A Reinterpretation of Temporal InSAR Coherence for Multitemporal SAR and Polarimetric SAR Data Classification

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J. Ni, C. López-Martínez, Z. Hu & F. Zhang, "*Multitemporal SAR and Polarimetric SAR Optimization and Classification: Reinterpreting Temporal Coherence*" IEEE TGRS, 2022

Context

Temporal information content in multitemporal time series of SAR data:

- SAR image's intensities or **T/C** matrices for PolSAR
- In repeat pass InSAR systems additional & complementary information is captured by the complex InSAR temporal coherence
  - Depends on the scatterer characteristics, but…
  - Non-exploitable in low coherence scenarios: temporal coherence, long temporal baseline, datasets affected by strong weather effects

GOAL

- Extraction of temporal information from multitemporal SAR and PolSAR datasets in low temporal coherence scenarios, and relation with the temporal information extracted from direct radar observables

Temporal InSAR Coherence

Temporal InSAR coherence $\rho = |\rho| e^{j\phi} = \frac{E\{S_1 S_2^*\}}{\sqrt{E\{|S_1|^2\} E\{|S_2|^2\}}}$

Decomposition: $\rho = \rho_{sym} \rho_{asym}$

Symmetric term $\rho_{sym} = \frac{E\{S_1 S_2^*\}}{\frac{E\{|S_1|^2 + |S_2|^2\}}{2}}$

Coherence under the symmetric assumption of no radiometric changes between SAR images $|S_1|^2 = |S_2|^2$

$$\rho_{sym} = \rho_{temp} \rho_{SNR} \rho_{rg} \rho_{vol} \rho_{other}$$

Classical coherence decomposition

Asymmetric term $\rho_{asym} = \frac{\frac{E\{|S_1|^2 + |S_2|^2\}}{2}}{\sqrt{E\{|S_1|^2\} E\{|S_2|^2\}}}$

Accounts for the departure from the symmetric assumption, $|S_1|^2 \neq |S_2|^2$, therefore accounting for non-coherent or radiometric changes

Temporal InSAR Coherence

Asymmetric term $\rho_{asym} = \frac{\frac{E\{|S_1|^2+|S_2|^2\}}{2}}{\sqrt{E\{|S_1|^2\}E\{|S_2|^2\}}}$ $\rho_{asym} \in [1,\infty)$

This term corresponds to the quotient of the arithmetic mean versus the geometric mean of the SAR images intensities

Ratio of SAR images intensities $\tau_{12} = \frac{E\{|S_1|^2\}}{E\{|S_2|^2\}}$ $\tau_{12} \in [0,\infty)$

Relation between both components $\rho_{asym} = \left(\frac{1}{2}\right)\left(\sqrt{\tau_{12}} + \frac{1}{\sqrt{\tau_{12}}}\right)$

${\rho_{asym}}^{-1} \in [0,1]$ takes the role of a temporal coherence-like parameter, accounting exclusively for radiometric changes

Temporal InSAR Coherence

Joint analysis of both decomposition terms

Coh. Ch.	Rad. Ch.	Coherence value
No	No	$\rho = \rho_{sym}\rho_{asym} = 1 \cdot 1 = 1$
Yes	No	$\rho = \rho_{sym}\rho_{asym} = \rho_{sym} \cdot 1 = \rho_{sym}$
No/Yes	Yes	$\rho = \rho_{sym}\rho_{asym}$ (General case)
Yes ($\rho_{sym} = 0$)	Yes	$\rho = \rho_{sym}\rho_{asym} = 0$

Case 1: No changes between SAR acquisitions
Case 2: Only coherent changes. Classical coherence analysis
Case 3: Coherent and Radiometric changes (**High coherence scenario**)
Case 4: Coherent and Radiometric changes in presence of total decorrelation (**Low coherence scenario**). ρ_{sym} cancels the information provided by ρ_{asym}

- Unification of concepts previously considered separately, the analysis of radiometric changes in terms of temporal coherence
- For low or null coherence, common information can be obtained from ρ_{asym} or the bounded term ${\rho_{asym}}^{-1} \in [0,1]$

Polarimetric Temporal InSAR Coherence

Temporal PolInSAR coherence $\rho = \frac{\omega_1^H \Omega_{12} \omega_2}{\sqrt{(\omega_1^H \mathbf{T}_{11} \omega_1)(\omega_2^H \mathbf{T}_{22} \omega_2)}}$

Decomposition: $\rho = \frac{\omega_1^H \Omega_{12} \omega_2}{\omega_1^H \mathbf{T} \omega_2} \frac{\omega_1^H \mathbf{T} \omega_2}{\sqrt{(\omega_1^H \mathbf{T}_{11} \omega_1)(\omega_2^H \mathbf{T}_{22} \omega_2)}} = \rho_{sym} \rho_{asym}$

The Symmetric term considers the symmetric assumption of equal scattering mechanism $\boldsymbol{T} = (\boldsymbol{T}_{11} + \boldsymbol{T}_{22})/2$

The Asymmetric term accounts for non-coherent polarimetric changes between both temporal acquisitions, allowing the characterization of multitemporal PolSAR data for low coherence scenarios

Polarimetric diversity allows optimization (maximization) of both decomposition terms

Polarimetric Temporal InSAR Coherence

The polarimetric optimization of the symmetric term follows classical PolInSAR optimization

The polarimetric optimization of the asymmetric term follows also classical PolInSAR optimization but:

- Considering $\boldsymbol{T} = (\boldsymbol{T}_{11} + \boldsymbol{T}_{22})/2$ instead of $\boldsymbol{\Omega}_{12}$
- The optimization of leads to $\omega_1 = \omega_2$

$$\rho_{\text{asym}} = \frac{\boldsymbol{\omega}^H \mathbf{T} \boldsymbol{\omega}}{\sqrt{(\boldsymbol{\omega}^H \mathbf{T}_{11} \boldsymbol{\omega})(\boldsymbol{\omega}^H \mathbf{T}_{22} \boldsymbol{\omega})}} \quad \rho_{\text{asym}} \in \mathbb{R}$$

