FRINGE 2026

2Much! Reducing phase ambiguities by combining DL-despeckled half-band SAR interferograms

Florent Michenot[1], Béatrice Pinel-Puysségur[1], Victor Gaya[2, (1, 4)], Loïc Denis[3], Florence Tupin[4]

(1) CEA, DAM, DIF, France

(2) National University of Singapore, Singapore

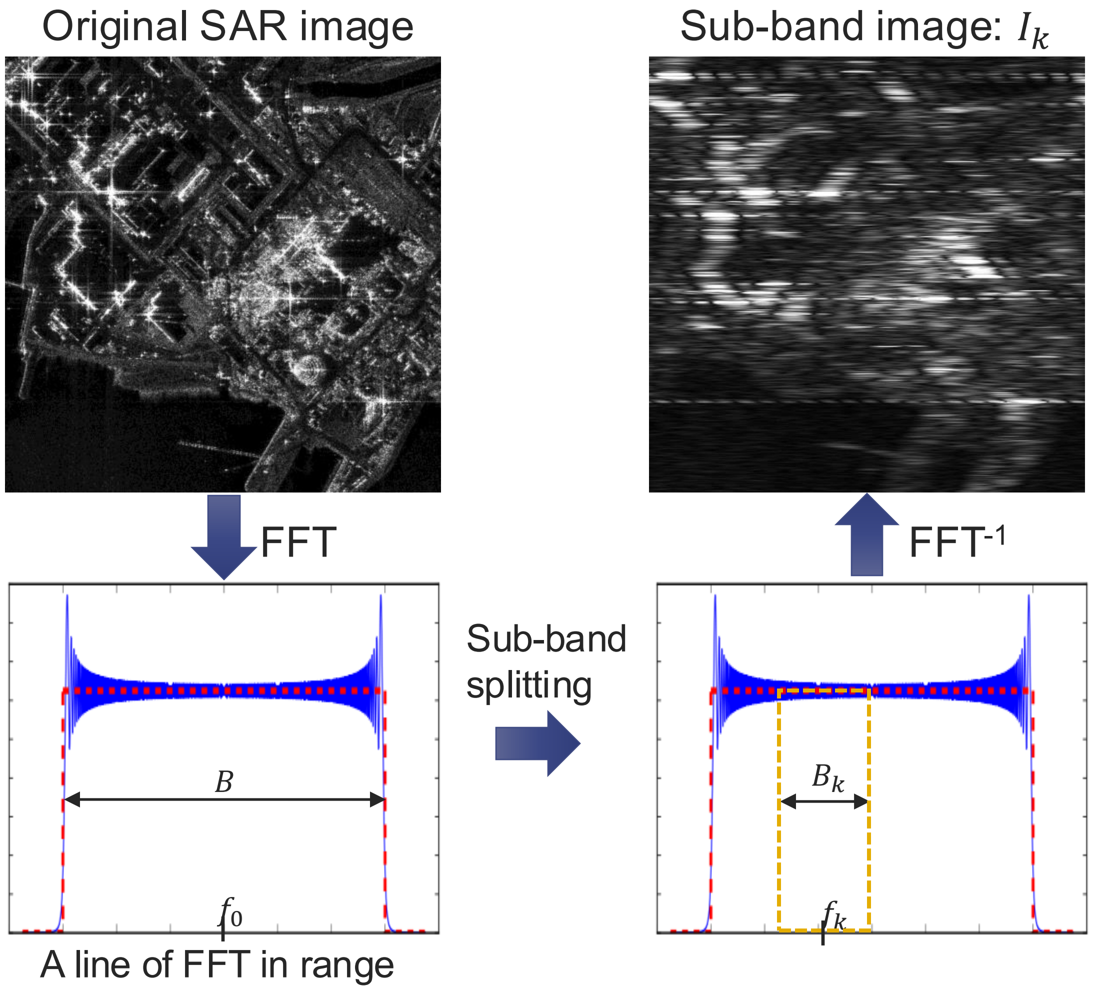
(3) UJM-Saint-Etienne, CNRS, Institut d'Optique Graduate School, Laboratoire Hubert Curien, France

(4) LTCI, Télécom Paris, Institut Polytechnique de Paris, Palaiseau, France

1. Introduction

A quick state of the art in split-band InSAR

- The radar antenna emits a wave around a central frequency f_0 with a chirp bandwidth B
  - Split-band interferometry divides the signal spectrum along the range frequencies to exploit the frequency diversity
  - Loss of range resolution



A quick state of the art in split-band InSAR

- Before 2007: concept of split-band InSAR
  - First paper on the concept of split-band interferometry : Madsen and Zebker (1992), 2 sub-bands, but small bandwidth at this time.
  - Veneziani et al. (2003): concept of using split-band interferometry with multiple sub-bands to estimate topography without unwrapping.
  - SAR sensors bandwidths were too small ➔ noisy results

Before 2007
f_0 ~ 5-10 GHz
B<50 MHz

- After 2007: first applications of split-band InSAR
  - SAR sensors bandwidths dramatically increased with X-band satellites (TerraSAR-X, Cosmo-SkyMed)
  - Inter-band interferometry: uses different bands of the same image (Derauw et al., 2010)
  - **Split-band interferometry or multi-chromatic analysis (MCA)**: needs two images
    - DEM estimation, e.g. (Bovenga et al., 2013; Libert, 2018)

After 2007
f_0 ~ 5-10 GHz
B>200 MHz

- Limitations
  - **Noise** increase compared to standard InSAR (with a factor ~f/B)
  - **Low point density**

Are recent DL-based filtering techniques able to overcome these limitations?

- **MuChaPro-R2**
- **2MuCh**

Madsen, S. & Zebker, H. (1992), Automated absolute phase retrieval in across-track interferometry, in '[Proceedings] IGARSS '92 International Geoscience and Remote Sensing Symposium', Vol. 2, pp. 1582–1584.
Veneziani, N. and Bovenga, F. and Refice, A., A Wide-Band Approach to the Absolute Phase Retrieval in SAR Interferometry, Multidimensional Systems and Signal Processing, vol. 14, pp.183-205, 2003.
Bovenga, F. and Giacovazzo, V. M. and Refice, A. and Veneziani, N., Multichromatic analysis of InSAR data, IEEE Transactions on Geoscience and Remote Sensing, Vol. 51, No. 9, pp. 4790-4799, 2013.
Derauw, D. and Orban, A. and Barbier, C., Wide band SAR sub-band splitting and inter-band coherence measurements,Remote Sensing Letters, Vol. 1, No. 3, pp. 133-140, 2010.
Libert, L, Towards Operational Use of Combined Split-Band Interferometry and Multidimensional Small Baseline Subset, 2018

2. DL interferogram filtering: MuChaPro-R2

MuChaPro-R^2 : Deep-Learning based method of interferometric denoising

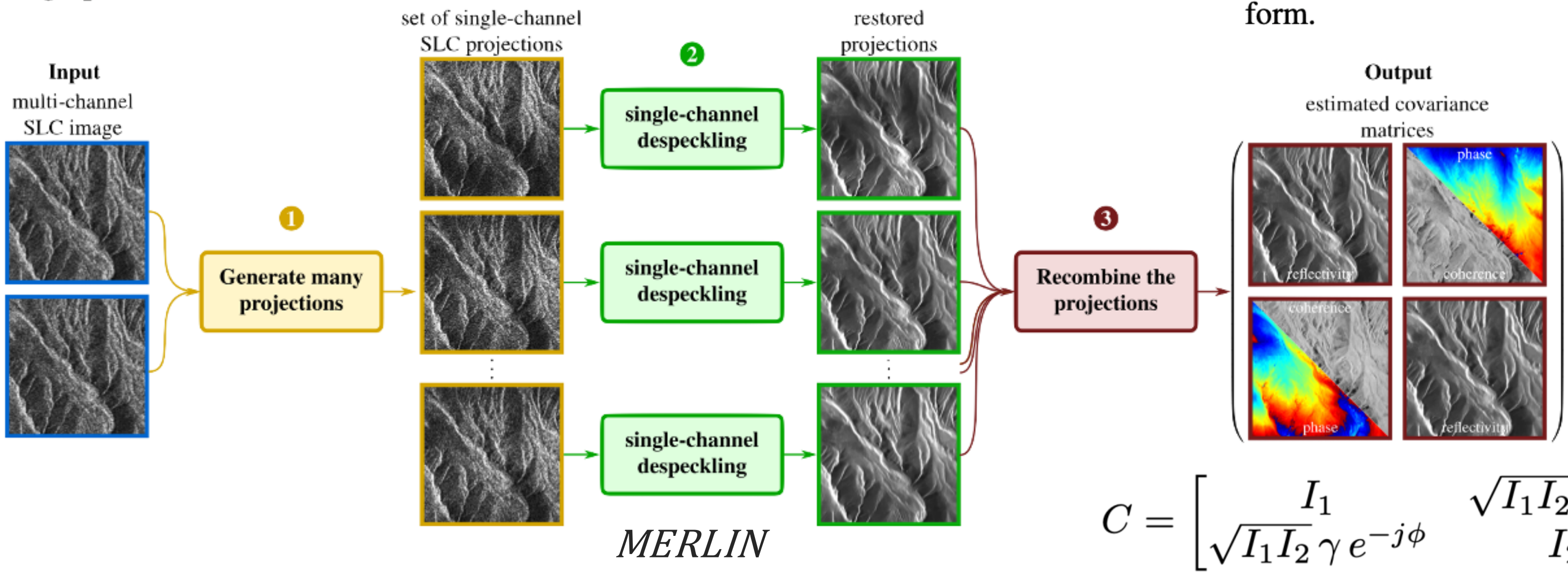
input : an N-pixels D-channels SLC image provided as a matrix $\mathbf{Z} \in \mathbb{C}^{D \times N}$

input : a single-channel despeckling function $f : \mathbb{C}^N \to \mathbb{R}_+^N$

output: the restored covariance matrices stored as an $D^2 \times N$ matrix $\widehat{\mathbf{C}}$ such that the ℓ-th column contains the D^2 values of $\mathrm{vec}\big(\widehat{\mathbf{C}}_\ell^{(\mathrm{MuChaPro})}\big)$, i.e., the covariance matrix at pixel ℓ in vectorized form.

