$

$|S_{hh}-S_{vv}|$

DLR

Polarimetric change analysis representation



Pauli RGB 3-10 dB

$|S_{hh}+S_{vv}|$

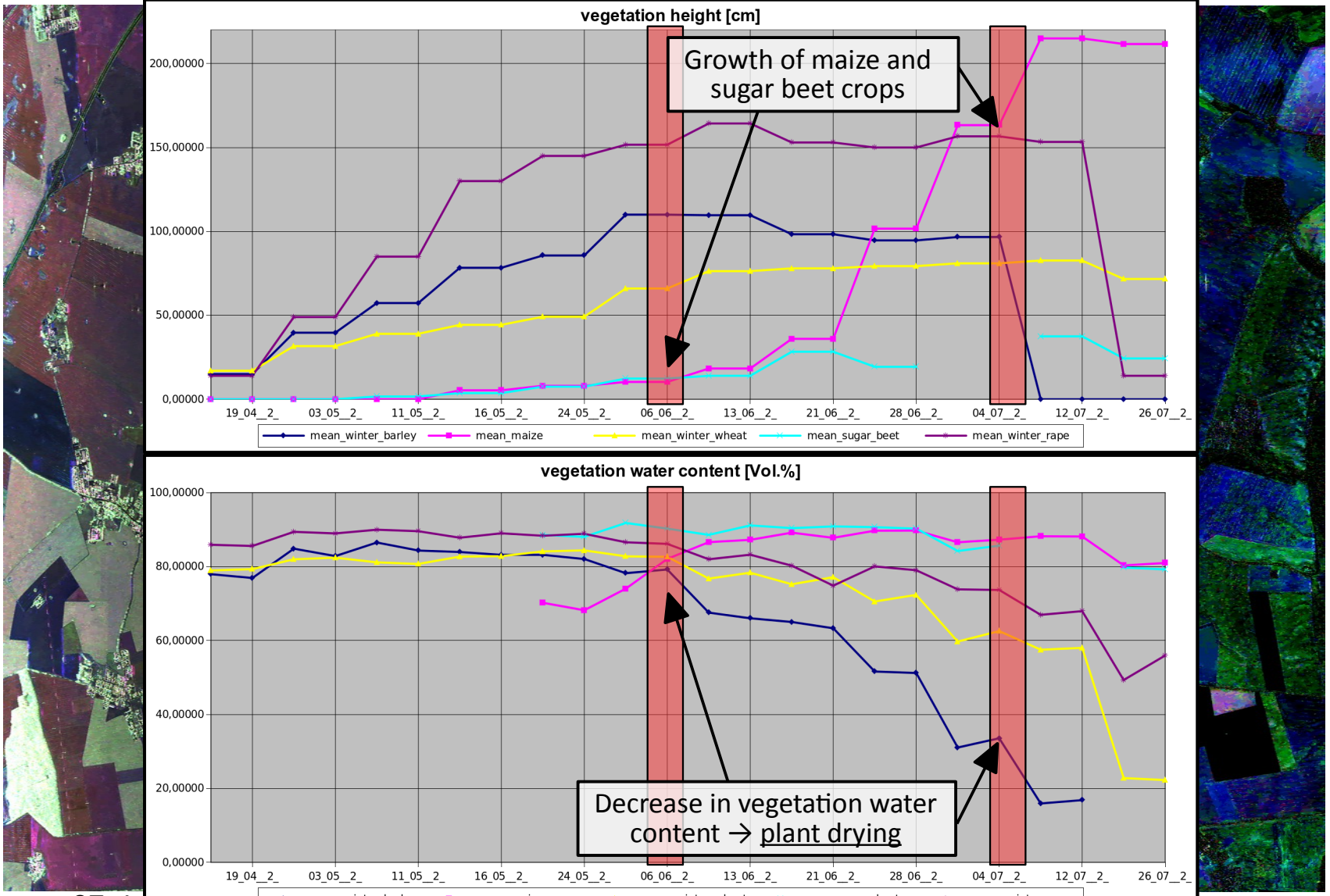
$|S_{hv}+S_{vh}|$

$|S_{hh}-S_{vv}|$

07. Ju ase