- The optimum values are $|\rho_{\text{asym,opt}_i}| = \sqrt{\nu_{\rho,i}}$ for *i*=1, 2, 3
- Considering the polarization optimization ratio $\tau_{12} = \frac{\boldsymbol{\omega}^H \mathbf{T}_{11} \boldsymbol{\omega}}{\boldsymbol{\omega}^H \mathbf{T}_{22} \boldsymbol{\omega}}$ with optimum values $\nu_{\tau,i}$ for *i*=1, 2, 3, the following relation holds

$$\rho_{\text{asym},i} = \frac{1}{2}\left(\nu_{\tau,i} + \nu_{\tau,i}^{-1}\right), \quad i = 1, 2, 3$$

Generalization of the single channel case

Generalization of the Distance Concept

ρ_{asym} and ν_τ , and their optimum values, are proposed for the analysis of multitemporal data for low coherence scenarios

Generalization of previous existing matrices distances concepts:

- Geometric distance

$$\delta_g(\mathbf{T}_{11}, \mathbf{T}_{22}) = \left(\sum_{i=1}^{3} \log^2 \lambda_{\mathbf{T}_{11}^{-1}\mathbf{T}_{22},i} \right)^{1/2}$$

- Symmetric revised Wishart dissimilarity

$$d_{\mathrm{sw}}(\mathbf{T}_{11}, \mathbf{T}_{22}) = \left(\mathrm{tr}\left(\mathbf{T}_{11}^{-1}\mathbf{T}_{22}\right) + \mathrm{tr}\left(\mathbf{T}_{22}^{-1}\mathbf{T}_{11}\right)\right)(n_1 + n_2)$$

- Likelihood-ratio test statistic

$$Q = 2^{6n} \frac{|\mathbf{T}_{11}|^n |\mathbf{T}_{22}|^n}{|\mathbf{T}_{11} + \mathbf{T}_{22}|^{2n}}$$

The use of ρ_{asym} and ν_τ, and their optimum values decompose the previous parameters intro three components allowing an improved analysis of changes between SAR acquisitions

Datasets

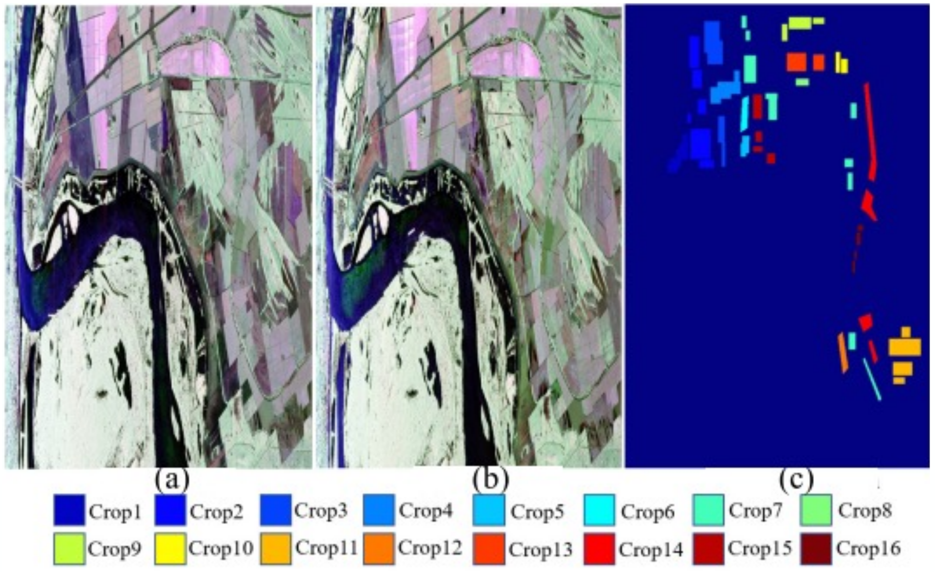
Use of 9 ML/DL classification techniques based on ρ vs ρ_{asym}/ν_{τ} to analyse their performances

- L-band UAVSAR Yucatan Lake (US)
  - 5 PolSAR acquisitions from Jul. 1, 2019 to Sep. 23, 2019, at intervals of 15, 9, 18, and 42 days
  - Ground-truth available: 16 classes
  - High temporal coherence scenario

- C-band Radarsat-2 Flevoland (NL)
  - 8 PolSAR acquisitions from Apr. 14, 2009 to Sep. 29, 2009 at an interval of 24 days
  - Ground-truth available: 11 classes
  - Low temporal coherence scenario

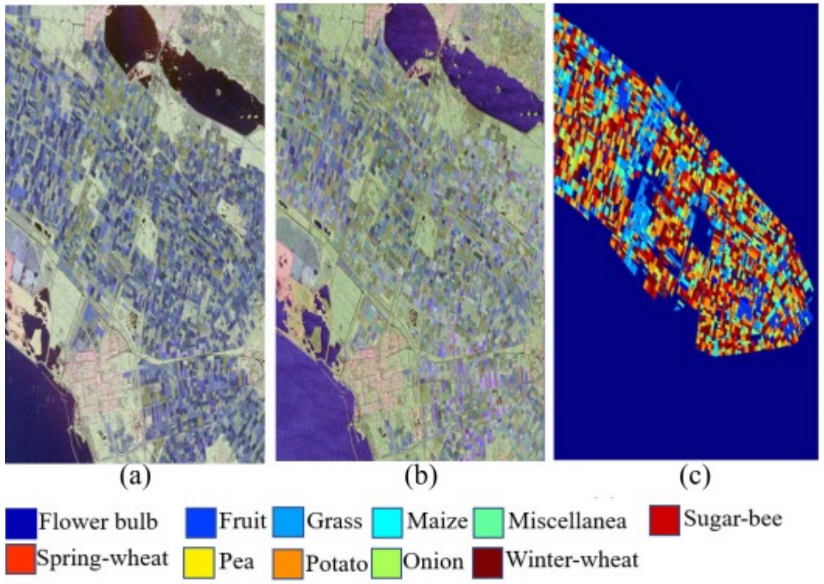
- C-band Sentinel-1 Barcelona (SP)
  - 32 dual Pol acquisitions from Apr, 2, 2018 to Oct. 5, 2018 at an interval of 6 days
  - Ground-truth available: 10 classes
  - Mixed coherence scenario