Interferometric case :

$$D = 2$$
$$K = 4$$



MuChaPro principle.
Extracted from
L. Denis et al. 2025.

$$C = \begin{bmatrix} I_1 & \sqrt{I_1 I_2}\,\gamma\, e^{j\phi} \\ \sqrt{I_1 I_2}\,\gamma\, e^{-j\phi} & I_2 \end{bmatrix}$$

MuChaPro-R^2

MuChaPro + Regularization

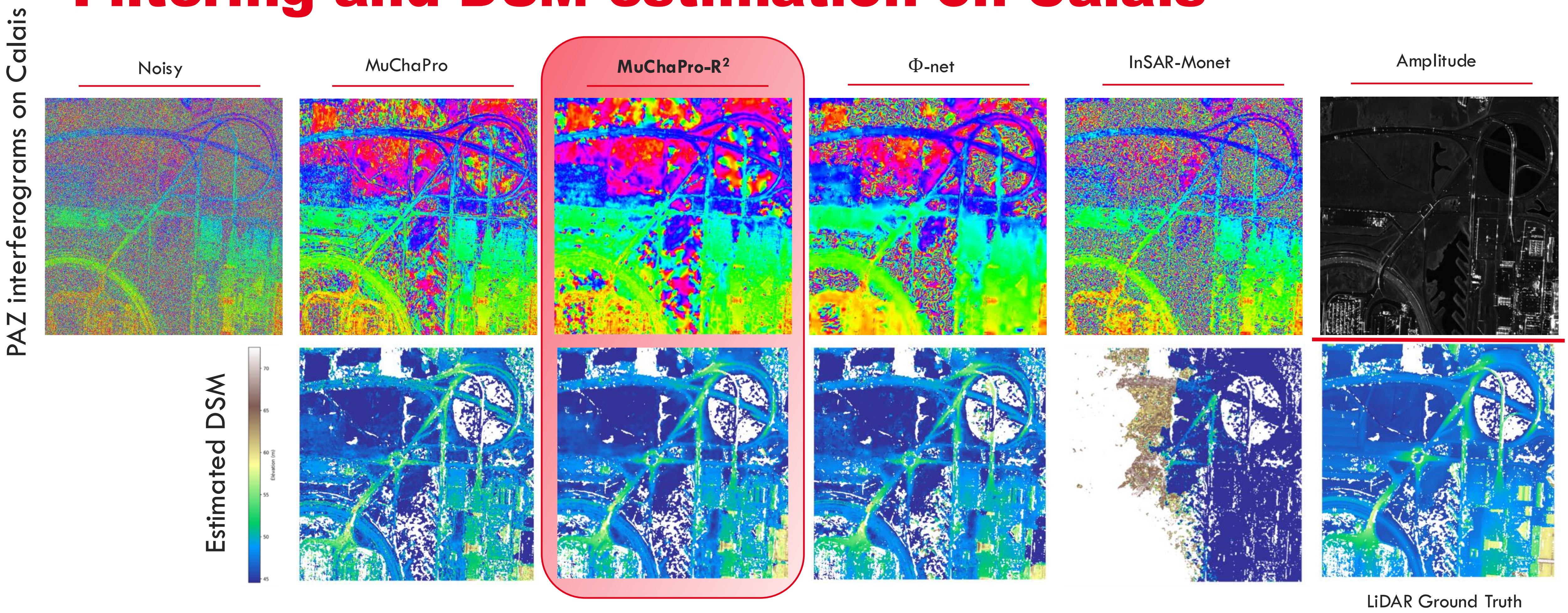
+ Post-Processing

Victor Gaya, Loïc Denis, Béatrice Pinel-Puysségur, Thomas Bultingaire, Florence Tupin, “Self-supervised interferogram restoration by regularized inversion of despeckled projections”, submitted to JSTARS

E. Dalsasso, L. Denis, and F. Tupin, “As if by magic: self supervised training of deep despeckling networks with MERLIN,” IEEE TGRS, vol. 60, pp. 1–13, 2021.

L. Denis, E. Dalsasso and F. Tupin, "Just Project! Multichannel Despeckling, the Easy Way," in IEEE Transactions on Geoscience and Remote Sensing, vol. 63, pp. 1-11, 2025, Art no. 5204311.

Filtering and DSM estimation on Calais



- Available Ground Truth: lidar DSM (Digital Surface Model) acquired by IGN (50 cm resolution)
- Effectiveness of MuChaPro-R2 filtering for DSM estimate in moderate topography area

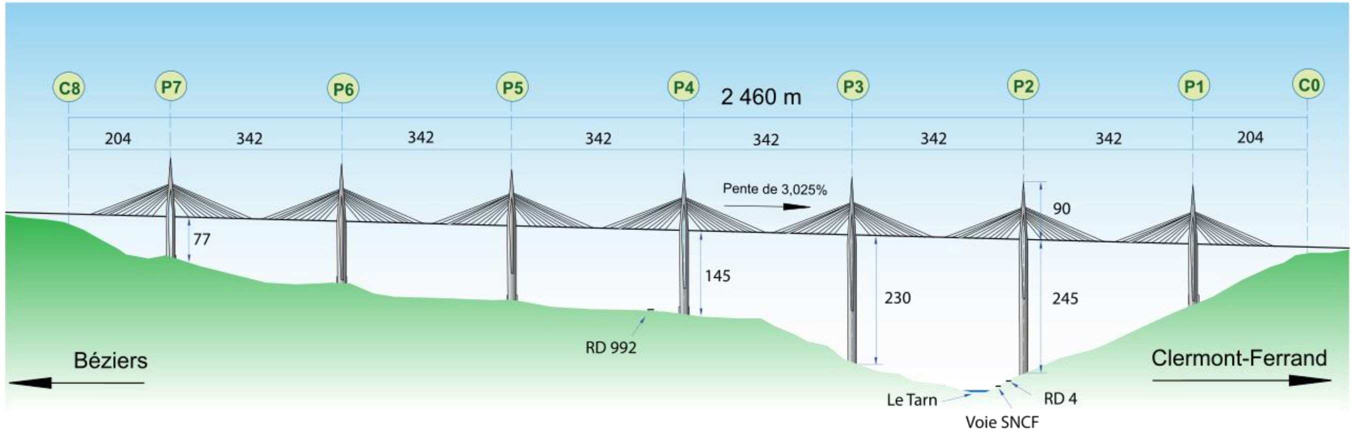
Method	φ Cosine ↑	RMSE (m) ↓	MAE (m) ↓	±0.5m (%) ↑	±2.0m (%) ↑
InSAR-Monet	0.54	40.159	33.552	0.8	4.0
MuChaPro	0.56	4.557	2.681	17.2	61.0
MuChaPro-R2	**0.71**	**3.283**	**1.864**	**22.9**	**75.7**
Phi-net	0.70	4.811	2.344	20.7	73.1

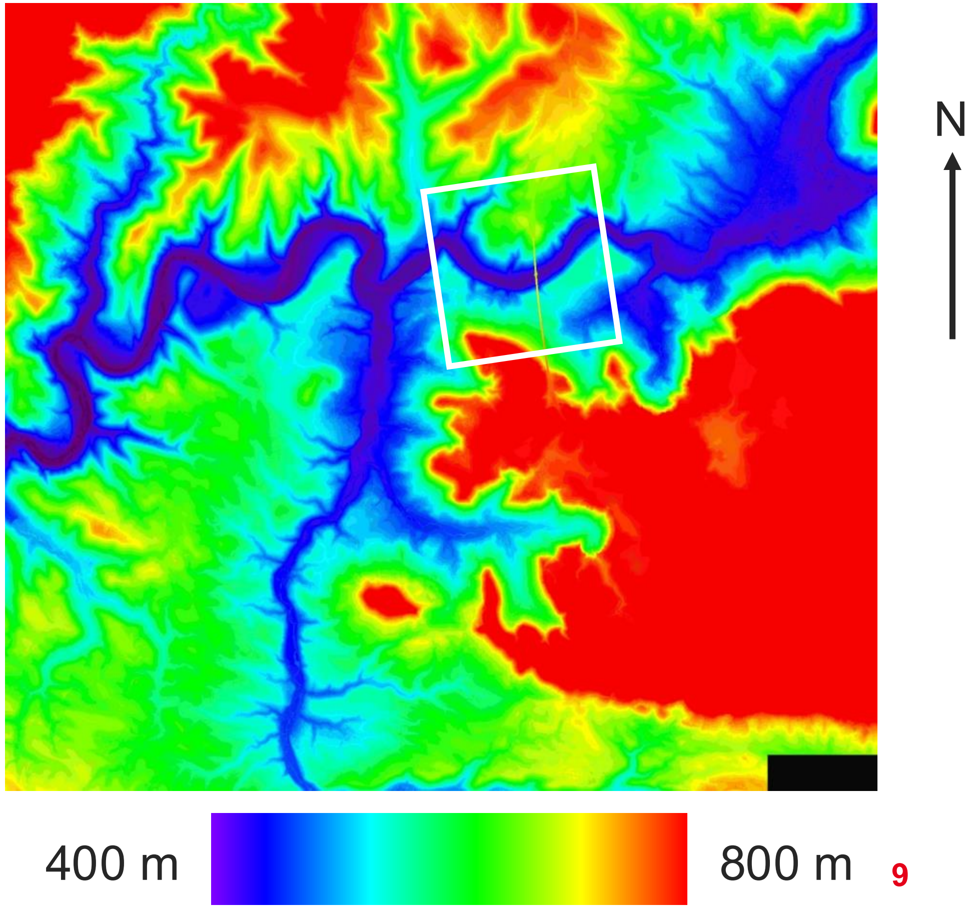
3. Multi-chromatic interferometry applied to steep topography

MCA and 2MuCh

Choice of the study area: Millau

- In some cases, it is **impossible** to retrieve topography with classical InSAR due to unwrapping constraints:
  - **Noise**
  - Areas separated by water
  - Layover, strong topography: high fringe density
- Millau viaduct (France)
  - Strong topography; well-documented viaduct dimensions
  - Reference: lidar-derived DSM (IGN)
- SAR Dataset
  - Cosmo-SkyMed interferometric images acquired in 2021
  - Spotlight mode, resolution az/rg: 0.70 m x 0.31 m



