PolSAR time series processing and analysis based on Binary Partition Trees

Alberto Alonso-González, Carlos López-Martínez and Philippe Salembier

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Universitat Politècnica de Catalunya – UPC
Signal Theory and Communications Dept.
Barcelona, Spain
alberto.alonso@tsc.upc.edu

Outline

- Multidimensional SAR
- Binary Partition Tree
- Time Series with BPT
- Results & Temporal Analysis
- Conclusions

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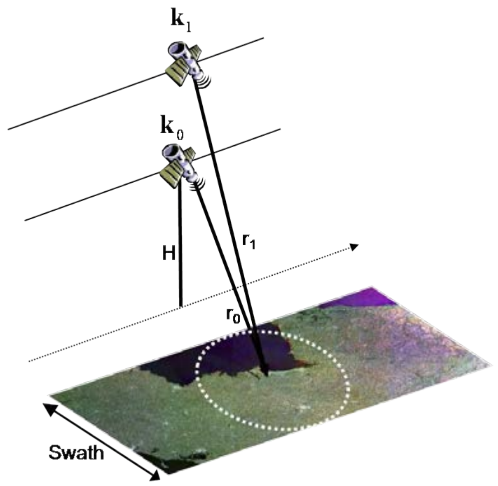
Multidimensional SAR

Multidimensional SAR systems acquire *m* complex SAR images

Target vector

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



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

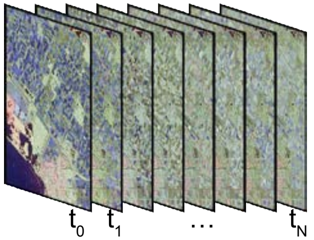
$$\boldsymbol{Z}=\langle \boldsymbol{k}\boldsymbol{k}^H\rangle=\frac{1}{N}\sum_{i=1}^{N}\boldsymbol{k}\boldsymbol{k}^H \qquad p_{\boldsymbol{Z}}(\boldsymbol{Z})=\frac{N^{QN}|\boldsymbol{Z}|^{N-Q}\exp(-N\,tr(\boldsymbol{C}^{-1}\boldsymbol{Z}))}{K(N,Q)|\boldsymbol{C}|^N}$$

Distributed Scattering Hypothesis

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

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

SAR Polarimetry



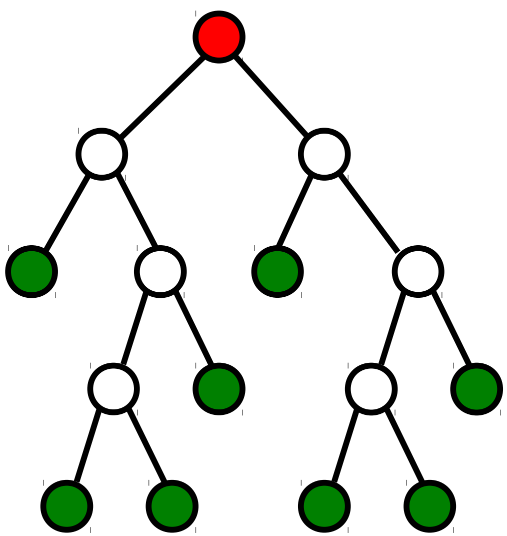
Temporal series

Some types of Multidimensional SAR data

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!

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

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

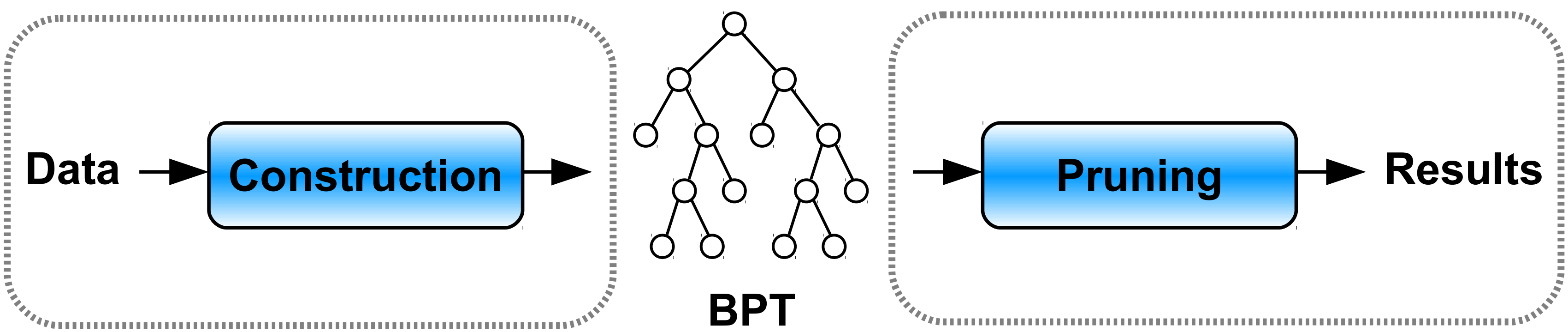
Alonso-González, A. & López-Martínez, C. & Salembier, P. “Filtering and segmentation of Polarimetric SAR images with Binary Partition Trees”, *Proc. IEEE IGARSS*, 2010

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



Application independent

Application dependent

- 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, ...

BPT construction

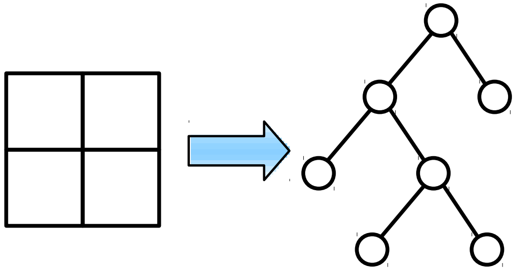
The BPT may be constructed by an iterative algorithm in a bottom-up approach

- 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

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

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



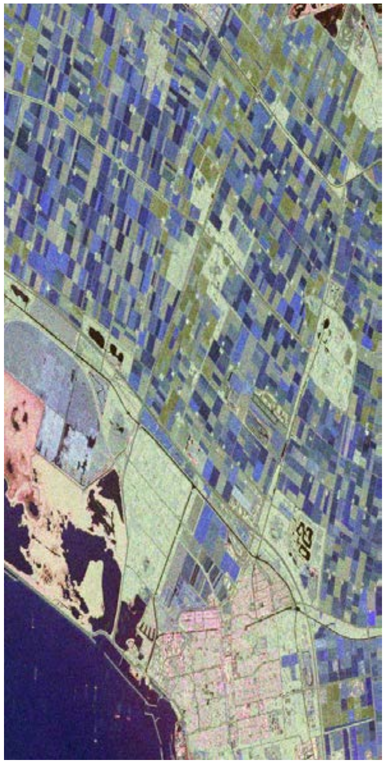
The dissimilarity measure is the keystone of the construction process

Different similarity measures have been defined and evaluated:

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

PolSAR time series

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 datasets

- An acquisition every 24 days

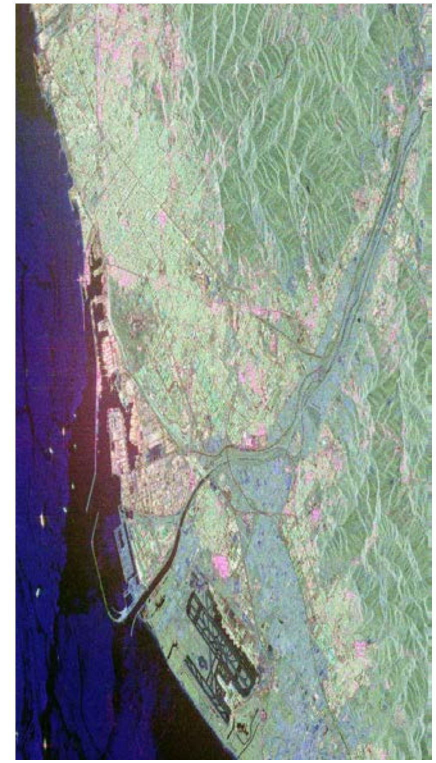
$|S_{hh}+S_{vv}|$

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

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

Flevoland,
The Netherlands
Beam FQ13
8 images
April 14th, 2009 to September 29th, 2009,
4000 x 2000 x 8 pixels

Barcelona, Spain
Beam FQ9
38 images
January 20th, 2010 to July 20th, 2012,
4000 x 2200 x 38 pixels



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

Data courtesy of ESA in the framework of the AgriSAR 2009 project

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

Temporal dimension of the data

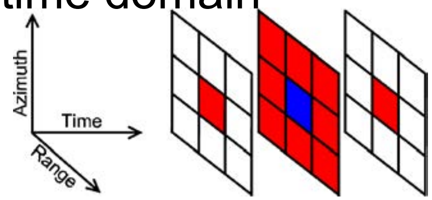
Two alternatives to deal with the temporal dimension of the data are proposed

Target is characterized by its polarimetric response	Target is characterized by its polarimetric temporal evolution
• Assume the temporal dimension as an additional independent dimension of the data • Same region model, the sample covariance matrix Z • Arbitrary regions in space-time dimensions, covering pixels of different acquisitions with **similar polarimetric response**	• Assume the temporal dimension as additional information within the region model • Extended region model, to include the temporal information $Z_E \ni [Z_1, Z_2, \dots, Z_N]$ • Arbitrary regions in space dimension, representing areas having **similar polarimetric temporal evolution**
Space-Time BPT	**Temporal Evolution BPT**

Temporal dimension of the data

Two alternatives to deal with the temporal dimension of the data are proposed

- 10-pixel connectivity in the space-time domain



- Estimated sample covariance matrix $\boldsymbol{Z}$ as region model

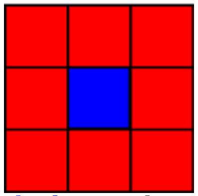
$$\boldsymbol{Z}=\langle \boldsymbol{k}\,\boldsymbol{k}^H\rangle=\frac{1}{N}\sum_{i=1}^{N}\boldsymbol{k}_i\boldsymbol{k}_i^H$$

- Dissimilarity measure → same as for PolSAR since region model has not changed

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

Space-Time BPT

- 8-pixel connectivity in the spatial domain



- 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

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

Temporal Evolution BPT

BPT-based estimation

A tree pruning strategy has to be defined for the target response estimation application

The goal is to extract the biggest homogeneous regions of the image

- A region homogeneity measure has to be defined:

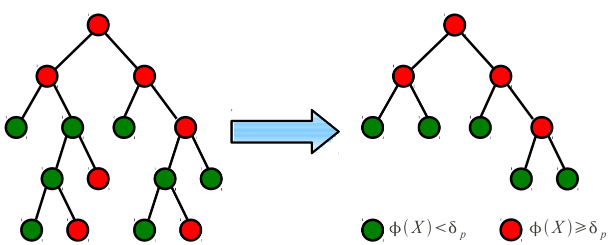
$$\phi(X)=\frac{1}{n_X\left\|\mathbf{Z}_X\right\|^2}\sum_{i=1}^{n_X}\left\|\mathbf{X}^i-\mathbf{Z}_X\right\|_F^2$$

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

Space-Time BPT | **Temporal Evolution BPT**

These measures may be interpreted as the relative MSE committed when representing all the pixels of the region X by its region model

