Processing Polarimetric SAR time series over urban areas with Binary Partition Trees

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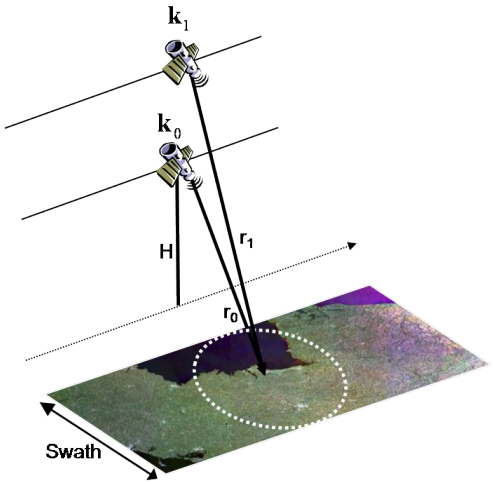
Multidimensional SAR

SAR are active systems acquiring images of the scene reflectivity at microwave frequencies

Target vector

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

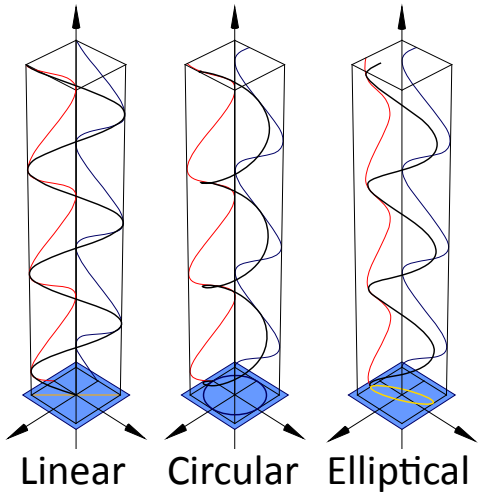


- SAR Polarimetry: distinct polarization states are employed for transmitted and received waves.

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

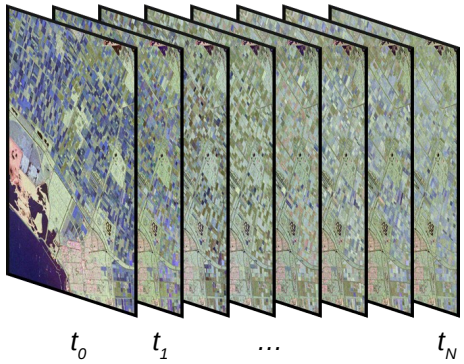
$$\boldsymbol{k} = [S_{hh}, \sqrt{2}S_{hv}, S_{vv}]^T$$

⇨ Information related to target structure and properties



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

⇨ Information related to the scene evolution



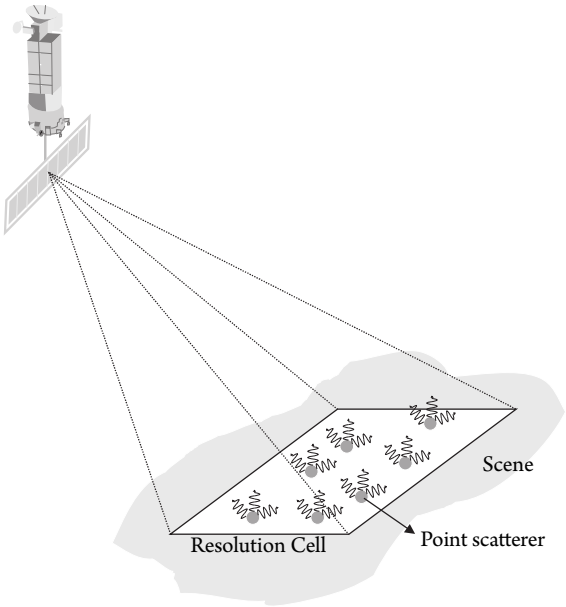
SAR Advantages:

- High spatial resolution
- All-weather imaging sensors
- Sensitive to target structure & properties

Some types of Multidimensional SAR data

Multidimensional SAR – Speckle

Typically in SAR data the spatial resolution is larger than the wavelength



The obtained response is the coherent combination of all the individual targets

⇒ **Speckle Noise** { It has to be characterized statistically

Gaussian hypothesis: the target is completely characterized by the second order moment

$$\boldsymbol{Z} = \langle \boldsymbol{k}\,\boldsymbol{k}^{H} \rangle = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{k}\,\boldsymbol{k}^{H} \qquad p_{\boldsymbol{Z}}(\boldsymbol{Z}) = \frac{N^{QN}\,|\boldsymbol{Z}|^{N-Q}\exp\left(-N\,tr\left(\boldsymbol{C}^{-1}\boldsymbol{Z}\right)\right)}{K(N,Q)\,|\boldsymbol{C}|^{N}}$$

Distributed Scattering Hypothesis

The estimated covariance matrix $\boldsymbol{Z}$ characterizes the target but it is only valid if estimated over locally stationary areas, but real data is strongly heterogeneous!

Some adaptation to the multidimensional scene morphology is needed to obtain a good target response estimation

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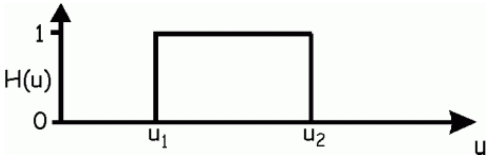
Multidimensional SAR – Speckle filtering

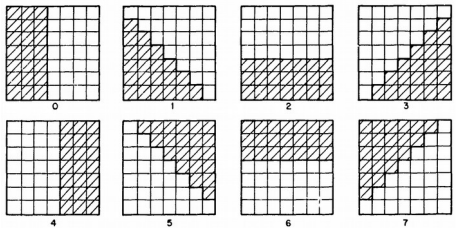
Some speckle filtering techniques have evolved to adapt to the scene morphology

Adaptation to image morphology

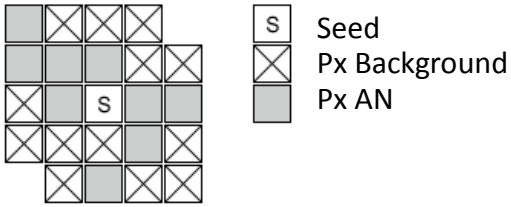
- Multilook: Linear filter with rectangular averaging window. Corresponds to the MLE. Spatial resolution loss due to non stationarity of the data.



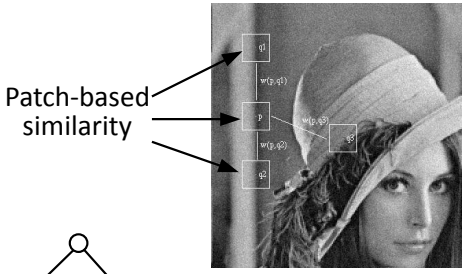
- (1999) Lee adaptive filter: Non-linear filter. The averaging window is selected from a set of predefined directional windows based on power information.