DLR

Polarimetric change analysis representation



Pauli RGB 3-10 dB

$|S_{hh}+S_{vv}|$

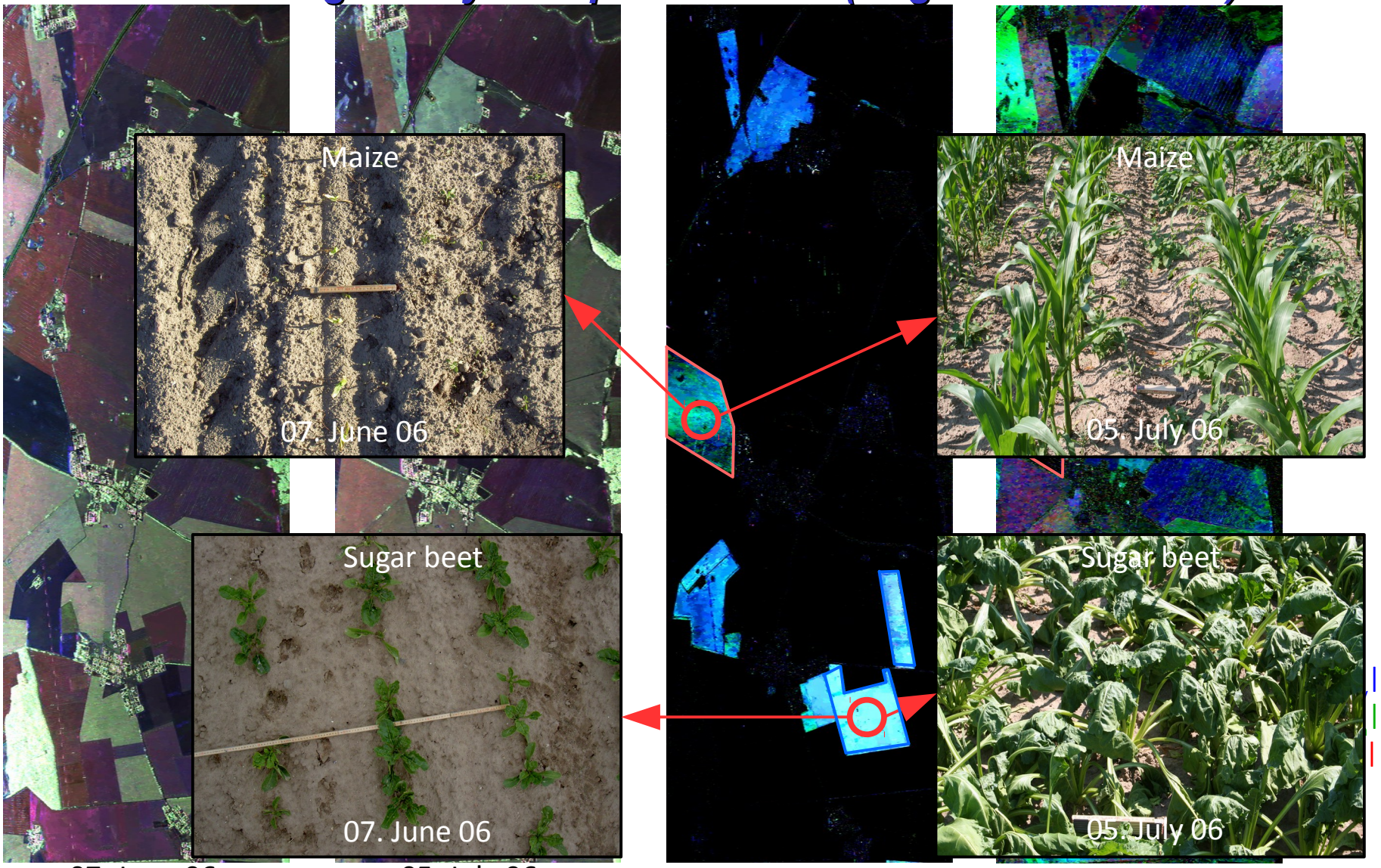
$|S_{hv}+S_{vh}|$

$|S_{hh}-S_{vv}|$

07. Ju ase

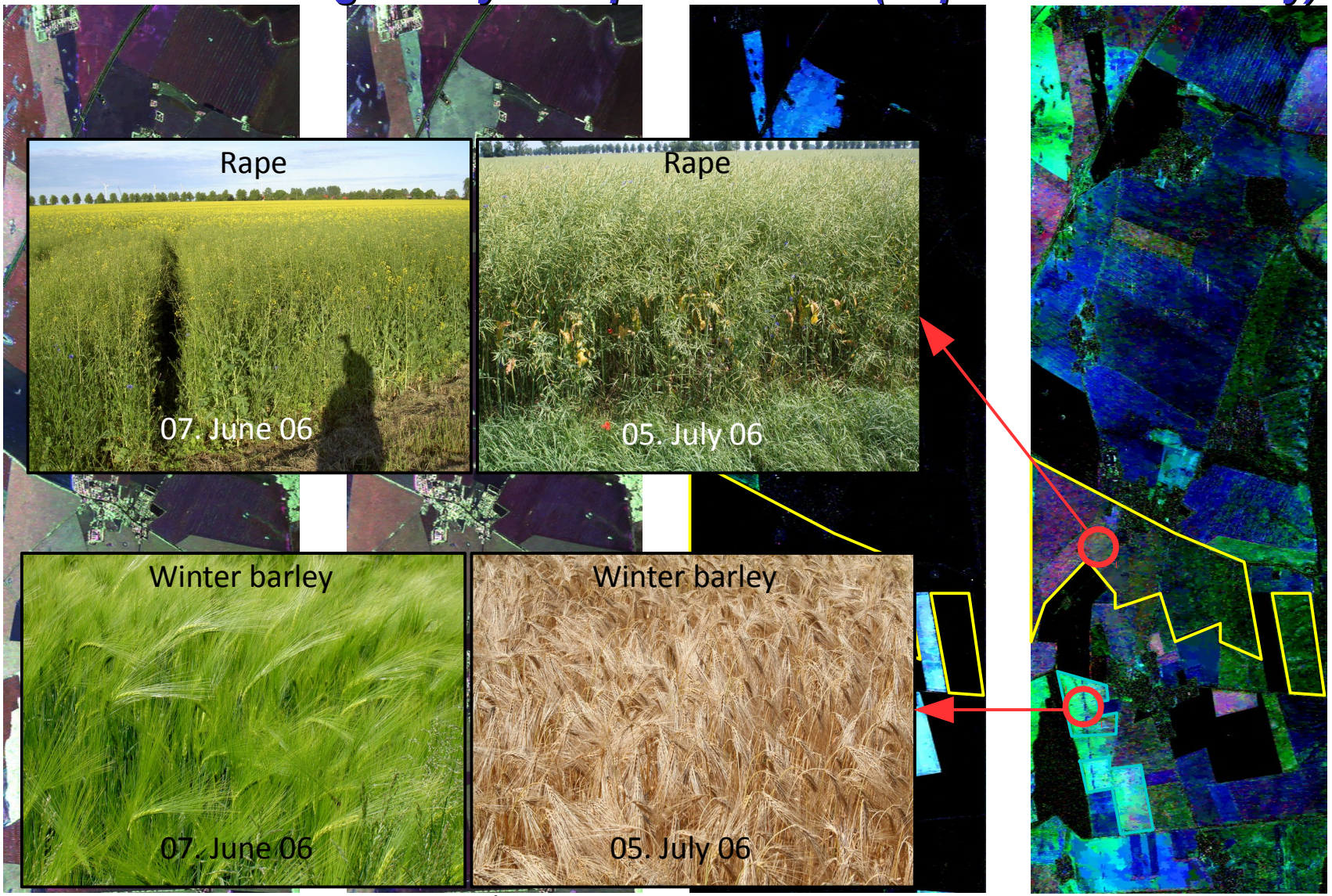