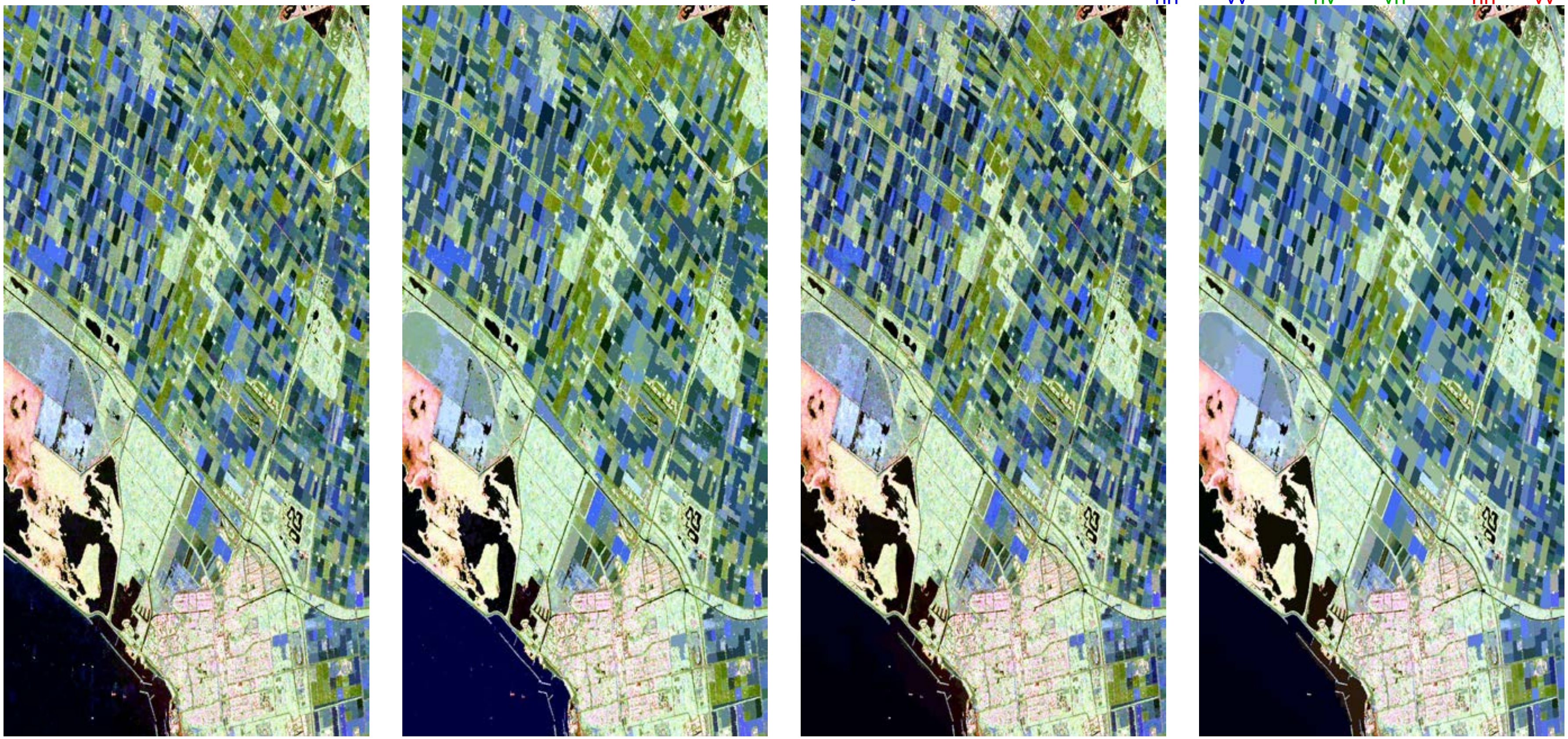
- A pruning threshold δ_p is defined over this error $\phi(X)<\delta_p$



BPT Pruning for estimation: In a top-down approach, select the first nodes that fulfill $\phi(X)<\delta_p$

BPT-based estimation

BPT-based estimation results over the first acquisition: $|S_{hh}+S_{vv}|$, $|S_{hv}+S_{vh}|$, $|S_{hh}-S_{vv}|$



$\delta_p = -5\ dB$ $\delta_p = -3\ dB$ $\delta_p = -5\ dB$ $\delta_p = -3\ dB$

Space-Time BPT (ST BPT)

- On ST BPT the polarimetric information is estimated combining samples of different acquisitions

Temporal Evolution BPT (TE BPT)

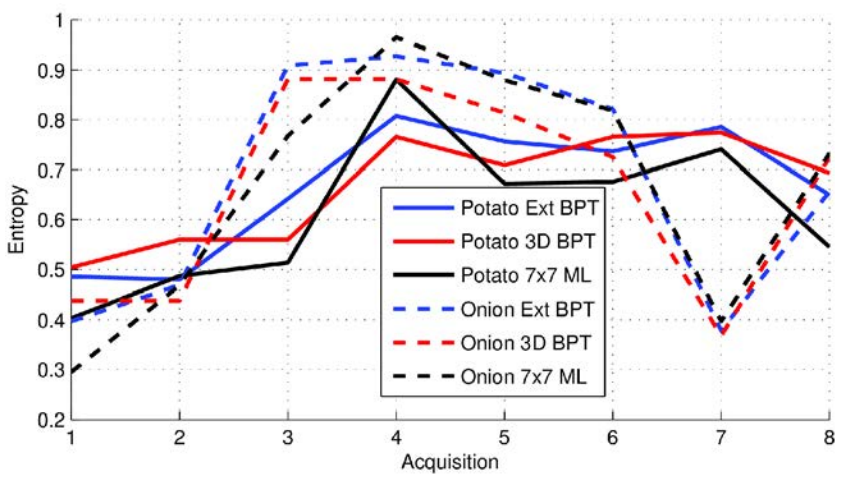
- On TE BPT the spatial contours are estimated employing temporal evolution among different acquisitions

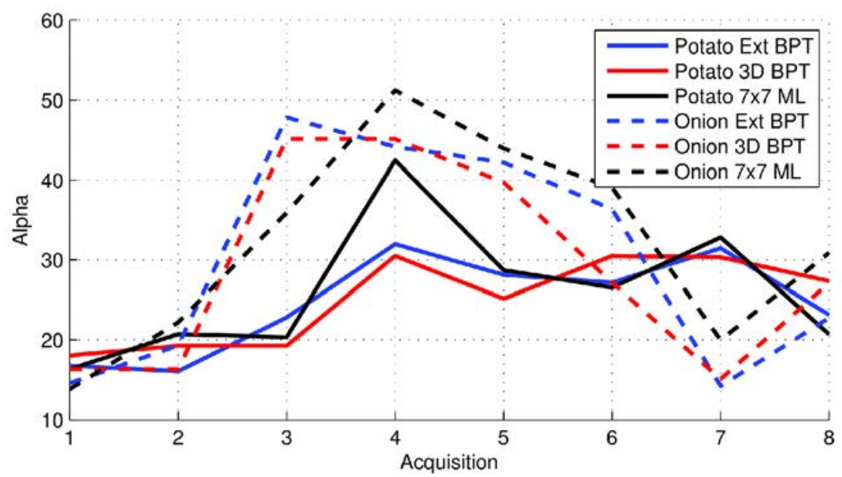
BPT-based estimation

The average region temporal span in the first slice:

Pruning factor	Regions at 1st acquisition	Average temporal span
-5 dB	359371	2,067
-4 dB	223969	2,652
-3 dB	127957	4,068
-2 dB	52077	6,727
-1 dB	14660	7,758
0 dB	4666	7,921

At $\delta_p = -3\,dB$ 4 times more samples are attained by the Space-Time BPT estimation with respect to a single PolSAR image estimation

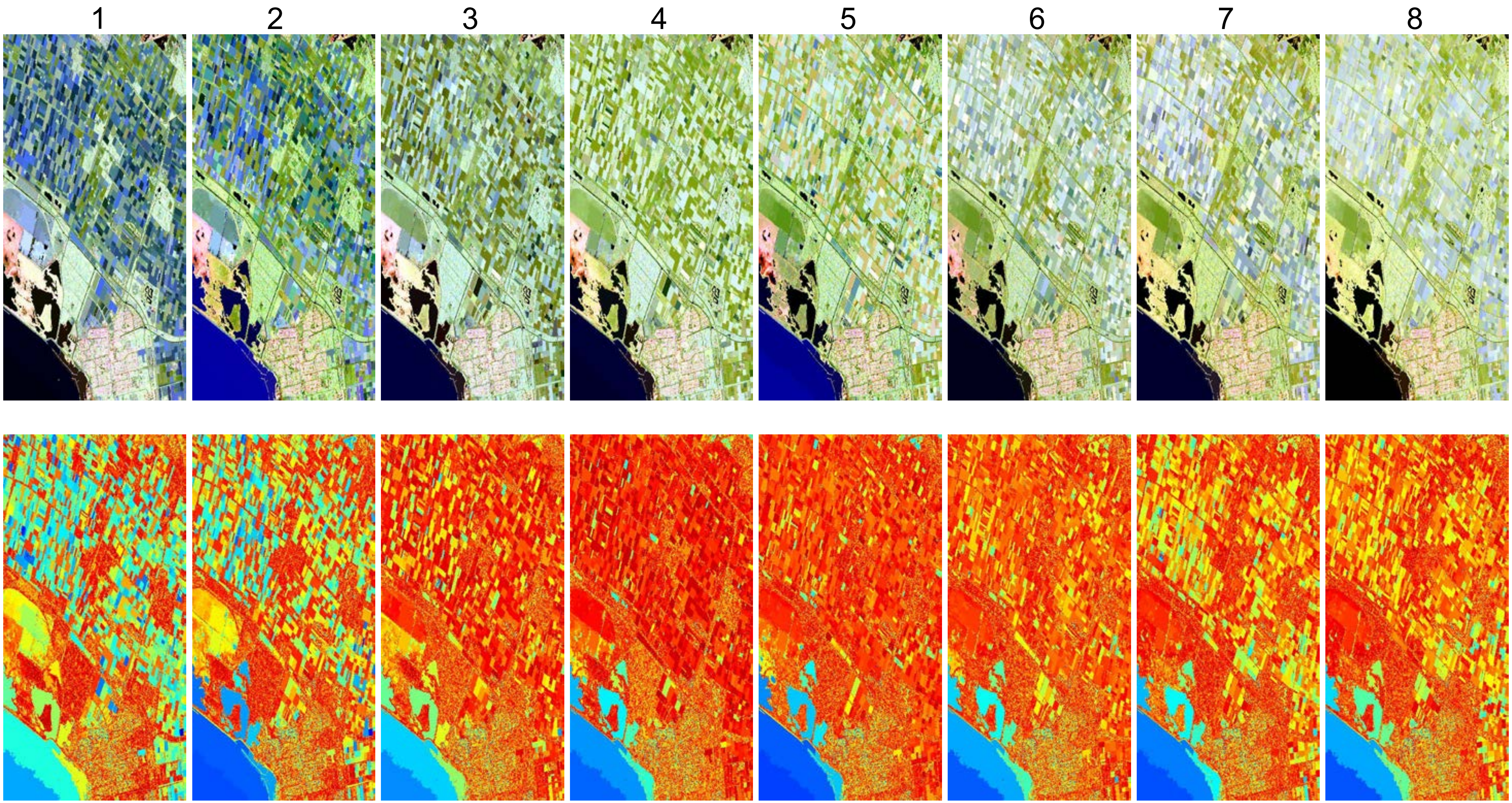




- The polarimetric information temporal evolution is preserved by both BPT approaches

