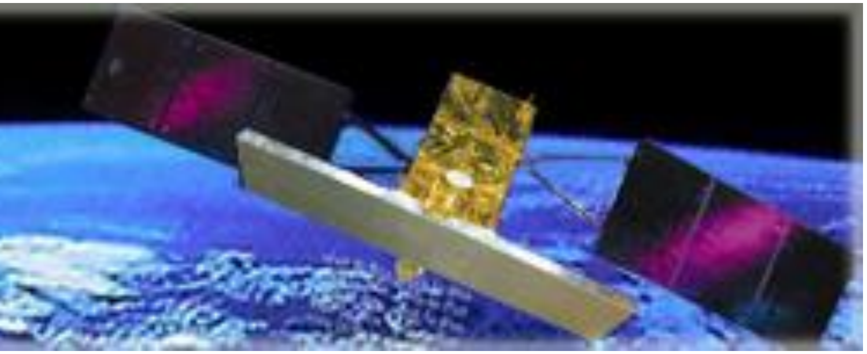
Séries SAR multi-temporelles : traitements et applications en milieu urbain

F. Tupin

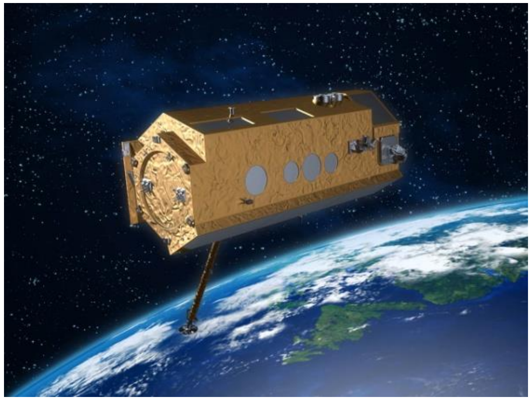
J-M Nicolas, L. Denis, C. Deledalle, G. Ferraioli, F. Dellinger, G. Quin, X. Su, S. Lobry, C. Rambour, W. Zhao

Context

- **Golden age of SAR sensors: improved spatial, polarimetric and temporal resolutions**

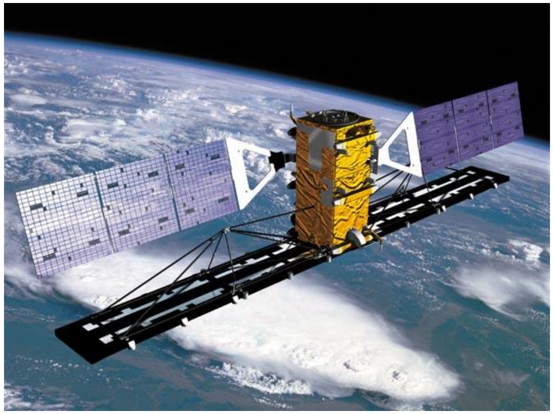


CSK



TerraSAR-X

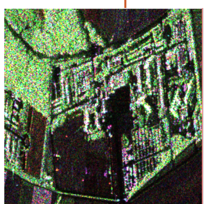
Sentinel I

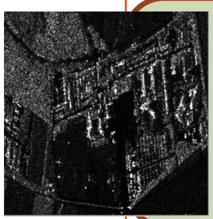


RadarSAT-2

SAR sensors – resolutions

Polarimetric resolution





Spotlight

Stripmap

ScanSAR

Alos-2 / PALSAR
(full polar)

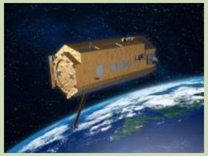
Radarsat-2
(full polar)

3m

100m

CosmoSkyMed

TerraSAR-X



1m

5m

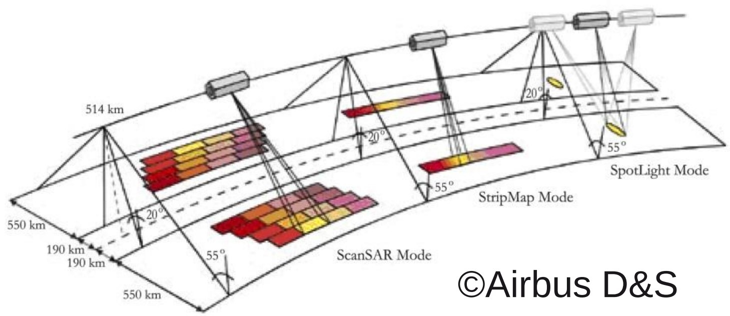
10m

20m

30m

Spatial
resolution (m)

Time resolution
(days)



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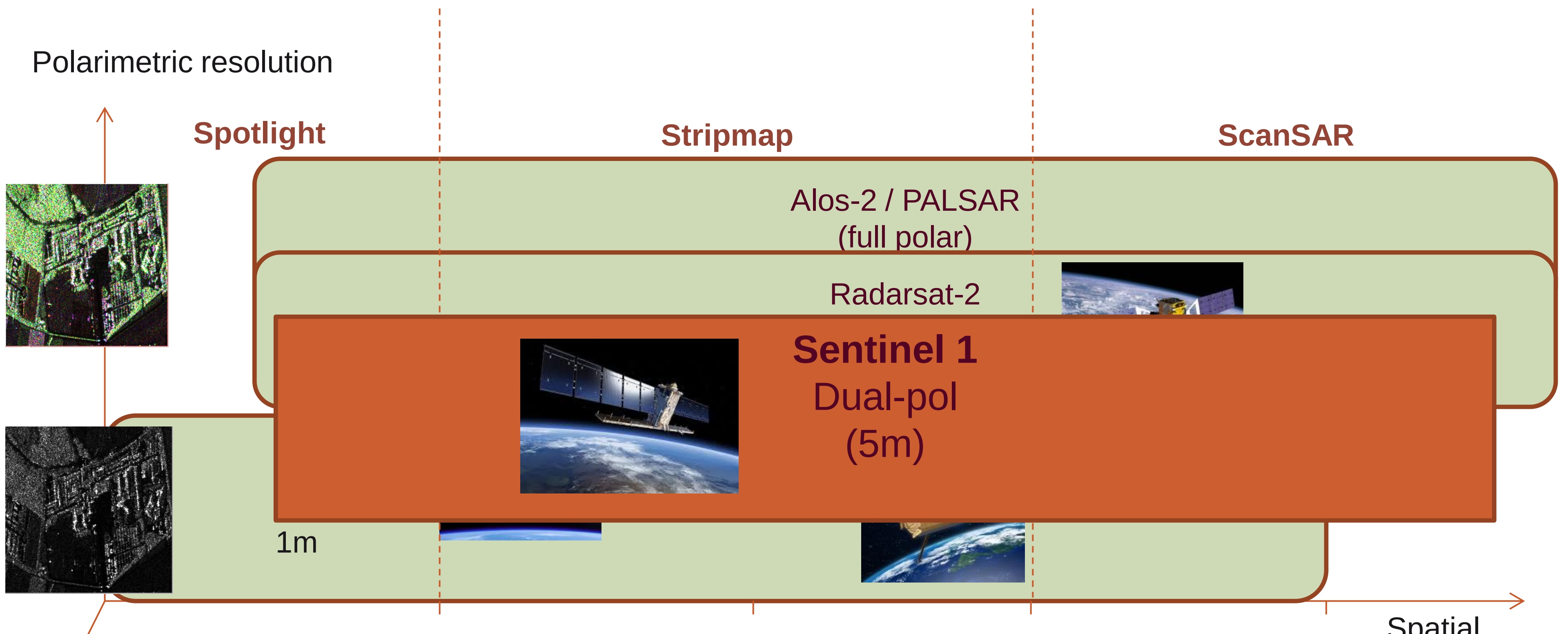
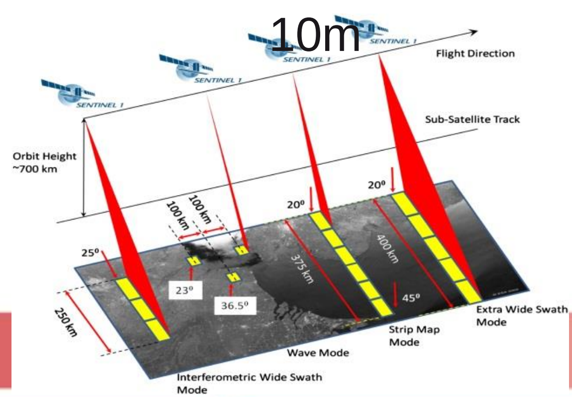
SAR sensors – resolutions

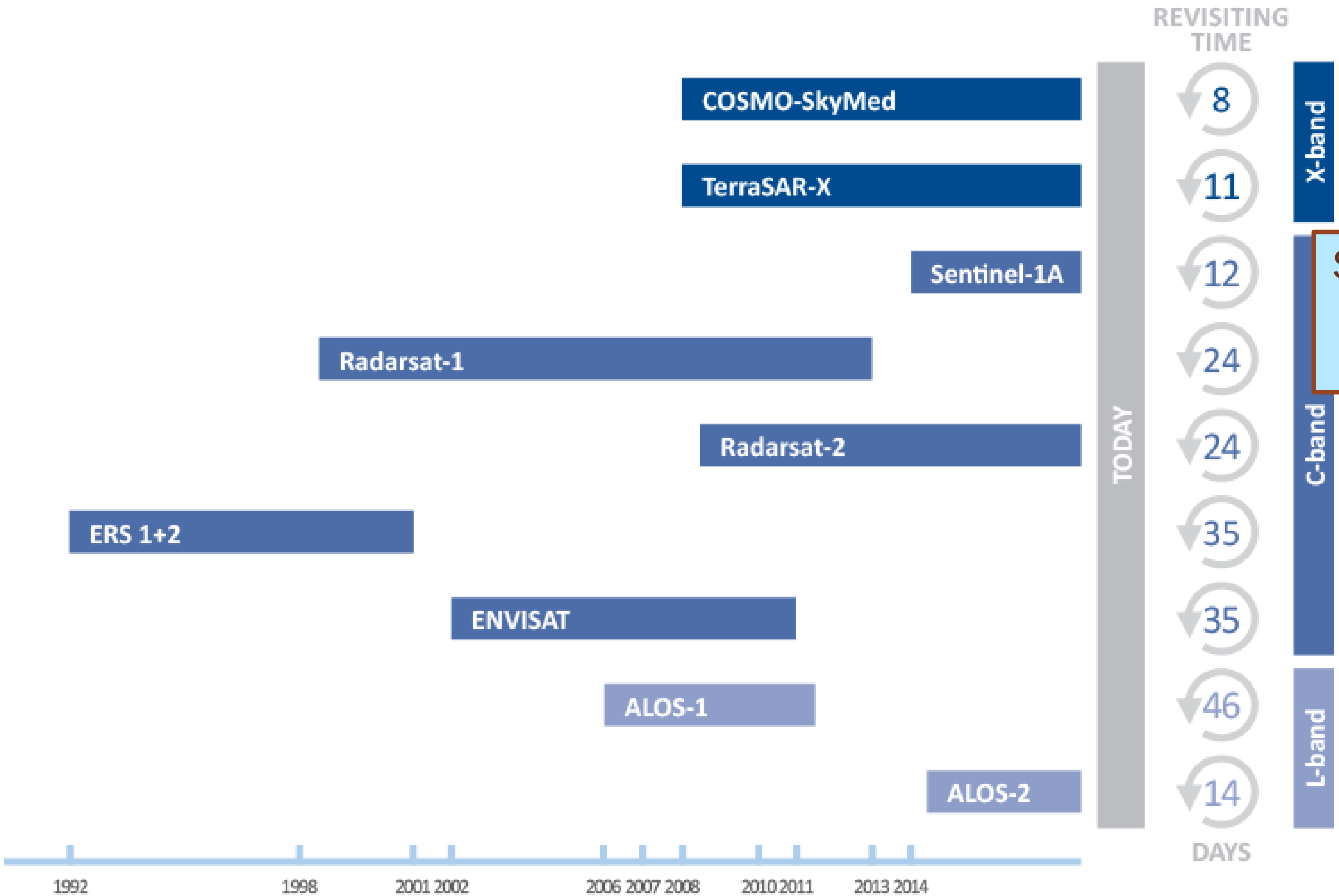


Time resolution
(days)



©ESA

SAR sensors – revisiting time

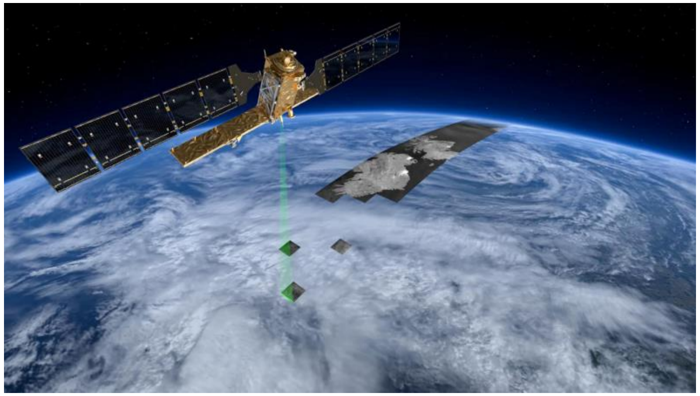


Sentinel1B
2016
6 jours

Figure from http://www.treuropa.com

Context

- **SAR imagery :**
  - 50 years of history: from Seasat to Sentinel-1
  - Long history of **multi-temporal** series starting with ERS
  - In the last years: improvement in *spatial and temporal* resolution thanks to multi-sensors and constellations



What is new ?
ESA policy for Sentinel data

New multi-temporal applications
New multi-temporal processing methods

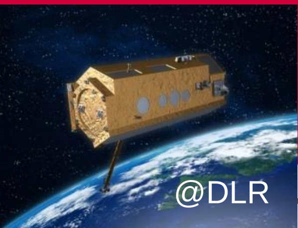
Challenges for urban areas

Urban mapping
(classification, DEM, …)

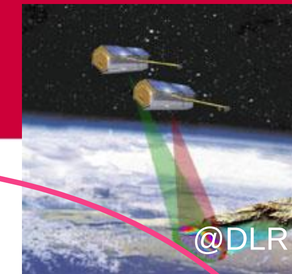
Building / ground movement monitoring

Urban monitoring
(temporal dynamics, urban growth, change detection, rapid mapping, …)

Different scales of analysis (local / regional / global)



SAR data and information



D=1 $z = Ae^{j\varphi}$

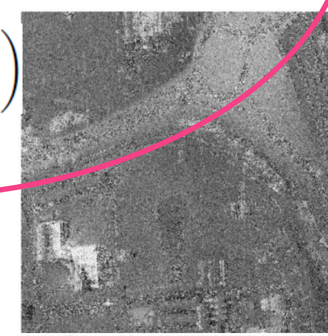
Amplitude data
(classification, object recognition,…)

D=2 $\mathbf{k} = \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$

different incidence angles

Interferometric data:
geometric information
(elevation, movement)

$$\begin{pmatrix} 1 & \gamma_{1,2}e^{j\psi_{1,2}} \\ \gamma_{1,2}e^{-j\psi_{1,2}} & 1 \end{pmatrix}$$



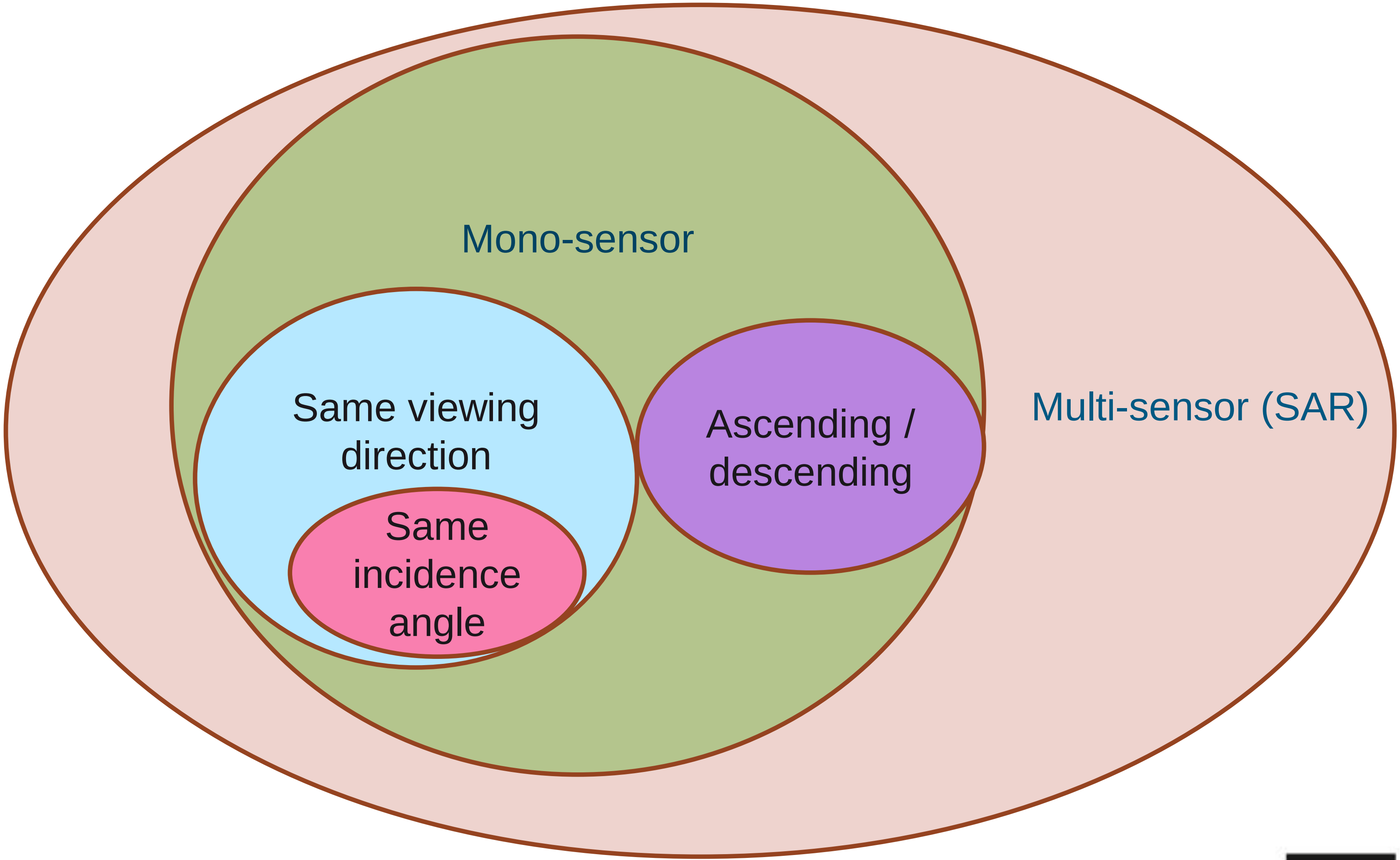
+ Time temporal series

D=3 $\boldsymbol{k} = (z_{hh}, z_{vv}, \sqrt{2}z_{hv})^t$

different polarizations

Polarimetric data
Backscattering mechanisms
(classification, object recognition,…)

Multi-temporal / multi-sensors ?