DLR

Polarimetric change analysis representation (Sugar beet & Maize)



DLR

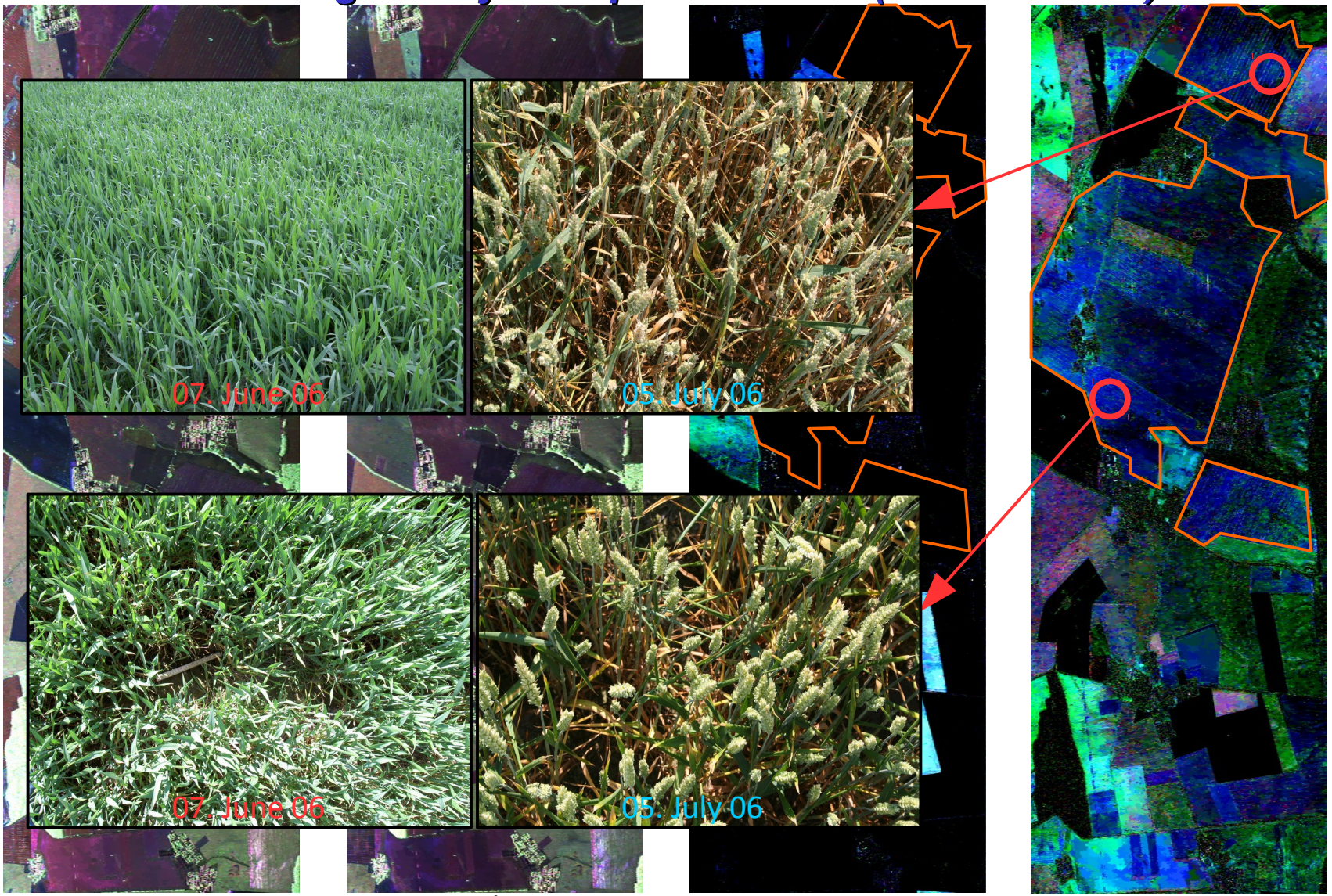
Polarimetric change analysis representation (Rape & Winter barley)