Temporal evolution of the TE BPT filtered dataset in Pauli and H/A/Alpha

Acquisition number: $|S_{hh}+S_{vv}|$, $|S_{hv}+S_{vh}|$, $|S_{hh}-S_{vv}|$



Entropy (H)

$$\delta_p = -3\ dB$$

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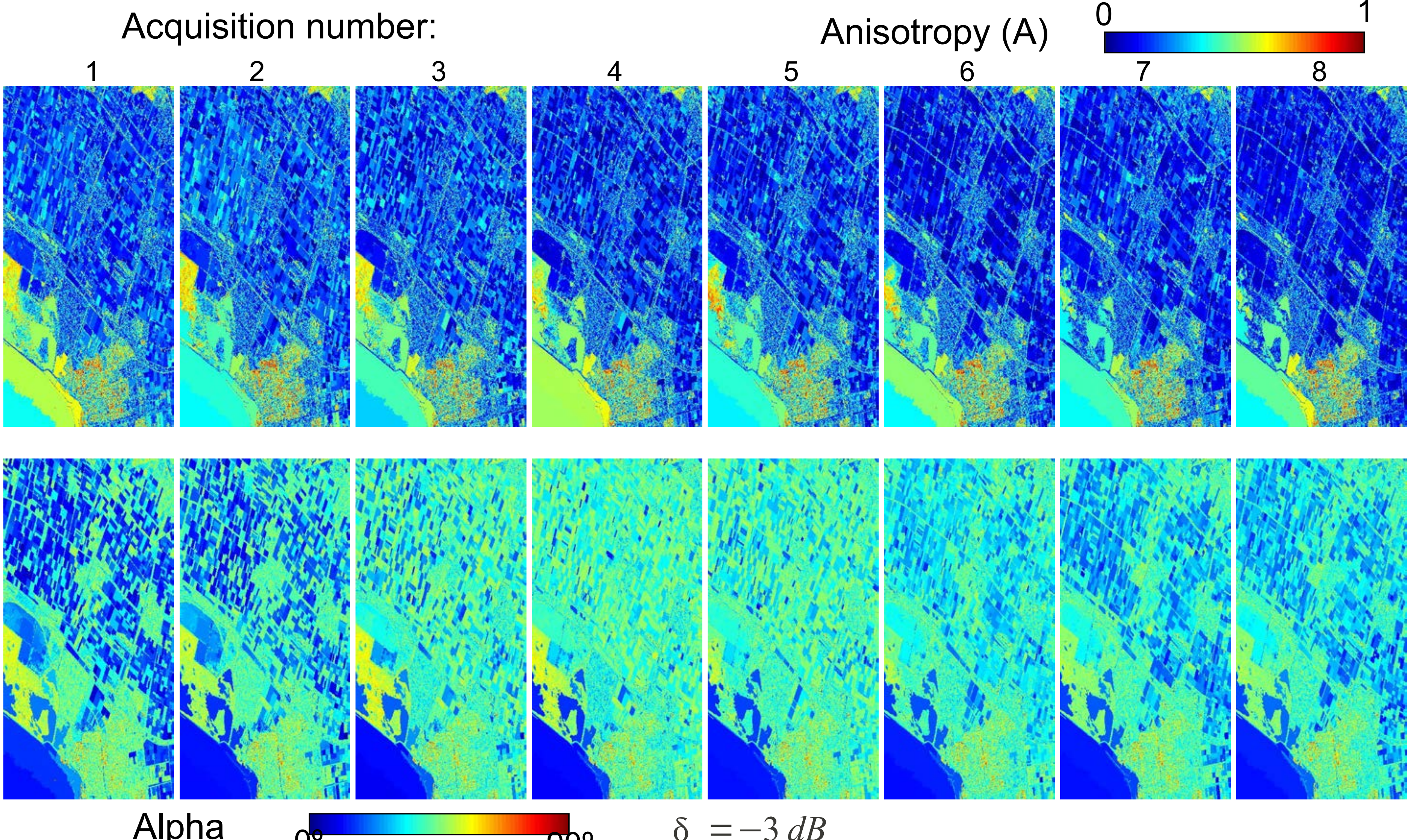
Temporal evolution

Temporal evolution of the TE BPT filtered dataset in Pauli and H/A/Alpha



$\delta_p = -3\ dB$

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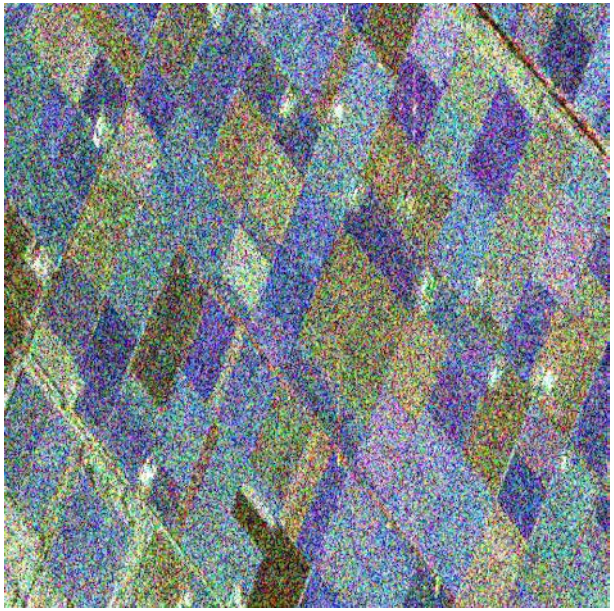
Spatial contours analysis

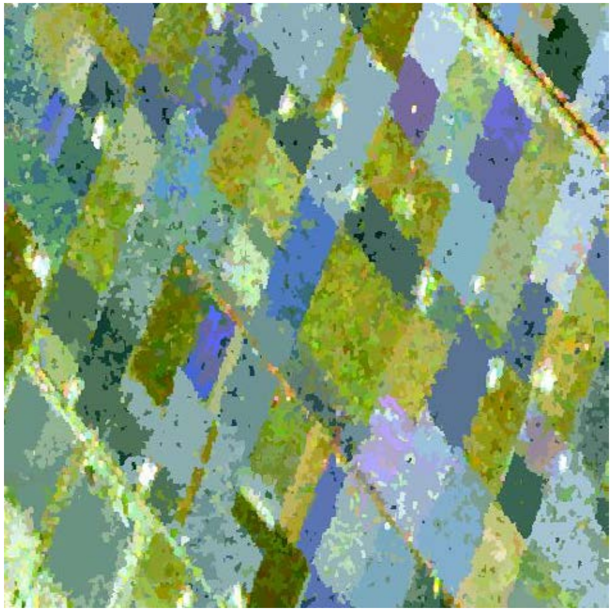
Analyzing closely the region contours obtained by both methods (2nd acquisition)

Original



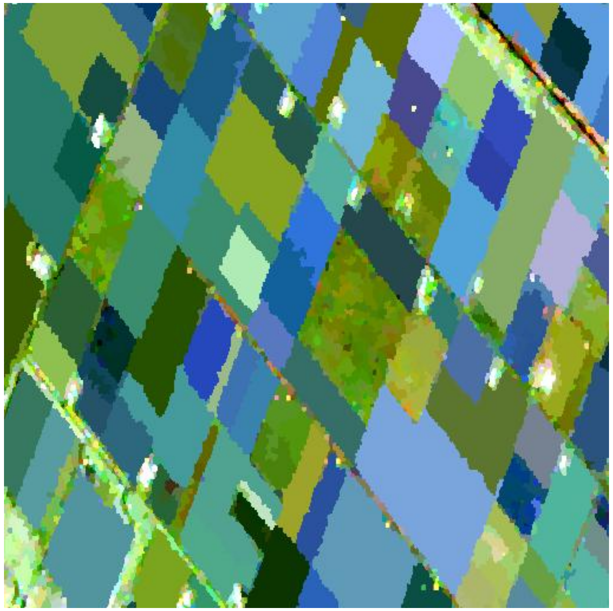
$|S_{hh}+S_{vv}|$, $|S_{hv}+S_{vh}|$, $|S_{hh}-S_{vv}|$

Space-Time BPT



$\delta_p = -3\ dB$

Temporal Evolution BPT



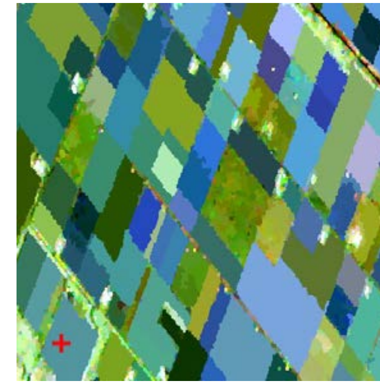
$\delta_p = -3\ dB$

More precise region contours may be observed for Temporal Evolution BPT →

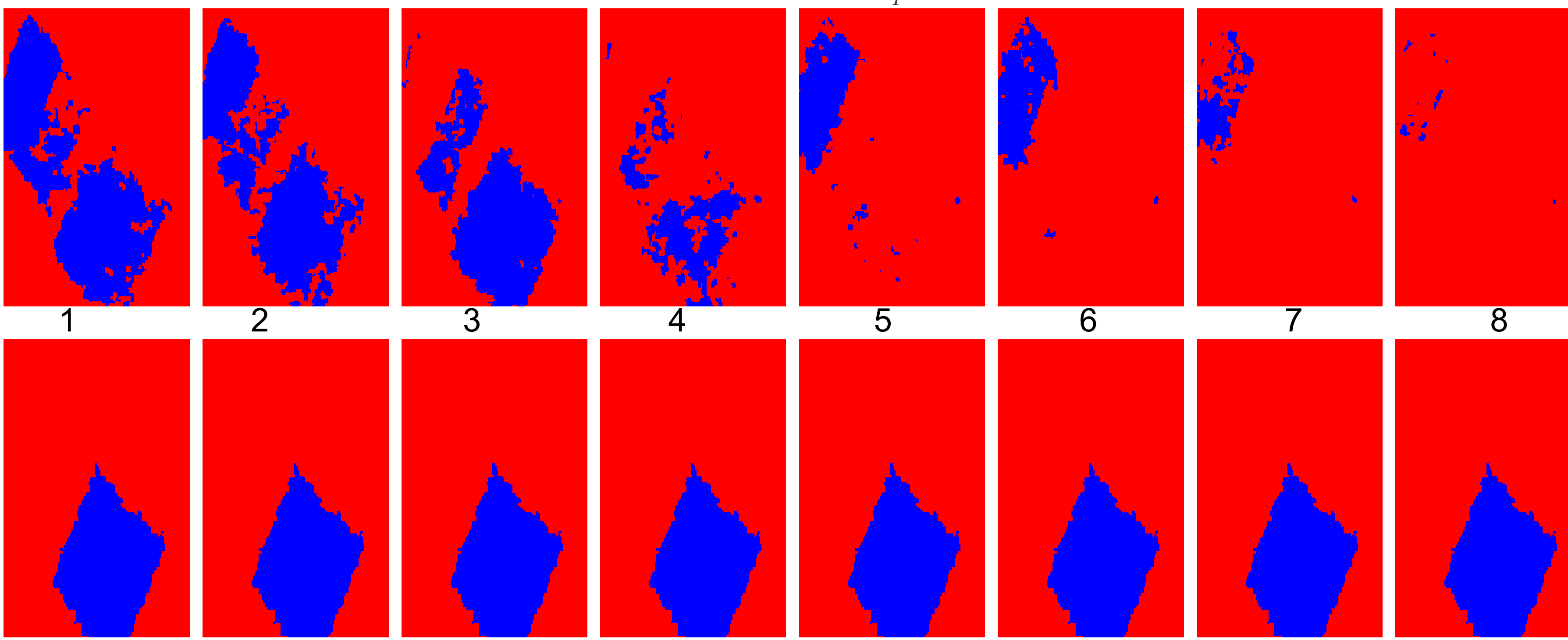
- Increased contrast due to taking into account polarimetric temporal evolution of regions
- Different realizations of the fields contours are observed through the acquisitions