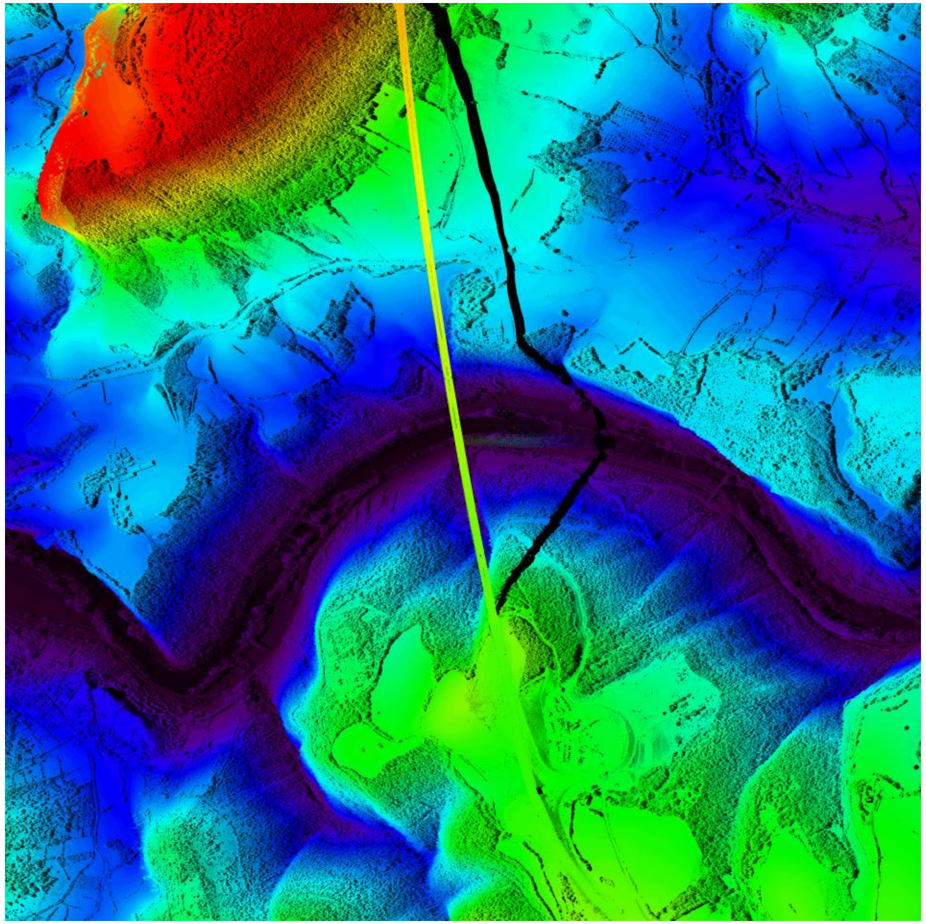


Millau viaduct

SAR image

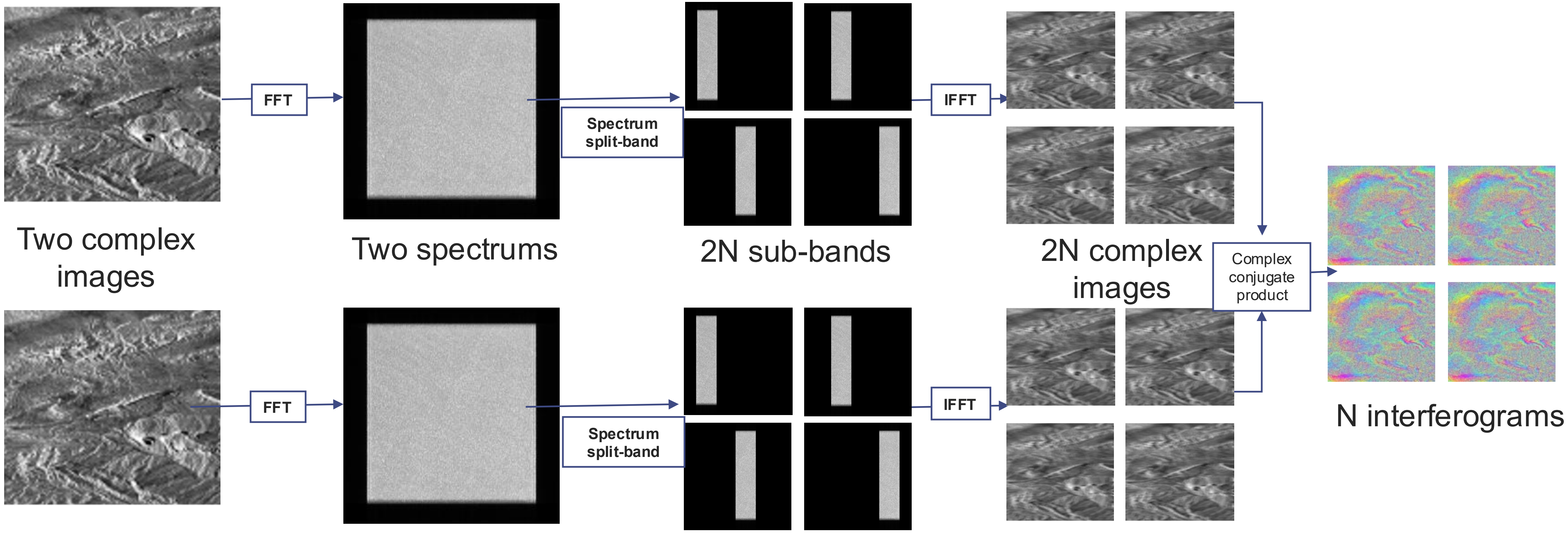
Look direction

Lidar DSM projected in SAR geometry



Multichromatic Analysis (MCA)

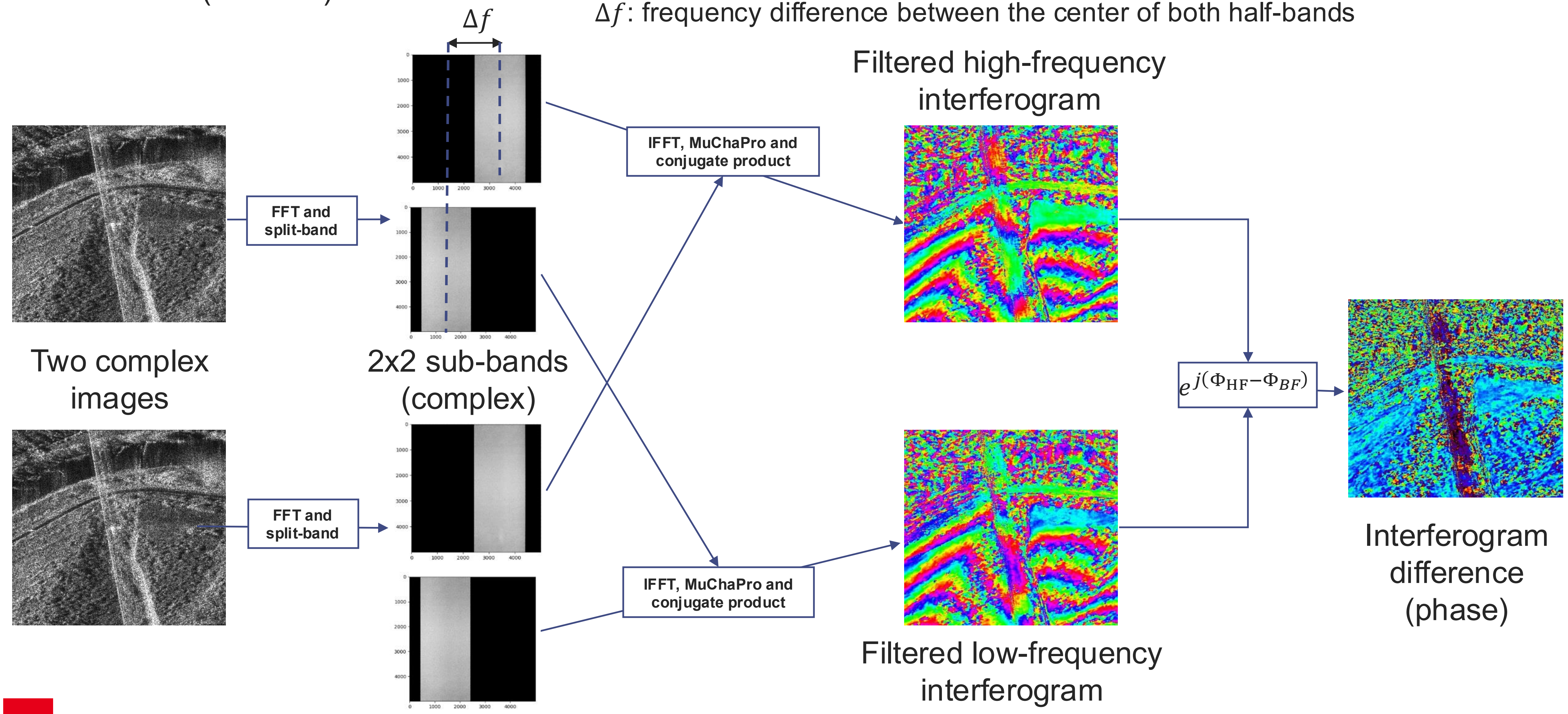
Or Split-Band Interferometry (SBI)



2MuCh : MultiChromatic MuChaPro

Half-Band MCA (HBMCA) + MuChaPro-R2

Δf: frequency difference between the center of both half-bands



Range of applicability

- Ambiguity height in classical monostatic InSAR:

$$h_a = \frac{\lambda R sin(\theta)}{2B_\perp} = \frac{cR sin(\theta)}{2f_0 B_\perp}$$

- With 2Much, the equivalent frequency is *Δf*. The ambiguity height becomes :