07. June 06 05. July 06 p_{inc} p_{dec}

DLR

Polarimetric change analysis representation (Winter wheat)



07. June 06

05. July 06

p_{inc}

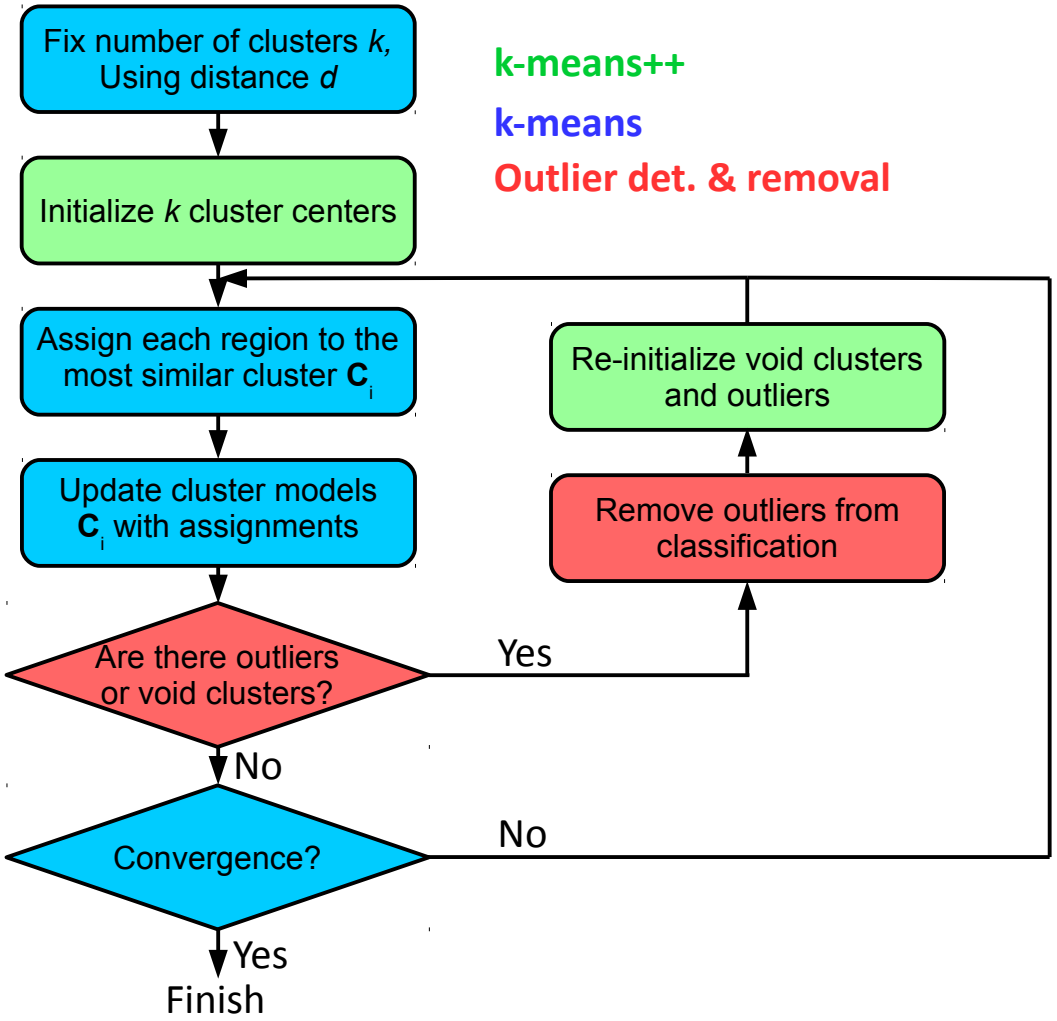
p_{dec}

DLR

Unsupervised classification

An unsupervised classification process is proposed based on the techniques:

- k-means: clustering technique based on a distance.
- k-means++: robust initialization process for k-means.
- Outlier detection and removal: improves cluster recognition and characterization.