Contour temporal evolution

- The spatial contours for Space-Time BPT change over time (3D regions)
- The spatial contours are fixed for Temporal Evolution BPT (2D regions)



Space-Time BPT $\delta_p = -3\ dB$



Temporal Evolution BPT $\delta_p = -3\ dB$

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Temporal analysis

Analyzing the contours on the temporal dimension of the Space-Time BPT, a map can be generated representing the number of changes per pixel

Similarly, for the Temporal Evolution BPT the temporal stability may be measured by comparing the different Z_{ii} matrices:

$$Z_N = \begin{pmatrix} Z_{11} & \Omega_{12} & \cdots & \Omega_{1N} \\ \Omega_{12}^H & Z_{22} & \cdots & \Omega_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \Omega_{1N}^H & \Omega_{2N}^H & \cdots & Z_{NN} \end{pmatrix}$$

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

The average similarity measure for all the combinations of Z_{ii} is computed

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

ST BPT measures the number of temporal changes (temporal change detection)

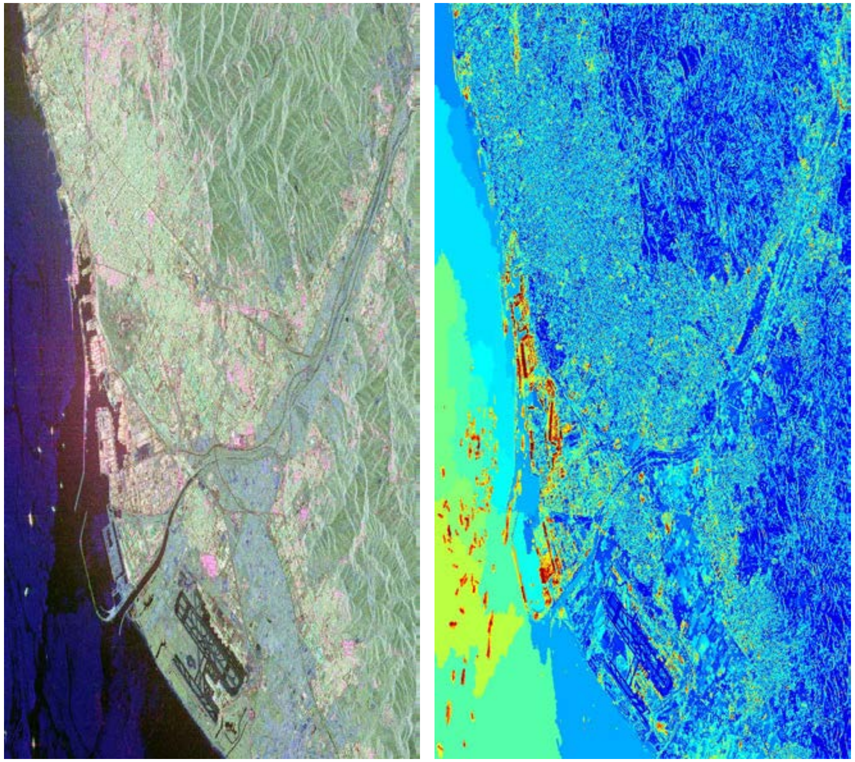
TE BPT measures the amount of polarimetric change among all the acquisitions (temporal stability)

- TE BPT results uniquely correspond to spatial areas of the scene due to fixed contours