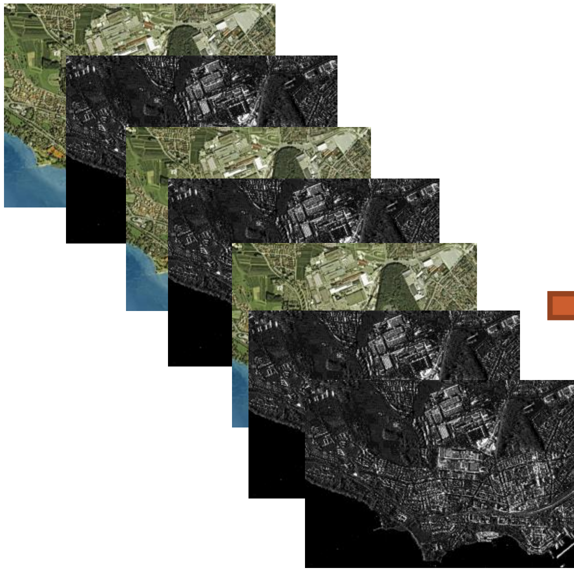
Overview

- Data and pre-processing
- Processing and applications for multi-temporal amplitude data
- Processing and applications for multi-temporal interferometric data

Overview

- **Data and pre-processing**
- **Processing and applications for multi-temporal amplitude data**
- **Processing and applications for multi-temporal interferometric data**

Pre-processing to combine multi-temporal data (pixel level)



Registration

Radiometric corrections

Multi-temporal processing

- Improvement
- Change detection
- Information extraction

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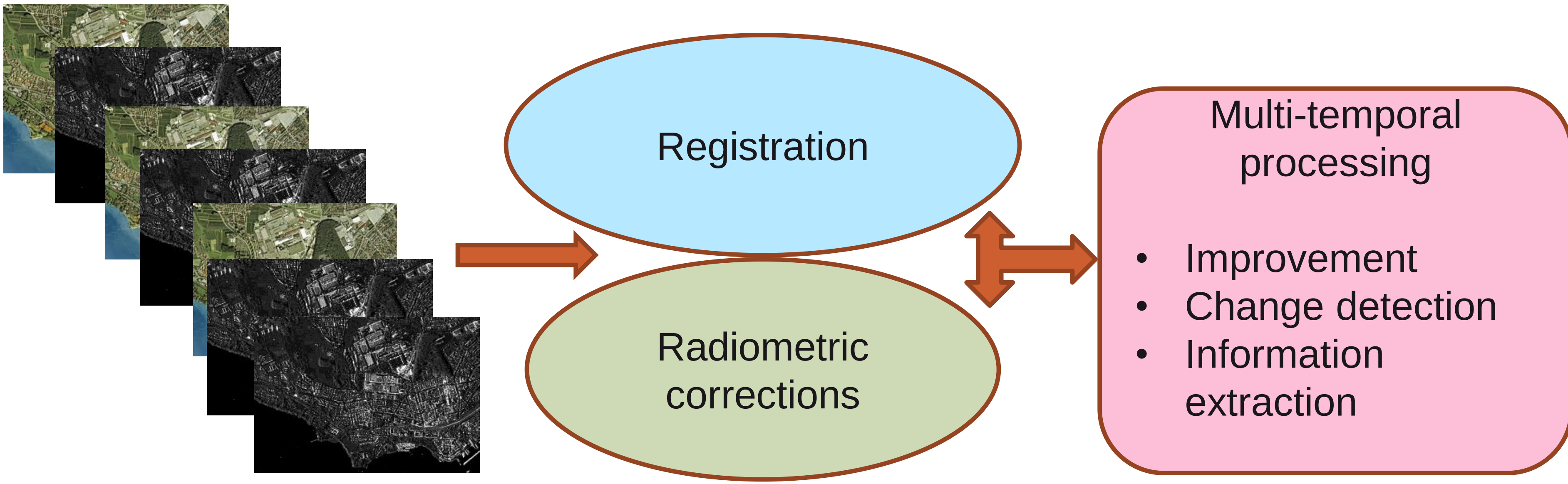
Pre-processing to combine multi-temporal data (pixel level)

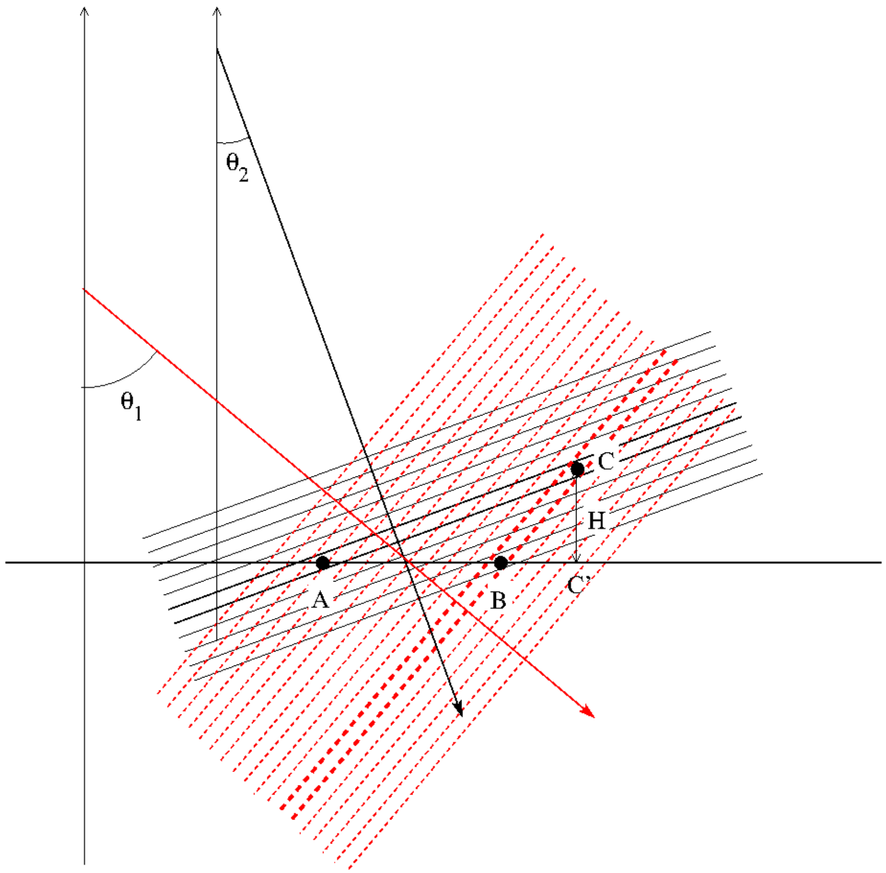


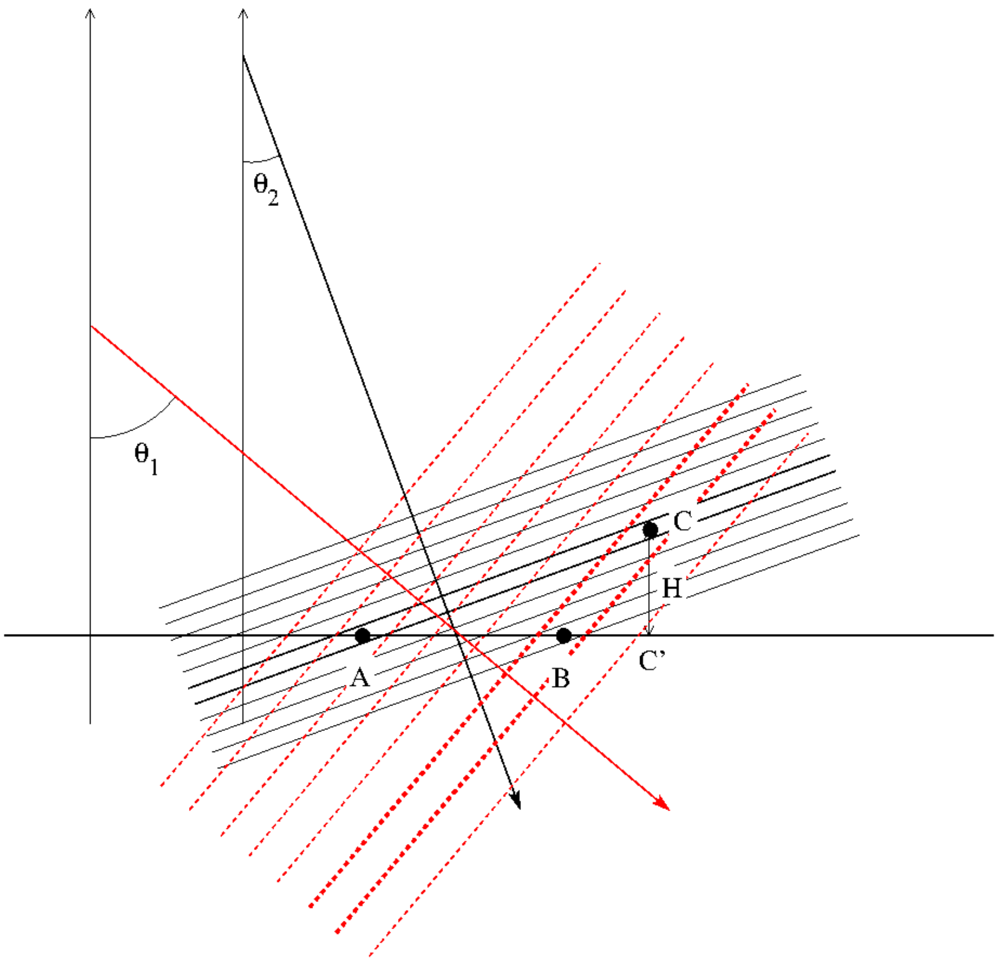
Registration:

- *Image processing methods* (key-point matching, deformation computation) ex: GeFolki (ONERA w3.onera.fr/medusa/geofolki)
- Remote sensing context: *geometric methods*; very accurate knowledge of the sensor parameters for the new generation of sensors (automatic registration in simple cases, use of a DEM if different incidence angles)

[Plyer et al. 15] [Dellinger 14]

Recalage : même pixel sol

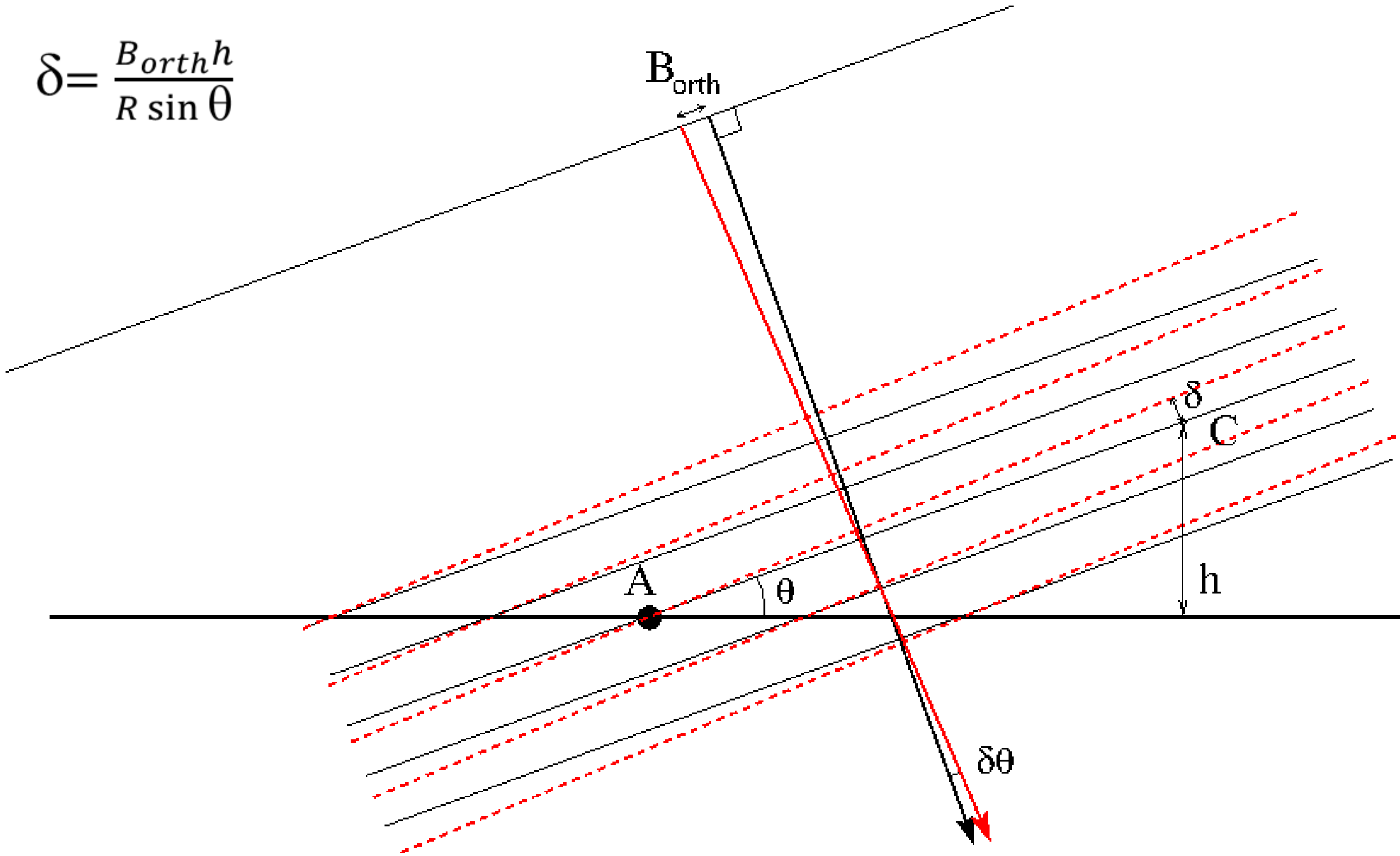




[Nicolas et al., 17]

Interférométrie

$$\delta = \frac{B_{orth} h}{R \sin \theta}$$

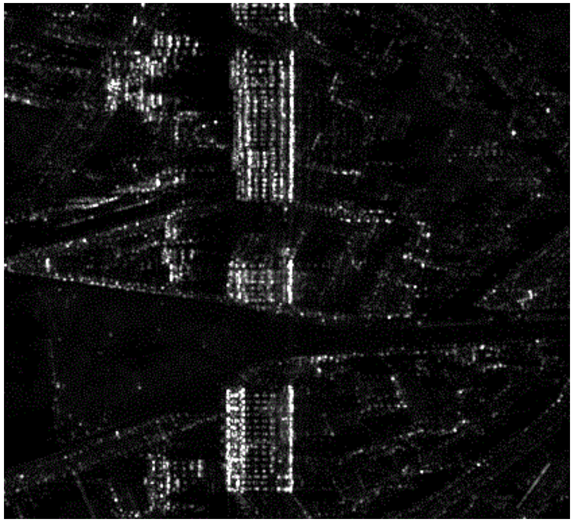
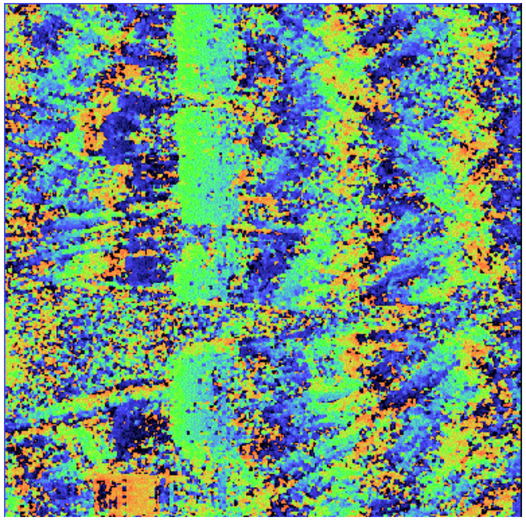
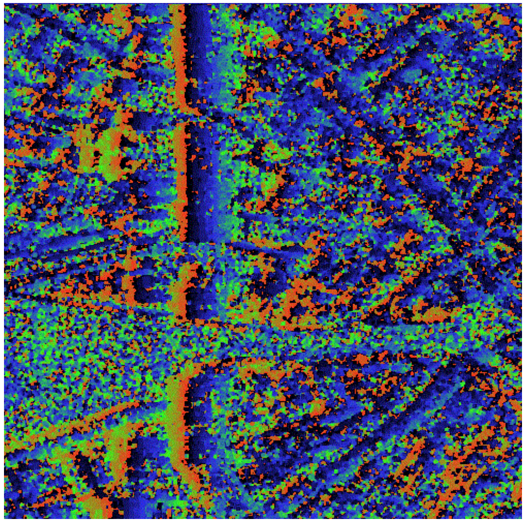


Recalage

- **Paramètres des capteurs (.xml) :**
  - Positions : x,y,z (repère : centre de la Terre)
  - Vitesses : Vx, Vy et Vz
  - Temps : tirs (lié à la PRF) et range
- **Pour un pixel sol donné :**
  - On retrouve la position sur les deux SLC

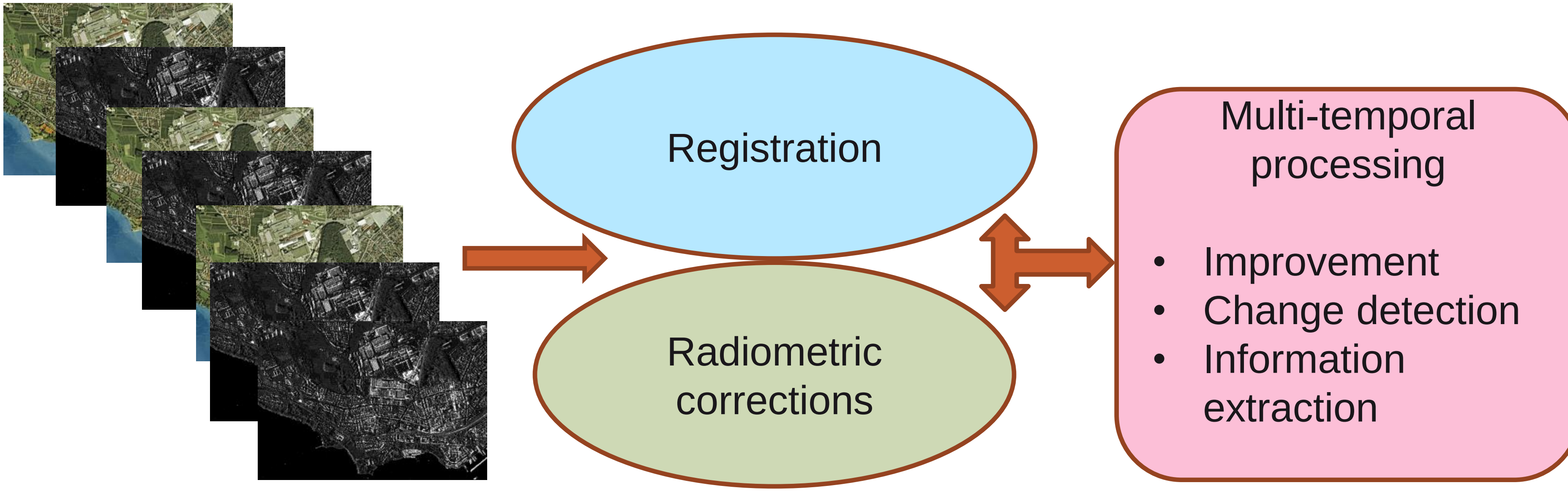
Exemple en urbain

- **Interférogrammes Terrasar-X**
  - Directement sur les fichiers .cos
  - Après recalage subpixellique