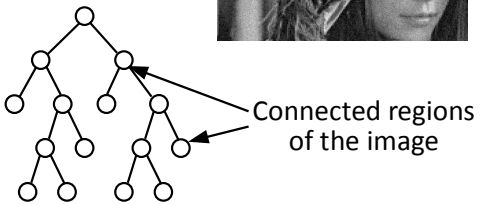
- (2006) IDAN (Intensity-Driven Adaptive Neighborhood): An adaptive averaging window is built for each pixel based on the region growing technique considering power information.



- (2010) NL-means (Non-local means): A weighted average is performed employing patch-based similarities. It may employ the full polarimetric information.



- (2010) BPT (Binary Partition Tree): Fully region-based. The image is segmented into homogeneous regions based on fully polarimetric information



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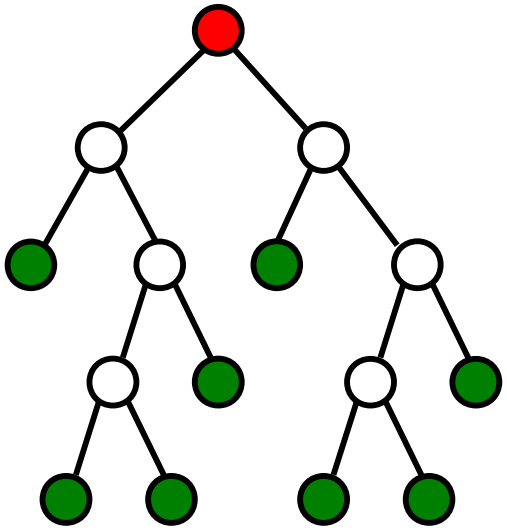
Binary Partition Tree

BPT is a region-based and multi-scale data representation



- Each node of the tree represents a connected region of the data, independently of its dimensionality

⇒ **Region model**

- Hierarchical structure: each node represents the region generated by merging of its two child nodes
  - The **leaves** of the tree represent single pixels
  - The **root node** represents the whole dataset

- Between the leaves and the root there are a wide number of nodes representing regions of the image having similar values at different detail levels

The BPT may be considered as a data abstraction

Due to its multi-scale nature, the BPT contains a lot of useful information about the image structure that may be exploited for different applications

Motivation

Salembier, P. & Garrido, L. "Binary partition tree as an efficient representation for image processing, segmentation, and information retrieval", *IEEE Trans. on Image Processing*, 2000

Alonso-González, A. & López-Martínez, C. & Salembier, P. "Filtering and segmentation of Polarimetric SAR images with Binary Partition Trees", *Proc. IEEE IGARSS*, 2010

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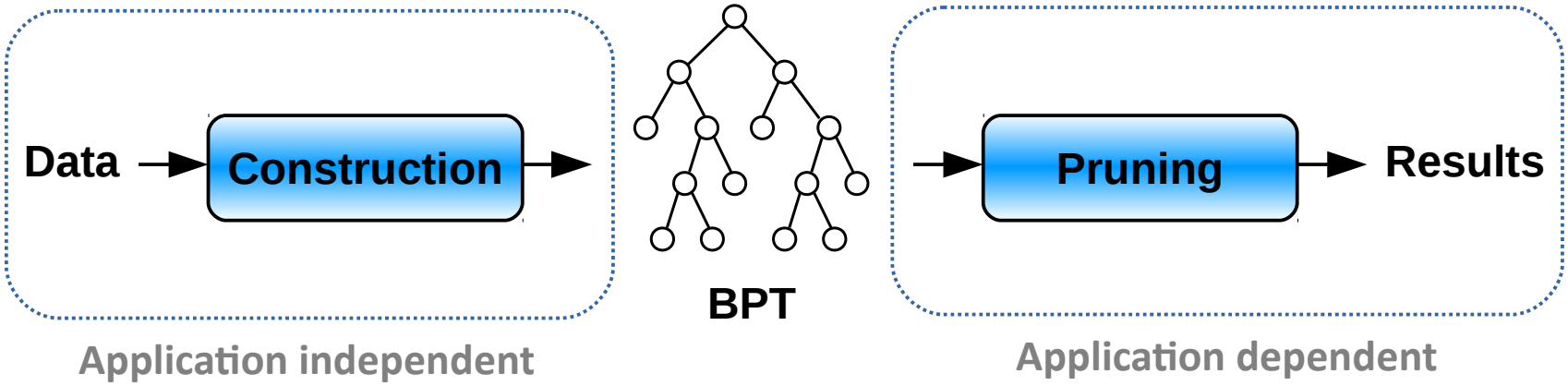
BPT – based processing

The BPT-based processing may be decomposed in two main steps:

- The BPT construction process generates the BPT from the data
- For BPT exploitation a tree pruning process is proposed

  The most *useful* or *interesting* regions for a particular application are selected from the tree



- The BPT construction process may be considered application independent since it only exploits the internal relationships within the data
- The BPT pruning process is application dependent since it searches for interesting regions within the tree for a particular purpose: Speckle filtering, segmentation, change detection, ...

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BPT construction

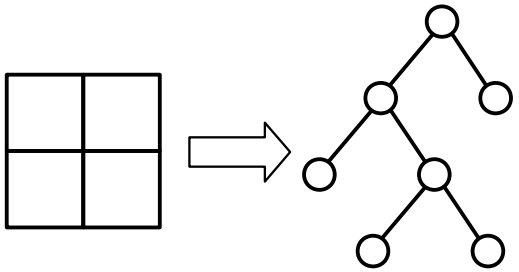
The BPT may be constructed by an iterative algorithm in a bottom-up approach

- Each iteration the two most similar neighboring regions are merged
- Starting from the pixels, the leaves of the tree, to the root node

Region Model: Estimated covariance matrix $\boldsymbol{Z}$ over all the pixels of the region

$$\boldsymbol{Z} = \langle \boldsymbol{k}\,\boldsymbol{k}^{\boldsymbol{H}} \rangle = \frac{1}{N} \sum_{i=1}^{N} \boldsymbol{k}_i \boldsymbol{k}_i^{\boldsymbol{H}}$$

Dissimilarity measure: Evaluates the similarity between two regions. It is a measure in the region model space



The dissimilarity measure is the keystone of the construction process

Different similarity measures have been defined and evaluated:

- Based on the Z pdf (Wishart) or based on its space geometry (Hermitian positive definite matrix cone)
- Employing the whole Z matrix or only the diagonal information, corresponding to the radiometric power information

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Dissimilarity measures

Dissimilarity measures are based in two region features:

- Polarimetric information (3 by 3 covariance matrix)
- Region size information (number of pixels of each region)

Revised Wishart dissimilarity: Based on the Wishart pdf

Full matrix: $$d_{sw}(A,B)=\left(tr\left(\boldsymbol{Z}_A^{-1}\boldsymbol{Z}_B\right)+tr\left(\boldsymbol{Z}_B^{-1}\boldsymbol{Z}_A\right)\right)\cdot\left(n_A+n_B\right)$$