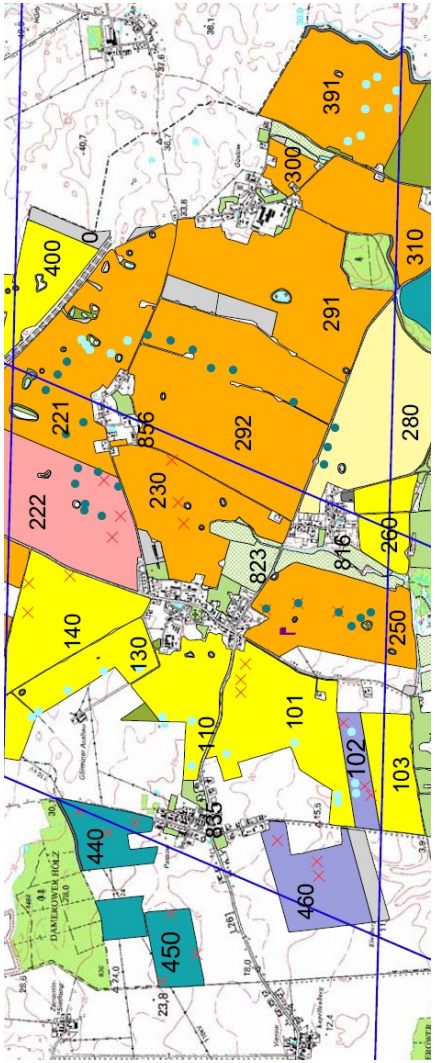


Two alternatives compared for BPT-based classification:

- Group regions with similar polarimetric temporal evolution.
- Group regions having similar polarimetric changes among the different acquisitions

DLR

Unsupervised classification results

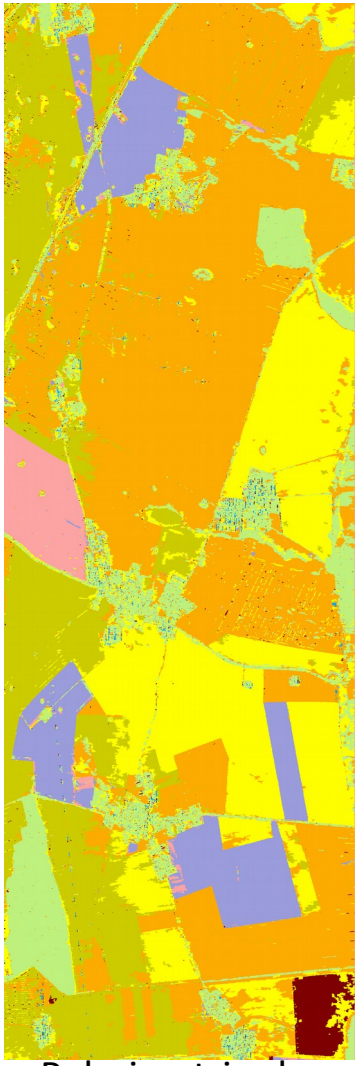


Land-use map
- rape
- set aside rape
- winter wheat
- maize
- sugar beet
- winter barley
- grassland
- no crop

Land-use map
Ground Truth

Classification map
- far-range rape
- near-range rape
- winter wheat 1
- winter wheat 2
- winter wheat 3
- maize
- sugar beet
- grassland 1
- grassland 2
- other crops
- other crops
- +5 smaller classes

Polarimetric temporal evolution-based classification (16 classes)

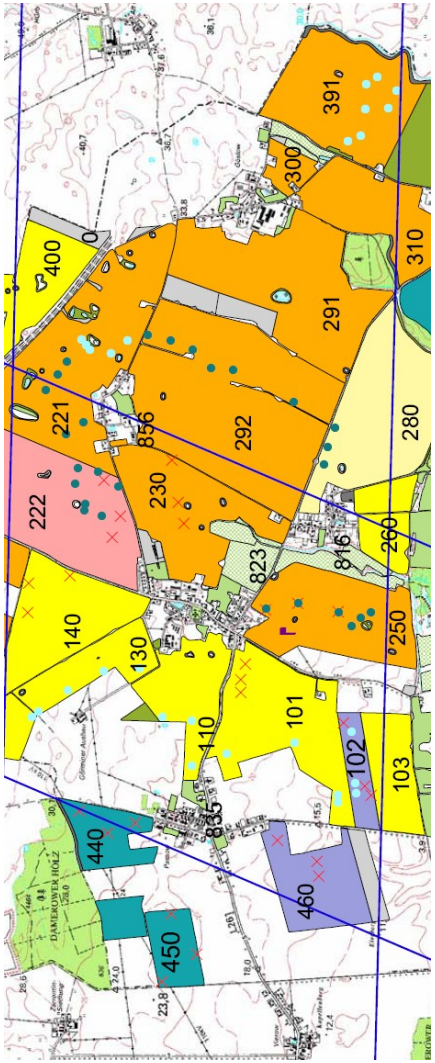


Classification map
- far-range rape
- near-range rape
- winter wheat
- maize
- sugar beet
- urban changes
- no change areas
- other crops