TerraSAR-X
DLR project
LAN 176

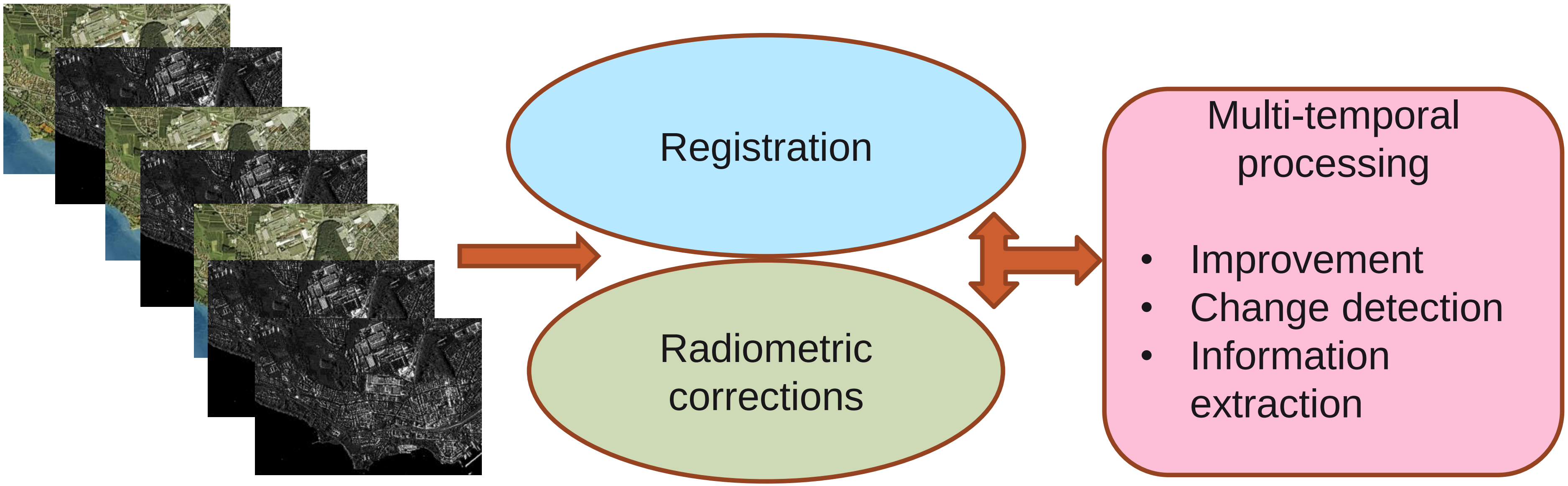
Pre-processing to combine multi-temporal data (pixel level)



Radiometric corrections:

- Image processing methods (histogram fitting)
- SAR imagery context: calibration step of the data

Pre-processing to combine multi-temporal data



Objectives of multi-temporal analysis:

- *Change detection* (stable / unstable areas)
- *Data improvement* (speckle noise reduction)
- *Information extraction (higher level)*: temporal evolution, temporal movement

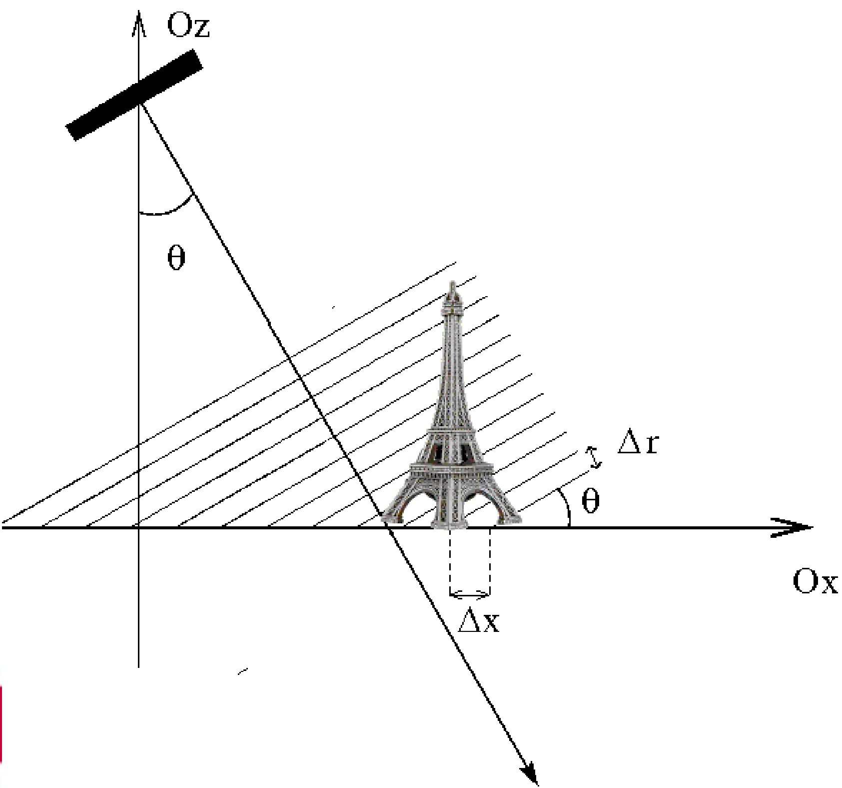
Pre-processing may not be necessary if higher-level information is combined (detected structures, object tracking, fusion of physical measurements…)

Overview

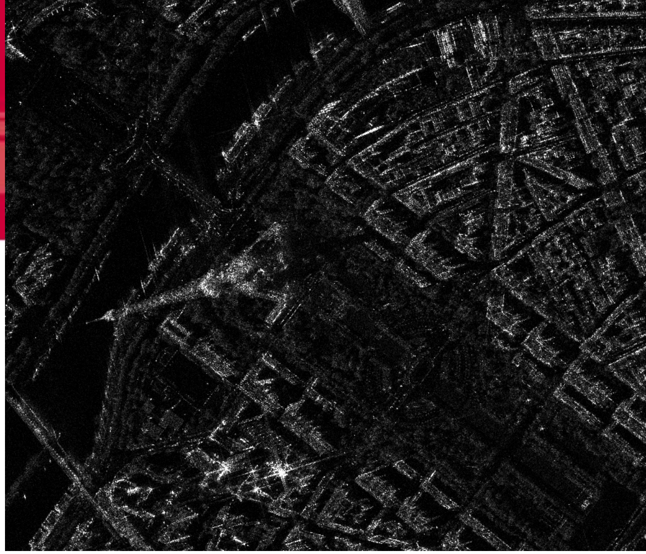
- Data and pre-processing
- Processing and applications for multi-temporal amplitude data
- Processing and applications for multi-temporal interferometric data

Muti-temporal SAR amplitude information

- **SAR amplitude images :**
  - Speckle noise
  - Strong influence of geometry (incidence angle / object geometry)

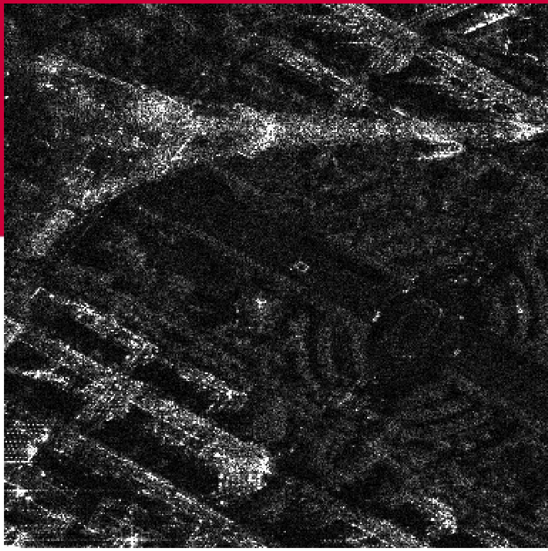


TerraSAR-X, θ~30°

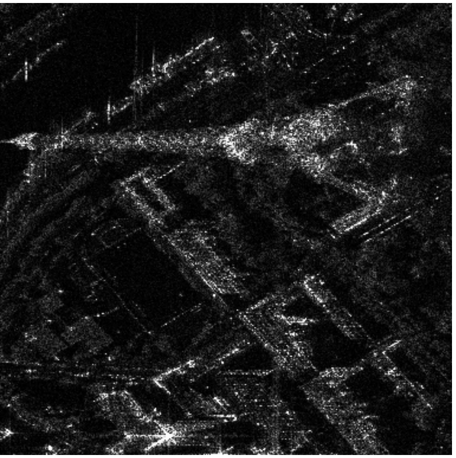


CSK A

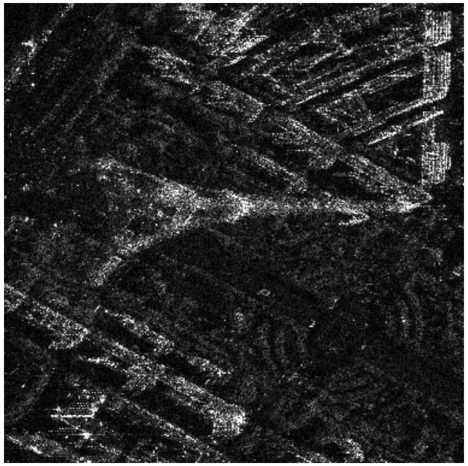
CSK D



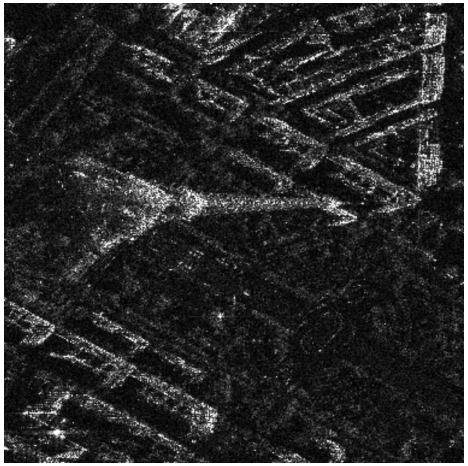
CSK D spe



CSK A 36°



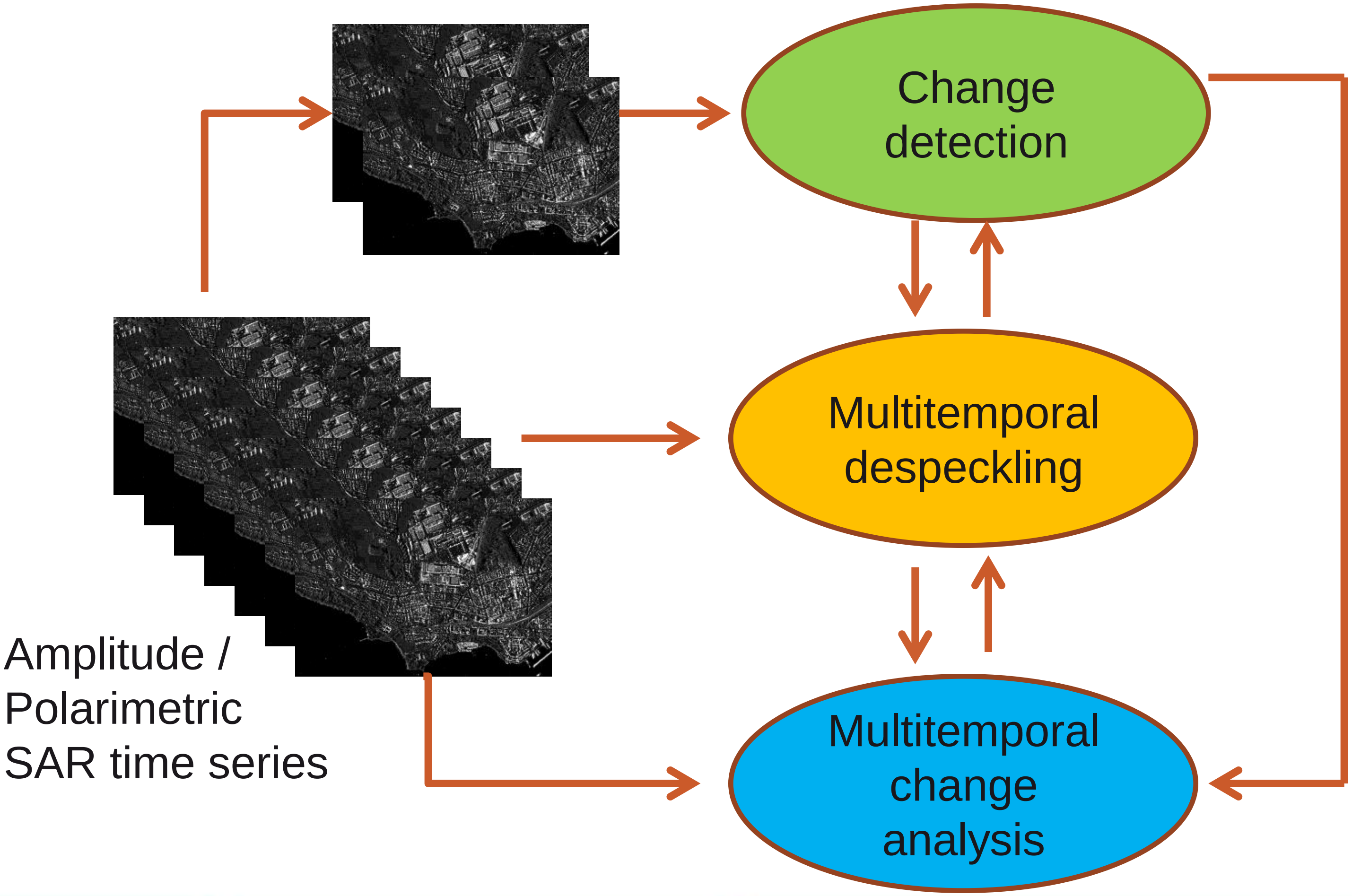
CSK D 36°



CSK D 43°

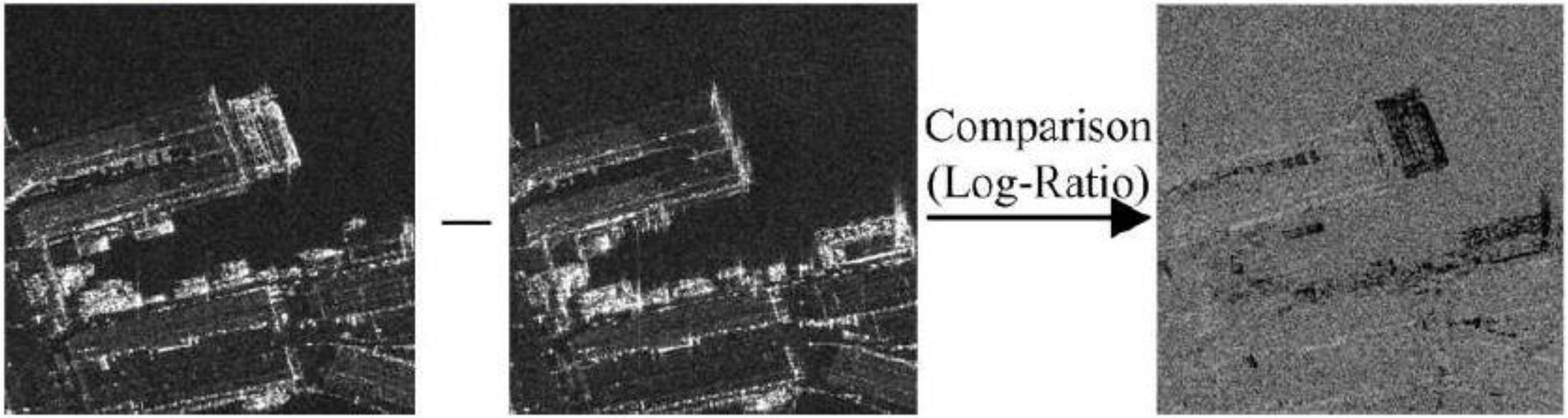
CSK D 58°

Processing and applications



1. Change detection

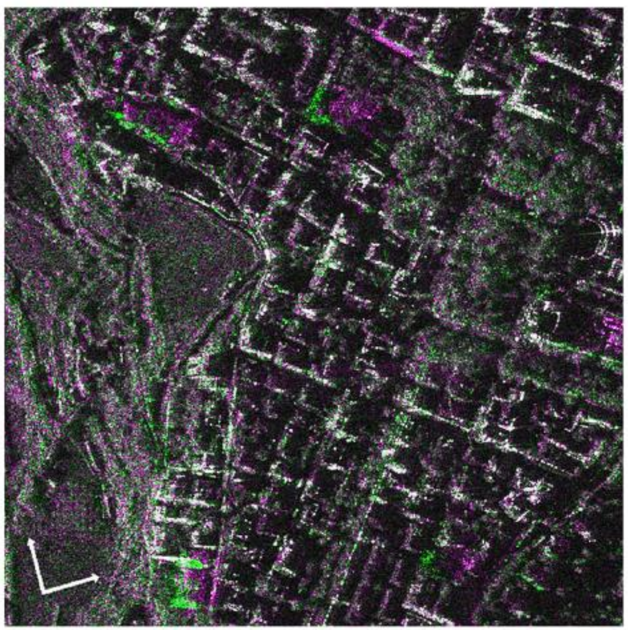
- **Bi-date change detection:**
  - Statistical similarity measure :
    - Ratio between images
    - Comparison of local gray-level distributions
    - Analysis of the joint pdf and « rare event » detection
    - Likelihood ratio test between no-change and change hypotheses