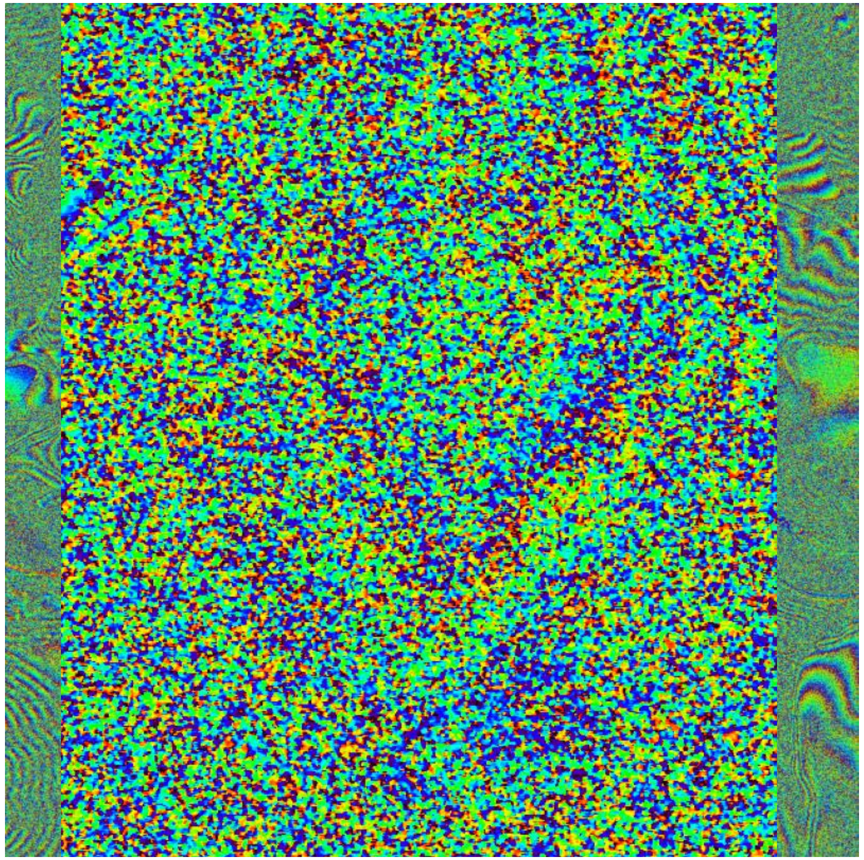
$$h_{a_{2MuCh}} = \frac{cR sin(\theta)}{2\Delta f B_\perp}$$

- *Δf* ≈ *191 MHz*, f_0 ≈ *9.6 GHz*, $\frac{h_{a_{2MuCh}}}{h_a} = \frac{f_0}{\Delta f} \approx 50$ ➔ 50 times less fringes
- The phase is within a fringe if $z_{max} - z_{min} < h_{a_{2Much}}$, here 445 m
  - No unwrapping needed if $z_{max} - z_{min} < h_{a_{2Much}}$
  - Limited unwrapping required otherwise

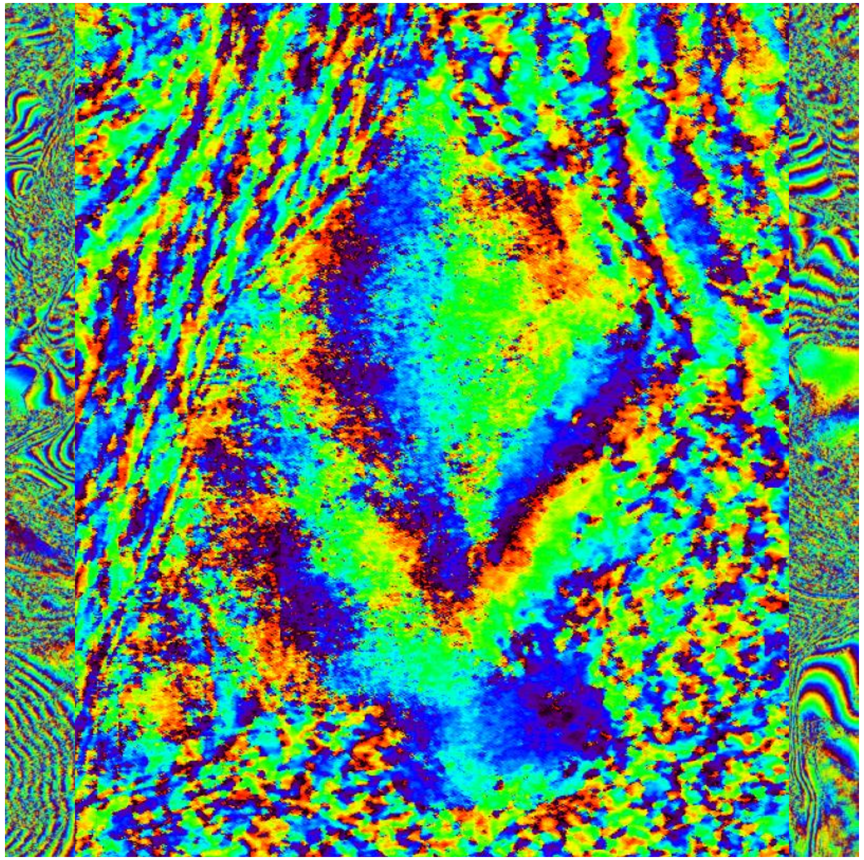
Comparison InSAR / MCA / 2MuCh

	Resolution	Unwrapping	Filtering	Noise	Precision	Point density
InSAR	Full resolution	Unwrapping errors	Simple	Lower than MCA	Precise but problematic in high fringe density areas	High
MCA	Degraded resolution in range	No unwrapping	Each band should be filtered separately	Higher than InSAR	Less precise but useful in high fringe density areas	Low
2MuCh (HBMCA + MuChaPro)	Better than MCA	No unwrapping (see range of applicability)	Two bands should be filtered separately	In between Lowered by filtering	Soon	In between

2MuCh : MultiChromatic MuChaPro

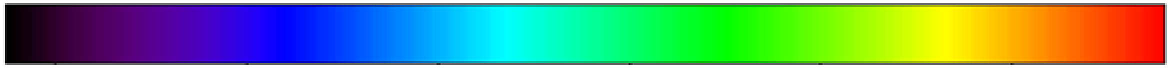


Half spectrum interferogram

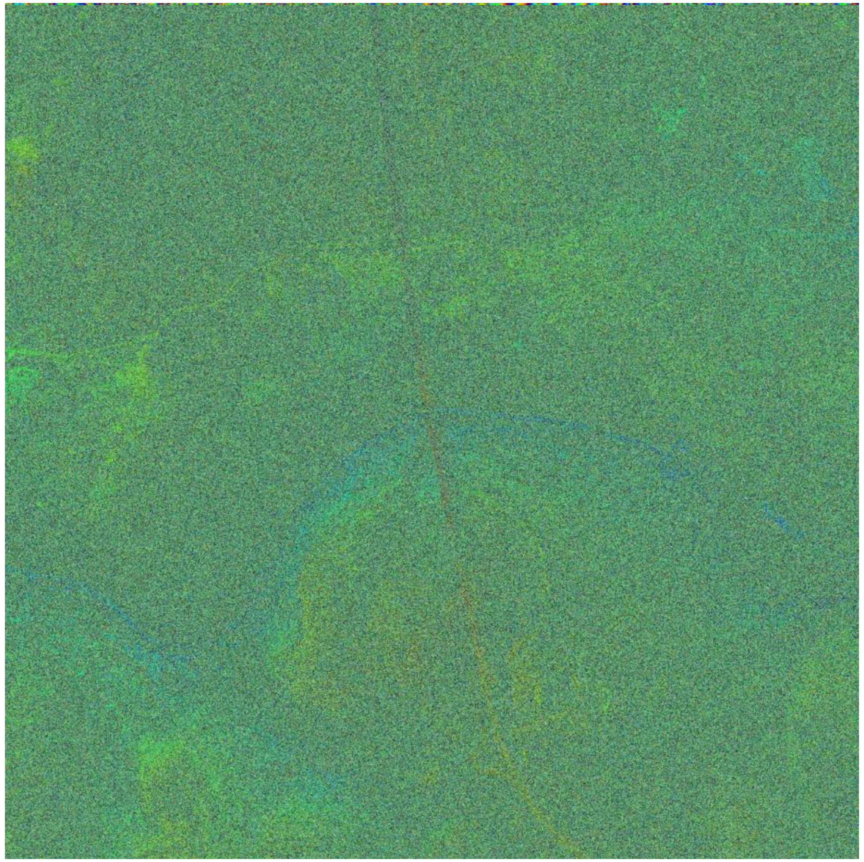


Half spectrum interferogram filtered using MuChaPro

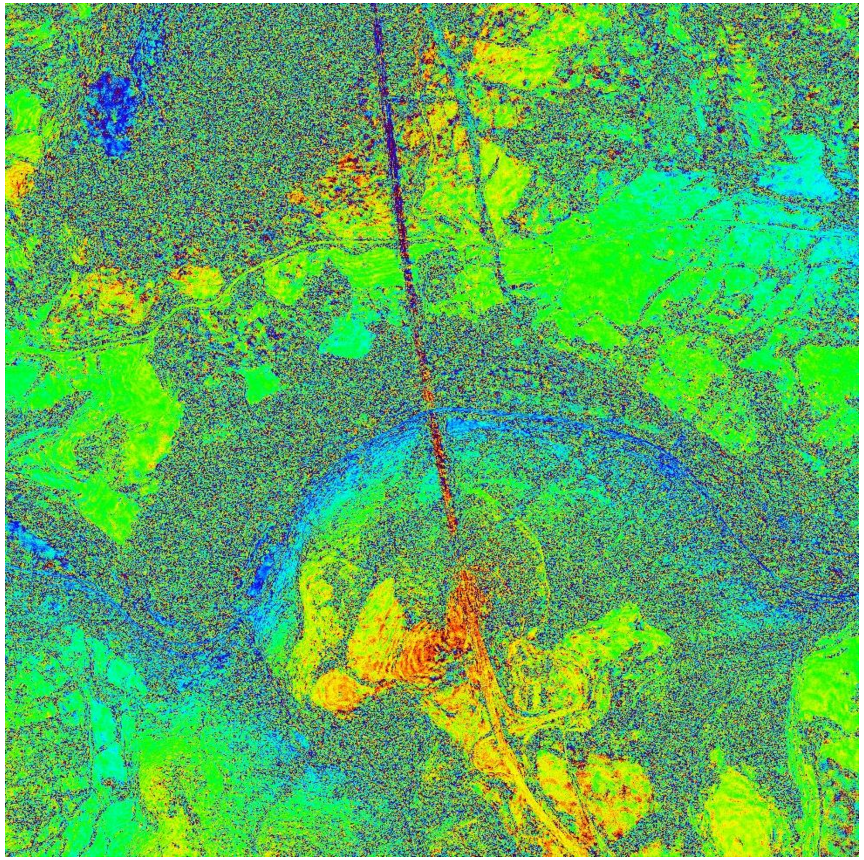
MuChaPro filtering greatly enhances the interferometric signal.