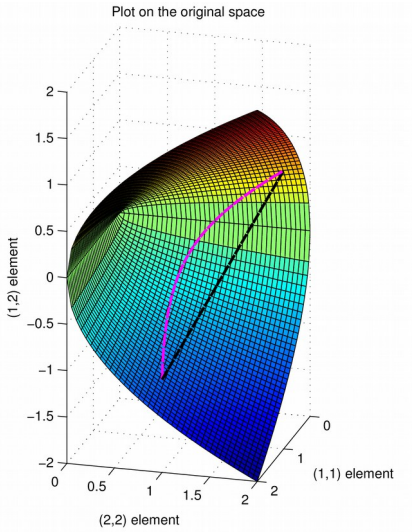
Diagonal: $$d_{dw}(A,B)=\left(\sum_{i=1}^{N}\left(\frac{Z_{A_{ii}}+Z_{B_{ii}}}{Z_{A_{ii}}Z_{B_{ii}}}\right)\right)\cdot\left(n_A+n_B\right)$$

Geodesic dissimilarity: Adapted to the hermitian positive definite matrix cone geometry

Full matrix: $$d_{sg}(A,B)=\left\|\log\left(\boldsymbol{Z}_A^{-1/2}\boldsymbol{Z}_B\boldsymbol{Z}_A^{-1/2}\right)\right\|_F+\ln\left(\frac{2\,n_A n_B}{n_A+n_B}\right)$$

Diagonal: $$d_{dg}(A,B)=\sqrt{\sum_{i=1}^{N}\ln^2\left(\frac{Z_{A_{ii}}}{Z_{B_{ii}}}\right)}+\ln\left(\frac{2\,n_A n_B}{n_A+n_B}\right)$$

$$\|\boldsymbol{A}\|_F=\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N}|a_{ij}|^2}=\sqrt{\mathrm{tr}\left(\boldsymbol{A}^{\boldsymbol{H}}\boldsymbol{A}\right)}=\sqrt{\sum_{i=1}^{N}\lambda_i^2}$$



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Time series – Temporal dimension of the data

The temporal dimension is employed to improve target characterization

- Extended model → include temporal evolution information among the *N* acquisitions

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

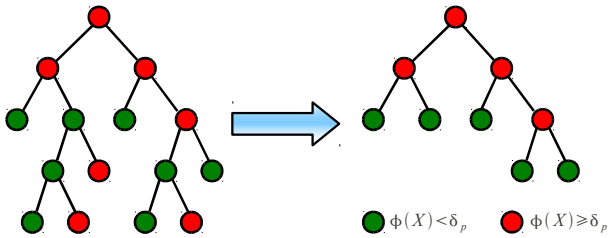
- Dissimilarity measure → extended to take into account all the temporal evolution

$$d_g(A,B) = \sqrt{\sum_{i=1}^{N} \left\| \log\left(\boldsymbol{Z}_{Aii}^{-1/2} \boldsymbol{Z}_{Bii} \boldsymbol{Z}_{Aii}^{-1/2} \right) \right\|_F^2} + \ln\left(\frac{2\, n_A n_B}{n_A + n_B} \right)$$

- A region homogeneity measure is defined for pruning:

$$\Phi_N(X) = \frac{1}{n_X \sum_{j=1}^{N} \left\| \boldsymbol{Z}_{X\,jj} \right\|_F^2} \sum_{i=1}^{n_X} \sum_{j=1}^{N} \left\| \boldsymbol{X}_{jj}^i - \boldsymbol{Z}_{X\,jj} \right\|_F^2$$

May be interpreted as the relative MSE when representing all the pixels of the region *X* by its region model



BPT Pruning for estimation: In a top-down approach, select the first nodes that fulfill

$$\Phi(X) < \delta_p$$

Temporal Analysis

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

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

The temporal stability is evaluated for each BPT region with a similarity measure

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

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

- Measures the average amount of polarimetric change among all the acquisition pairs
- Results uniquely correspond to spatial areas of the scene due to fixed spatial contours

Alonso-González, A. & López-Martínez, C. & Salembier, P. "PolSAR Time Series Processing with Binary Partition Trees", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 52, no. 6, pp. 3553-3567, June 2014

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PolSAR time series – The Barcelona dataset

Space-borne SAR systems have empowered the construction of PolSAR time series datasets, having some acquisitions of the same scene at different times

RADARSAT-2, C-band, Fine Quad-Pol real dataset

- An acquisition every 24 days

Pauli RGB

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

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

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

Optical image

Barcelona, Spain
Beam FQ9
35 images
January 20th, 2010
to July 20th, 2012,
4000 x 2200 x 35 pixels

These datasets contain relevant information related to the temporal evolution of the scene

Data provided by MDA in the framework of the scientific project SOAR-EU 6779

MDA

Google earth

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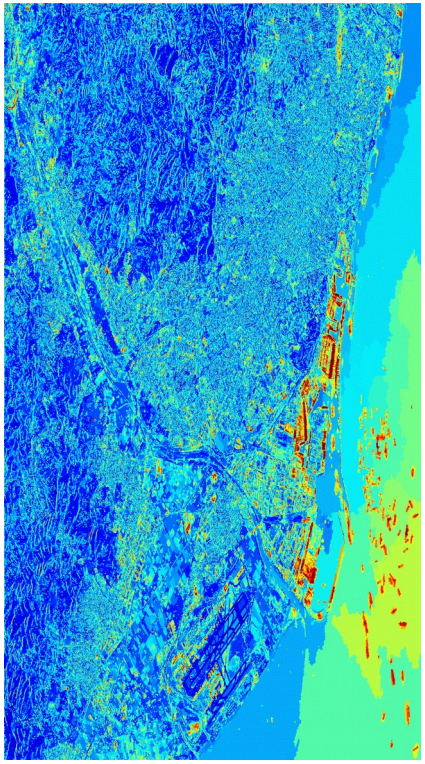
Temporal stability results