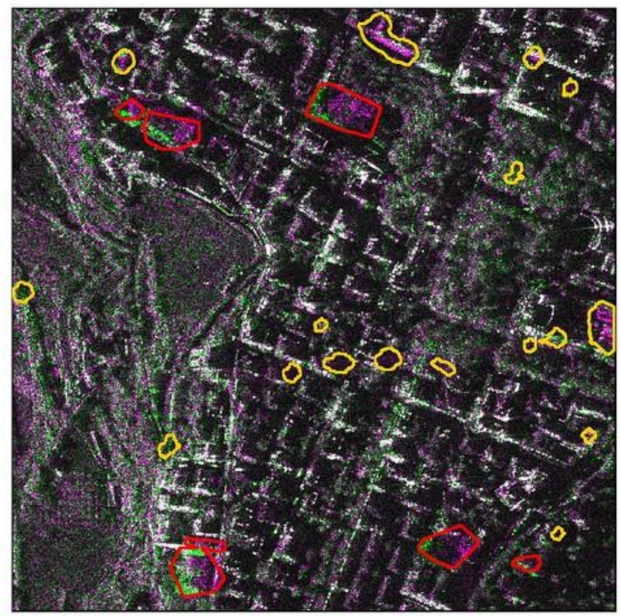


1. Change detection

Bi-date change detection:

- Based on a statistical modeling of the data (Gamma, Fisher, …)
- Trade off between resolution and precision of the statistical tests
- Usually need some post-processing or prior information (like object shape)



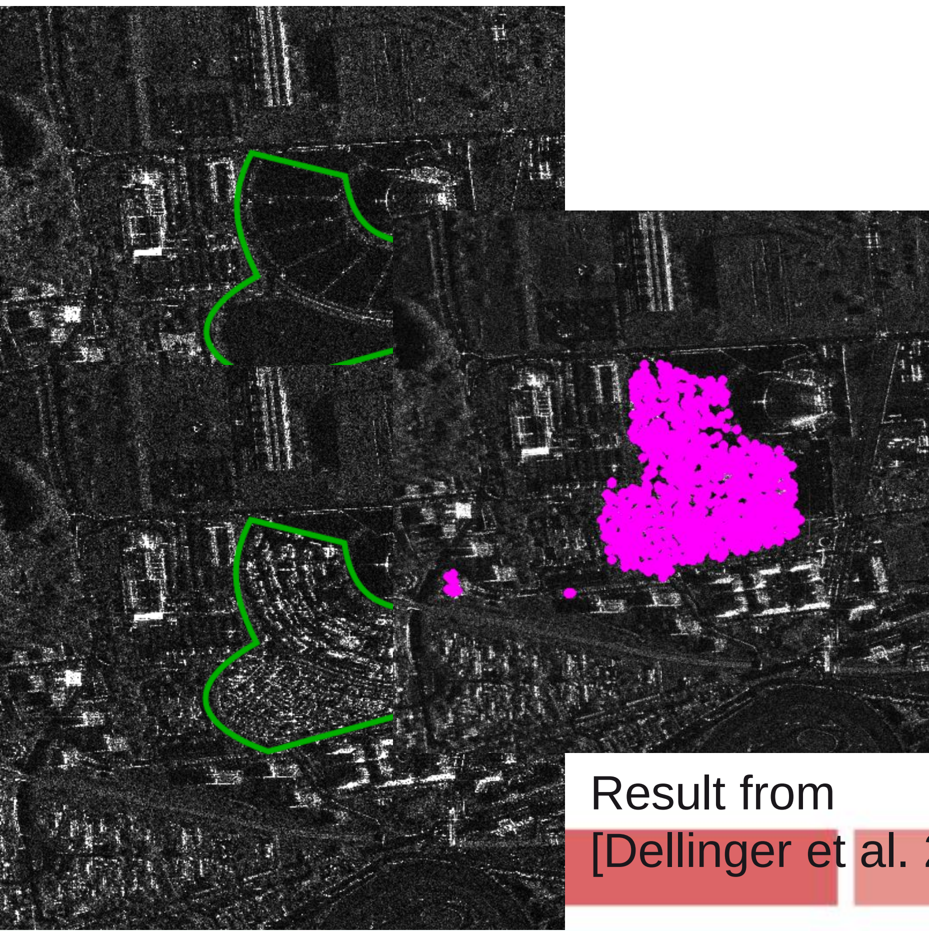


Result from [Marin et al. 2015]

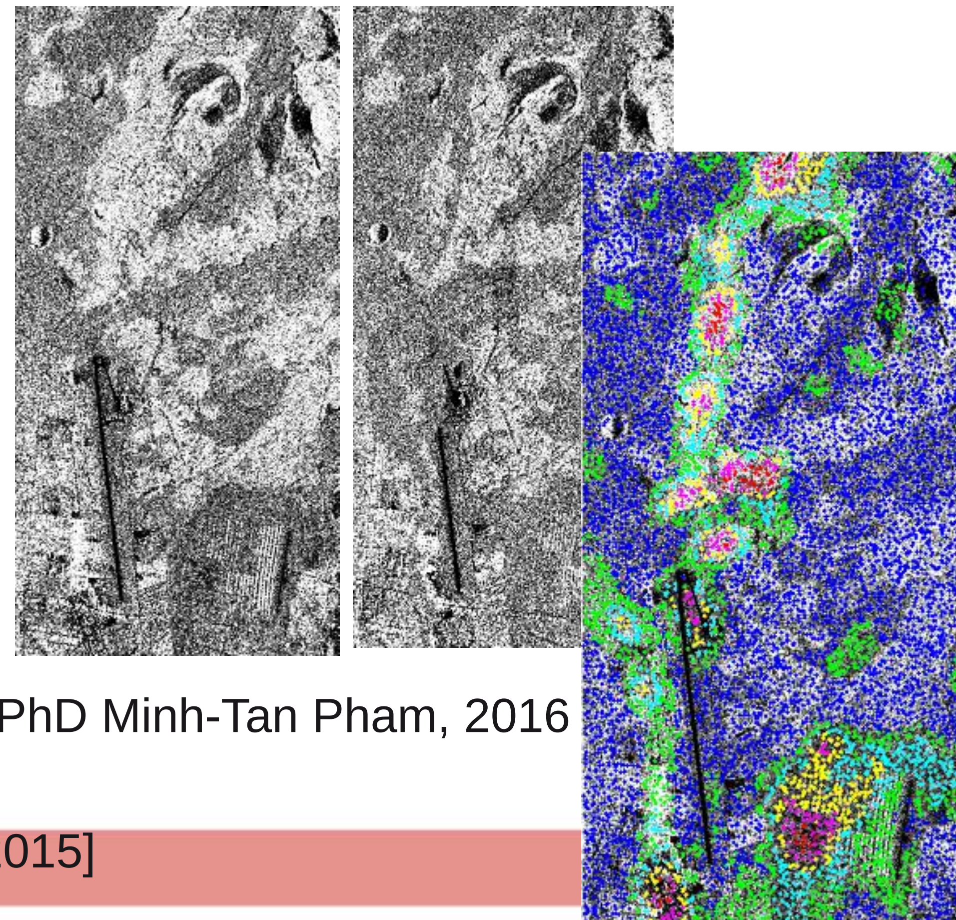
1. Change detection

■ Strucural change detection:

- Based on local descriptor (SAR-SIFT, local signature,…)
- Analyzing local structure (a contrario, graphs,…)



Result from
[Dellinger et al. 2015]

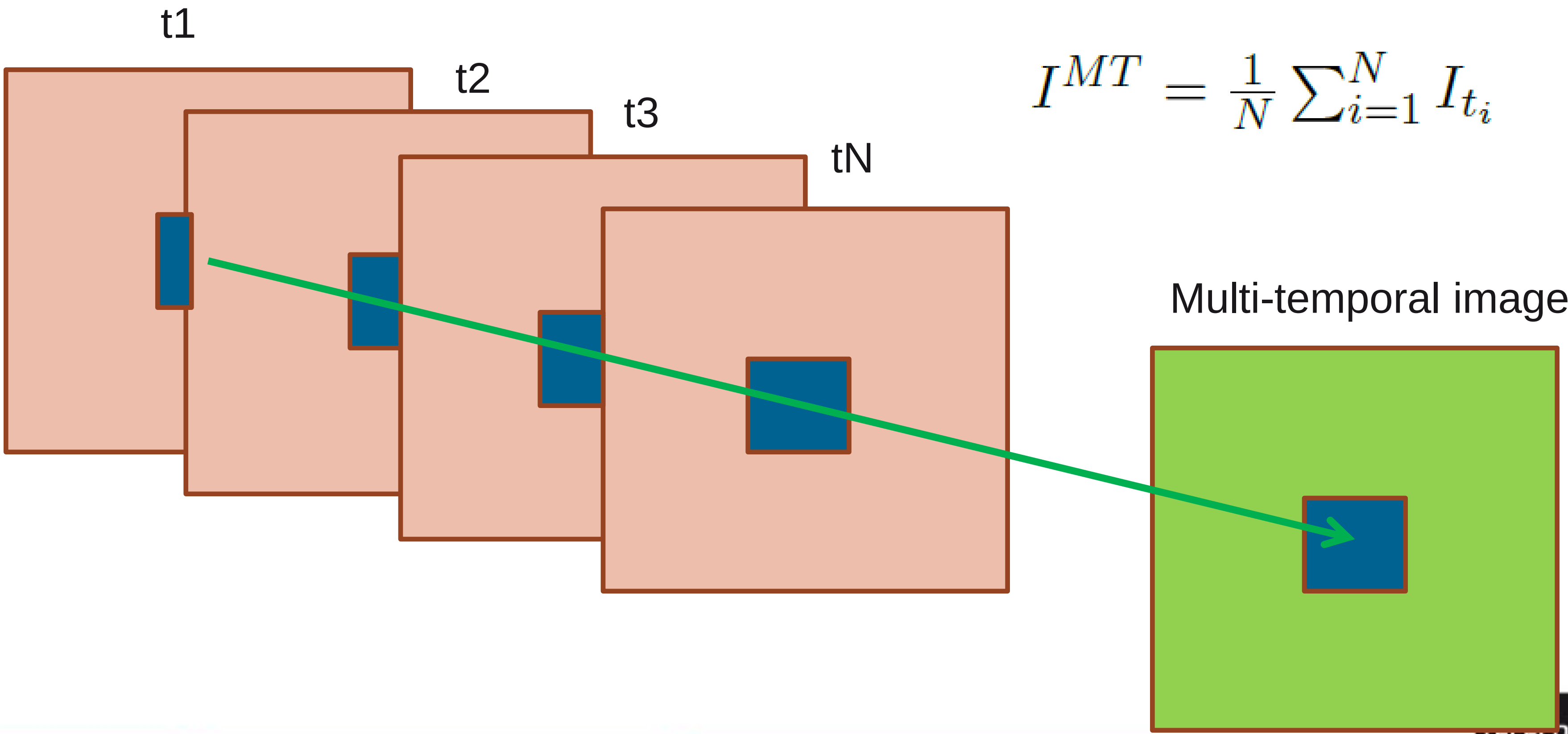


PhD Minh-Tan Pham, 2016

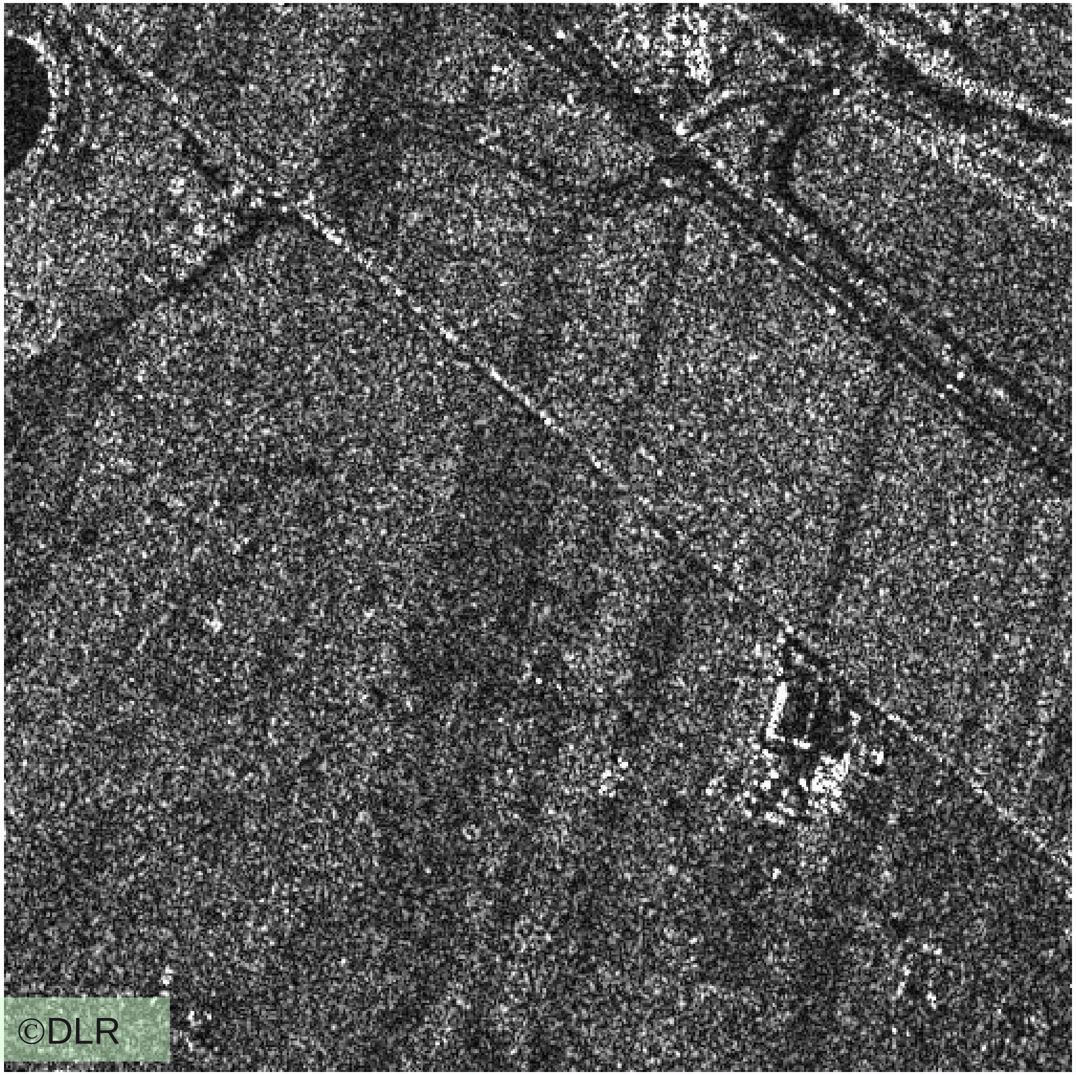
2. Multi-temporal filtering

- **Objective: speckle reduction**
  - Simplest way: just average temporally images !

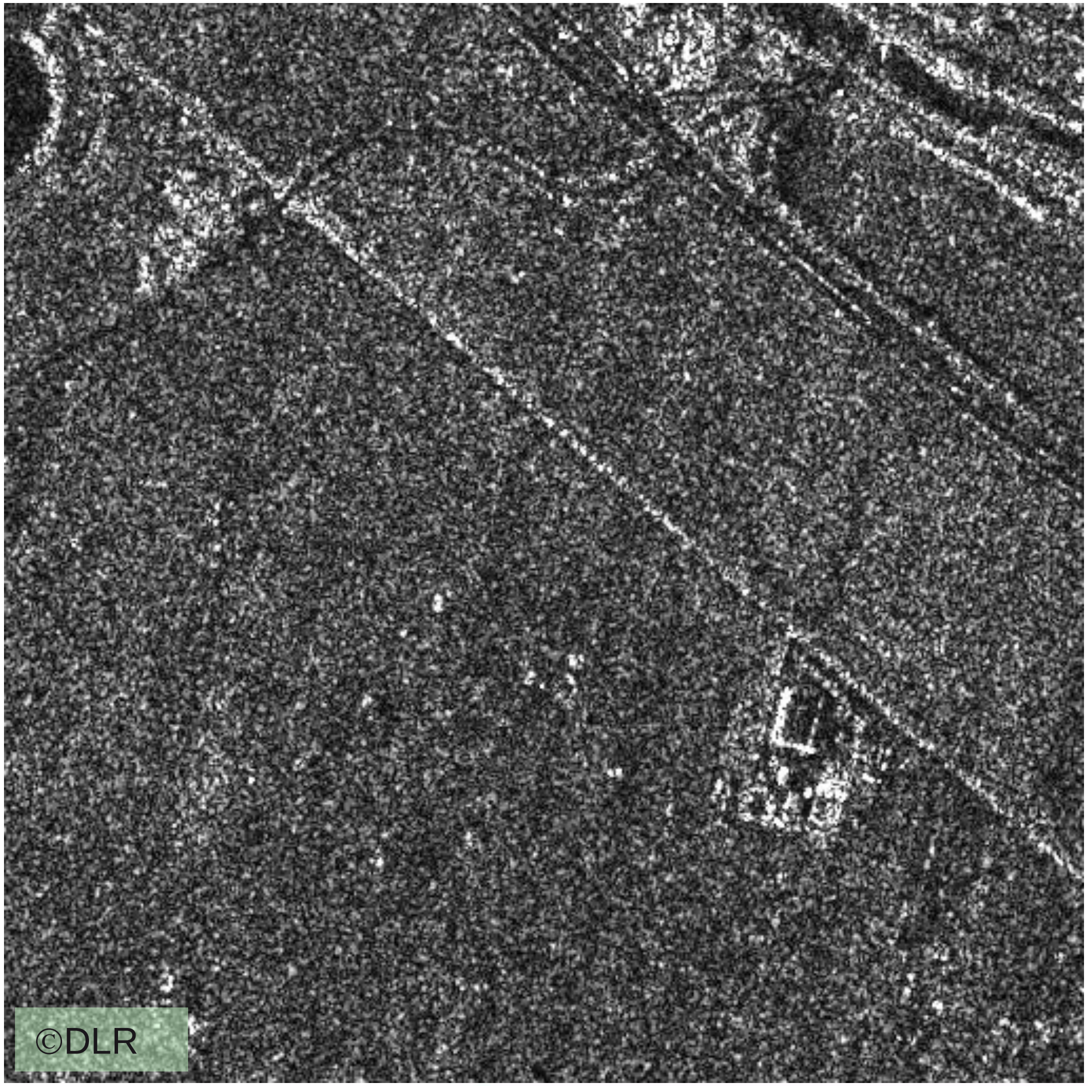
$$I^{MT} = \frac{1}{N} \sum_{i=1}^{N} I_{t_i}$$