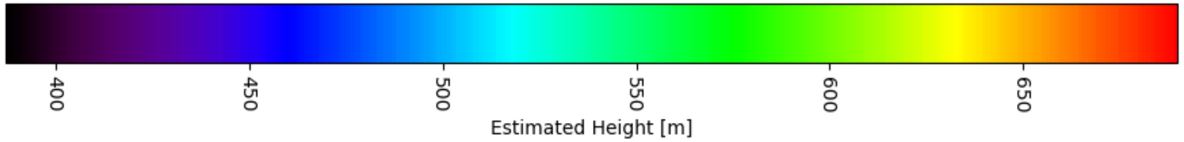
2MuCh : MultiChromatic MuChaPro



HBMCA interferogram



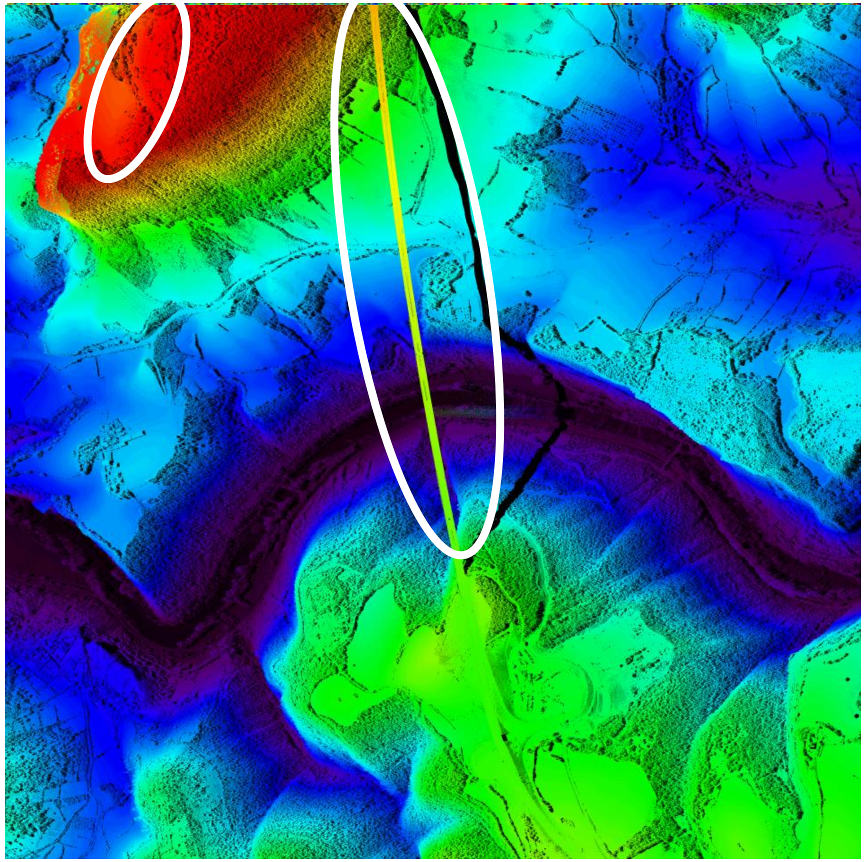
2MuCh interferogram



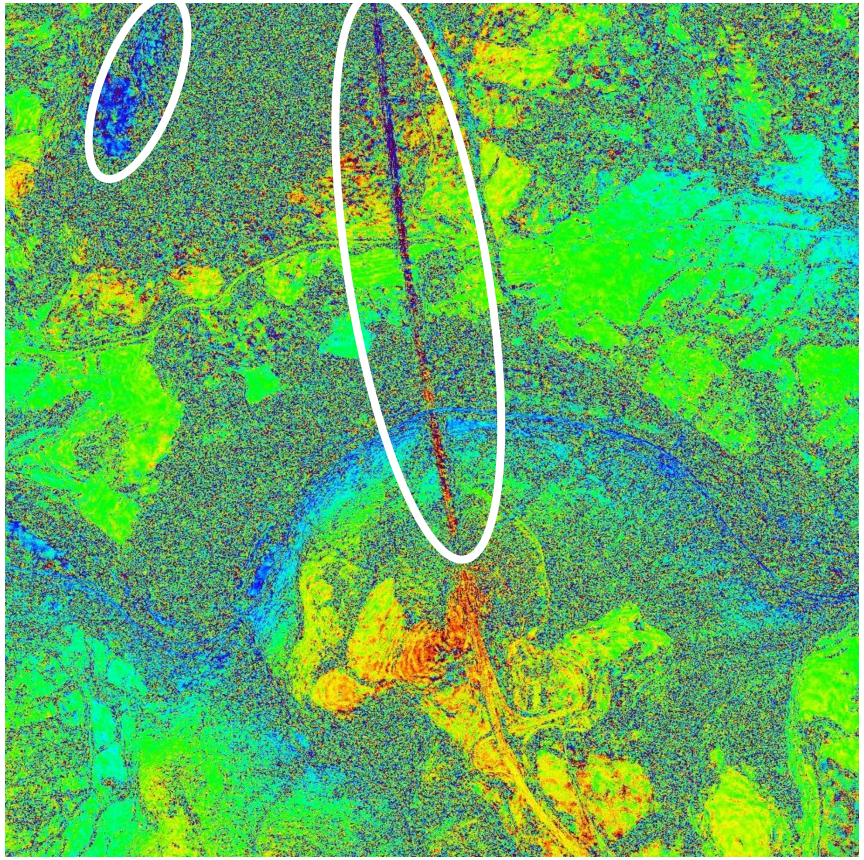
HBMCA processing greatly reduces the fringe rate (by ~50 in our case)

MuChaPro successfully denoised the difference of interferograms.

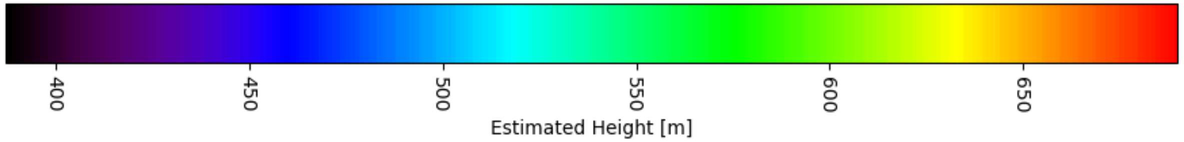
2MuCh : MultiChromatic MuChaPro



IGN's LiDAR HD DSM (projected)



2MuCh

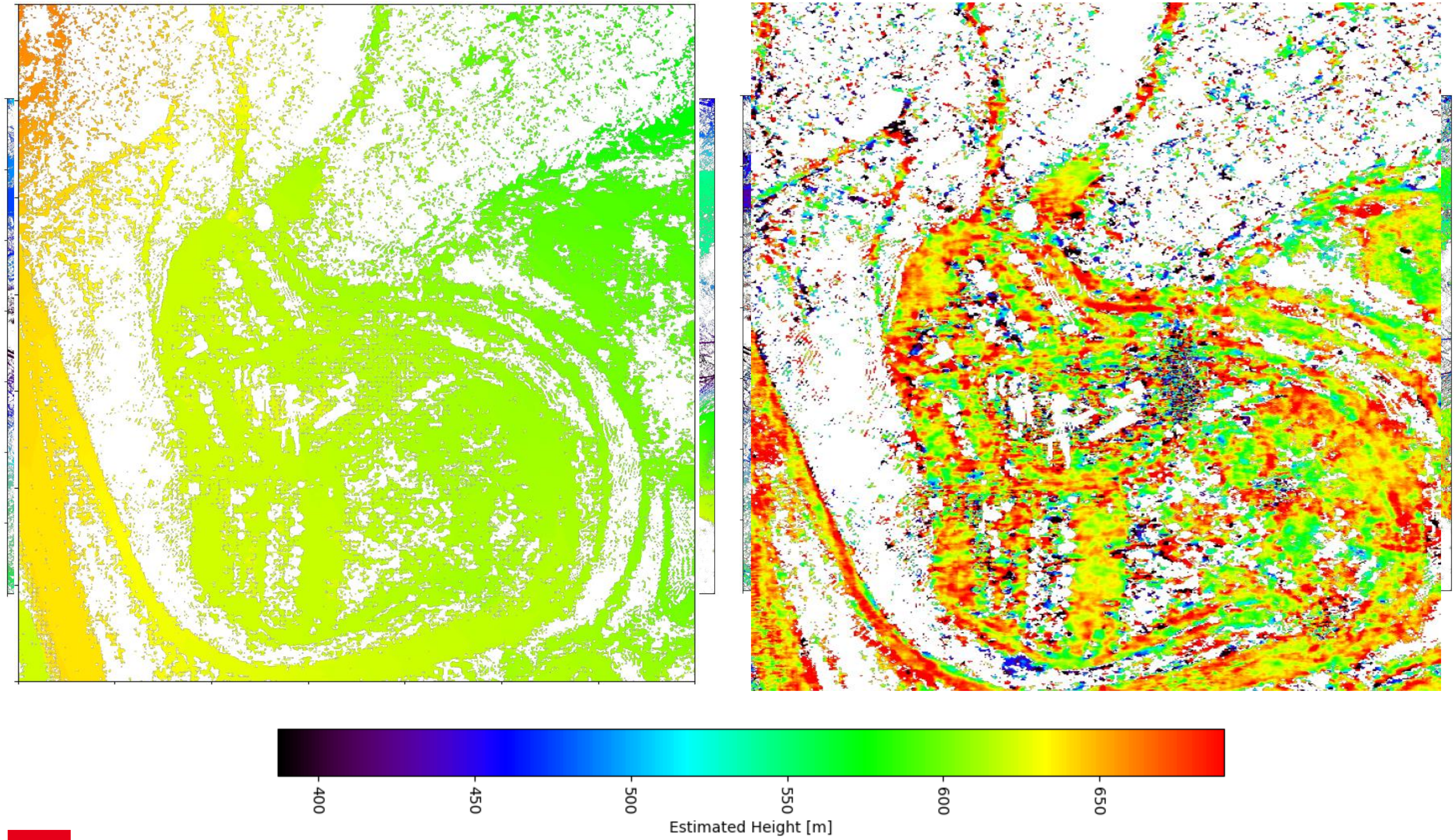


Qualitatively, 2MuCh height estimates match IGN's LiDAR DSM, except for low coherence areas and ....