Temporal stability results over Barcelona and Flevoland datasets

Barcelona

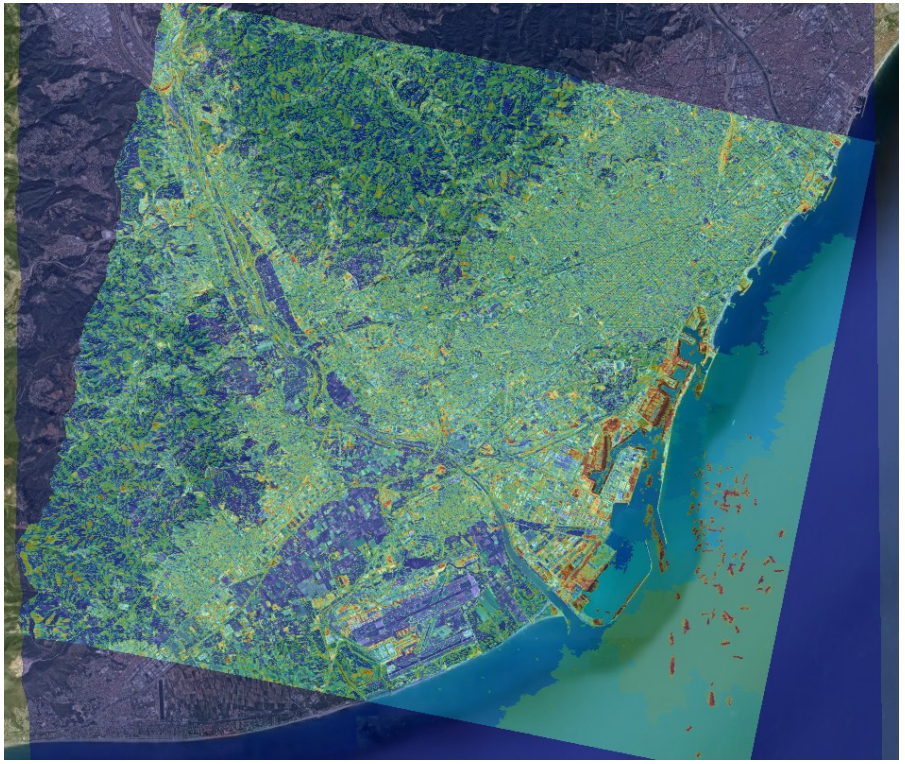
1st acq.
Original
Pauli
$|S_{hh}+S_{vv}|$
$|S_{hv}+S_{vh}|$
$|S_{hh}-S_{vv}|$



0 Temporal stability 3

(35 acqs.)

$t_s, \delta_p = -3\ dB$



$t_s, \delta_p = -3\ dB$

Small change — Large change

Geocoded result, overlay with an optical image

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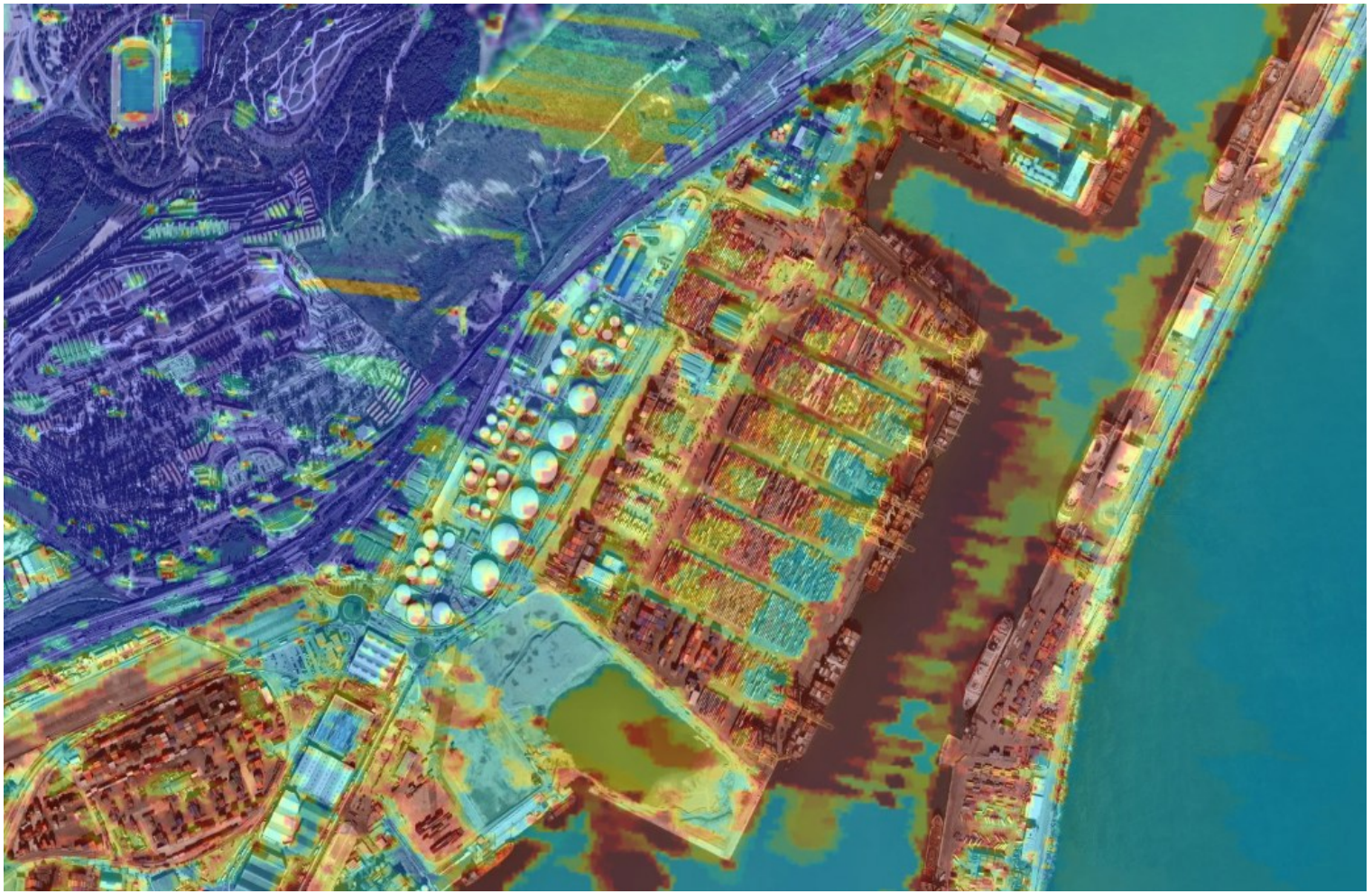
Temporal stability results

Detail of the geo-coded results for the harbor area, Barcelona, Spain:



Temporal stability measure $\delta_p = -3\,dB$

Google earth

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Temporal stability results

Ship container storage areas

Temporal stability measure

$\delta_p = -3\,dB$

Google earth

Panoramio

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Temporal stability results

Ship loading bay and cranes

Temporal stability measure

$\delta_p = -3\,dB$

Panoramio

Google earth

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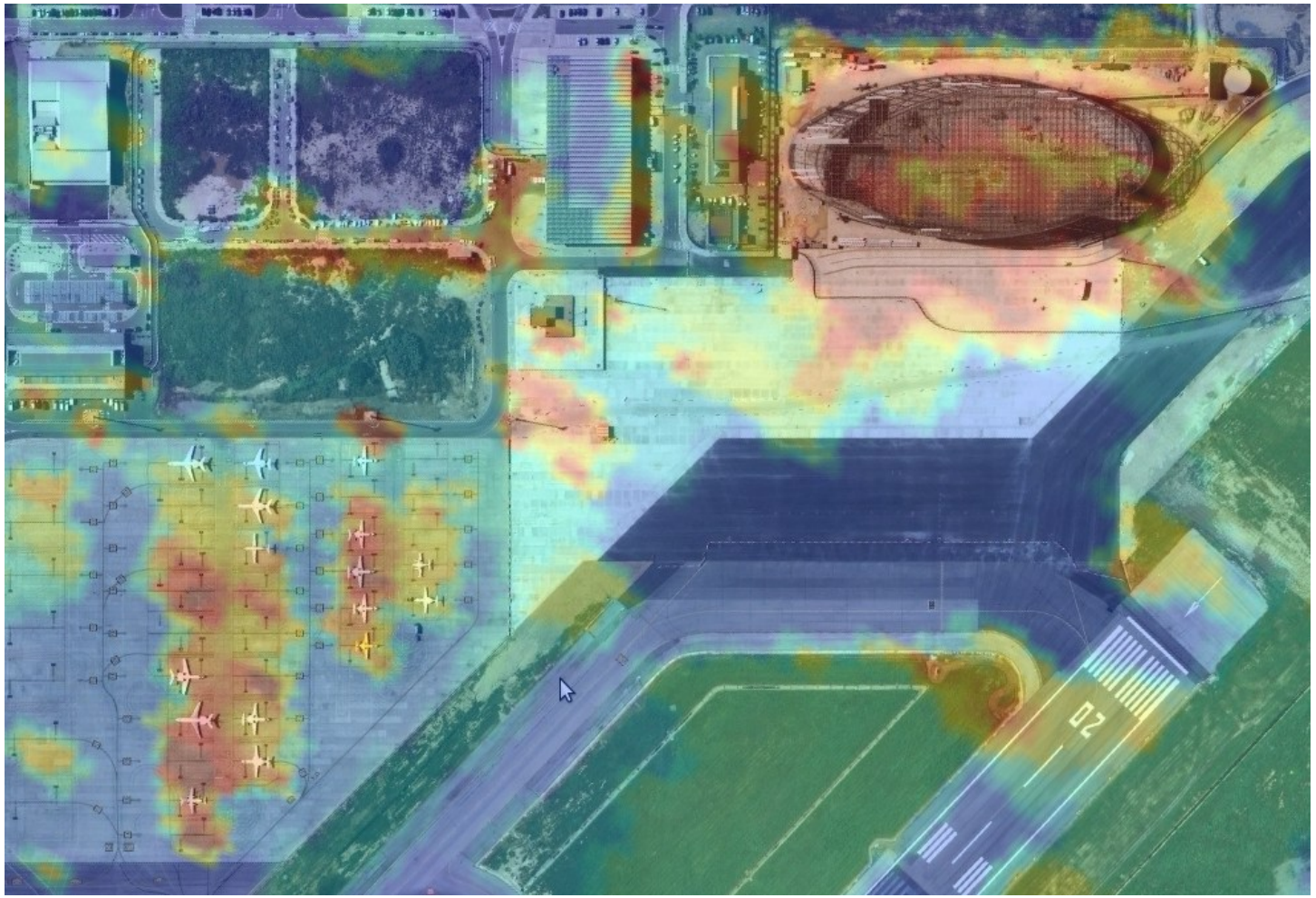
Temporal stability results

Detail of the geo-coded results for the Barcelona airport hangar area:



Temporal stability measure $\delta_p = -3\,dB$

Google earth

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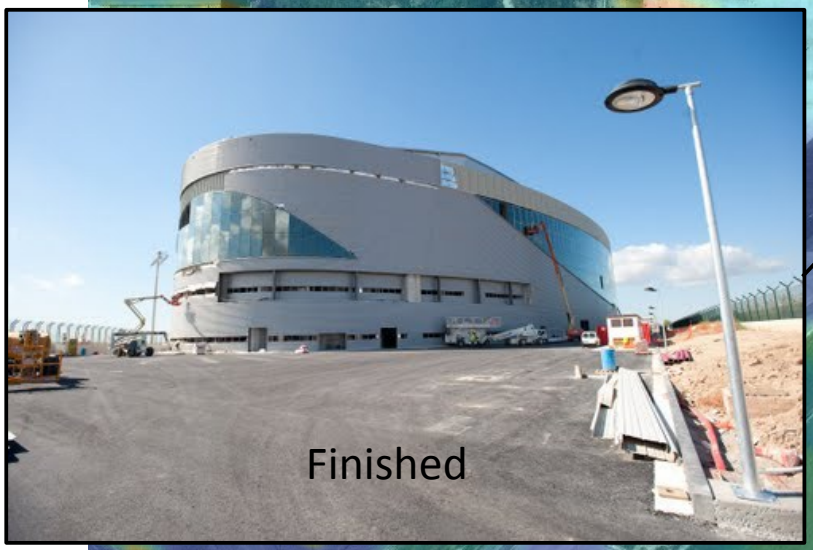
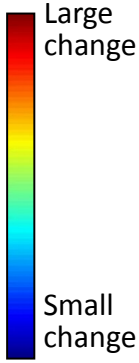
Temporal stability results

Detail of the geo-coded results for the Barcelona airport hangar area:





Temporal stability measure

$$\delta_p = -3\,dB$$

Panoramio

Google earth

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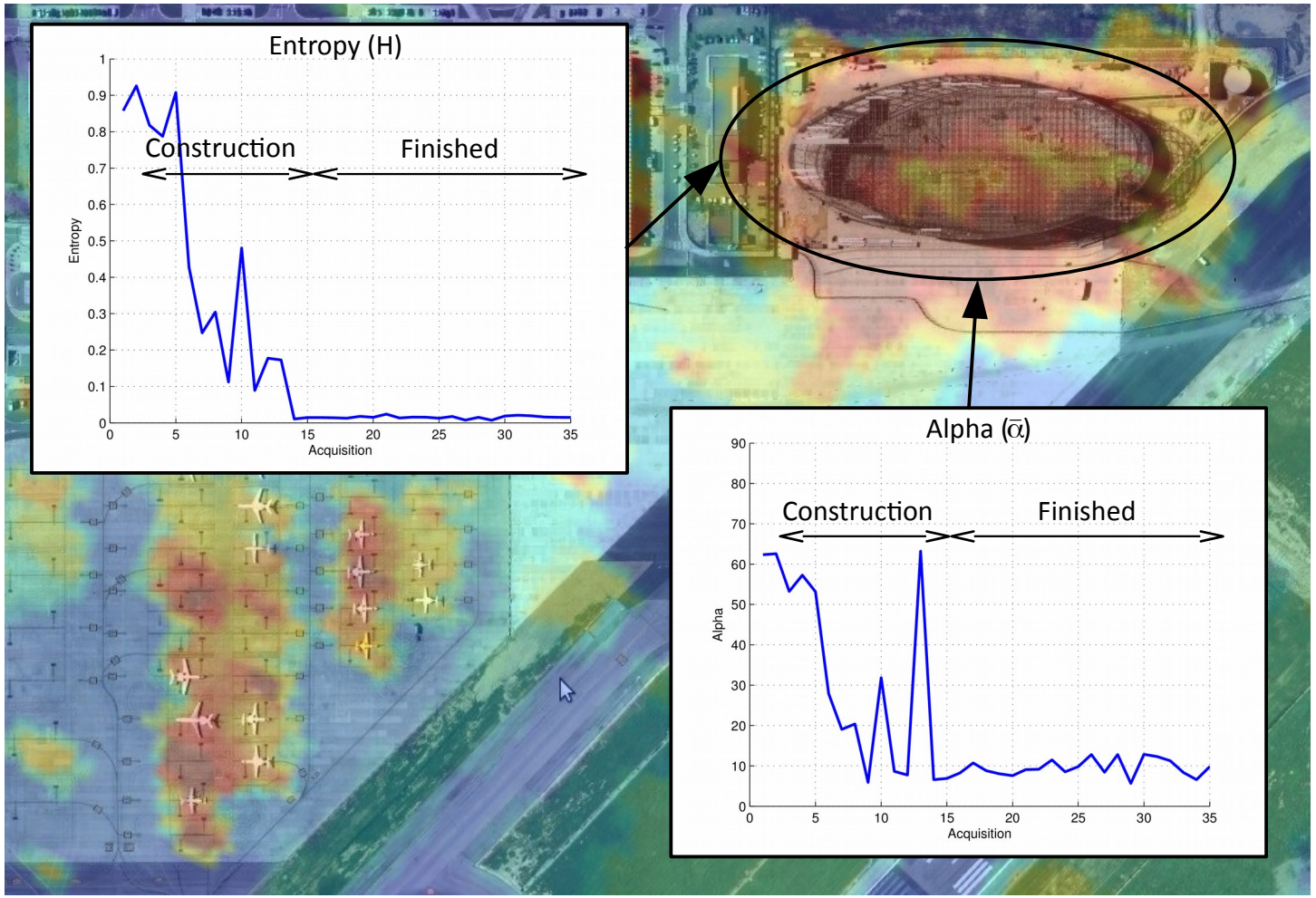
Temporal stability results

The polarimetric characterization of the temporal evolution may be performed:



Temporal stability measure $\delta_p = -3\,dB$

Google earth

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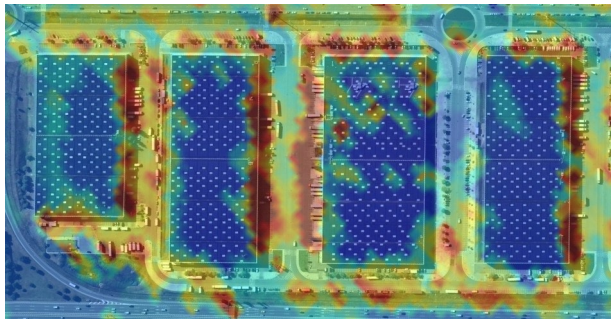
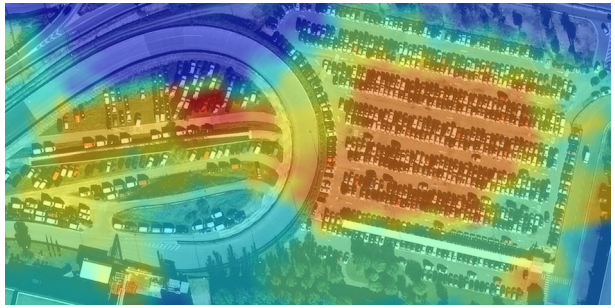
Temporal stability results – Summary

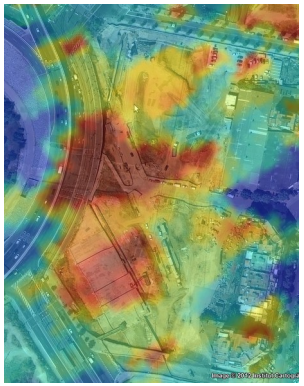
Detail of the geo-coded results over Barcelona, Spain



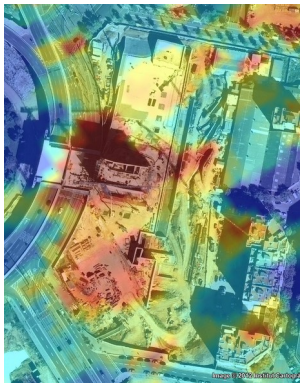
Trucks around industrial buildings



Parking areas



2010



2011

Larger changes detected are associated with human activities, construction and transportation.

⇩

Change on the geometry of the scene producing substantial variations in terms of the PolSAR response

$$\delta_p = -3\,dB$$

Google earth

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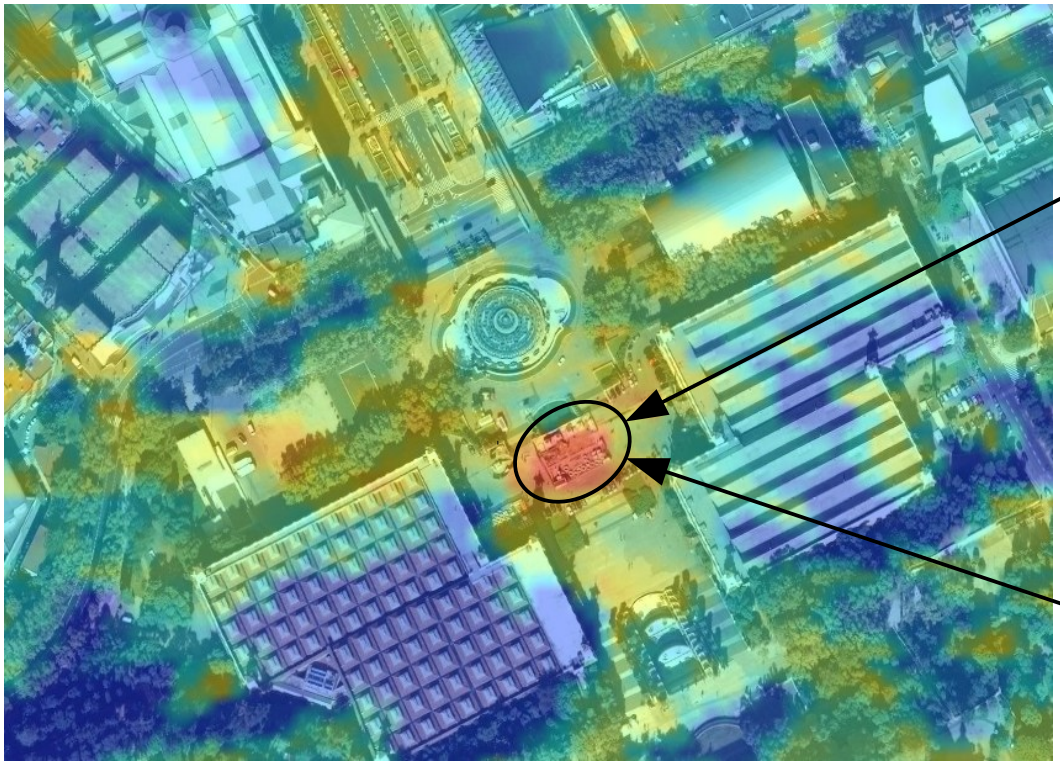
Temporal stability results – Spatial resolution