Original TerraSAR-X image



Video of temporal multi-looking



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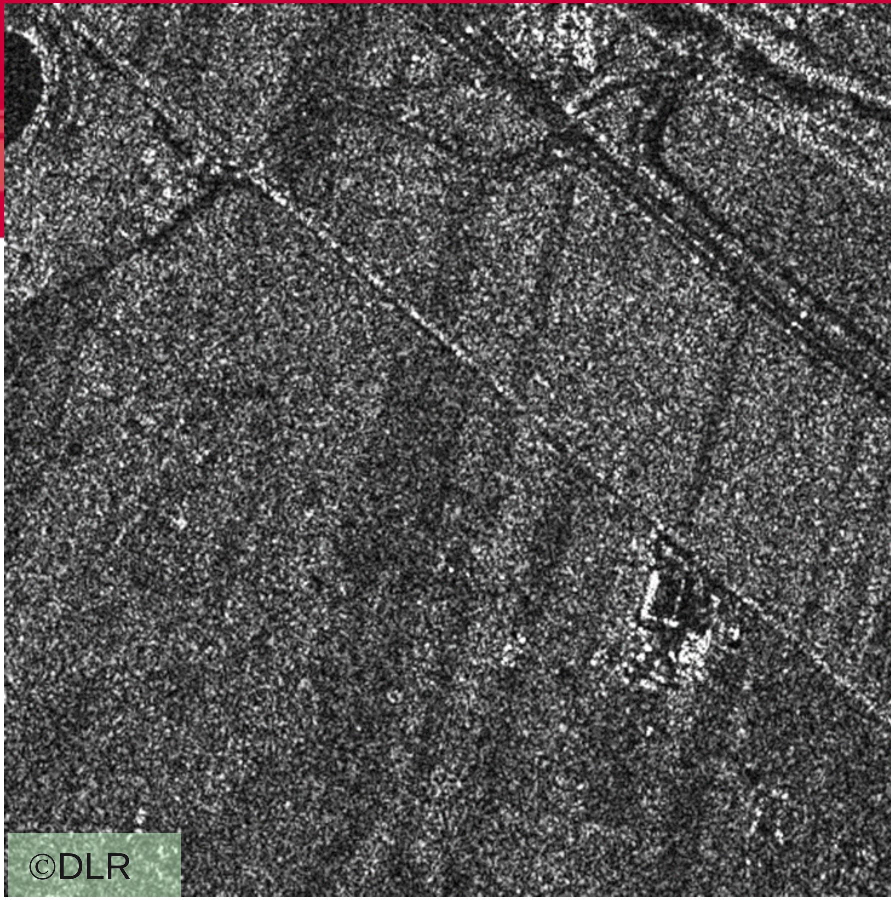
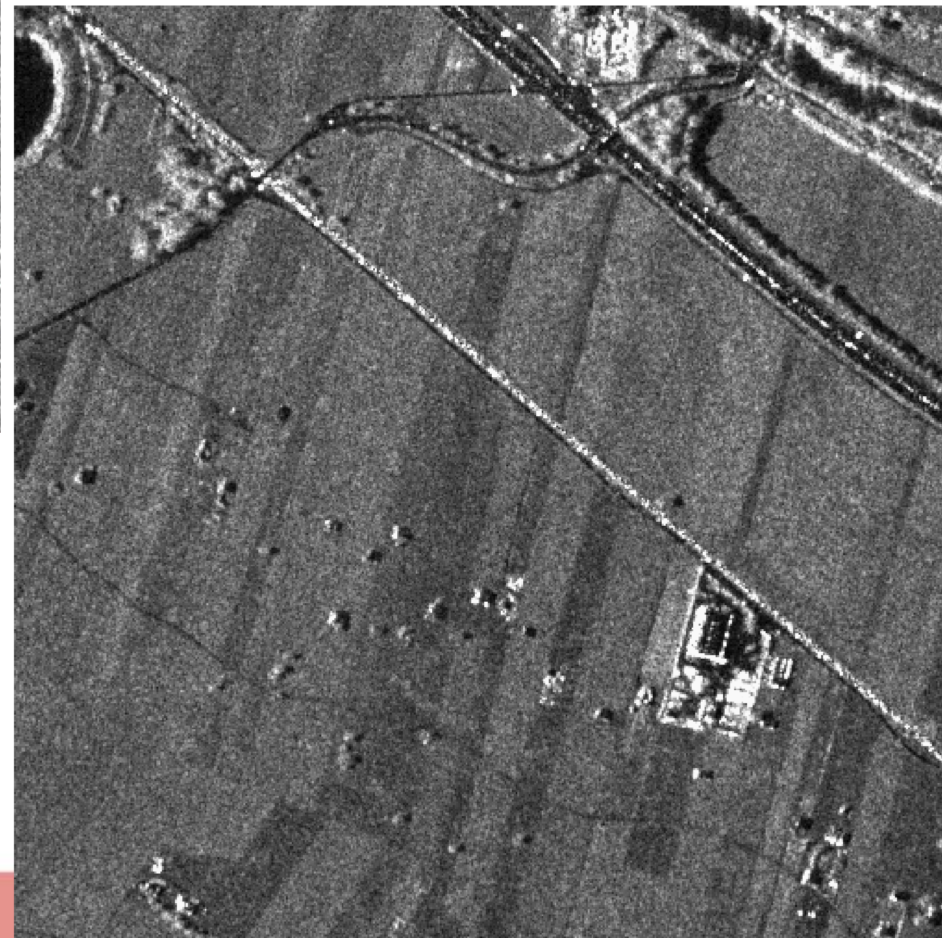


Temporal average of 26 TSX images

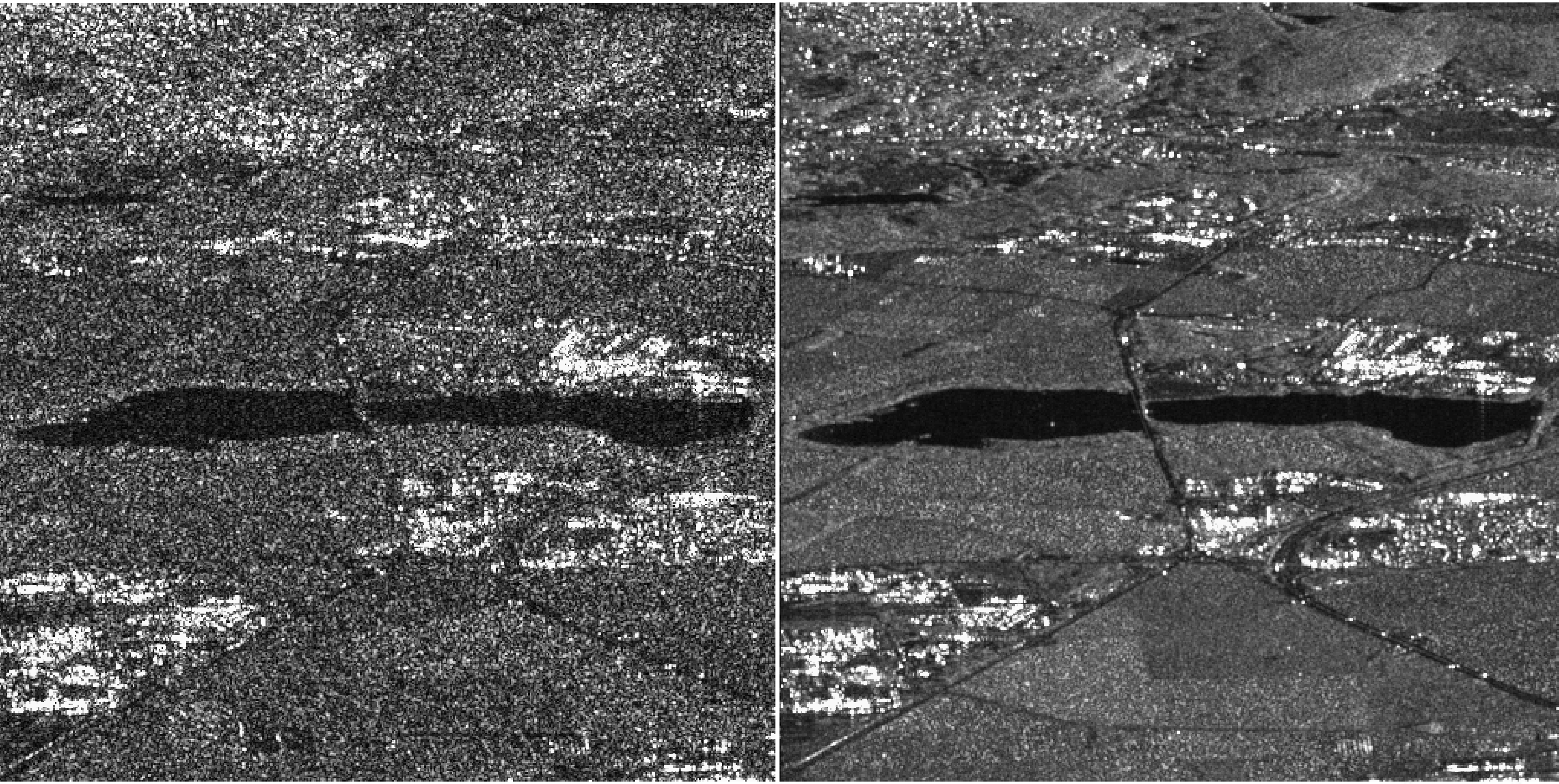


Very efficient
Very simple
Only for **stable** areas

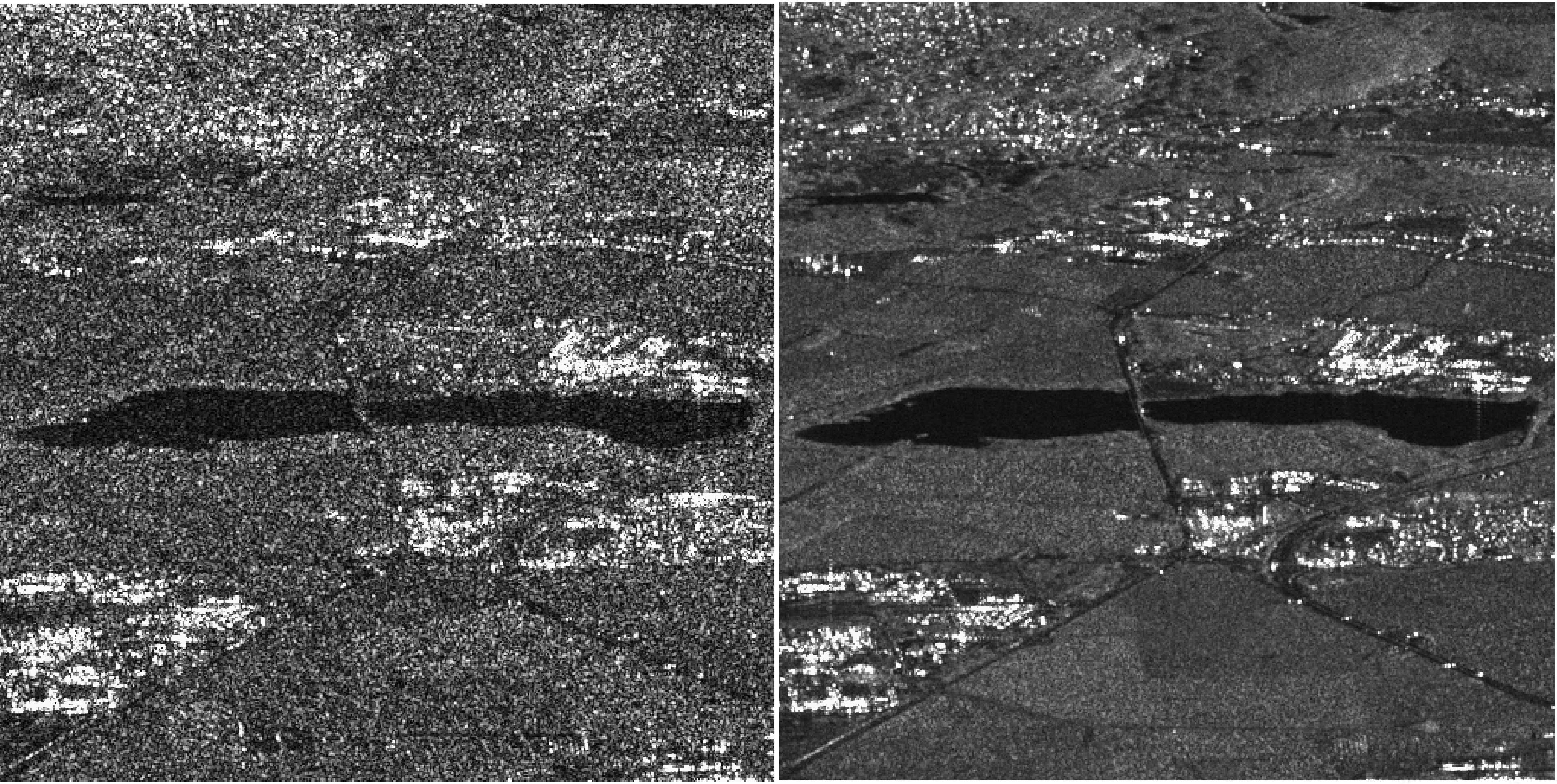
TerraSAR-X
DLR project
LAN 176

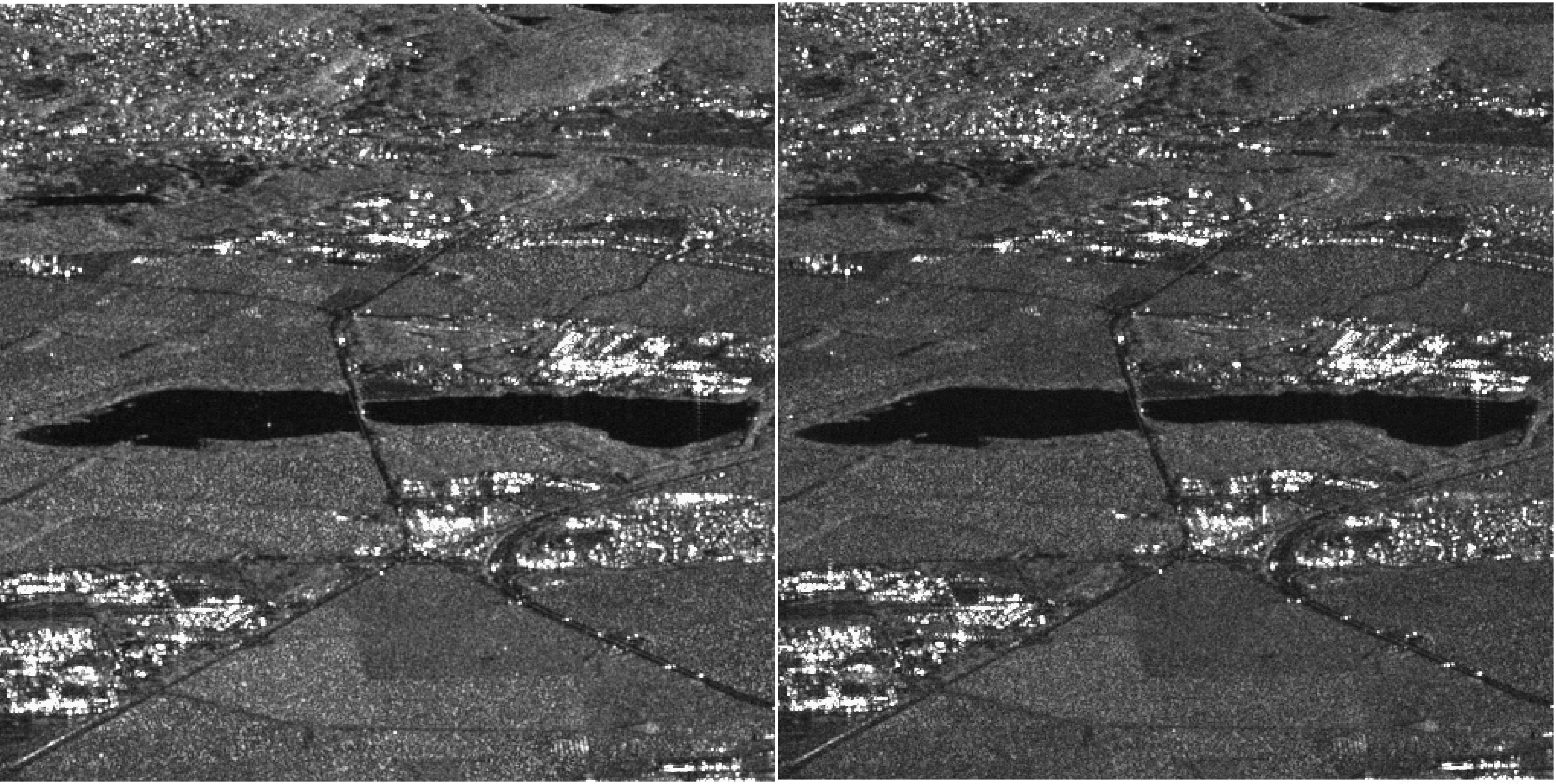
Terrasar-X SpotLight 2007 (1m)
Temporal multi-looking (26 images)