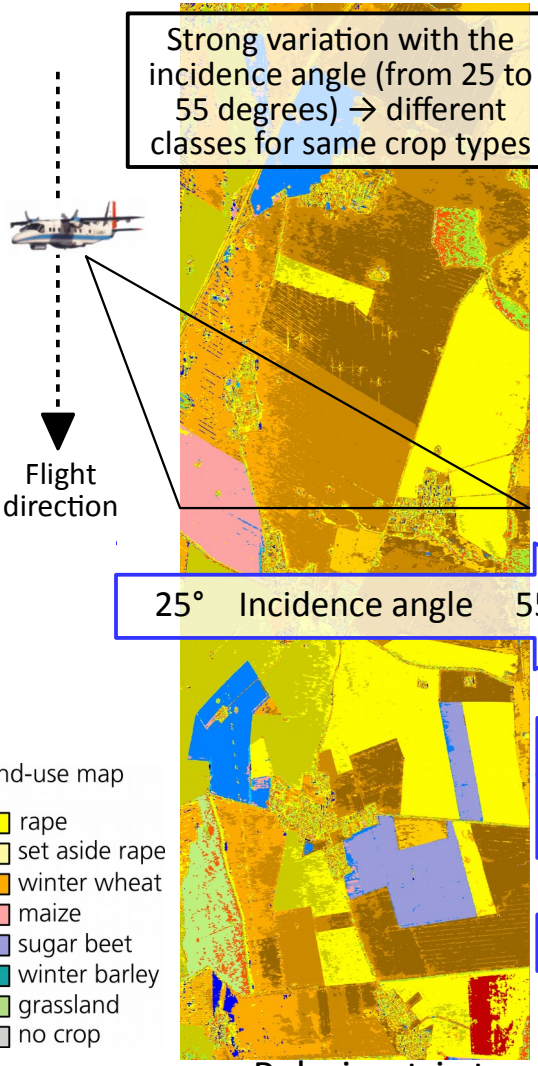
Polarimetric change-based classification (8 classes)

DLR

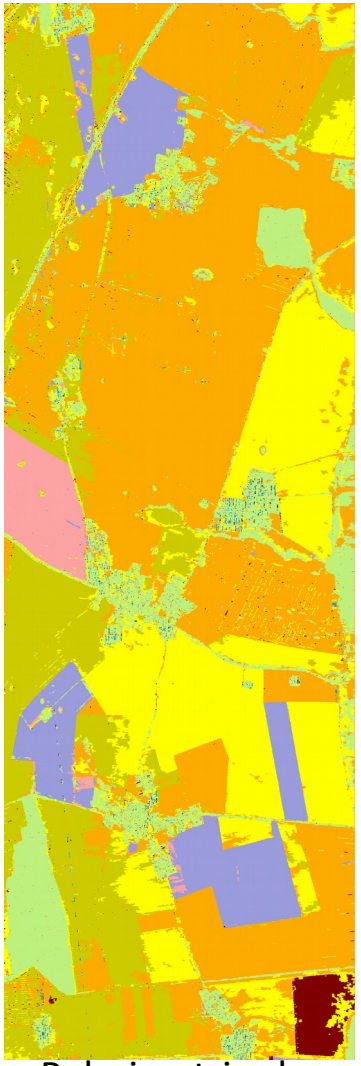
Unsupervised classification results



Land-use map
Ground Truth



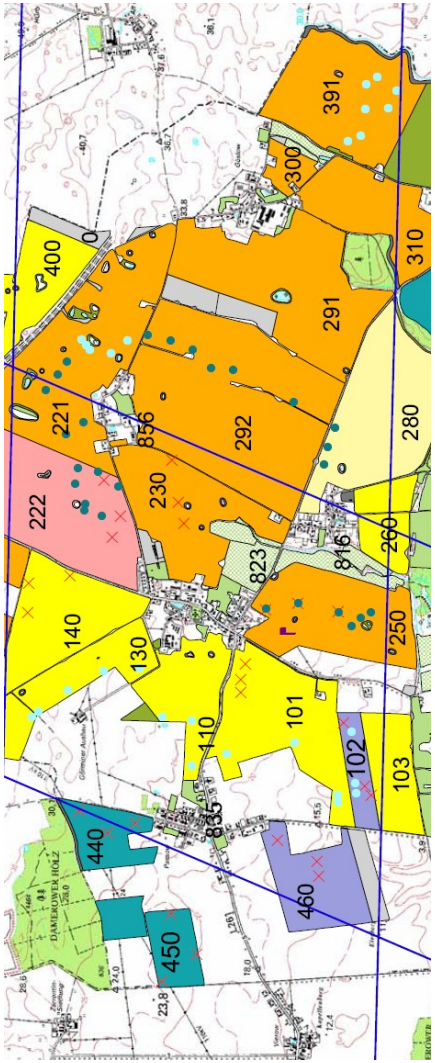
Polarimetric temporal evolution-based classification (16 classes)