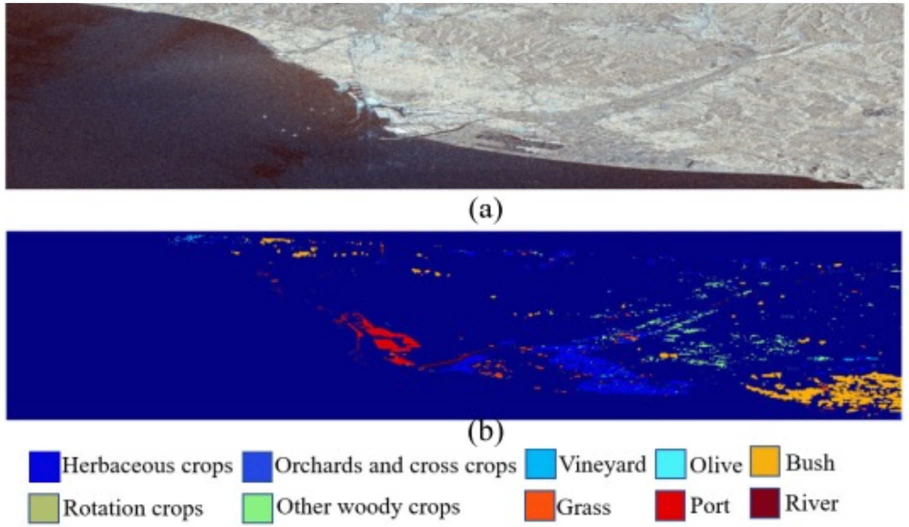
Datasets



UAVSAR Yucatan lake data. Pauli images on (a) July 1st, (b) July 15th, and (c) ground truth

Radarsat-2 Flevoland data. Pauli images on (a) April 14, 2009, (b) May 8, 2009, and (c) ground truth