Detail of the geo-coded results near *Palacio Nacional*, in Montjuic area:



Temporal stability measure $\delta_p = -3\,dB$

Before

After

➔ A monument consisting of 4 columns has been constructed during the acquisition campaign

- Due to the multi-scale nature of the BPT this technique can detect very localized changes

Panoramio Google earth

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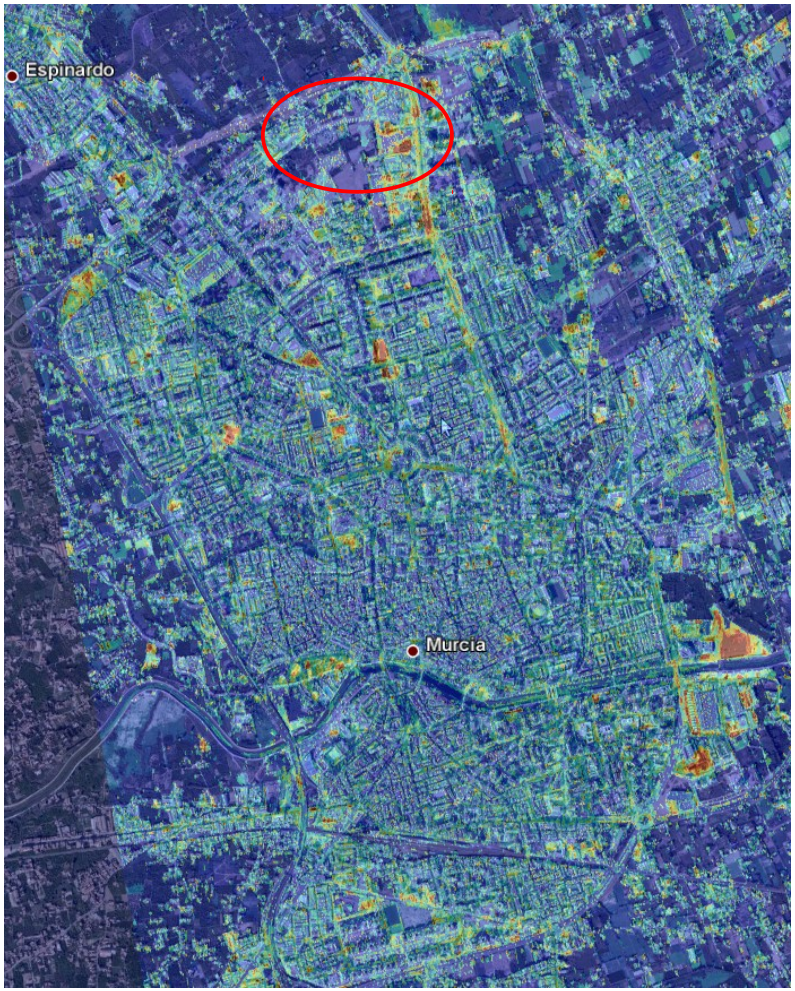
Temporal stability results – Spatial resolution

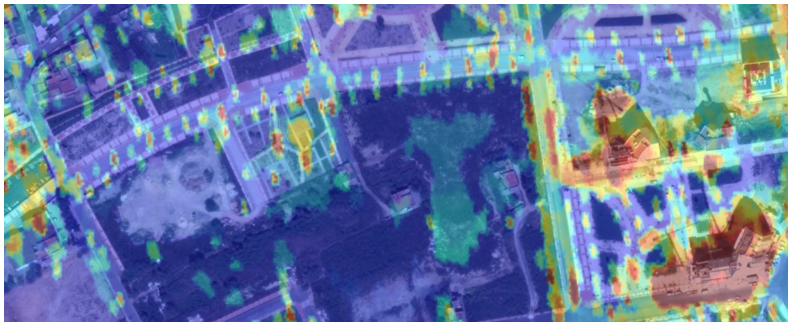
Geo-coded Dual-Pol TerraSAR-X temporal stability results, Murcia, Spain



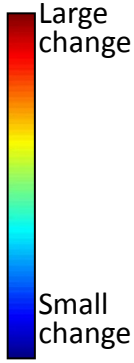
X-band, Dual-Pol (HH,VV), 1.9 x 6.6m res.
19th, February 2009 – 24th, January 2011
49 acquisitions, 3000 x 3000 pixel crop

2008

2012



Google earth



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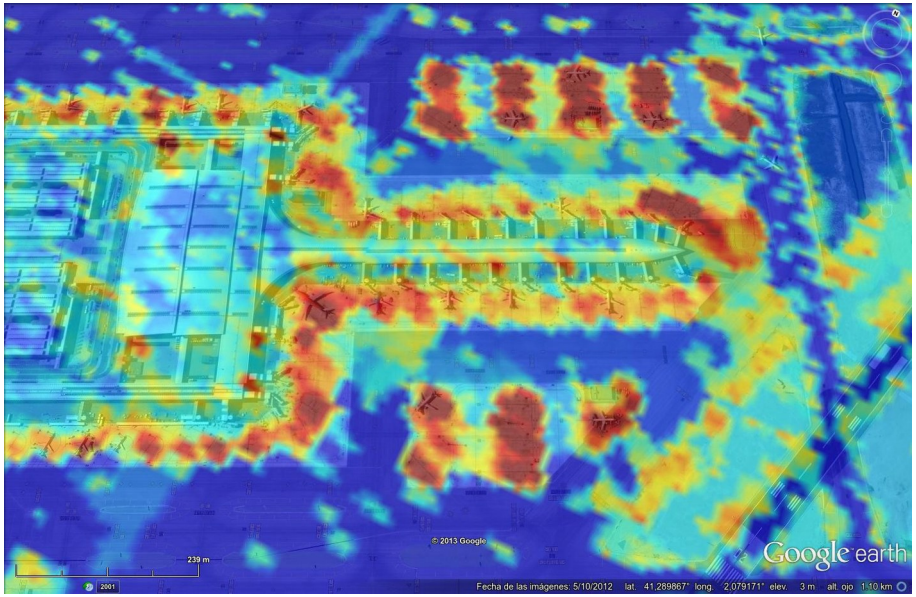
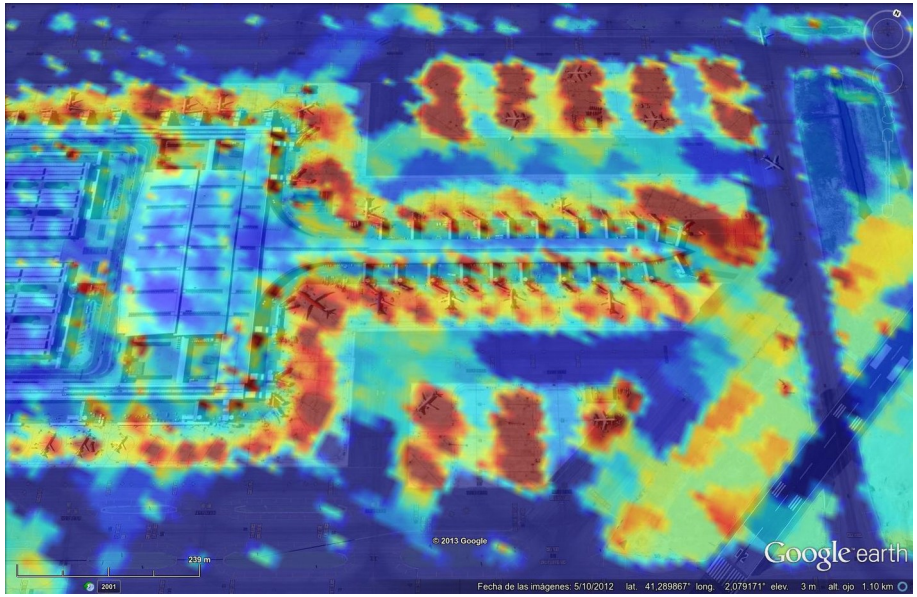
Temporal stability results – Matrix regularization