Polarimetric change-based classification (8 classes)

DLR

Unsupervised classification results



Land-use map
- rape
- set aside rape
- winter wheat
- maize
- sugar beet
- winter barley
- grassland
- no crop

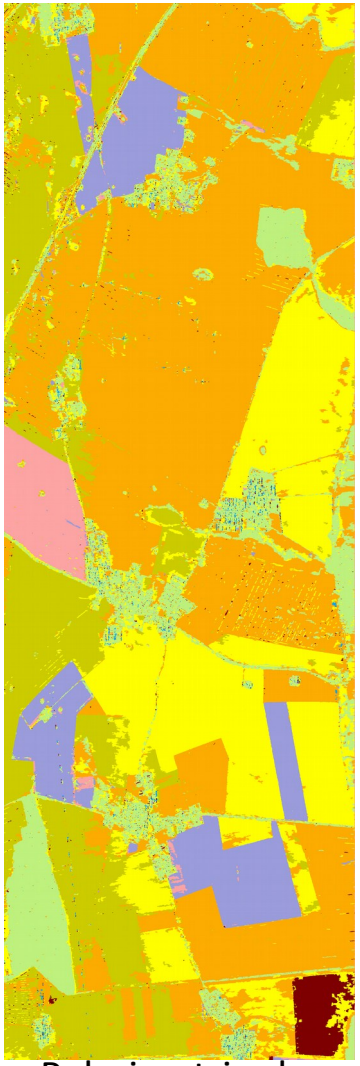
Land-use map
Ground Truth

Small details of urban areas into different classes → Increase number of classes

Classification map
- far-range rape
- near-range rape
- winter wheat 1
- winter wheat 2
- winter wheat 3
- maize
- sugar beet
- grassland 1
- grassland 2
- other crops
- other crops

+5 smaller classes

Polarimetric temporal evolution-based classification (16 classes)

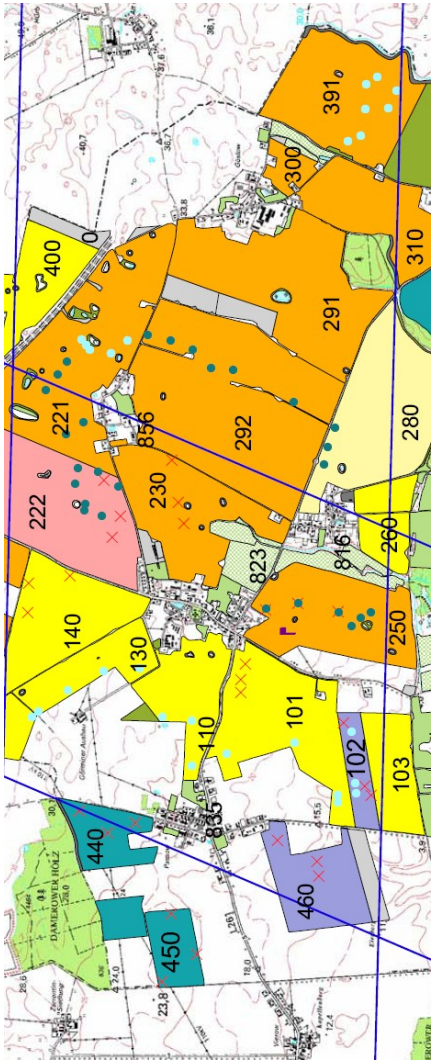


Classification map
- far-range rape
- near-range rape
- winter wheat
- maize
- sugar beet
- urban changes
- no change areas
- other crops

Polarimetric change-based classification (8 classes)

DLR

Unsupervised classification results



Land-use map
- rape
- set aside rape
- winter wheat
- maize
- sugar beet
- winter barley
- grassland
- no crop

Land-use map
Ground Truth

Classification map
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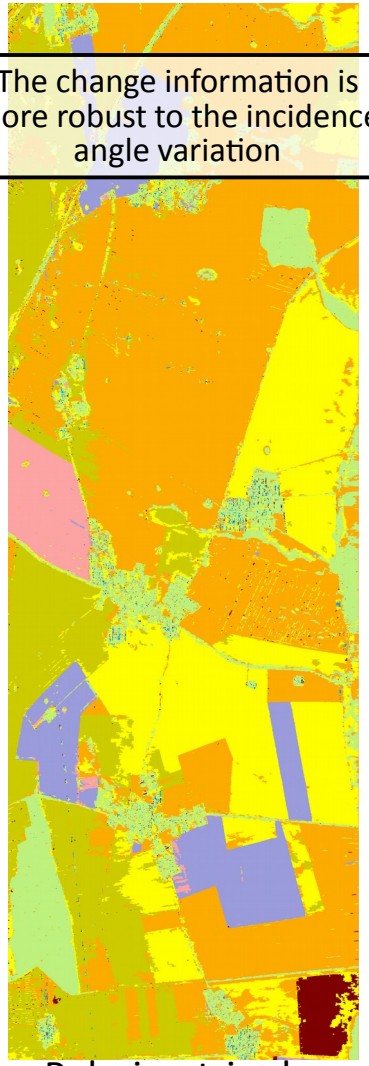
- near-range rape
- winter wheat 1
- winter wheat 2
- winter wheat 3
- maize
- sugar beet
- grassland 1
- grassland 2
- other crops
- other crops