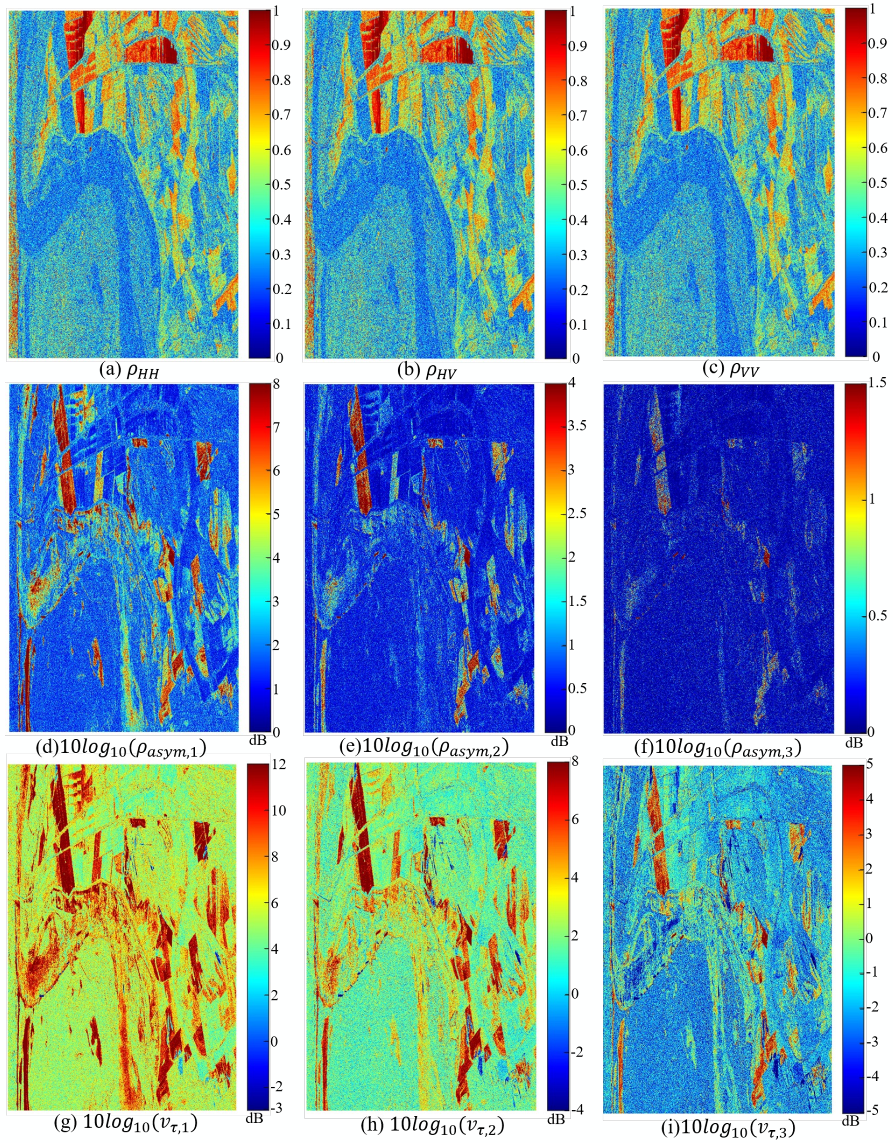




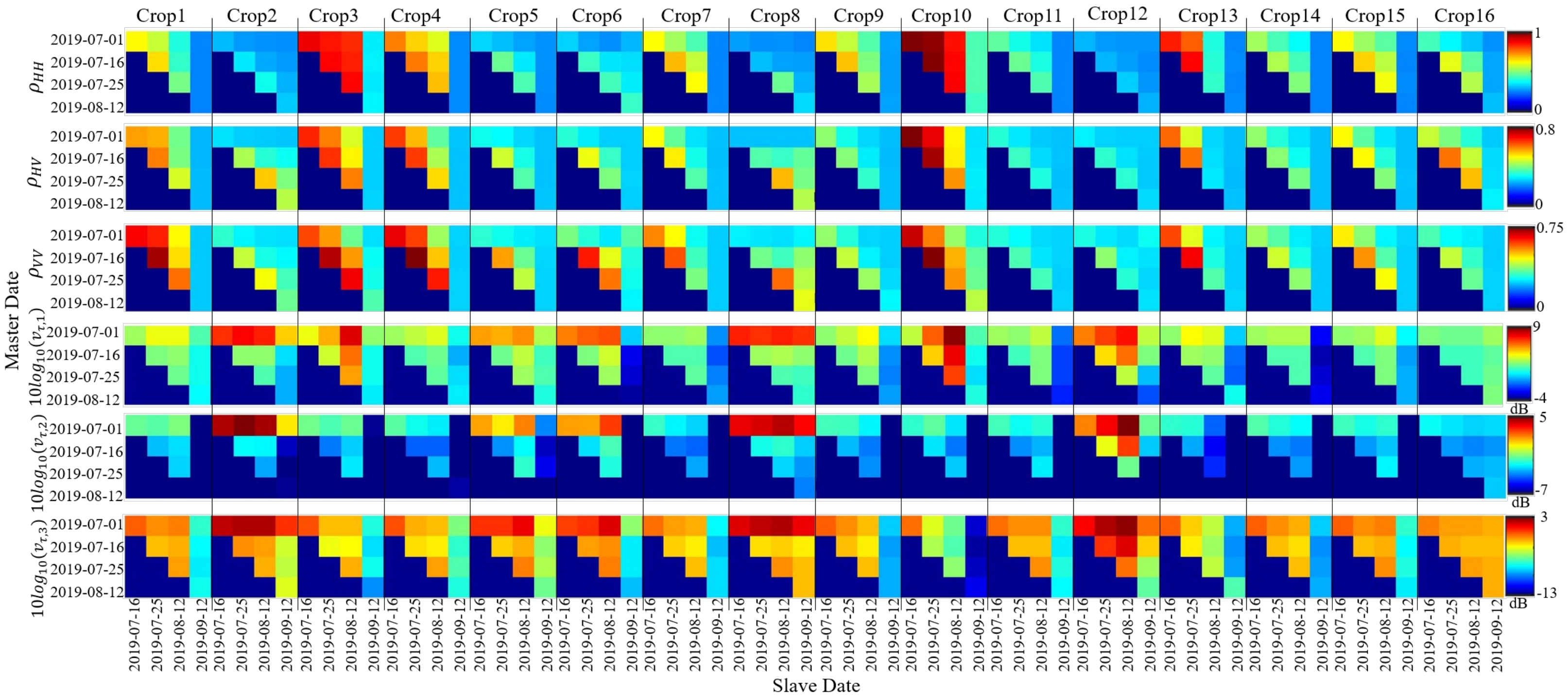
Sentinel-1 Barcelona dataset. (a) Pauli Image on May 20, 2018. (b) Ground truth