… in wrapped areas!

$$z_{max} - z_{min} > h_{a_{2Much}} \;!$$

2MuCh : MultiChromatic MuChapro



Areas of “LiDAR shadow” and low coherence (< 0.1) are masked

Estimated heights after median correction (relative height → altitude) and residual phase ramp removal

Large surfaces pass the filter, but the height estimates are noisy

2MuCh : MultiChromatic MuChapro

- **Classical ambiguity height:** $h_a = 8.9\ m$
- **2Much ambiguity height:** $h_{a_{2MuCh}} = 50\ h_a = 445\ m$

- According to Madsen & Zebker, height retrieval noise should also increase by 50!
- MuChaPro-R2 RMSE in Calais was 3.3 m. We can expect an RMSE of up to 165 m.

Method	φ Cosine ↑	RMSE (m) ↓	MAE (m) ↓	±0.5ha (%) ↑	±1.0ha (%) ↑
2MuCh	**1.00**	**89.79**	**60.39**	**6.6**	**13.2**
HBMCA	0.99	142.7	116.8	2.3	4.6

- HBMCA does slightly better than this, at 143 m.
- Thanks to MuChaPro-R2, 2MuCh RMSE drops to 90 m, about 10 h_a.
- In fact, 2MuCh is better than classical HBMCA in every metrics (except computation time).
- The percentage of pixels within half an ambiguity height is small but hopefully enough for assisting the unwrapping of standard interferograms in difficult areas.

Conclusion

- MuChaPro is very effective at filtering interferograms even in split-band InSAR.
- It has no negative impact on height retrieval, only benefits.

- Ongoing work:
  - 2MuCh with more than two sub-bands (4MuCh?)
  - Merging topography estimates derived from different techniques
  - Tests on more sites, validation

Thank you

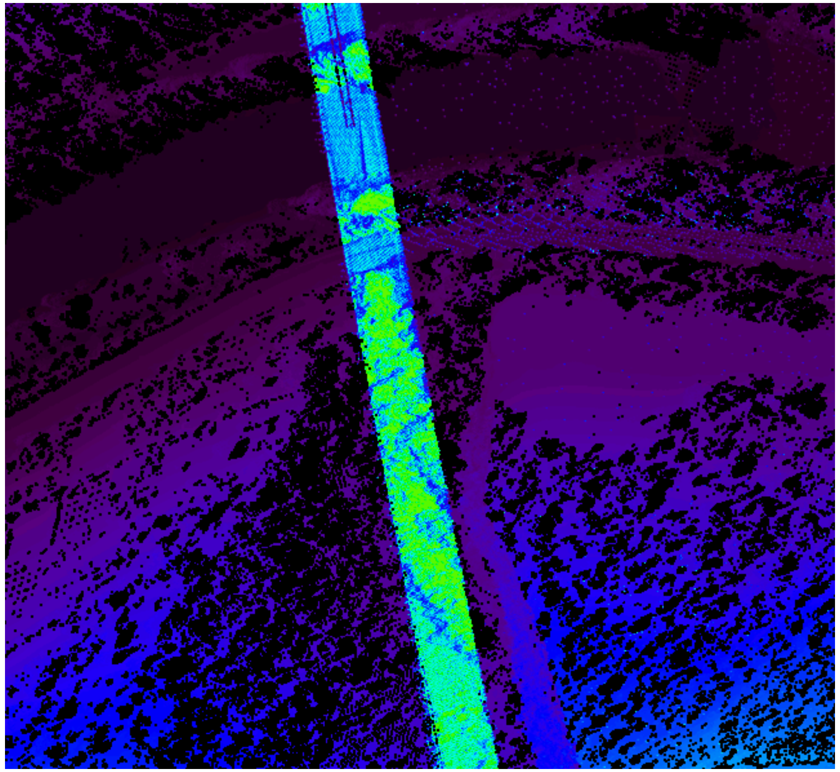
florent.michenot@cea.fr

Qu’est-ce qu’un MNS projeté en géométrie radar?

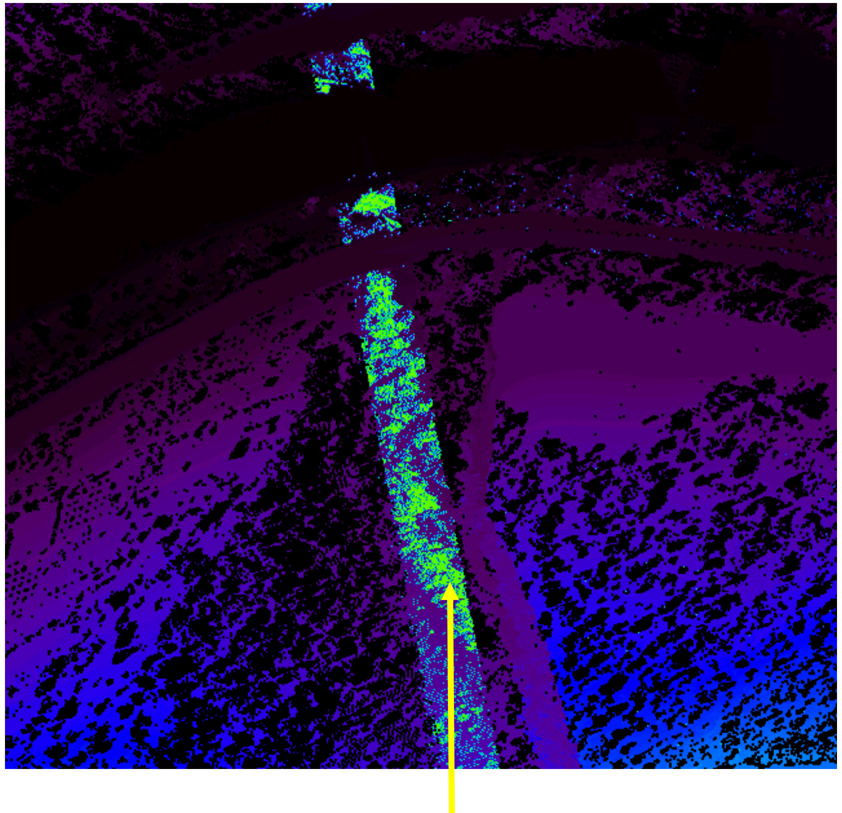
Différents points du sol sont projetés sur un même pixel radar : phénomène de « repliement »

Un MNS projeté en radar peut prendre en compte l’ensemble de ces pixels ou seulement une partie.

MNS moyen

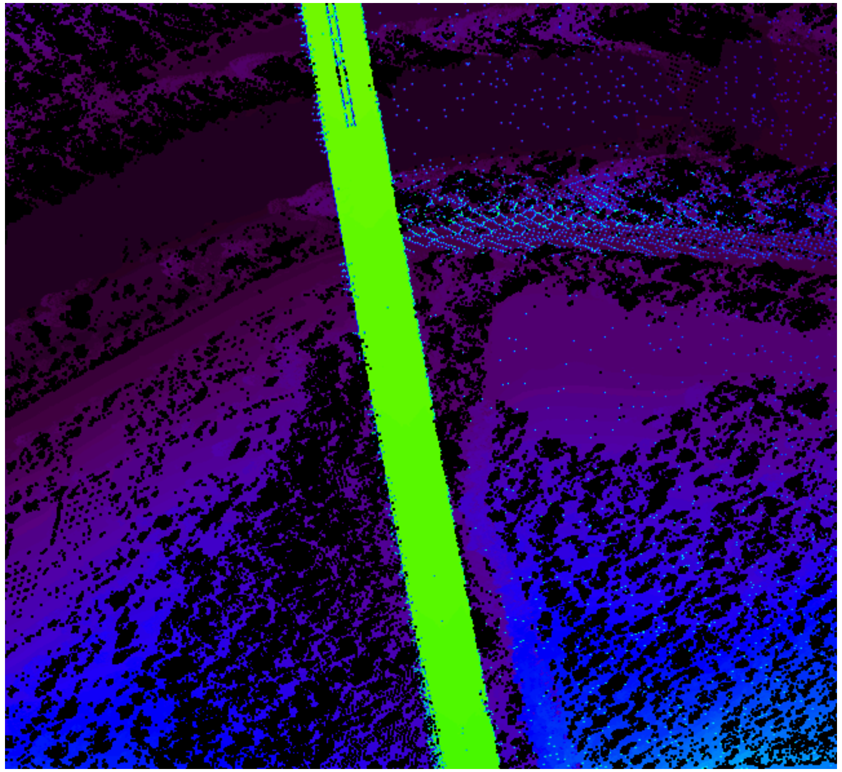


MNS « sol »