Distance-based Bilateral Filtering (DBF) as initial step for matrix regularization in the BPT based processing





3x3 ML

Temporal stability measure

5x5 DBF

The DBF technique may also be used for matrix regularization in polarimetric time series datasets

- Better spatial resolution preservation is observed, also in the temporal stability measure, when DBF is employed
- More contrasted and less noisy results are obtained

Alonso-González, A. & López-Martínez, C. & Salembier, P. & Deng, X. "Bilateral Distace Based filtering for Polarimetric SAR data", *Remote Sensing, 2013.*

Google earth

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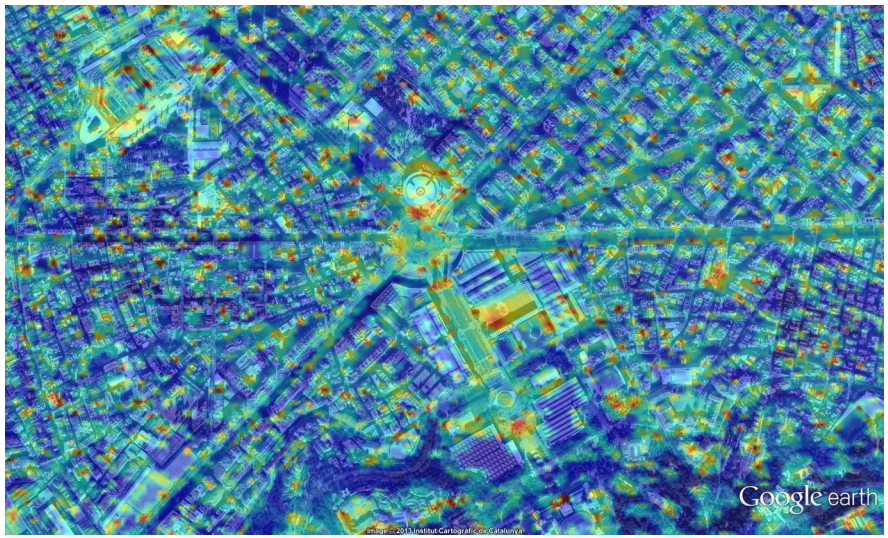
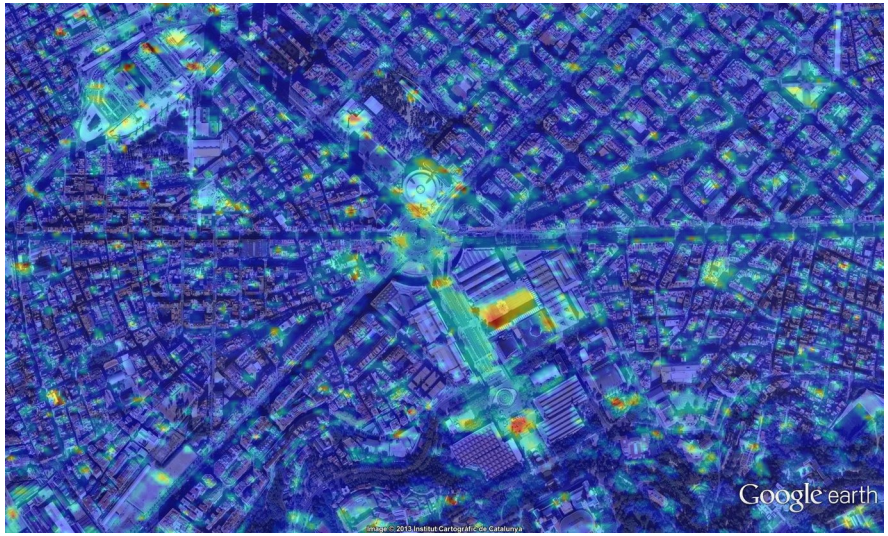
Temporal stability and dissimilarity measures



Full matrix measure



Diagonal measure

➔ BPT construction and temporal stability are based on dissimilarity measures

- Classified in diagonal & full matrix measures

Alonso-González, A. & López-Martínez, C. & Salembier, P. "Filtering and Segmentation of Polarimetric SAR Data based on Binary Partition Trees", *IEEE TGRS, 2012.*

Alonso-González, A. & López-Martínez, C. & Salembier, P. "PolSAR speckle filtering and segmentation based on Binary Partition Tree representation", *Proc. PolInSAR 2011*

➔ Evaluation in terms of temporal stability measurements

- Full matrix → sensitivity to channel correlation but more noise and false alarms are observed over small regions (specially over urban area)

⇩

Initial hypothesis may not hold

- ✗ Distributed scattering hypothesis
- ✗ Gaussian hypothesis

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Conclusions

- Polarimetric SAR time series are suitable for the detection and analysis of the changes over urban areas. The radar is sensitive to changes in the target geometry and changes → very suitable for urban monitoring.

- The Binary Partition Tree has proven to be a region-based and multi-scale SAR data representation useful for this application. Additionally, it is based on simple mathematical concepts as a region model and a similarity measure.

- The BPT extended to process PolSAR time series is sensitive to the full polarimetric temporal evolution of the target. It achieves large filtering over homogeneous areas while preserving small details and polarimetric information & evolution.

- The BPT may be employed to analyze and characterize the scene evolution over time. The proposed temporal stability measure is able to detect different urban changes. The extended region model contains the complete evolution to analyze and characterize the changes.

- Thanks to the multi-scale nature of the BPT, very localized changes are preserved and detected with the proposed technique.

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Thank you for your attention!

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