Analysis of Temporal Behaviour: UAVSAR

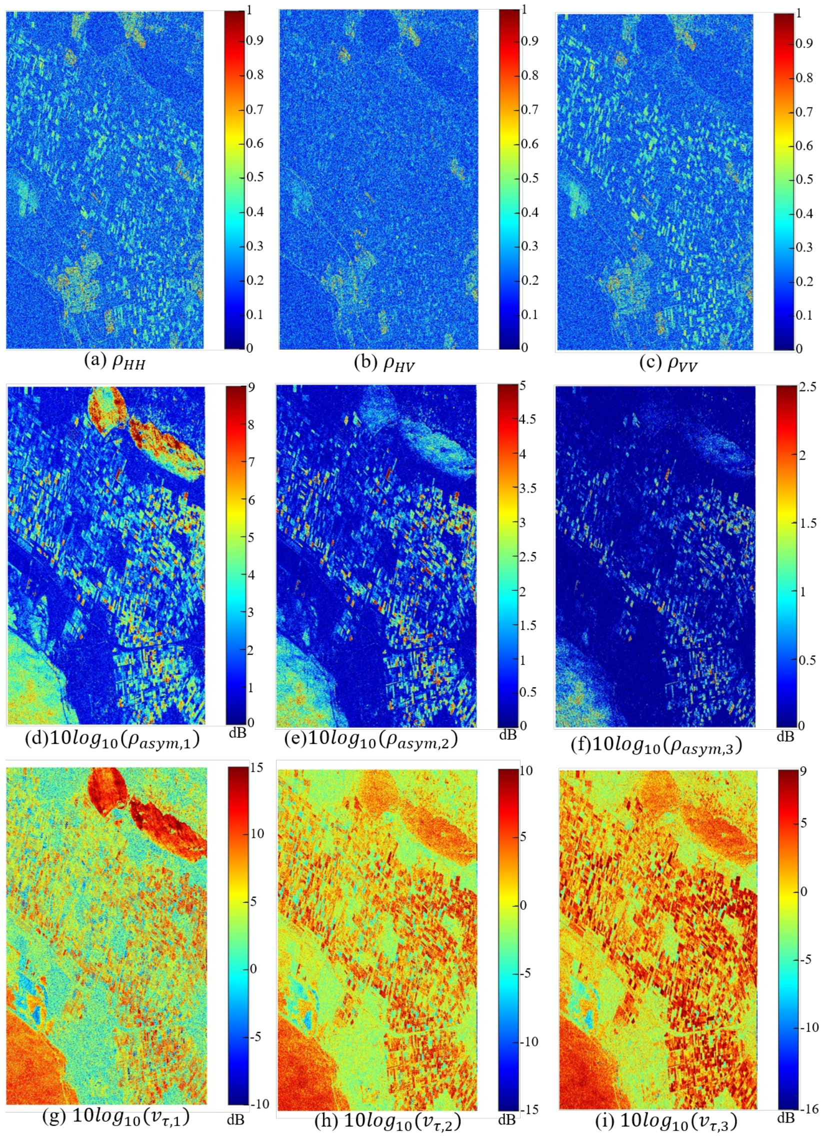
Spatial analysis Jul. 1st. – Jul. 15th.