+5 smaller classes

Polarimetric temporal evolution-based classification (16 classes)

The change information is more robust to the incidence angle variation

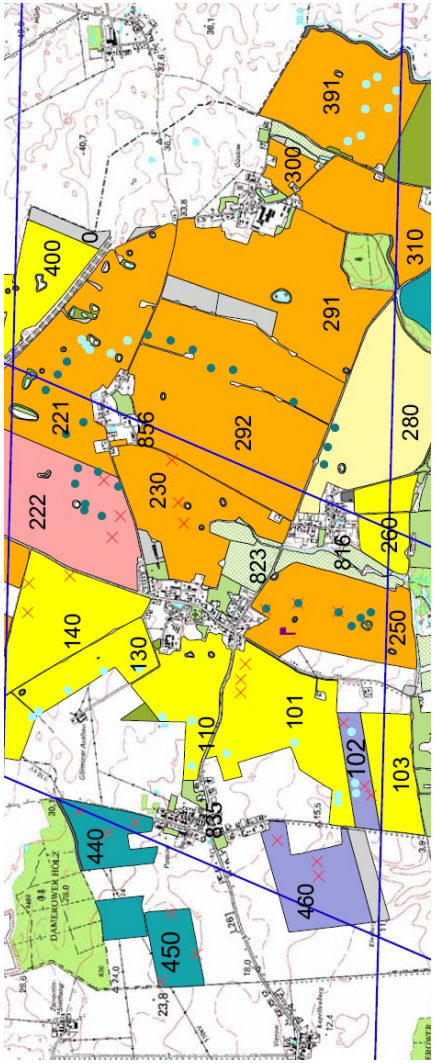


Classification map
- far-range rape
- near-range rape
- winter wheat
- maize
- sugar beet
- urban changes
- no change areas
- other crops

Polarimetric change-based classification (8 classes)

DLR

Unsupervised classification results



Land-use map
- rape
- set aside rape
- winter wheat
- maize
- sugar beet
- winter barley
- grassland
- no crop

Land-use map
Ground Truth

Classification map
- far-range rape
- near-range rape
- winter wheat 1
- winter wheat 2
- winter wheat 3
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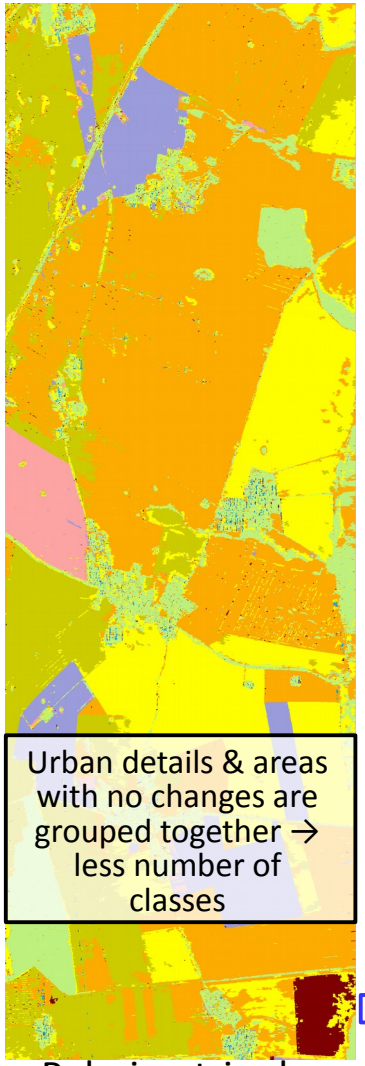
- sugar beet
- grassland 1
- grassland 2
- other crops
- other crops

+5 smaller classes

Polarimetric temporal evolution-based classification (16 classes)



Urban details & areas with no changes are grouped together → less number of classes

Classification map
- far-range rape
- near-range rape
- winter wheat
- maize
- sugar beet
- urban changes
- no change areas
- other crops

Polarimetric change-based classification (8 classes)

DLR

Conclusions

- Polarimetric SAR time series contain valuable information for the monitoring and characterization of agricultural areas.
- The proposed temporal stability measure is able to detect the changes of the scene, containing information about the amount of change.
- The polarimetric change analysis is a useful mechanism for detecting the type of change. It is related with the polarimetric contrast.
- A polarimetric change representation is proposed which has proven to be sensitive to distinct phenological changes and plant evolution.
- This polarimetric change analysis information is useful for unsupervised classification. It is able to identify and separate into classes the different content of the scene, improving considerably the agricultural land-use classification performance.

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Thank you for your attention!

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