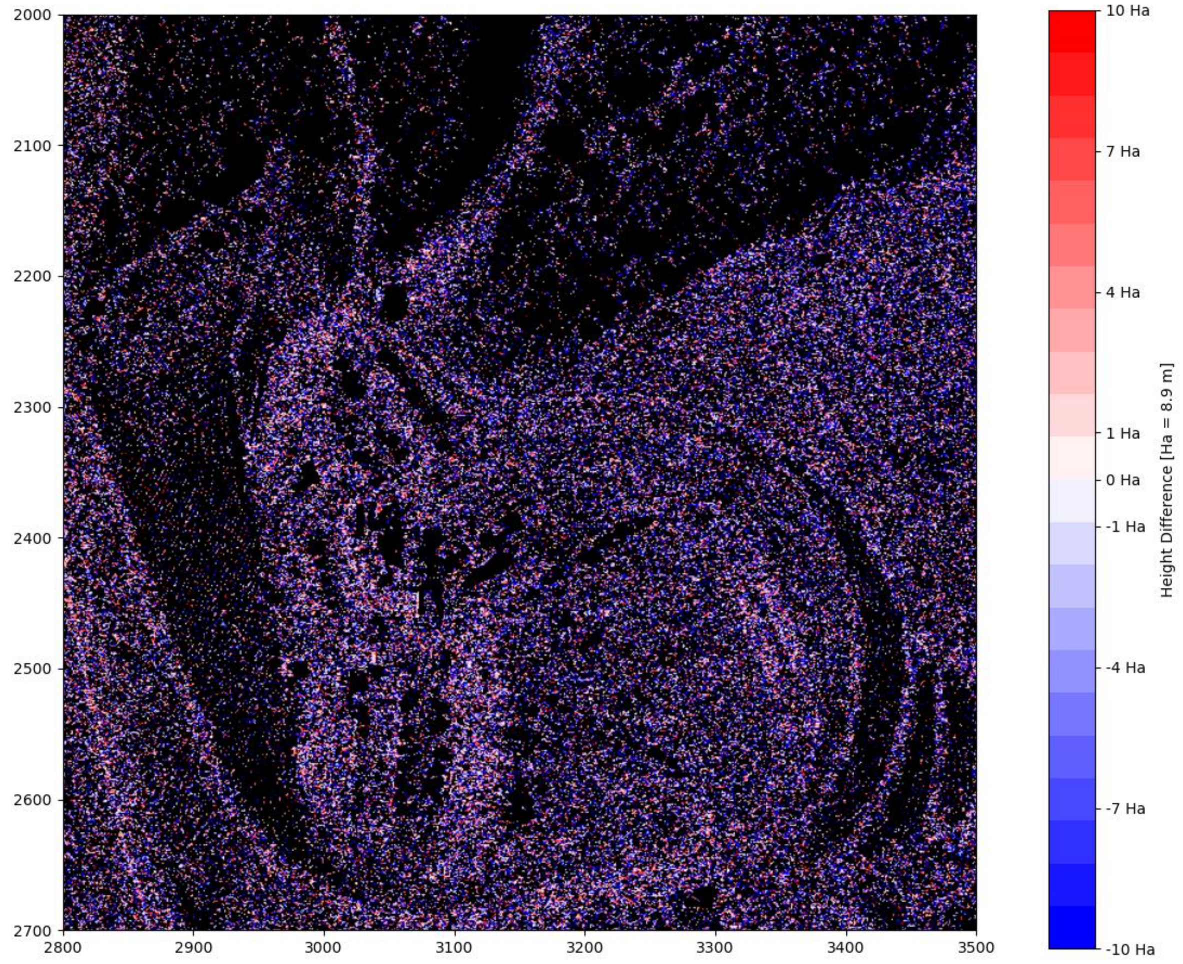


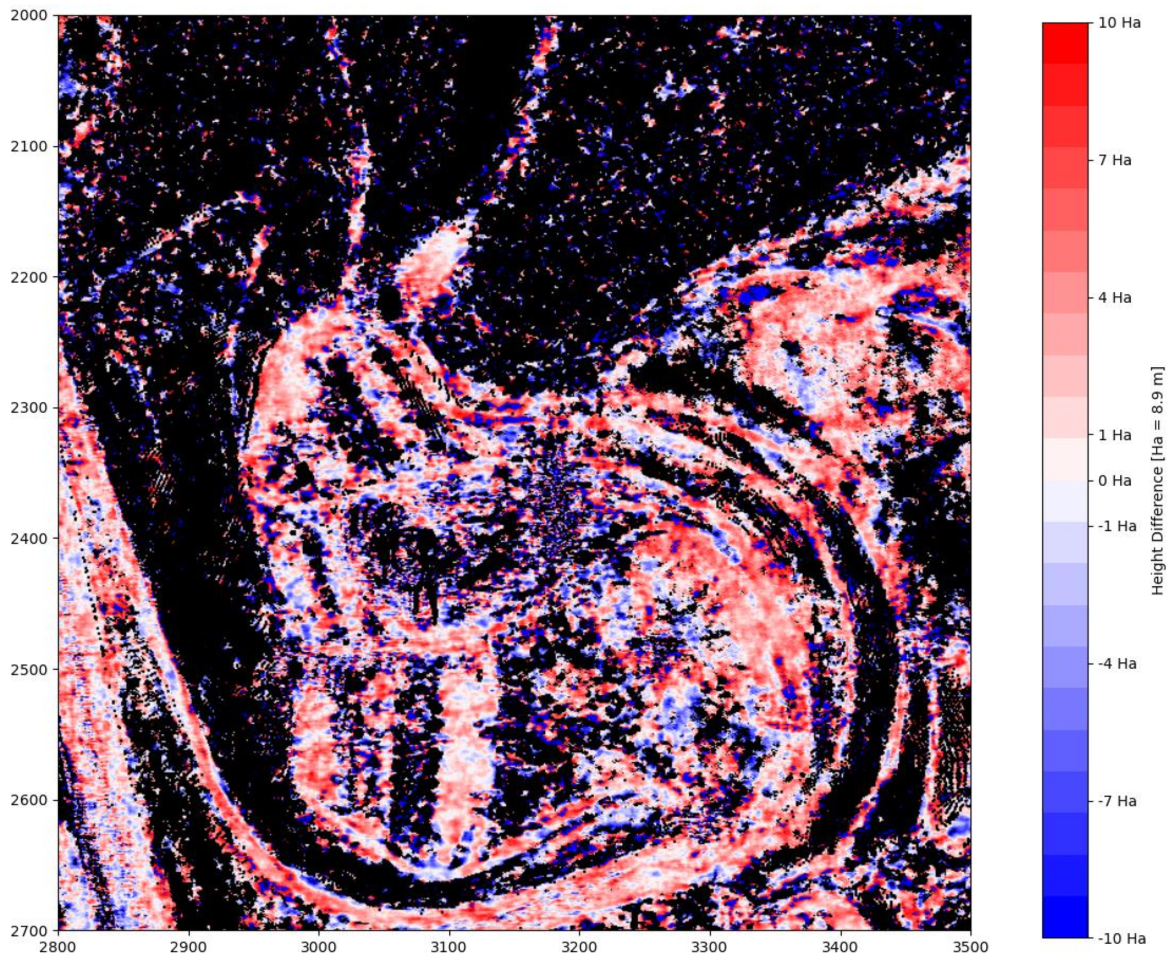
Pour les pixels dans l’ombre au sol, on associe la hauteur du viaduc.

MNS « objets hauts »



2MuCh : MultiChromatic MuChapro





MuChaPro-R²

- MuChaPro limitations: residual noise in low coherence areas and sensitivity to temporal changes
- MuChaPro-R2 improvement: separate reflectivity estimation, regularization and coherence post-processing

z_1 z_2

$$\sqrt{\boldsymbol{r}_1} \leftarrow \texttt{despeckle}(z_1),$$
$$\sqrt{\boldsymbol{r}_2} \leftarrow \texttt{despeckle}(z_2)$$

$$\forall \ell,\ \forall k,\ [\boldsymbol{S}_k]_\ell \leftarrow \boldsymbol{P}_k^\dagger \cdot [\boldsymbol{Z}]_\ell,$$
$$\hat{\boldsymbol{V}}_k \leftarrow \texttt{despeckle}(\boldsymbol{S}_k)$$

Regularized estimation of γ, ϕ

1 Reflectivity Estimation

2 Projection & Despeckling

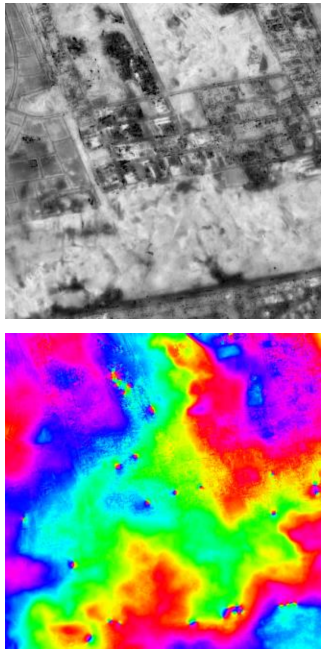
3 Joint Inversion with regularization

4 Robustness to temporal changes

Post-processing on coherence

$\sqrt{r_1}$ $\sqrt{r_2}$

$\hat{\gamma}$



$\hat{\phi}$

Victor Gaya, Loïc Denis, Béatrice Pinel-Puysségur, Thomas Bultingaire, Florence Tupin, "Self-supervised interferogram restoration by regularized inversion of despeckled projections", submitted to JSTARS

MuChaPro-R² : loss function

Minimization of the loss with L-BFGS for joint inversion with spatial regularization:

$$(\boldsymbol{\gamma}, \boldsymbol{\phi}) \leftarrow \underset{\boldsymbol{\gamma}, \boldsymbol{\phi}}{\arg\min}\ \mathcal{L}(\boldsymbol{\gamma}, \boldsymbol{\phi}) = \mathcal{L}_{\text{data}}(\boldsymbol{\gamma}, \boldsymbol{\phi}) + \alpha \cdot \mathcal{L}_{\text{reg}}(\boldsymbol{\gamma}, \boldsymbol{\phi})$$

Data fidelity term

$$\mathcal{L}_{\text{data}}(\boldsymbol{\gamma}, \boldsymbol{\phi}) = \sum_{\ell=1}^{N} \sum_{k=1}^{K} \left(\log m_{k,\ell}([\boldsymbol{\gamma}]_\ell, [\boldsymbol{\phi}]_\ell) - \log [\widehat{\boldsymbol{V}_k}]_\ell \right)^2$$

With

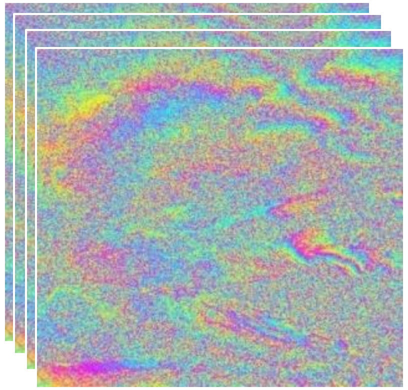
$$\underbrace{\boldsymbol{p}_k^\dagger \cdot \mathbf{C}_\ell \cdot \boldsymbol{p}_k}_{m_{k,\ell}(\gamma,\phi)} = [\boldsymbol{r}_1]_\ell \cdot |[\boldsymbol{p}_k]_1|^2 + [\boldsymbol{r}_2]_\ell \cdot |[\boldsymbol{p}_k]_2|^2$$

$$+2\boldsymbol{\gamma}\sqrt{[\boldsymbol{r}_1]_\ell [\boldsymbol{r}_2]_\ell} \cdot |[\boldsymbol{p}_k]_1| \cdot |[\boldsymbol{p}_k]_2| \cdot \cos(\arg([\boldsymbol{p}_k]_1^* [\boldsymbol{p}_k]_2) + \boldsymbol{\phi})$$