Multitemporal matrices analysis

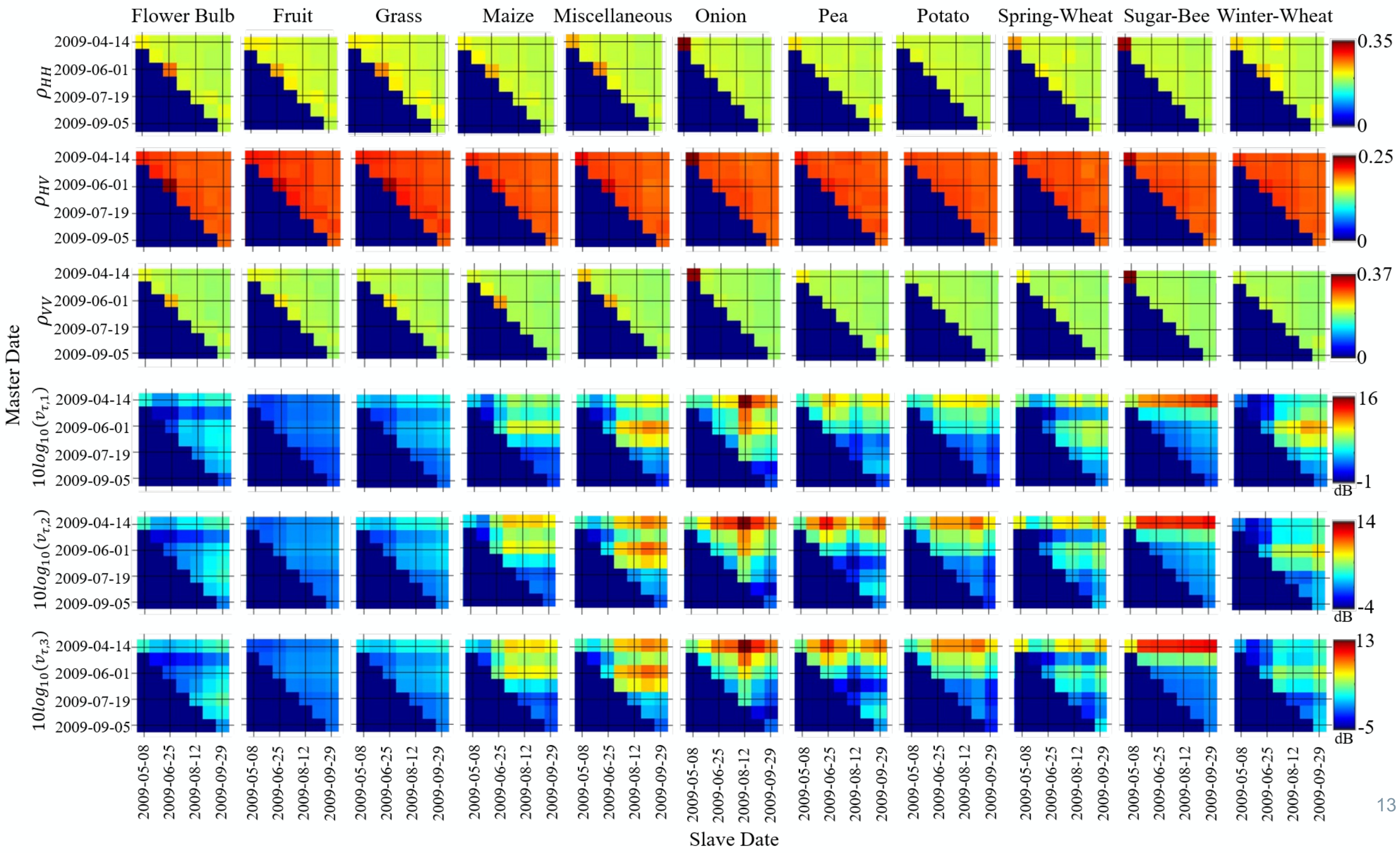


Analysis of Temporal Behaviour: Radasat-2

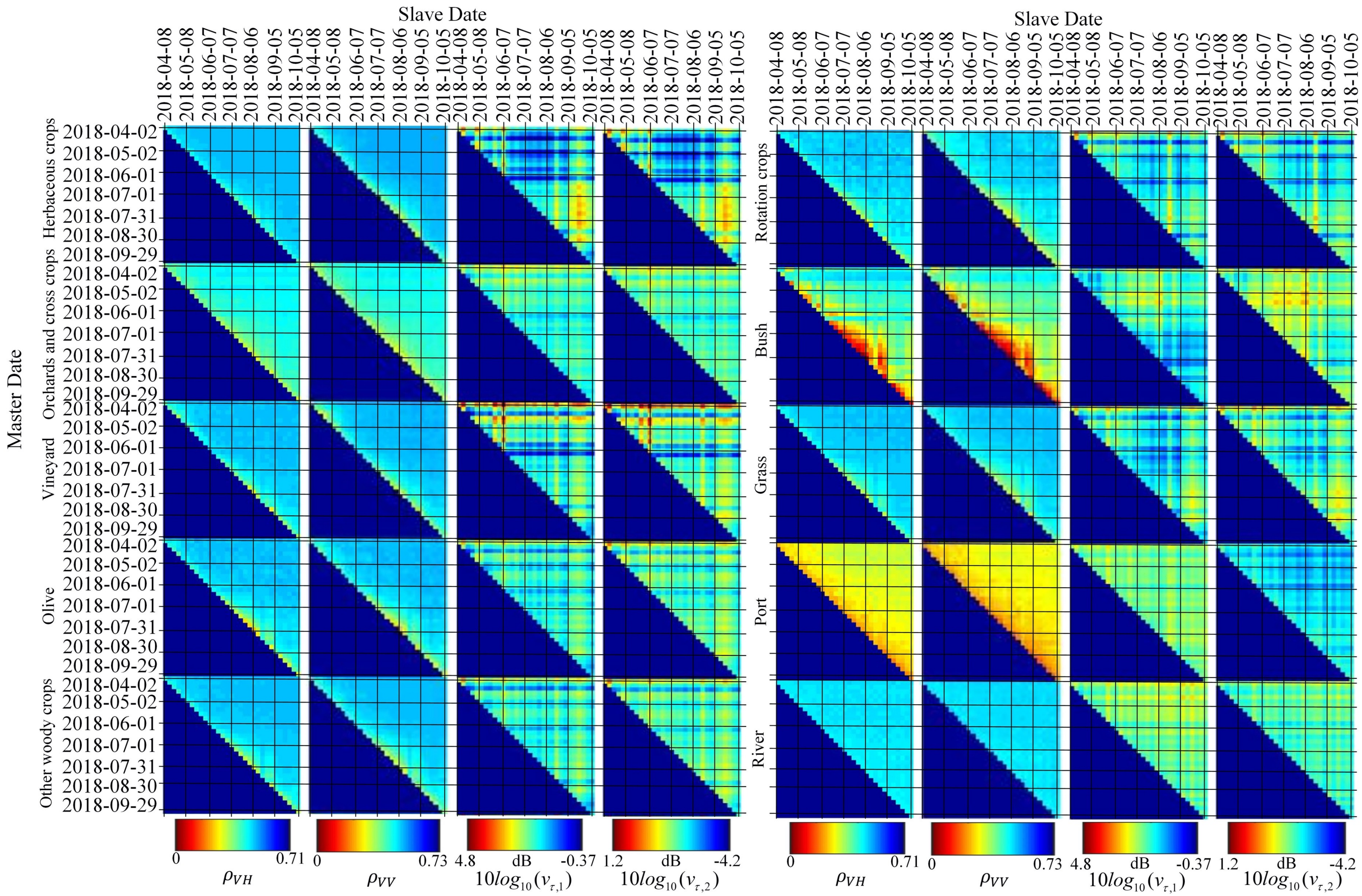


Spatial analisis Apr. 14th. - May 8th.