Temporal stability results

Temporal stability results over Barcelona and Flevoland datasets

Barcelona



1st acq. Original Pauli

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

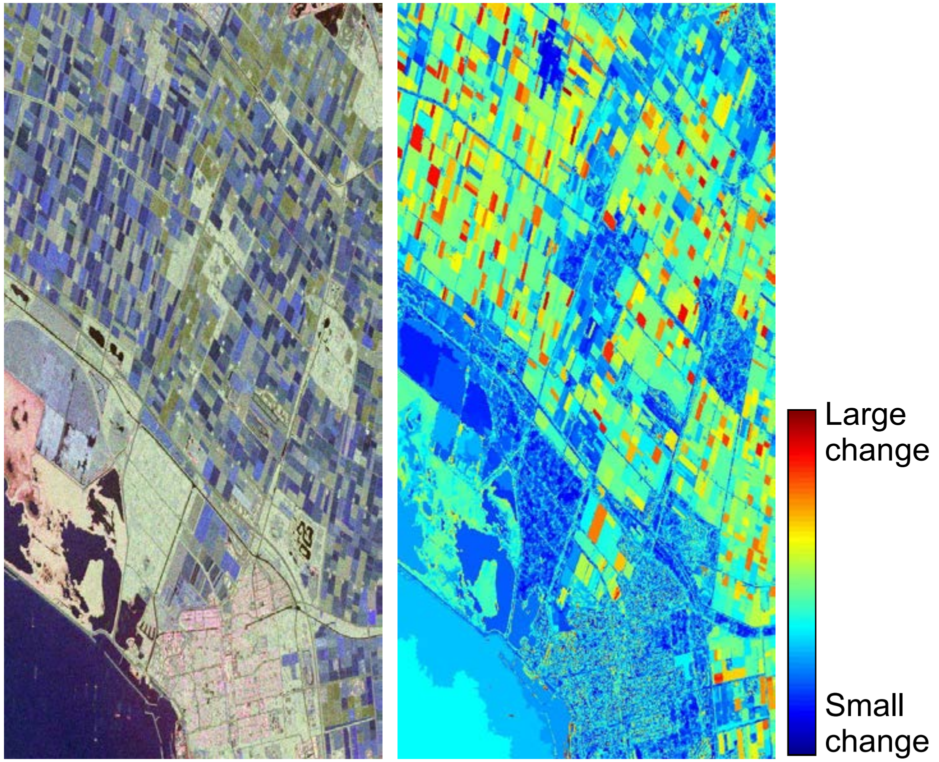
$|S_{hv}+S_{vh}|$

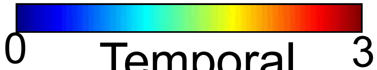
$|S_{hh}-S_{vv}|$

Temporal stability measure

$t_s, \delta_p = -5\ dB$

Flevoland





1st acq. Original Pauli

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

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

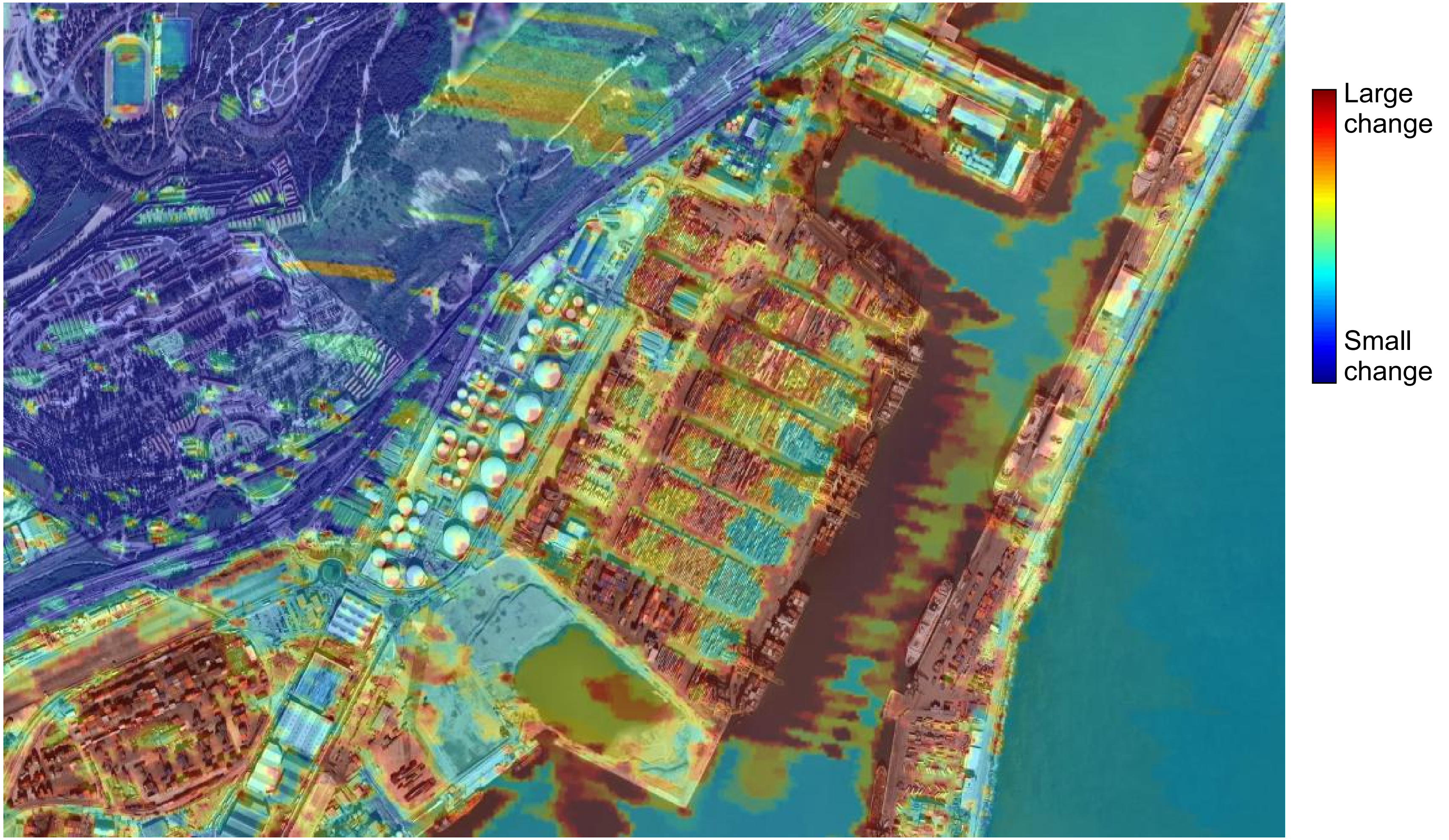
$|S_{hh}-S_{vv}|$

Temporal stability measure

$t_s, \delta_p = -5\ dB$

Temporal stability results

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

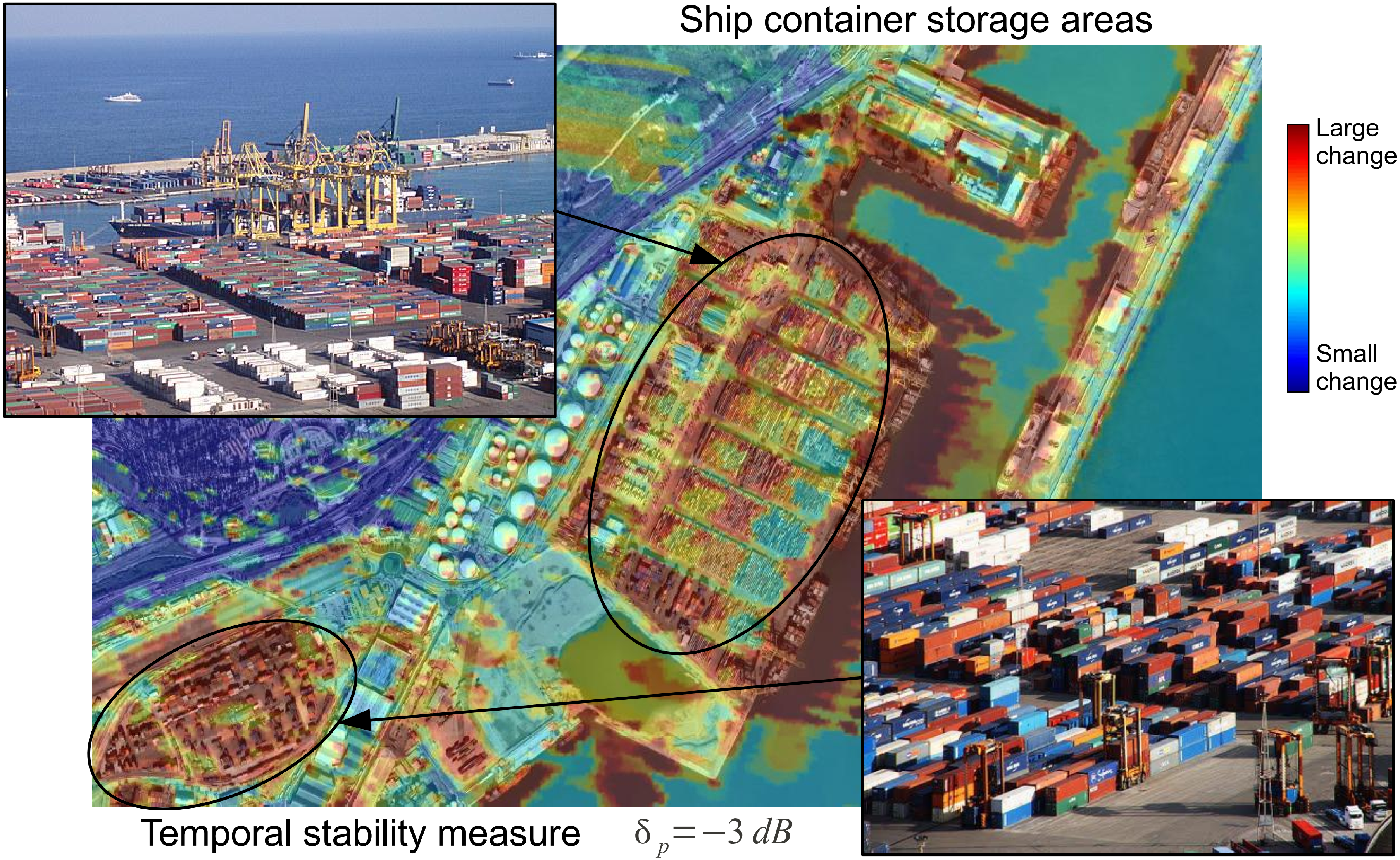


Temporal stability measure $\delta_p = -3\ dB$

Google earth

Temporal stability results

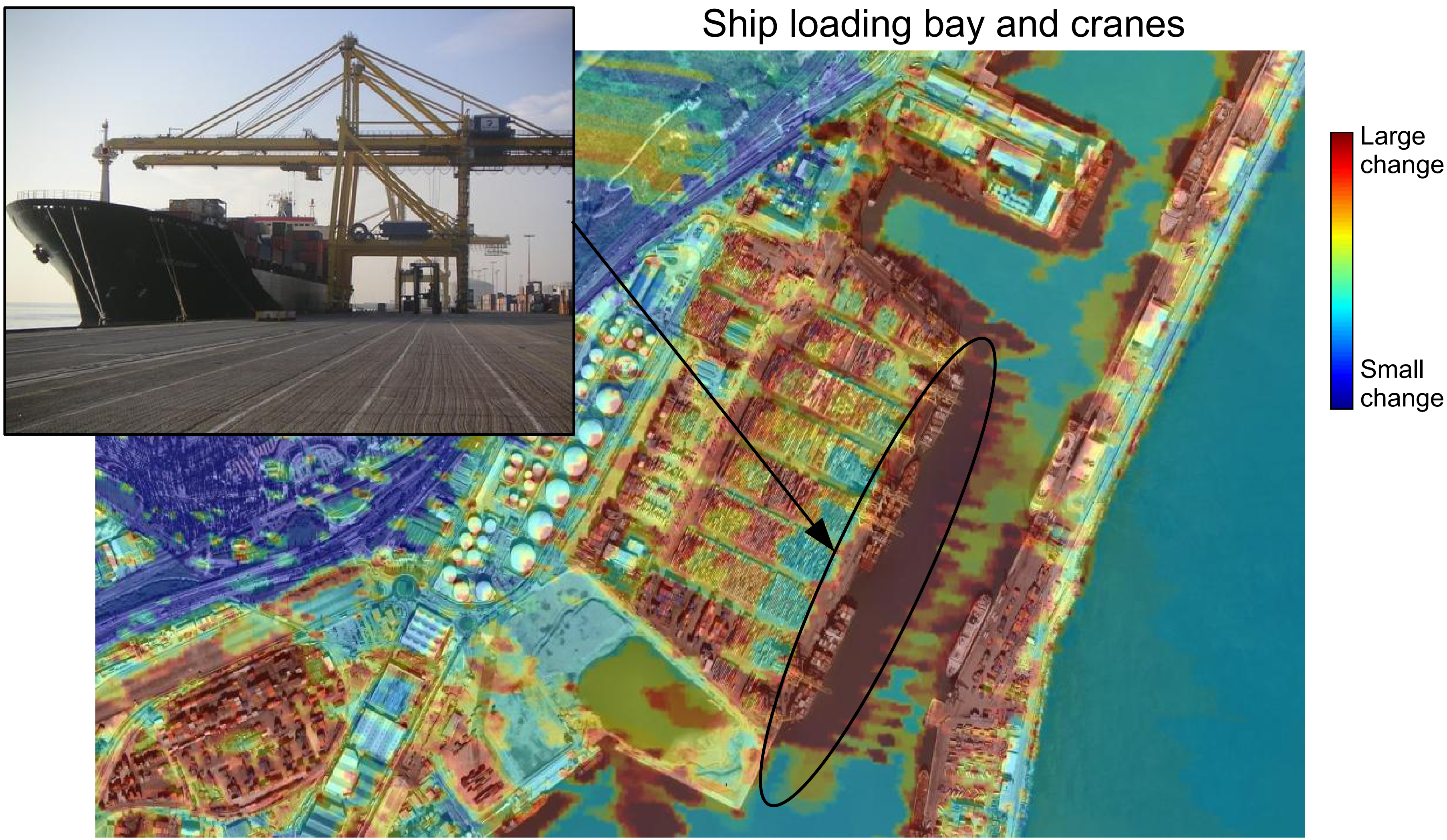
Ship container storage areas



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

Panoramio Google earth

Temporal stability results

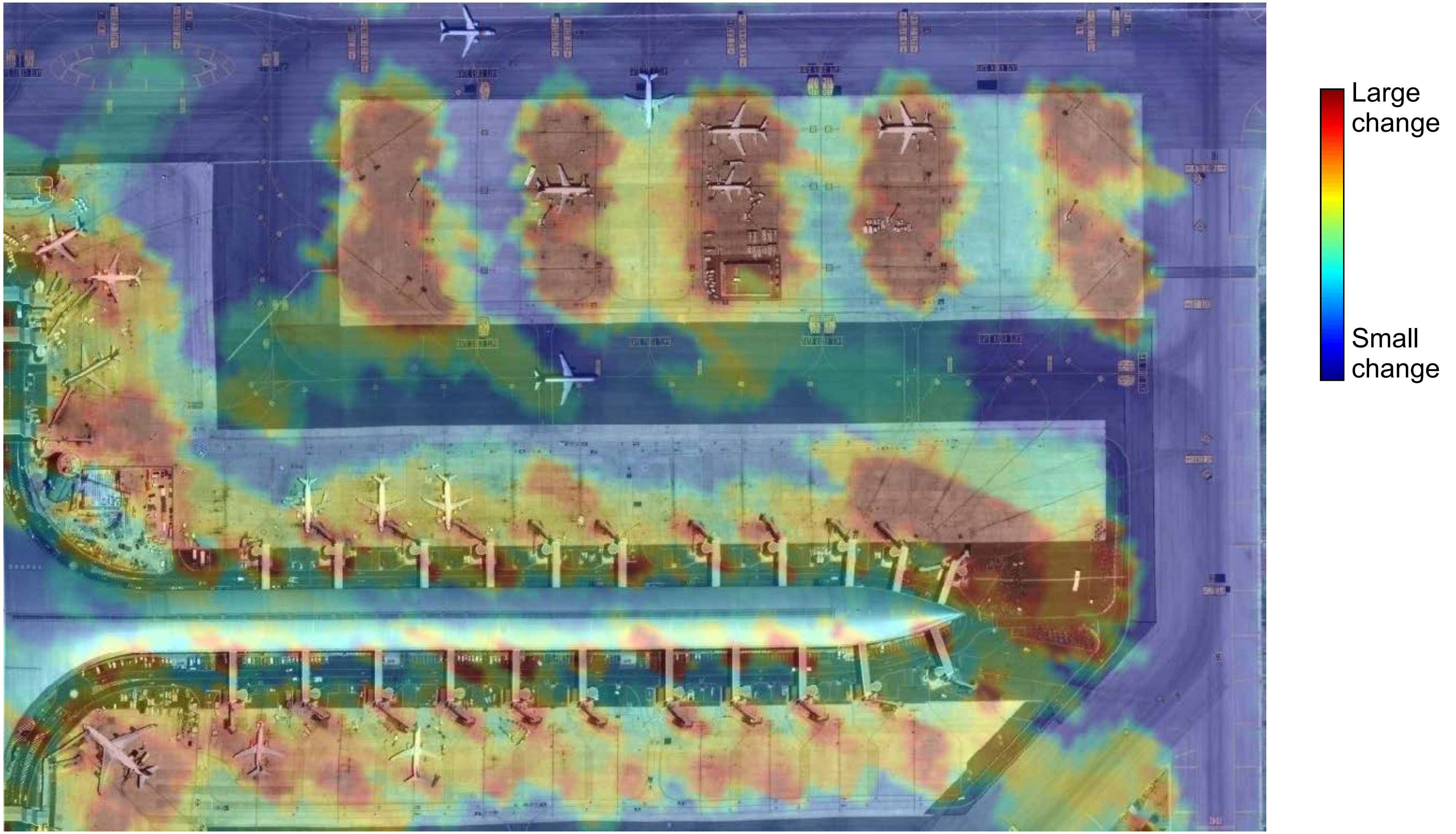


Temporal stability measure $\delta_p = -3\ dB$

Panoramio Google earth

Temporal stability results

Detail of the geo-coded results for the T1 airport area, Barcelona, Spain:

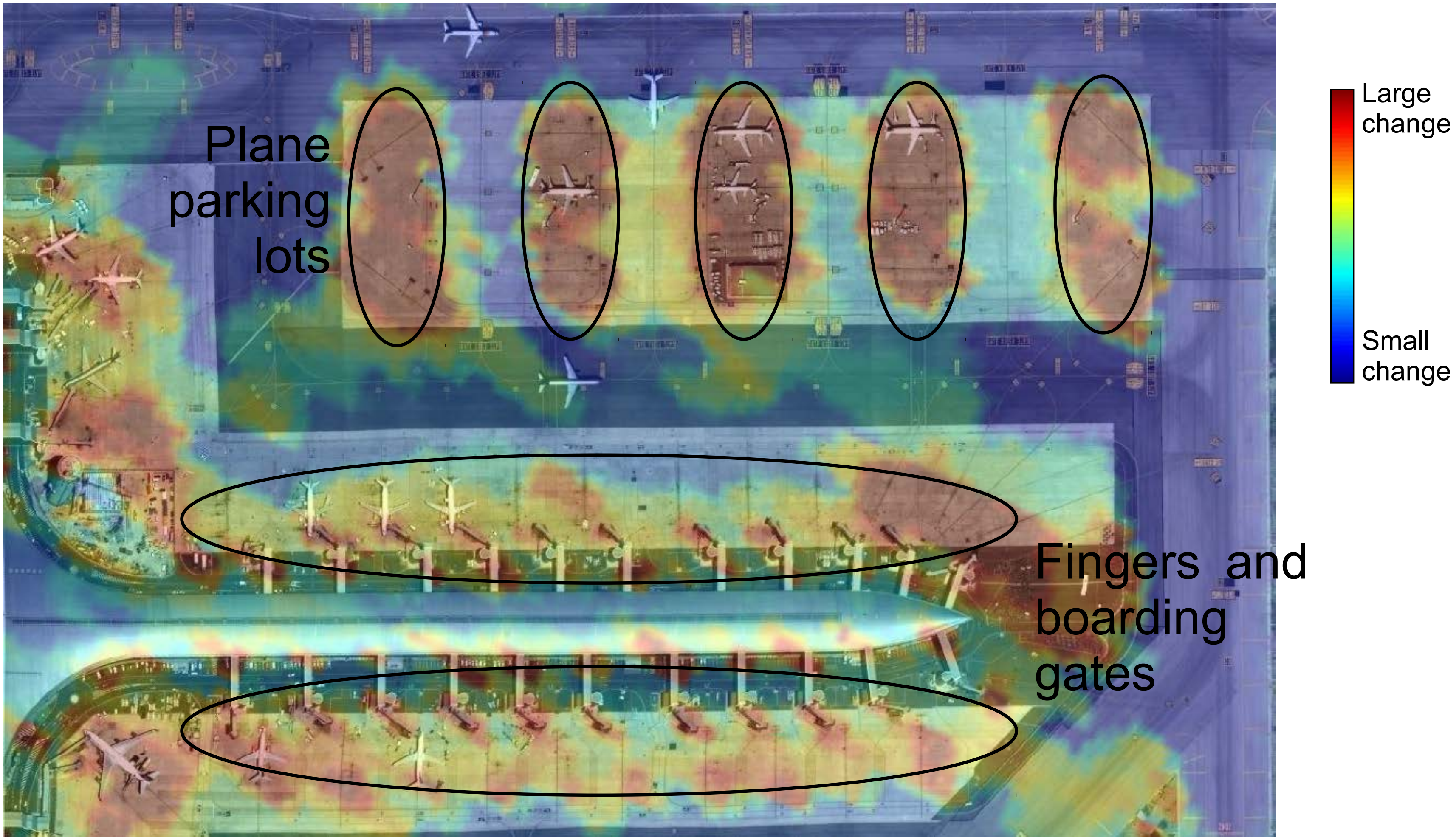


Temporal stability measure $\delta_p = -3\ dB$

Google earth

Temporal stability results

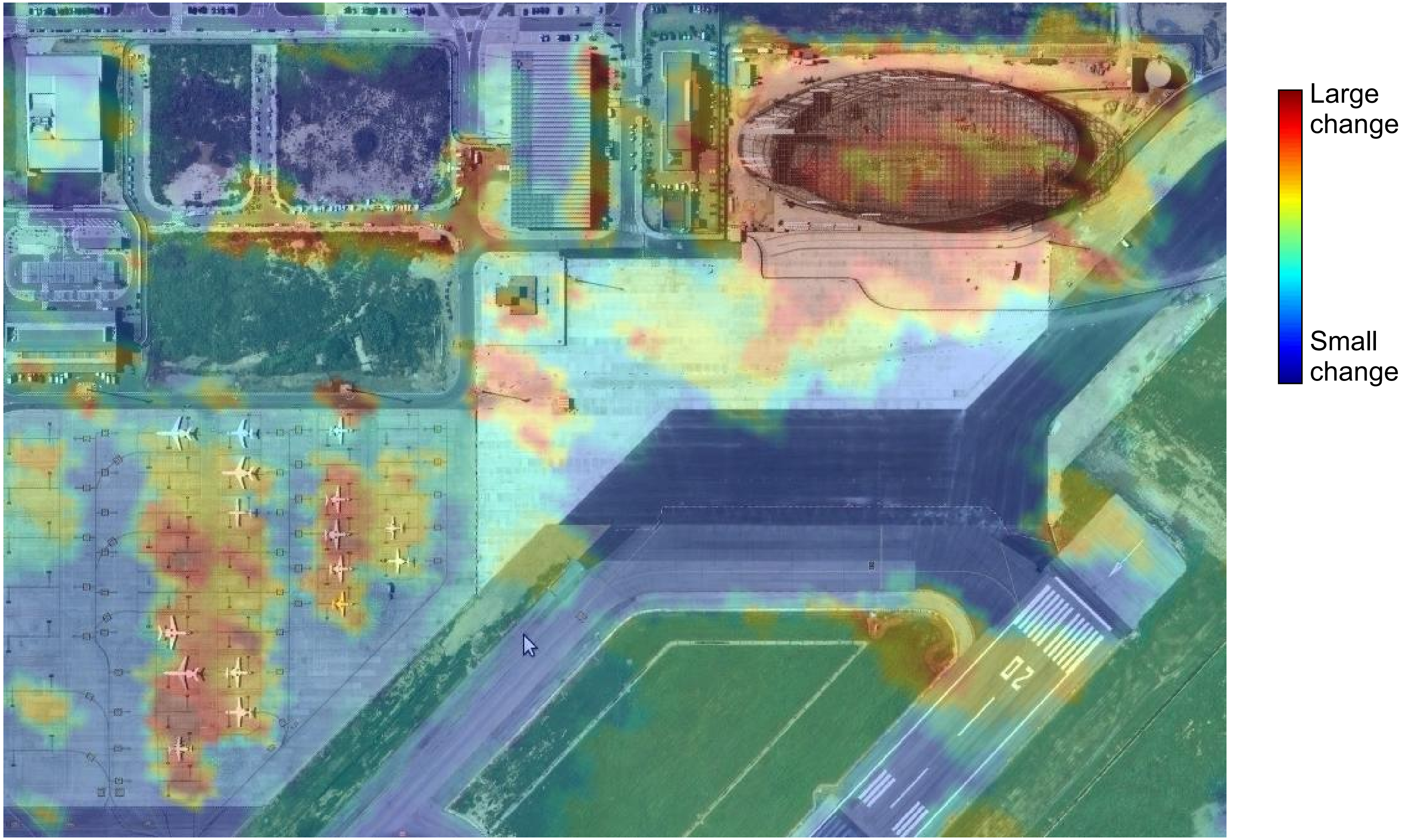
Detail of the geo-coded results for the T1 airport area, Barcelona, Spain:



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

Temporal stability results

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

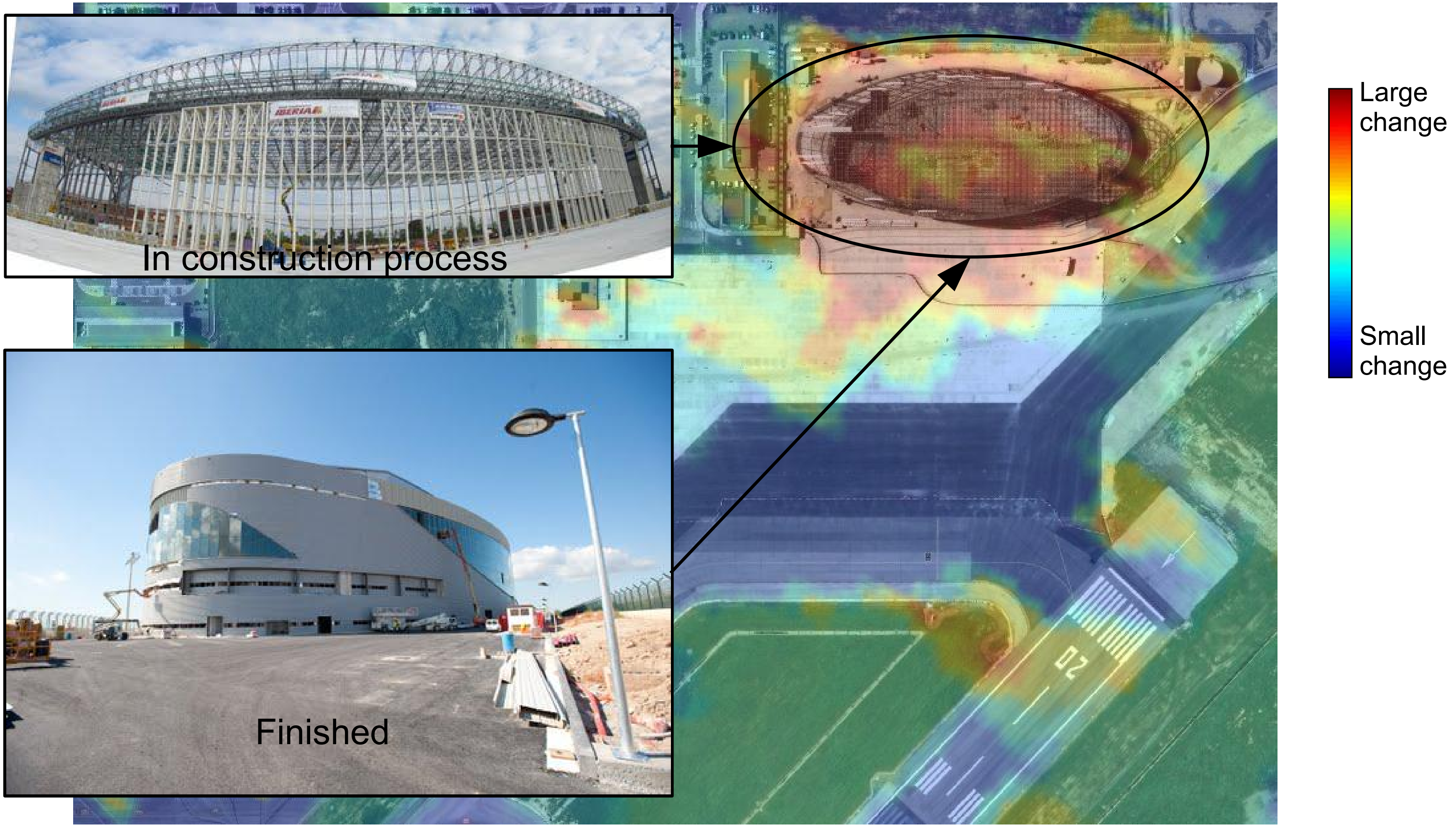


Temporal stability measure $\delta_p = -3\ dB$

Google earth

Temporal stability results

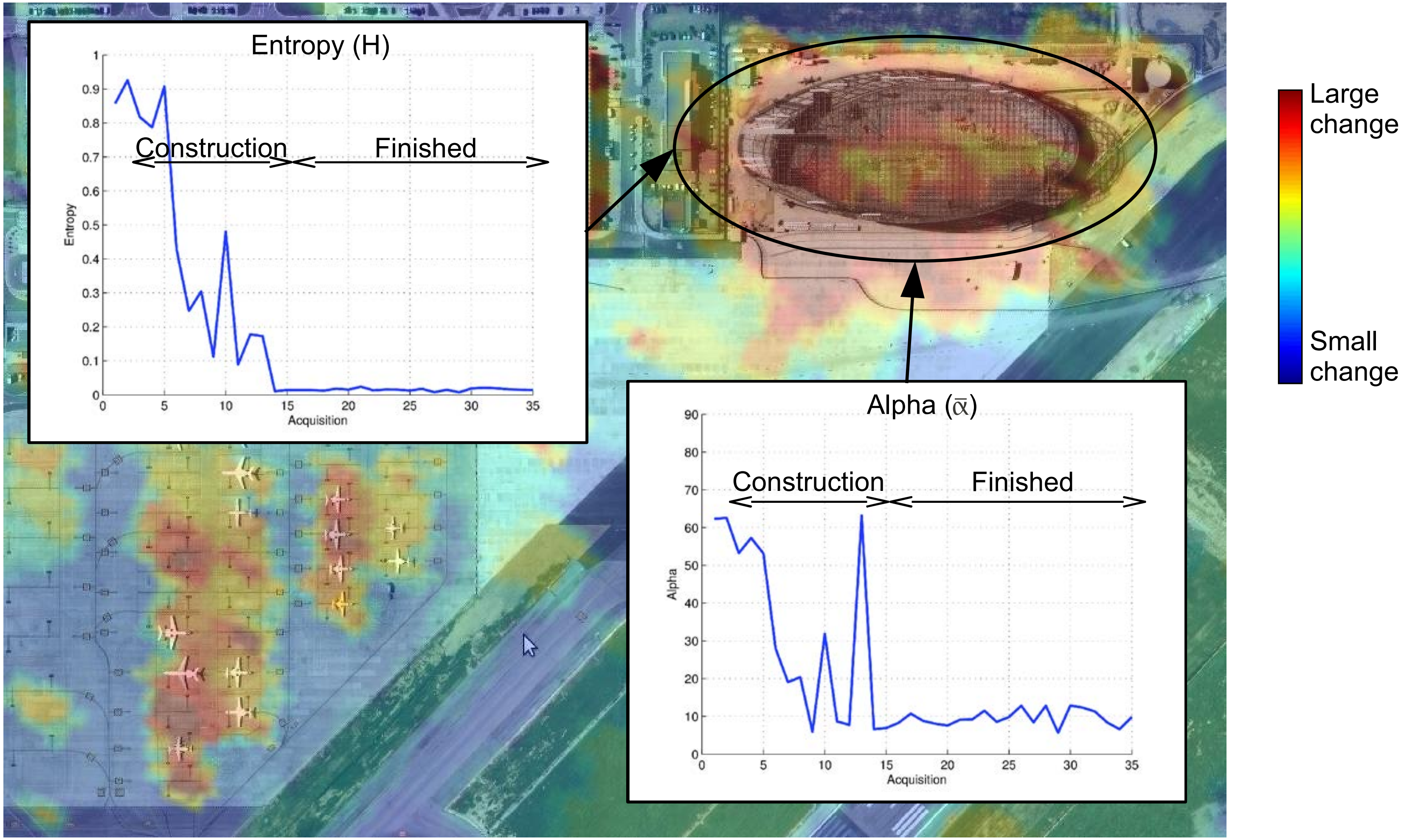
Detail of the geo-coded results for the Barcelona airport hangar area:



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

Panoramio Google earth

The polarimetric characterization of the temporal evolution may be performed:

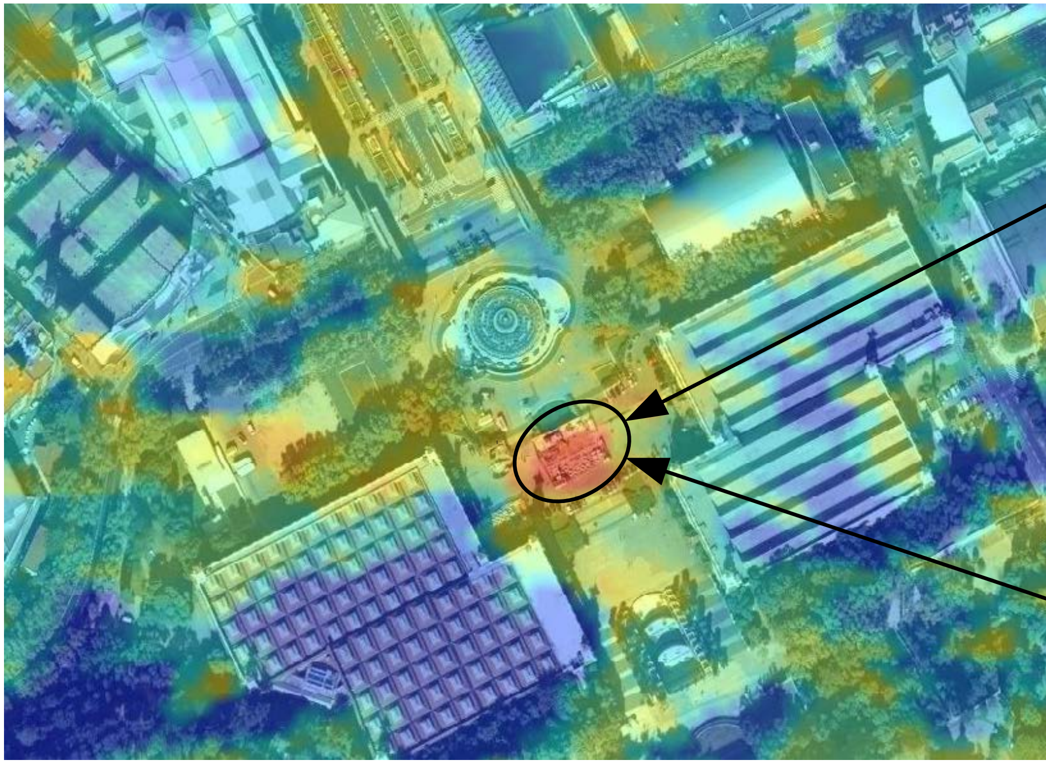


Temporal stability measure $\delta_p = -3\ dB$

Google earth

Temporal stability results

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



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

Before

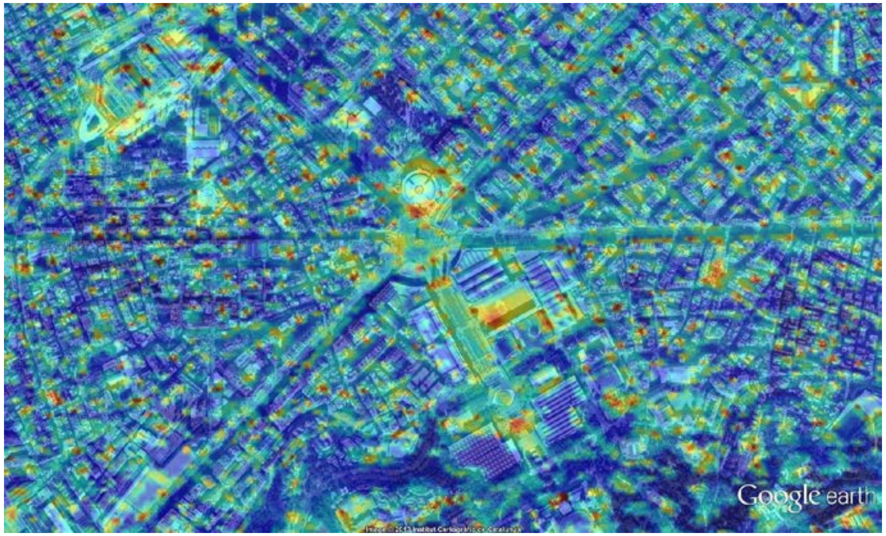
After

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

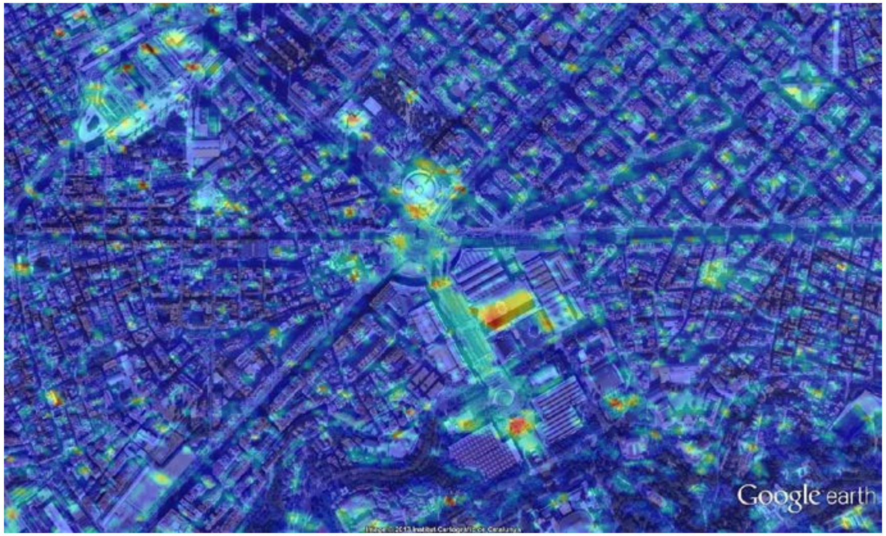
- Due to the multi-scale nature of the BPT this technique can detect very localized changes

Panoramio Google earth

Temporal stability and similarity 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

Conclusions

- The BPT may be extended to process PolSAR time series with two different target characterization approaches: polarimetric response (Space-Time BPT) and polarimetric temporal evolution (Temporal Evolution BPT)

- The ST BPT produces 3-dimensional regions in space and time having similar polarimetric response. It may be better to characterize regions having not fixed contours over time and may produce a better estimation of polarimetric response by combining samples of different acquisitions