Arithmetic mean



Geometric mean





Multi-temporal filtering

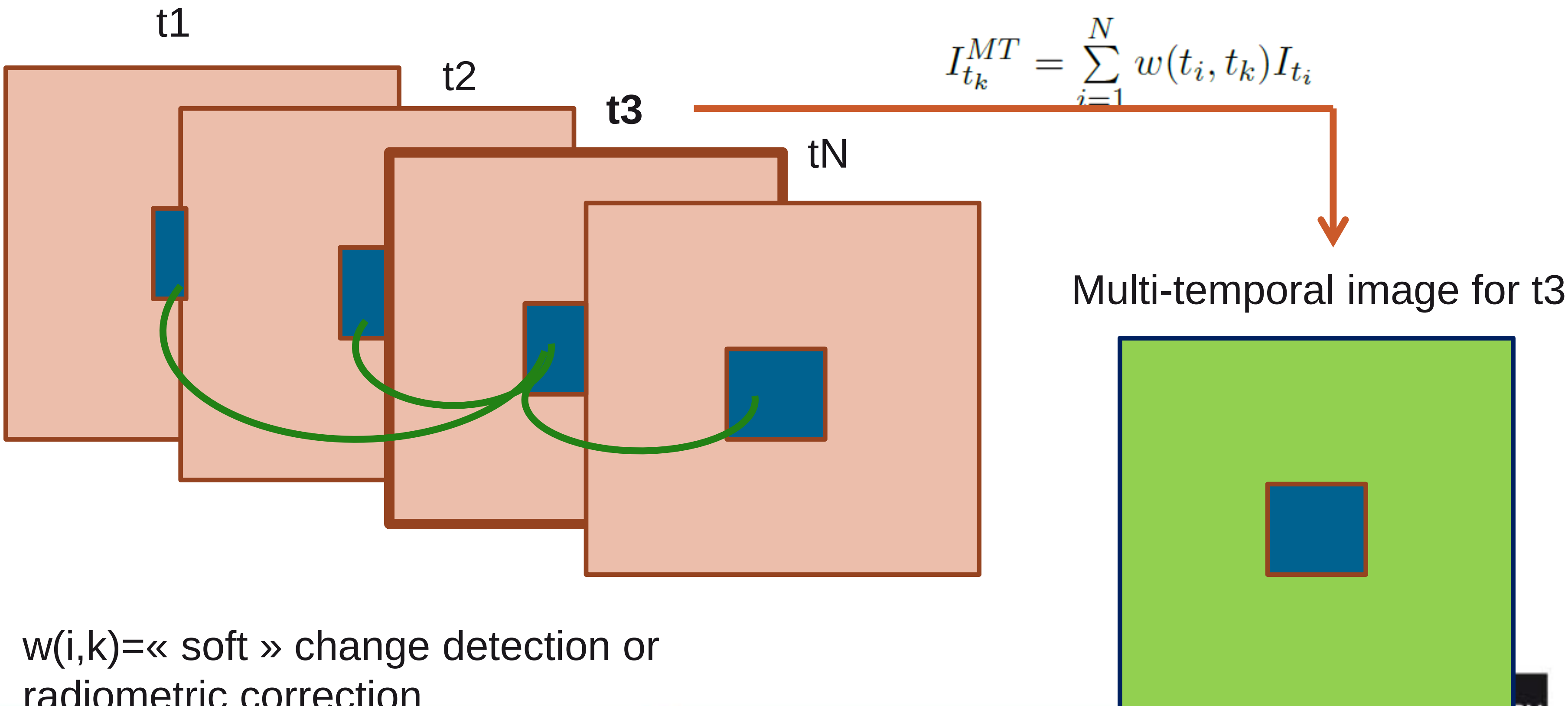
- **Objective: speckle reduction**
  - Simplest way: just temporally average images !
  - Variance reduction (divided by N)

$$I^{MT} = \frac{1}{N}\sum_{i=1}^{N} I_{t_i}$$

  - Limits :
    - *Stable* areas only
    - Maximal improvement for *decorrelated* samples (not the case when spectrum overlap –interferometric configuration)
  - In practice :
    - Combination with weights to take into account **changes:** filter each image separately (preserve new information)
    - Could be combined with **spatial information**

Multi-temporal filtering

- **Temporal regularization: weighted average**
  - One multi-temporal image for each date
  - Temporal weights depending on the similarity



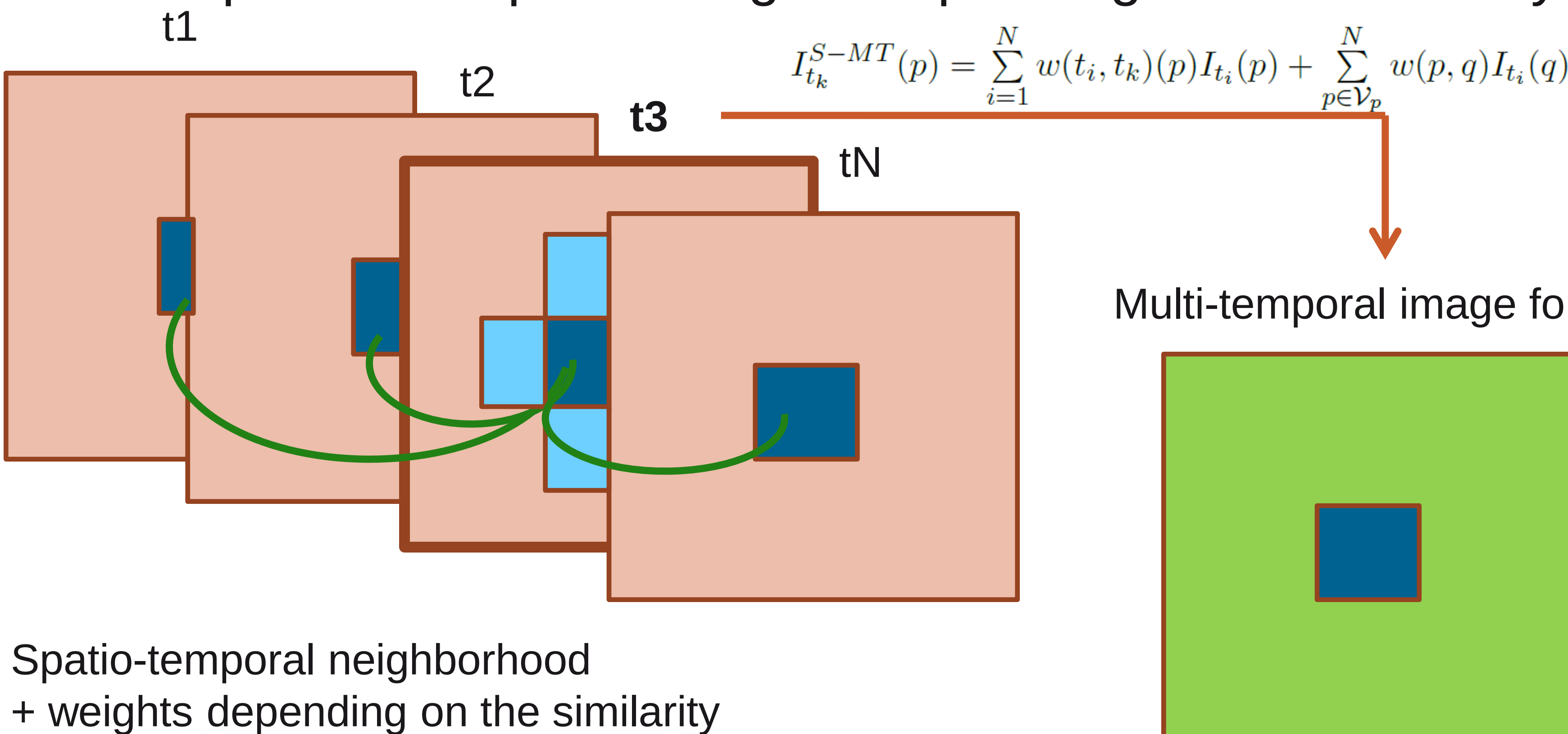
w(i,k)=« soft » change detection or radiometric correction

[Quegan, 2001

Multi-temporal filtering

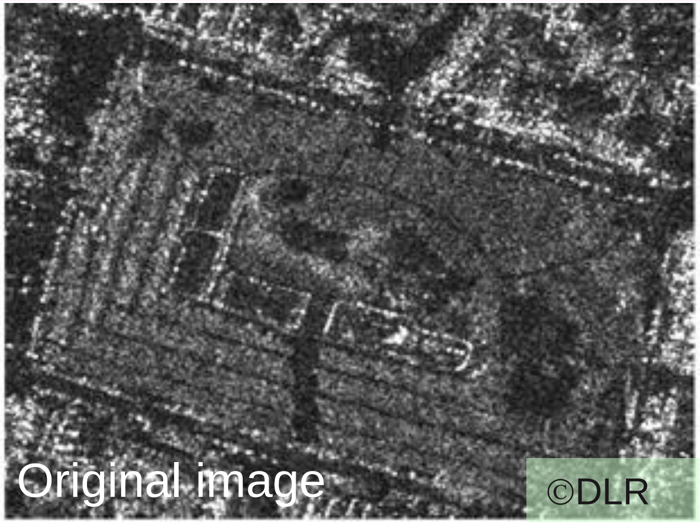
- **Spatio-temporal regularization: weighted average**
  - One multi-temporal image for each date
  - Temporal and spatial weights depending on the similarity

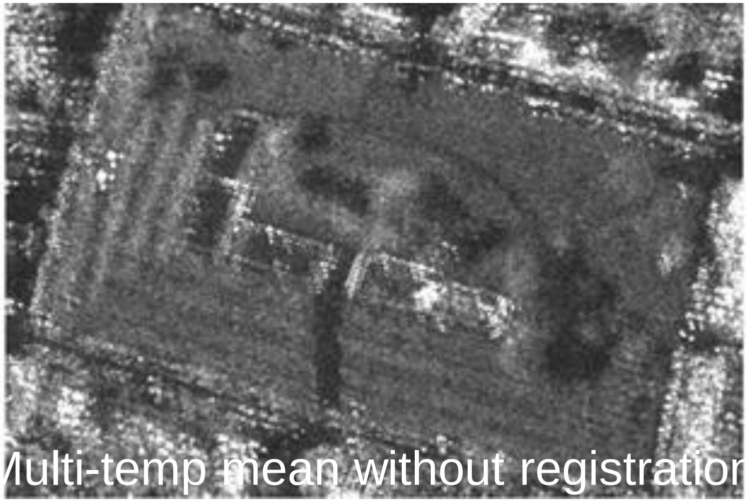
$$I_{t_k}^{S-MT}(p) = \sum_{i=1}^{N} w(t_i, t_k)(p) I_{t_i}(p) + \sum_{p \in \mathcal{V}_p}^{N} w(p,q) I_{t_i}(q)$$



Spatio-temporal neighborhood
+ weights depending on the similarity

Spatio-temporal filtering (6 TSX images)

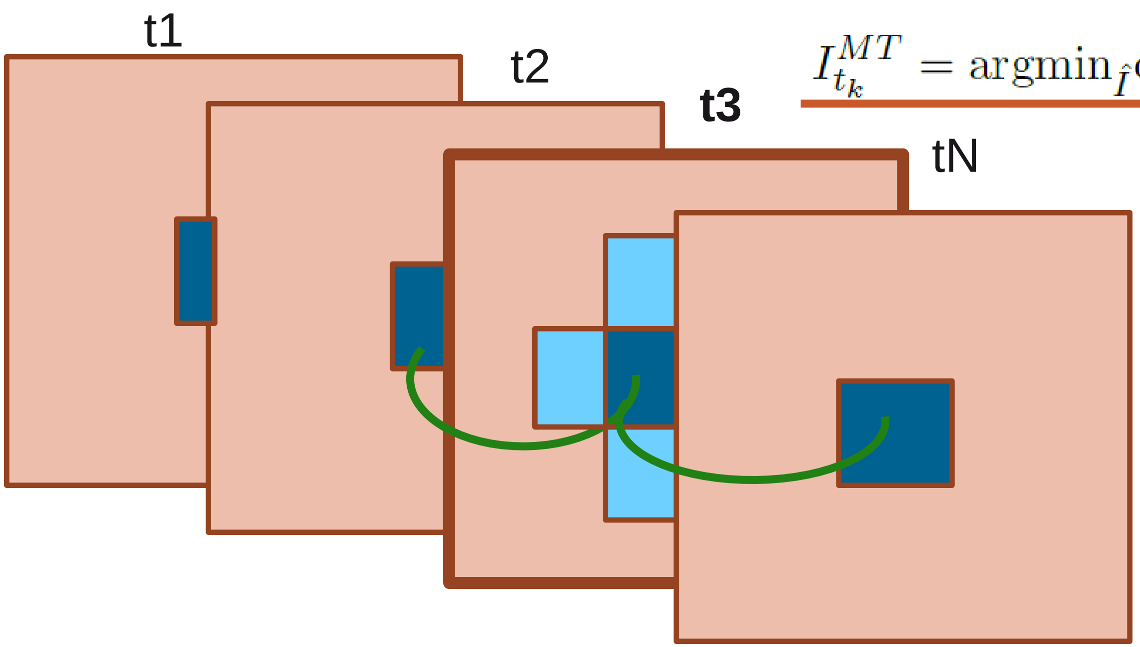


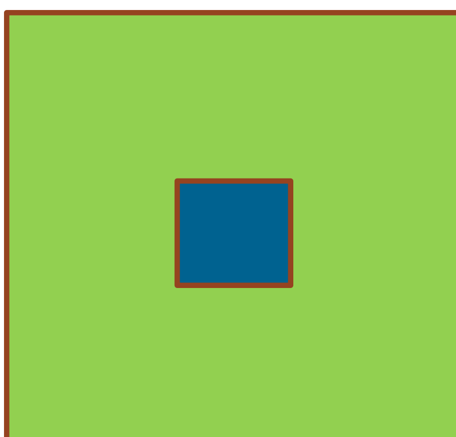


[Su et al. 2014]

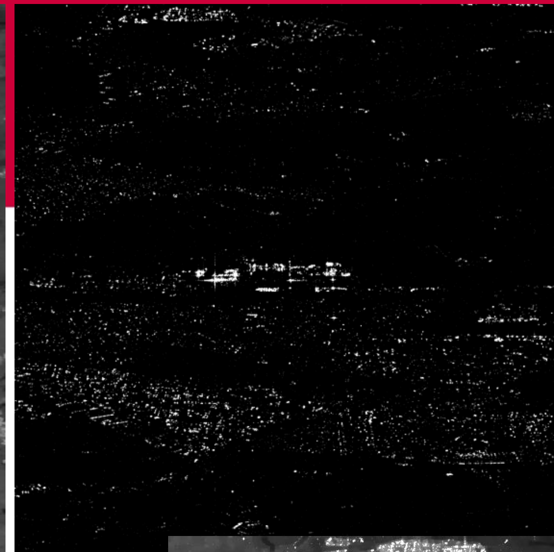
Multi-temporal filtering (markovian)

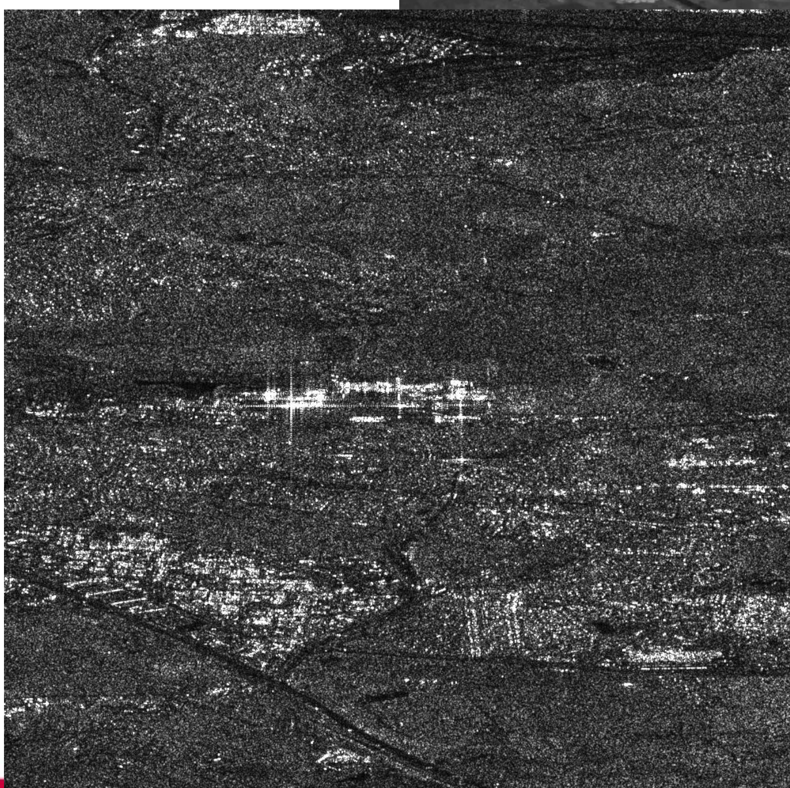
- **Spatio-temporal regularization**
  - Spatio-temporal neighborhood
  - Data term + (weighted) regularization





Could also be done for *classification*





[Lobry et al. 2016]

- **Extraction of multi-temporal behaviour in a serie:**
  - Temporal patterns extraction (ex: seasonal behaviour)
  - Change classification (kind of changes)

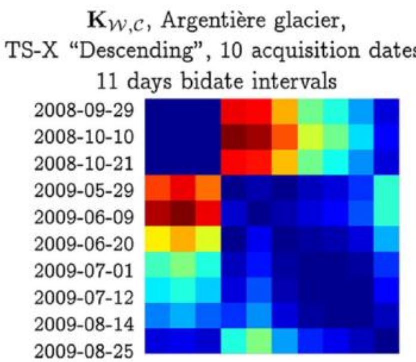
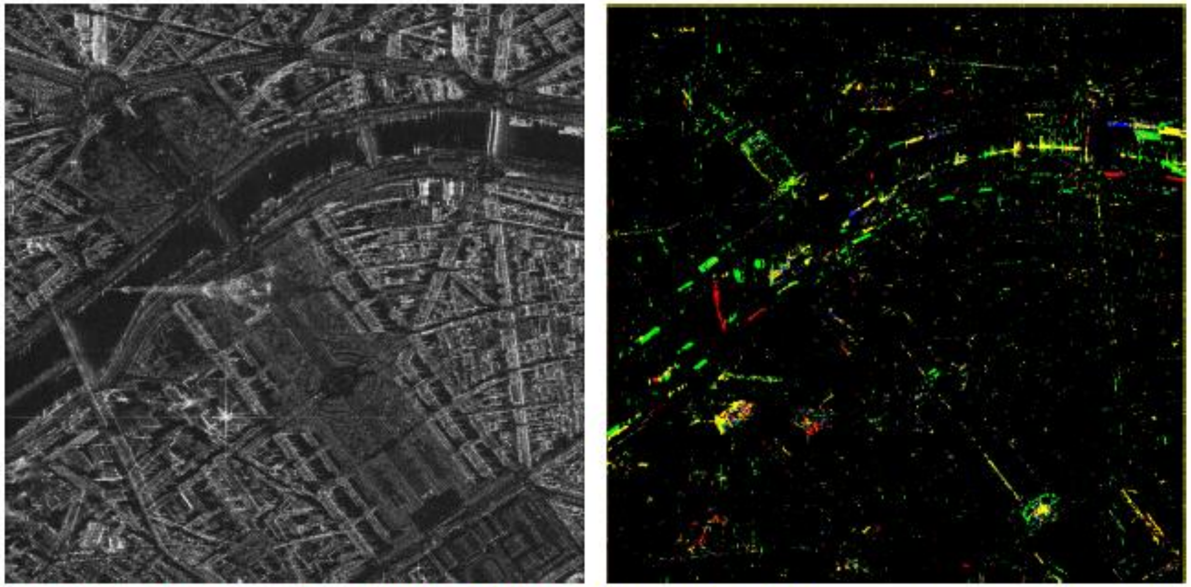


Fig. 7. MDDM $\mathbf{K}_{\mathcal{W},\mathcal{C}}$ for a sequence of TS-X images acquired over Argentière glacier in descending orbit. Changes are abrupt (the first row of the KL MDDM has a step located at the acquisition date 4 whereas the second diagonal has a unique outlier located at date 4) and progressive (decay of semi-row sequences after acquisition date 4). Images are with size 3072 × 4864.