Multitemporal matrices analysis



Analysis of Temporal Behaviour: Sentinel-1



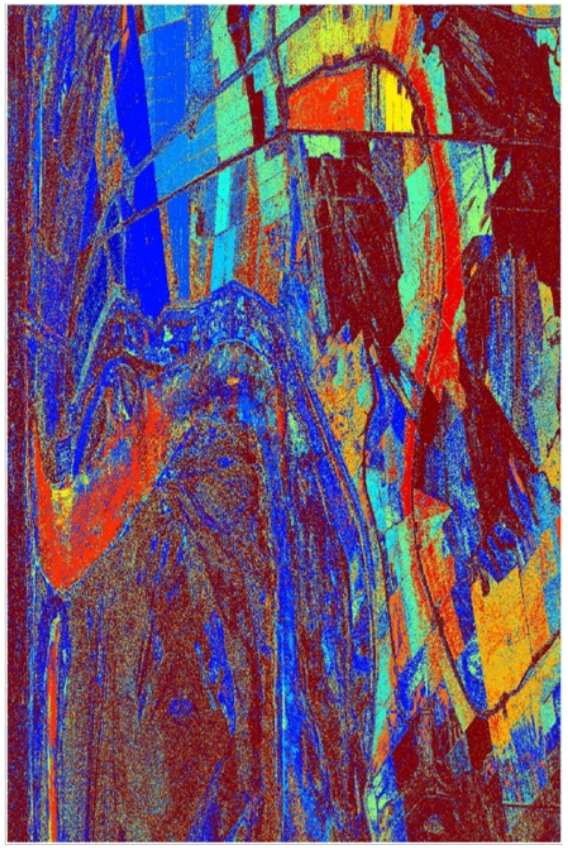
Multitemporal matrices analysis

Analysis of Classification Results: UAVSAR

GRU: RNN with gated recurrent unit (GRU) to account for the temporal dimension

Overall classification accuracy

(a) GRU, Coh., 59.08%

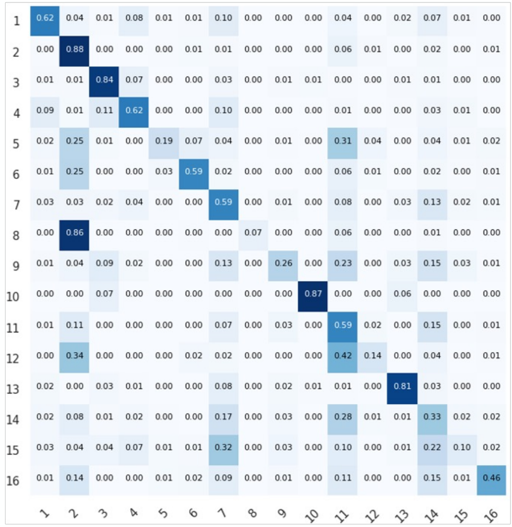


(b) GRU, Eig., 79.88%

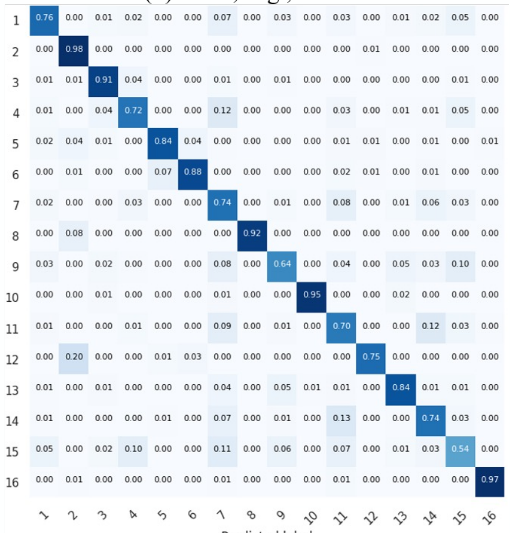
Reference: Int.: 89.94%, T3: 83.88%

Confusion matrices for class analysis

(b) GRU, Coh., 59.08%



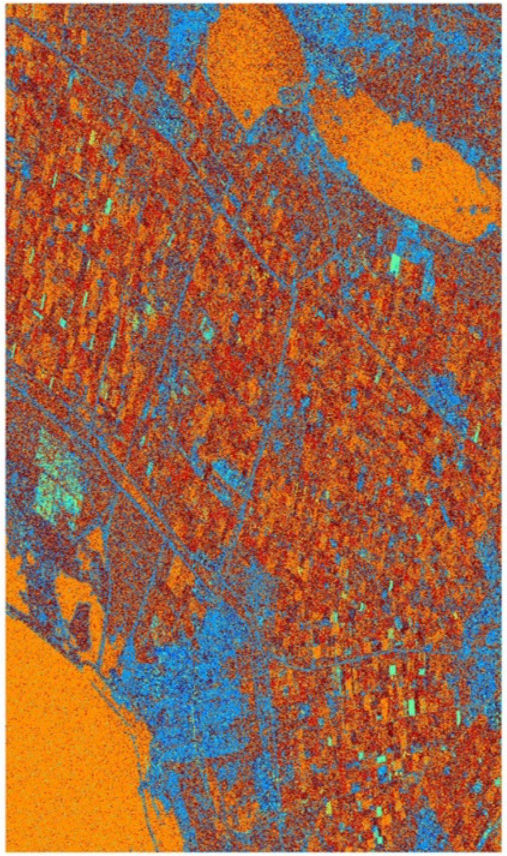
(d) GRU, Eig., 79.88%



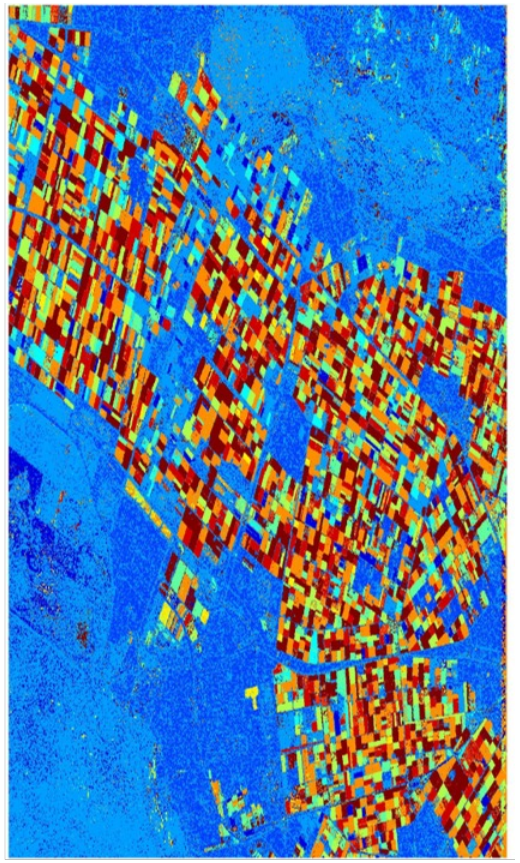
Analysis of Classification Results: Radarsat-2

GRU: RNN with gated recurrent unit (GRU) to account for the temporal dimension

Overall classification accuracy



(a) GRU, Coh., 35.23%



(b) GRU, Eig., 84.18%

Reference: Int.: 88.7%, T3: 88.71%

Confusion matrices for class analysis

(b) GRU, Coh., 35.23%

	1	2	3	4	5	6	7	8	9	10	11
1	0.01	0.00	0.22	0.01	0.04	0.01	0.00	0.32	0.00	0.07	0.33
2	0.00	0.00	0.22	0.00	0.01	0.01	0.00	0.30	0.00	0.06	0.39
3	0.00	0.00	0.28	0.00	0.01	0.01	0.00	0.26	0.00	0.06	0.38
4	0.00	0.00	0.14	0.02	0.03	0.02	0.00	0.44	0.00	0.09	0.26
5	0.00	0.00	0.11	0.01	0.09	0.04	0.00	0.41	0.00	0.14	0.19
6	0.00	0.00	0.05	0.00	0.01	0.13	0.00	0.21	0.00	0.42	0.18
7	0.00	0.00	0.08	0.00	0.00	0.02	0.01	0.46	0.00	0.11	0.31
8	0.00	0.00	0.07	0.00	0.01	0.00	0.00	0.61	0.00	0.07	0.25
9	0.00	0.00	0.11	0.00	0.01	0.02	0.00	0.35	0.00	0.12	0.40
10	0.00	0.00	0.05	0.00	0.01	0.08	0.00	0.22	0.00	0.48	0.16
11	0.00	0.00	0.12	0.00	0.00	0.01	0.00	0.29	0.00	0.06	0.51

(d) GRU, Eig., 84.14%

	1	2	3	4	5	6	7	8	9	10	11
1	0.76	0.00	0.18	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02
2	0.00	0.73	0.24	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
3	0.02	0.07	0.79	0.01	0.01	0.01	0.00	0.03	0.00	0.01	0.04
4	0.00	0.00	0.05	0.68	0.07	0.02	0.00	0.12	0.00	0.02	0.03
5	0.01	0.01	0.05	0.03	0.71	0.03	0.01	0.06	0.00	0.03	0.06
6	0.00	0.00	0.02	0.01	0.01	0.89	0.00	0.03	0.00	0.01	0.02
7	0.01	0.00	0.04	0.00	0.01	0.02	0.67	0.18	0.00	0.06	0.01
8	0.00	0.00	0.02	0.01	0.01	0.01	0.00	0.91	0.00	0.03	0.01
9	0.01	0.00	0.07	0.00	0.04	0.05	0.00	0.01	0.49	0.03	0.30
10	0.00	0.00	0.03	0.00	0.01	0.01	0.00	0.06	0.00	0.89	0.01
11	0.00	0.00	0.03	0.00	0.01	0.01	0.00	0.02	0.01	0.01	0.91