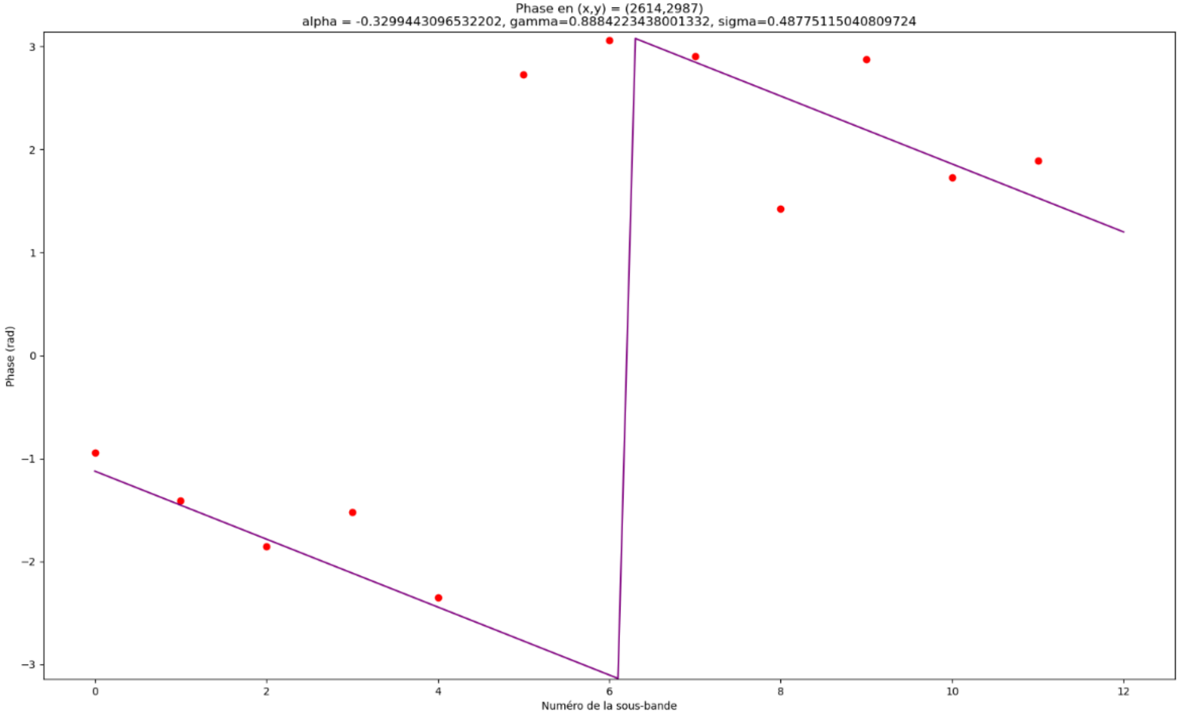
Spatial regularization term

$$\mathcal{L}_{\text{reg}}(\boldsymbol{\gamma}, \boldsymbol{\phi}) = \sum_{\ell=1}^{N} \lambda_\gamma \left[(\Delta_\ell^{\text{vert}} \boldsymbol{\gamma})^2 + (\Delta_\ell^{\text{horiz}} \boldsymbol{\gamma})^2 \right]$$
$$+ \lambda_\phi \left[2 - \cos(\Delta_\ell^{\text{vert}} \boldsymbol{\phi}) - \cos(\Delta_\ell^{\text{horiz}} \boldsymbol{\phi}) \right]$$

Multichromatic Analysis (MCA)



Pile de N phases interférométriques



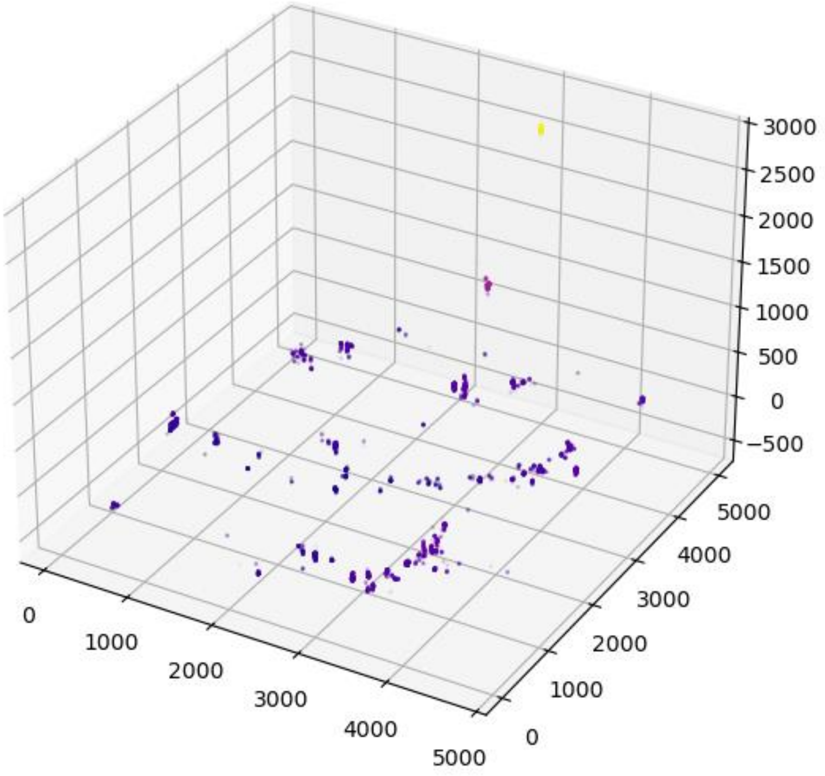
Etude de la phase en fonction des sous-bandes pour chaque pixel de l'image

Linéaire (à un enroulement près) si la cohérence est bonne, aléatoire sinon.

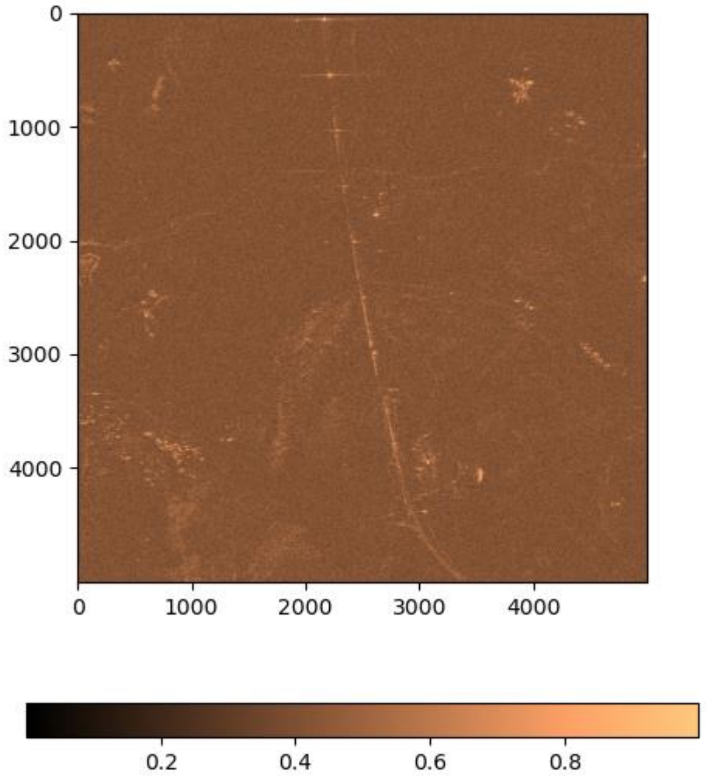
Hauteur relative directement proportionnelle à la pente: **pas de déroulement**

Le nombre de sous-bande robustifie l'estimation de la pente, mais dégrade la résolution en distance. Risque de mélange de cibles de hauteur (et donc de pente) différentes.

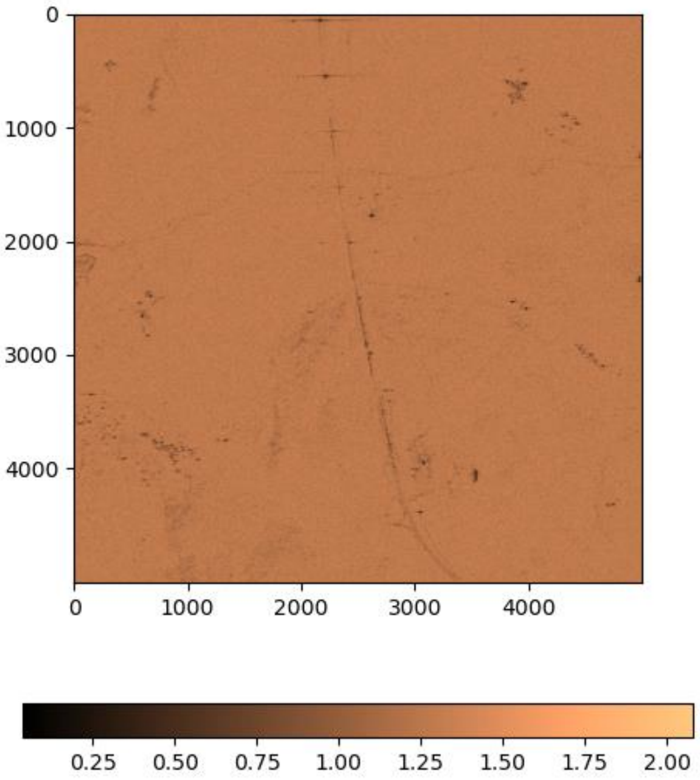
Multichromatic Analysis (MCA)



Hauteurs (seuillées sur gamma)



Gamma (spectral coherence)



Sigma (écart-type)