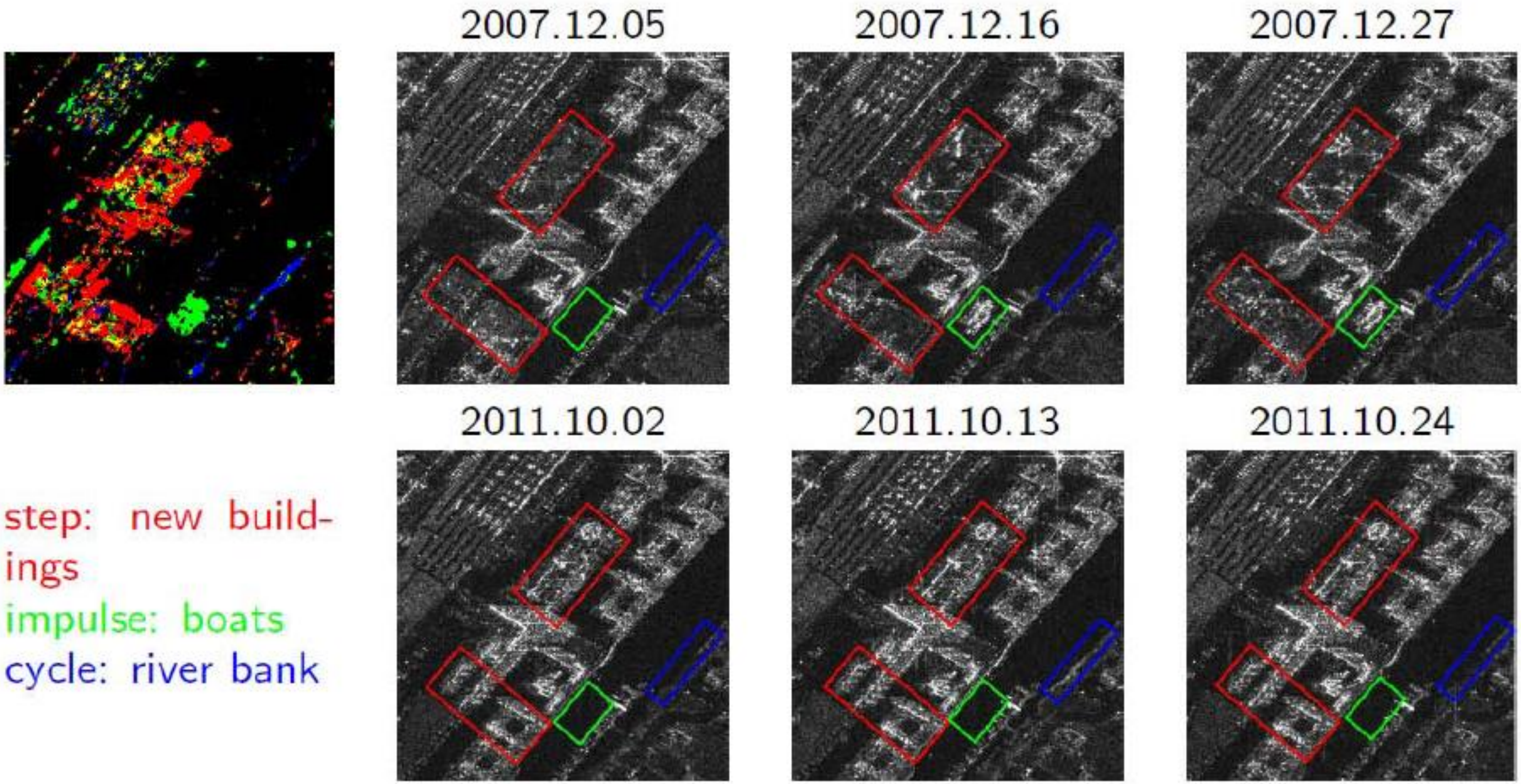
Multi-date divergence matrix [Atto et al. 2013]



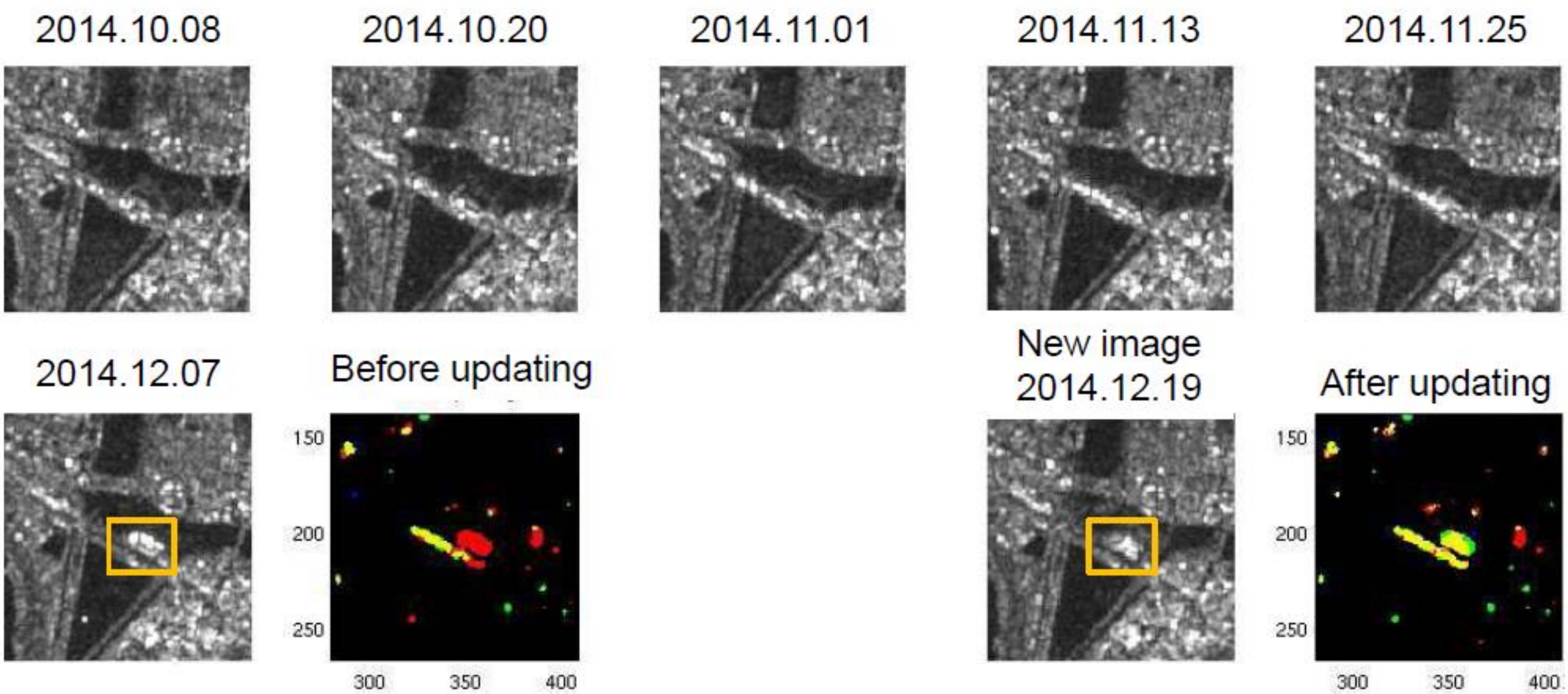
red: step change, green: impulse change, blue: cycle change, yellow: complex change

NORCAMA likelihood ratio change matrix clustering [Su et al. 2015]

- San-Francisco data set



NORCAMA likelihood ratio change matrix clustering
[Su et al. 2015]

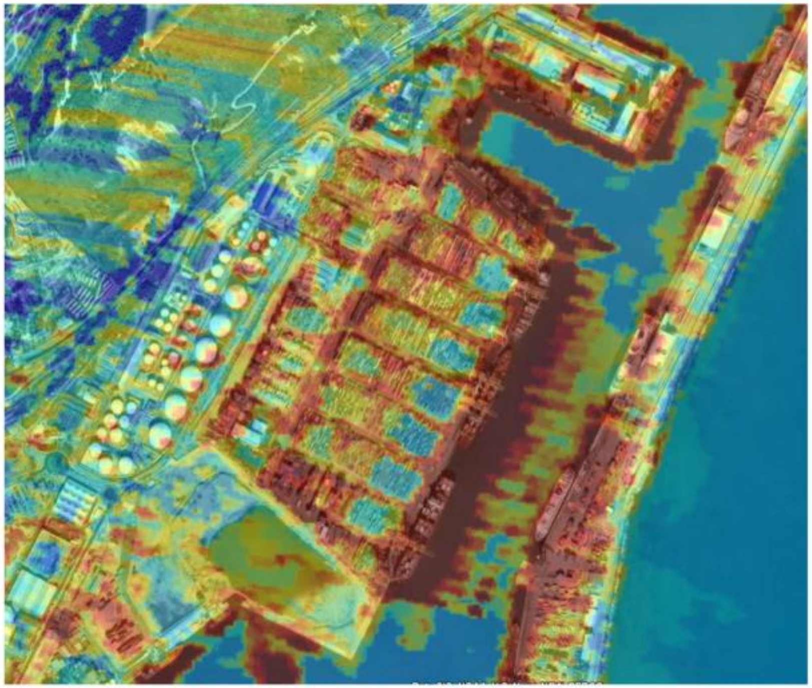


Red: step; Green: impulse; Blue: cycle; Yellow: complex

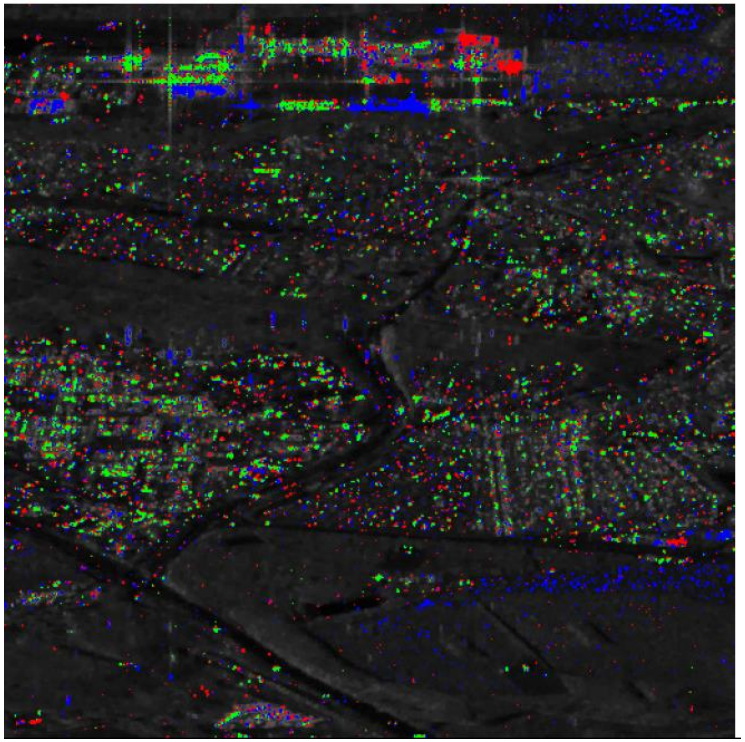
[Su et al. 2015]

3. Multi-temporal information extraction

- **Extraction of multi-temporal behaviour in a serie:**
  - Temporal patterns extraction (ex: seasonal behaviour)
  - Change classification (kind of changes)



Temporal PolSAR BTP
[Alonso-Gonzales et al. 2014]



Multi-temporal change detection by hierarchical hypothesis testing [Lobry et al. 2017]

Overview

- Data and pre-processing

- Processing and applications for multi-temporal amplitude data

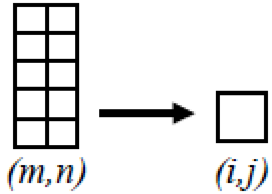
- Processing and applications for multi-temporal interferometric data

SAR interferometric data

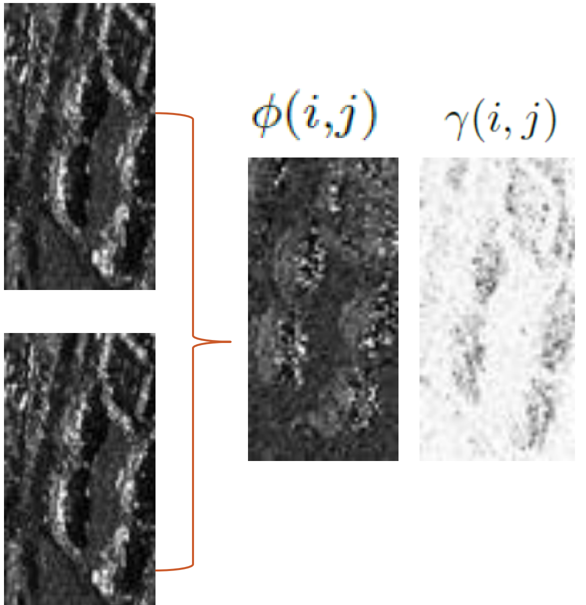
Interferometry:

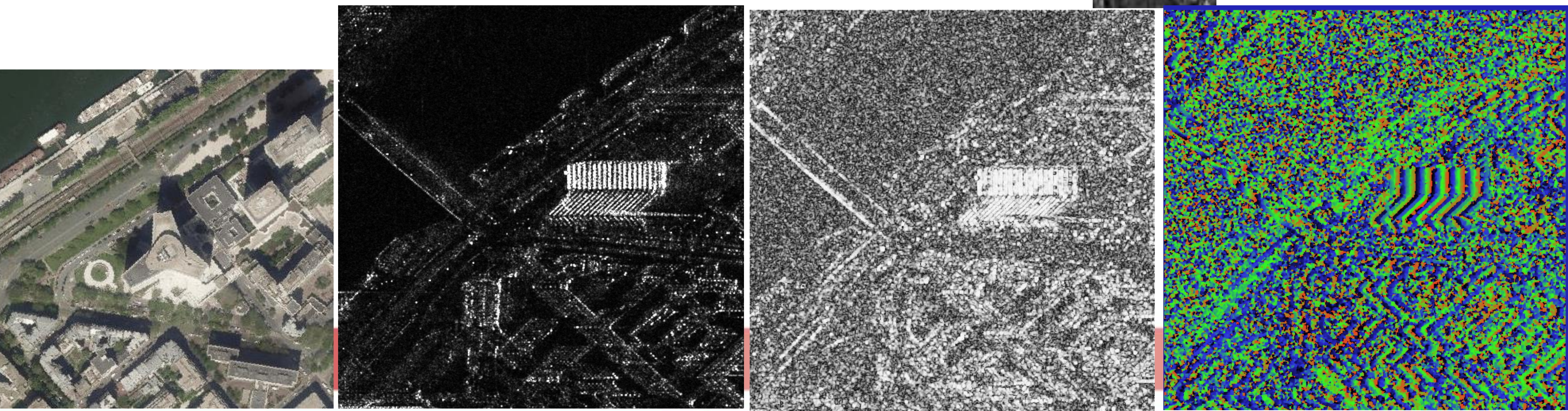
$$z_1(m,n) = A_1(m,n)e^{i\phi_1(m,n)}$$

$$z_2(m,n) = A_2(m,n)e^{i\phi_2(m,n)}$$



$$\gamma(i,j)e^{i\phi(i,j)} = \frac{\sum_{(m,n)} z_1(m,n) z_2^*(m,n)}{\sqrt{\sum_{(m,n)} |z_1(m,n)|^2}\sqrt{\sum_{(m,n)} |z_2(m,n)|^2}}$$



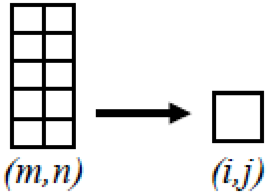


SAR interferometric data

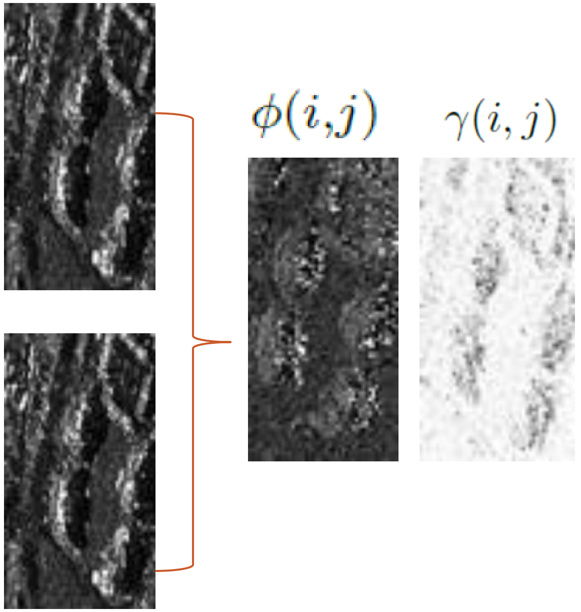
Interferometry:

$$z_1(m,n) = A_1(m,n)e^{i\phi_1(m,n)}$$

$$z_2(m,n) = A_2(m,n)e^{i\phi_2(m,n)}$$



$$\gamma(i,j)e^{i\phi(i,j)} = \frac{\sum_{(m,n)} z_1(m,n) z_2^*(m,n)}{\sqrt{\sum_{(m,n)} |z_1(m,n)|^2}\sqrt{\sum_{(m,n)} |z_2(m,n)|^2}}$$

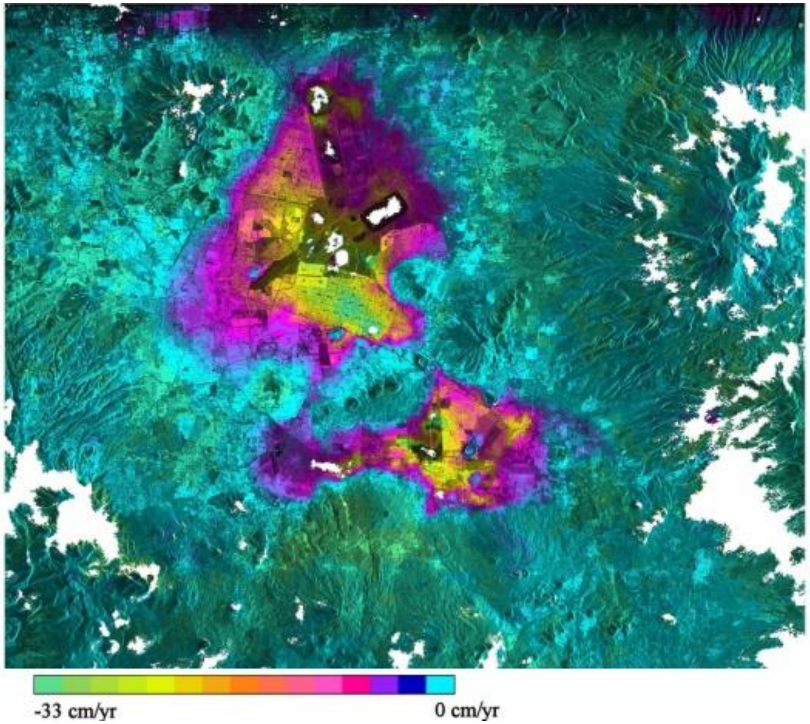


Multi-temporal InSAR:

- Topography
- Displacement (D-InSAR)
- Perturbations:
  - Phase decorrelation noise
  - Systemic errors (atmosphere, orbit,…)

Multi-temporal SAR interferometric data

- **Multi-temporal InSAR objectives:**
  - Uncertainty reduction
    - Reduction of phase decorrelation noise
    - Detection and correction of systemic errors (atmosphere, orbit,…)
  - Small displacement measurements (D-InSAR)
    - Ground deformation model
    - Assimilation methods



[P. Lopez-Quiroz et al. 2009]
[Y. Yan et al. 2012]

Multi-temporal SAR interferometric data

- **Point target analysis**
  - Exploitation of highly stable points

    limited temporal and geometric decorrelation

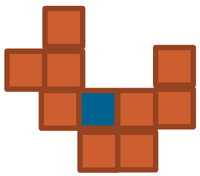
    (corners –man-made structures-, rocks,…)
  - Permanent scatterers (PS) approaches
    - Exploitation of the whole set of interferograms
    - Inversion constrained by a deformation model

- **Distributed targets**
  - Small Baseline (SBAS approaches)
    - Selection of interferograms with sufficient correlation (limited temporal and geometric decorrelation)
    - Temporal inversion

Multi-temporal interferometric filtering

Distributed targets:

- Improvement of spatial averaging for phase and coherence computation by sample selection



$$\gamma(i,j)e^{i\phi(i,j)} = \frac{\sum\limits_{(m,n)} z_1(m,n)z_2^*(m,n)}{\sqrt{\sum\limits_{(m,n)} |z_1(m,n)|^2}\sqrt{\sum\limits_{(m,n)} |z_2(m,n)|^2}}$$

- *Space adaptive filtering*: DespecKS algorithm (Ferretti et al. 2011)

Selection of connected pixels having a similar temporal behaviour

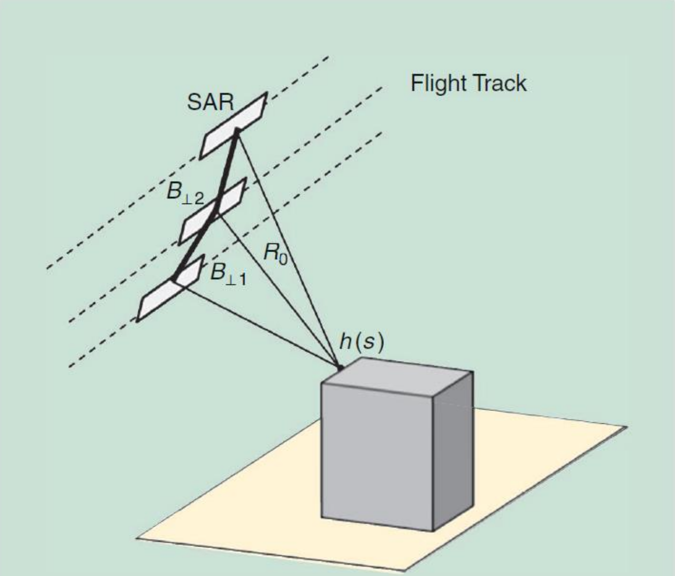
(test on temporal amplitude distribution)

- *Patch-based approaches:*

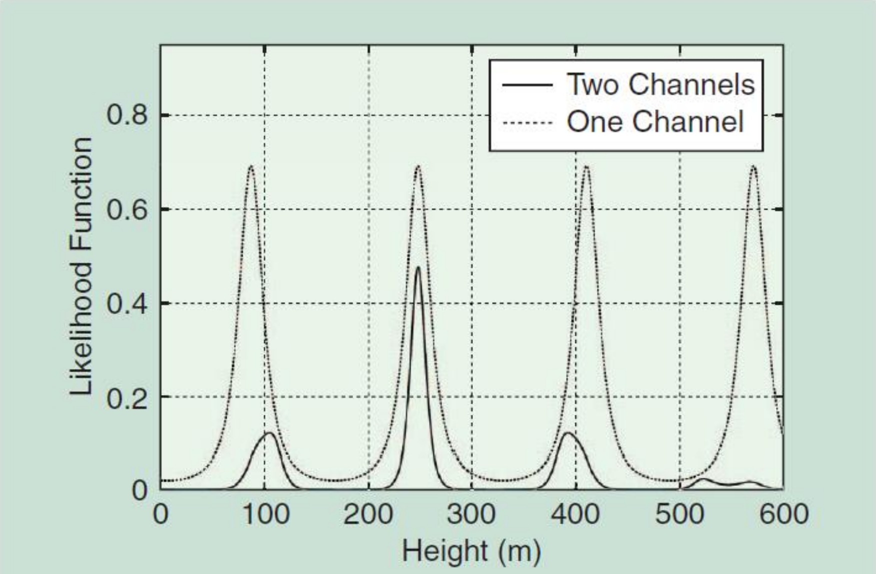
Selection of similar temporal cubes

+ regularization constraint on the estimated elevation (or movement)

Multi-channel InSAR data



Baselice et al., IEEE SP 2014



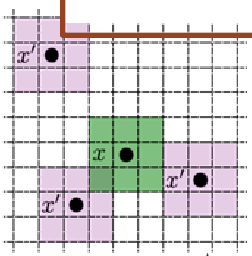
Baselice et al., IEEE SP 2014

$$\mathbf{\Sigma} = R \begin{pmatrix} 1 & \gamma_{1,2}\exp(j\psi_{1,2}) & \cdots & \gamma_{1,D}\exp(j\psi_{1,D}) \\ \gamma_{1,2}\exp(-j\psi_{1,2}) & 1 & & \gamma_{2,D}\exp(j\psi_{2,D}) \\ \vdots & & \ddots & \vdots \\ \gamma_{1,D}\exp(-j\psi_{1,D}) & \gamma_{2,D}\exp(-j\psi_{2,D}) & & 1 \end{pmatrix}.$$

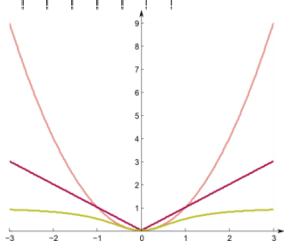
Image processing methods

- **Formulation of a global optimization problem:**

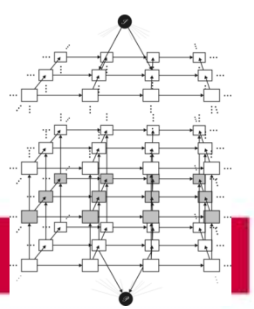
$$\hat{\boldsymbol{h}}^{(\text{R-NL})} = \arg\min_{\boldsymbol{h}} \; -\sum_i \lambda_i \log\det(\boldsymbol{\Sigma}_i(h_i)) + \lambda_i \mathrm{tr}(\boldsymbol{\Sigma}_i(h_i)^{-1}\boldsymbol{C}_i) \; + \sum_{(i,j)} |h_i - h_j|$$



- **Likelihood term: exploiting image redundancy**
  - NL-SAR based regularization



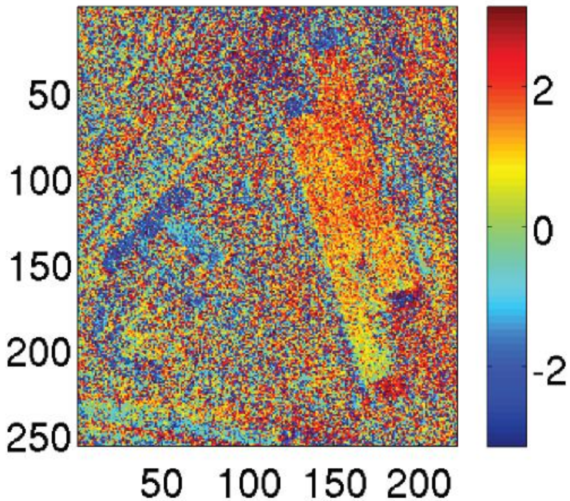
- **Prior term: exploiting elevation regularity**
  - Enforce smooth reconstruction with discontinuities



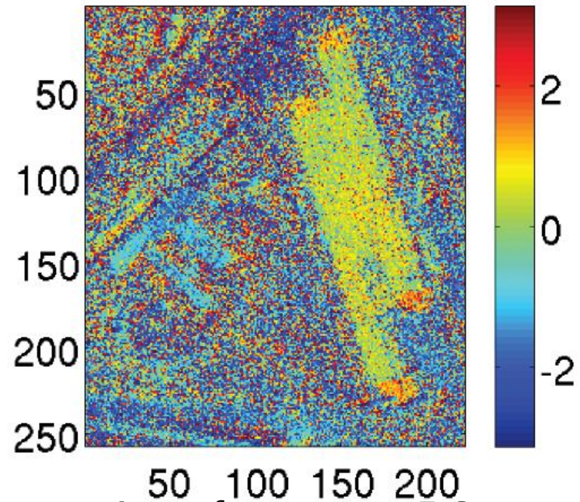
- **h optimization: graph-cut based algorithm**

[Ferraioli et al., 17]

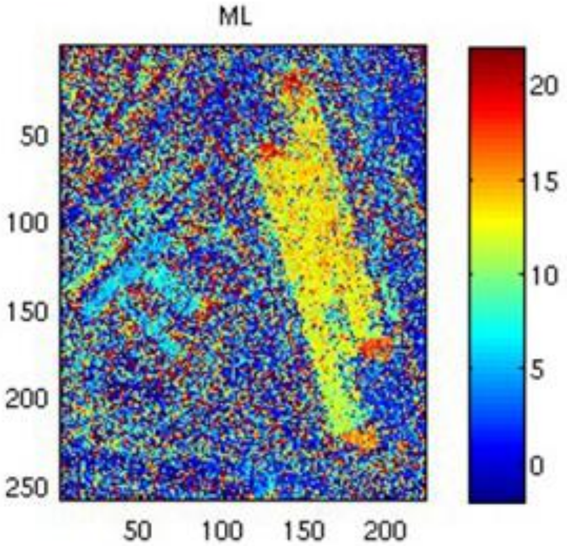
Multi-baseline InSAR



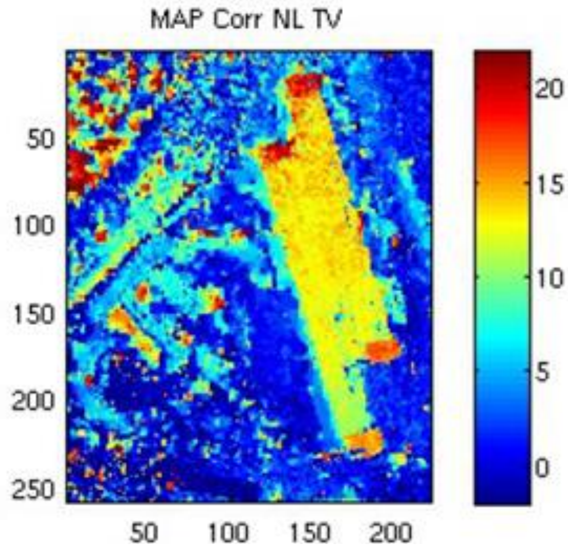
Interferogram B1



Interferogram B2



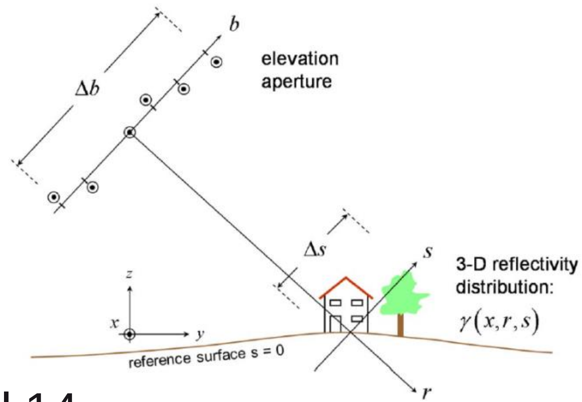
Without regularization

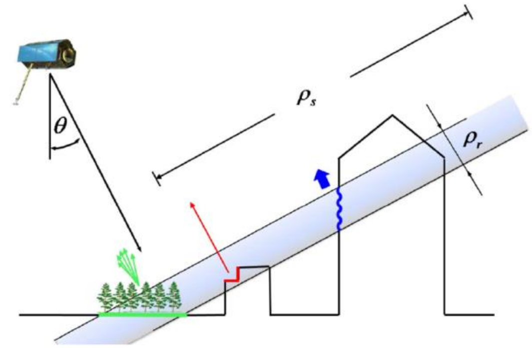


With regularization

PARISAR
Non-local + total variation regularization
(3 CSK data)
[Deledalle et al. 2015]
[Ferraioli et al. 2017]

SAR tomography

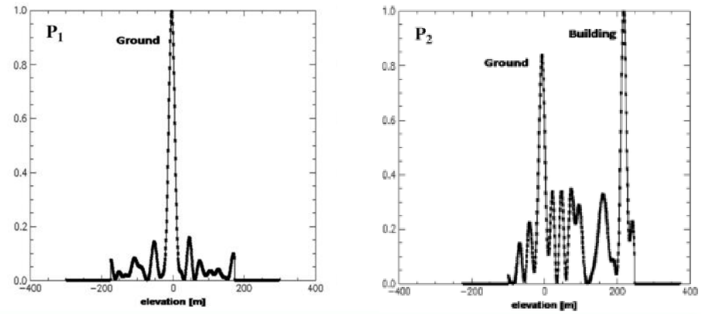




Zhu et al.14

$$g_n = \int_{\Delta s} \gamma(s) \exp(-j2\pi\xi_n s)\, ds, \qquad n = 1, \ldots, N$$

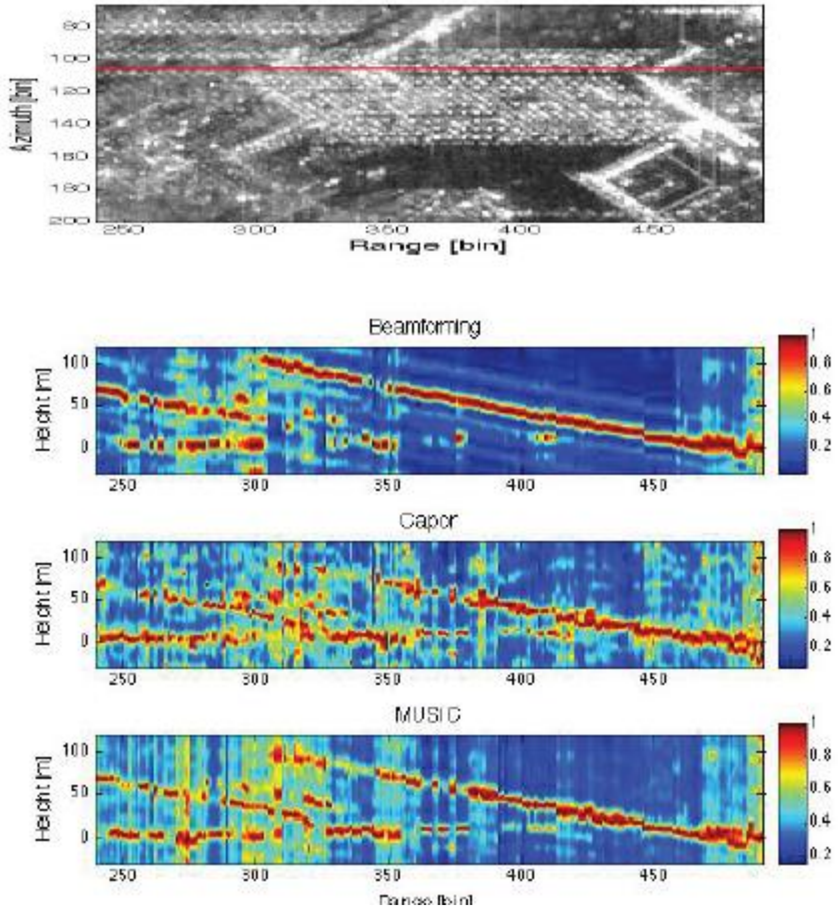
$$\mathbf{g} = \mathbf{R}\boldsymbol{\gamma}$$

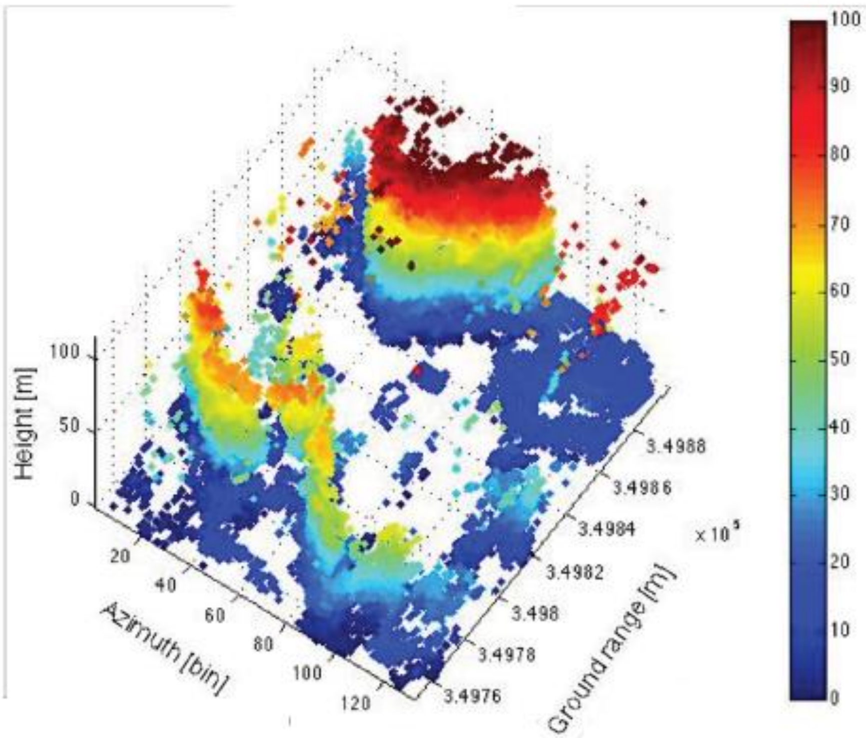


Inversion methods:

- Spectral analysis
- Sparse approaches

SAR tomography





[Porfiri et al., Multitemp 2015]

Conclusion and perspectives

- **Multi-temporal SAR imagery:**
  - Many available methods for specific configurations (amplitude data, polarimetric data, differential interferometry,…)

- **Challenges:**
  - Benchmarking ?
  - « big data » processing (updating)
  - Full SAR exploitation (asc/desc, multi-angles)
  - Combination of heterogeneous sensors (multi-SAR, multi-sensors)
  - User / application oriented platforms

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