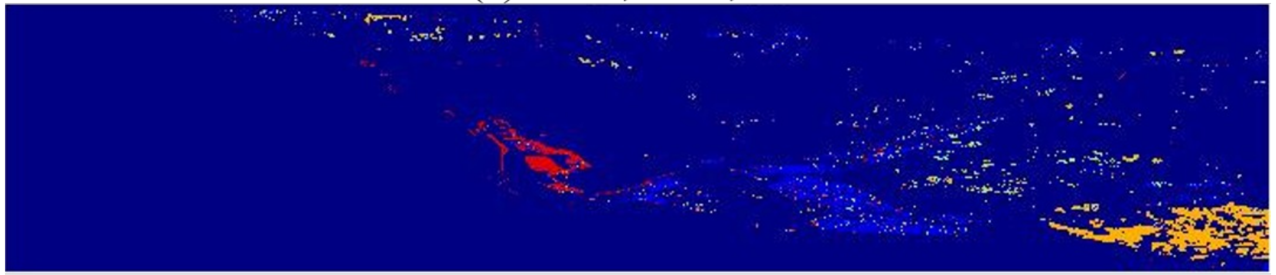
Predicted label

Analysis of Classification Results: Sentinel-1

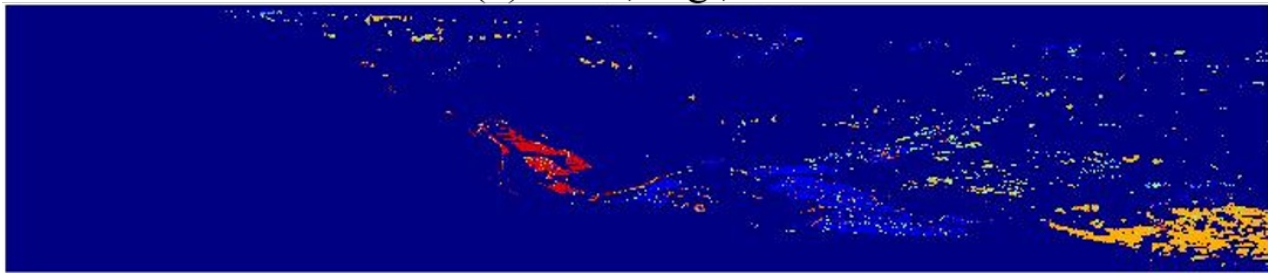
GRU: RNN with gated recurrent unit (GRU) to account for the temporal dimension

Overall classification accuracy

(a) GRU, Coh., 72.17%



(b) GRU, Eig., 73.98%



Reference: Int.: 78.21%, C2: 74.14%

Confusion matrices for class analysis

(b) GRU, Coh., 72.17%

	1	2	3	4	5	6	7	8	9	10
1	0.87	0.00	0.00	0.00	0.05	0.00	0.02	0.03	0.02	0.01
2	0.48	0.16	0.01	0.00	0.10	0.00	0.06	0.05	0.12	0.02
3	0.54	0.01	0.14	0.00	0.17	0.00	0.08	0.04	0.02	0.00
4	0.42	0.00	0.01	0.07	0.31	0.00	0.13	0.04	0.02	0.00
5	0.43	0.01	0.01	0.00	0.37	0.00	0.10	0.05	0.03	0.01
6	0.47	0.00	0.00	0.00	0.22	0.04	0.15	0.06	0.05	0.01
7	0.05	0.00	0.00	0.00	0.05	0.00	0.89	0.01	0.00	0.00
8	0.47	0.01	0.00	0.00	0.14	0.00	0.09	0.23	0.04	0.02
9	0.16	0.01	0.00	0.00	0.01	0.00	0.01	0.02	0.76	0.03
10	0.41	0.01	0.00	0.00	0.03	0.00	0.01	0.07	0.22	0.25

(d) GRU, Eig., 73.98%

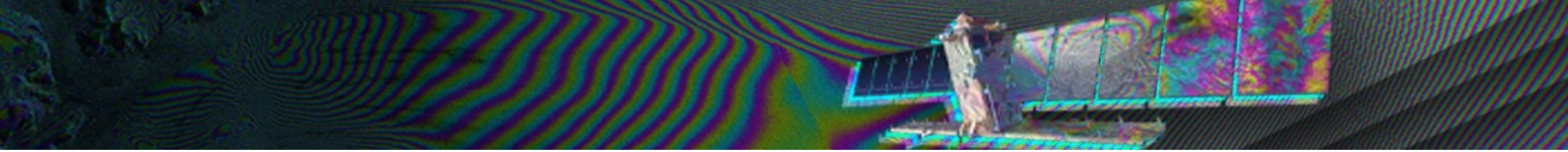
	1	2	3	4	5	6	7	8	9	10
1	0.85	0.00	0.01	0.00	0.07	0.00	0.03	0.03	0.01	0.00
2	0.27	0.20	0.01	0.00	0.20	0.00	0.18	0.06	0.06	0.01
3	0.28	0.01	0.33	0.00	0.21	0.00	0.09	0.05	0.01	0.00
4	0.25	0.01	0.01	0.10	0.37	0.00	0.17	0.06	0.03	0.00
5	0.20	0.01	0.01	0.00	0.49	0.00	0.19	0.06	0.02	0.01
6	0.36	0.03	0.03	0.00	0.27	0.06	0.16	0.06	0.03	0.00
7	0.02	0.00	0.00	0.00	0.06	0.00	0.87	0.02	0.01	0.00
8	0.28	0.01	0.01	0.00	0.16	0.00	0.13	0.36	0.03	0.01
9	0.09	0.01	0.00	0.00	0.03	0.00	0.07	0.02	0.77	0.01
10	0.14	0.01	0.01	0.00	0.15	0.00	0.16	0.07	0.15	0.31

Predicted label

Conclusions

- New interpretation of the temporal InSAR coherence (SAR & PolSAR)
- InSAR temporal coherence can be decomposed into two terms:
  - Symmetric term: Coherent changes under the symmetric assumption of no radiometric/polarimetric changes
  - Asymmetric term: Noncoherent or radiometric/polarimetric changes
  - The decomposition is useful as it relates both types of changes, showing that common information between SAR acquisitions can still be extracted in low temporal coherence scenarios

- The usefulness of these terms is demonstrated on three different datasets by means ML/DL classification techniques with improvements of 50% in the classification OA in low temporal coherences scenarios, whereas for high temporal coherence scenarios, the improvement is about 20%



Thank you !!!

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