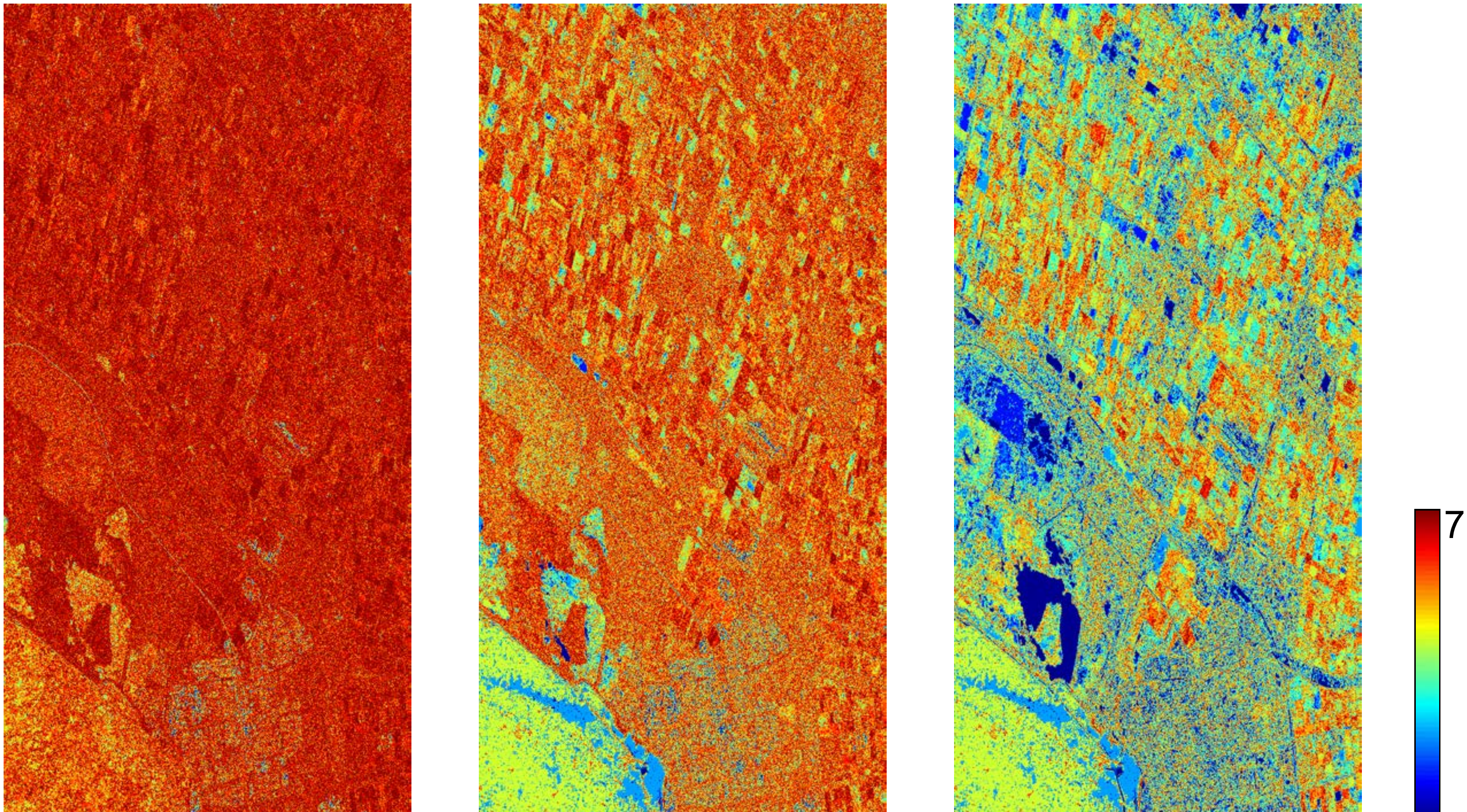
- On TE BPT spatial regions having similar polarimetric temporal evolution are obtained. It results in a better estimation of the spatially fixed contours and, additionally, the interferometric information may be exploited

- These BPT structures may be employed to analyze and characterize the scene evolution over time. The proposed temporal stability measure is able to detect large and localized scene changes

Thank you for
your atention!

Temporal number of changes

Analyzing the contours on the temporal dimension of the Space-Time BPT, a map can be generated representing the number of changes:



$\delta_p = -5\ dB$ $\delta_p = -3\ dB$ $\delta_p = -1\ dB$

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Temporal stability results

Detail of an industrial area in Castellbisbal, Barcelona, Spain:


2009

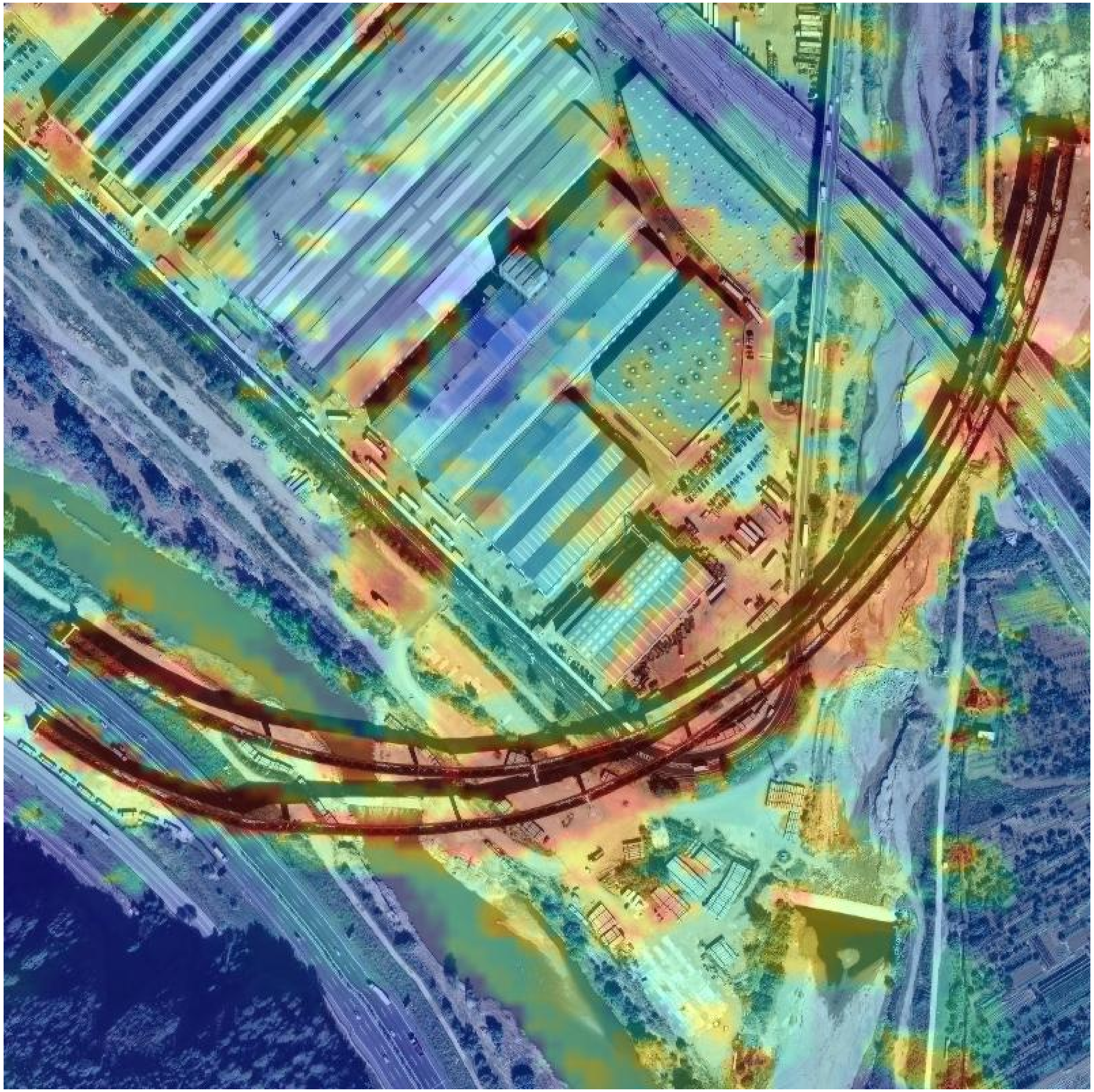

2010


2011

- Two bridges have been constructed over the Llobregat river during the temporal span of the dataset

Google earth

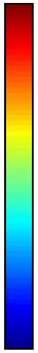
Temporal stability results



Temporal stability measure

$$\delta_p = -3\ dB$$

Detail of the geo-coded results for a bridge construction area in Castellbisbal, Barcelona, Spain

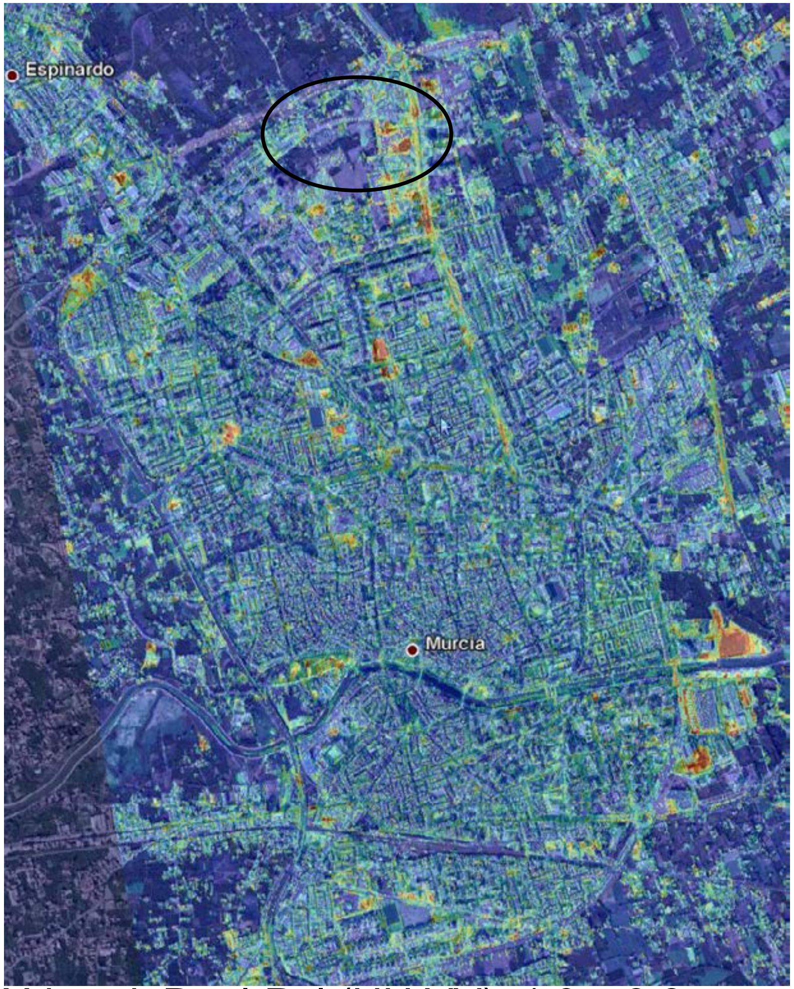


The two bridges are correctly identified, appearing in red color

Google earth

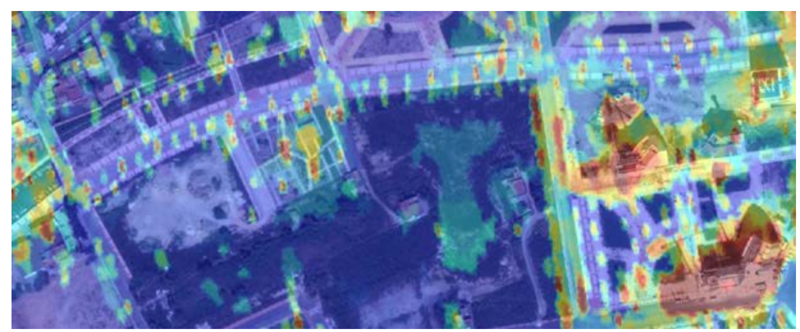
Temporal stability results

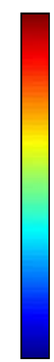
Geo-coded Dual-Pol TerraSAR-X temporal stability results, Murcia, Spain



2008

2012





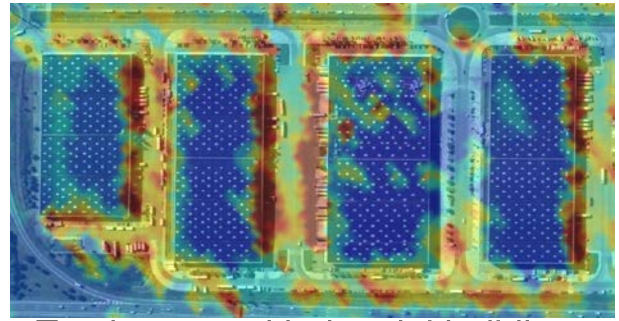
X-band, Dual-Pol (HH,VV), 1.9 x 6.6m res.
19th, February 2009 – 24th, January 2011
49 acquisitions, 3000 x 3000 pixel crop

Google earth

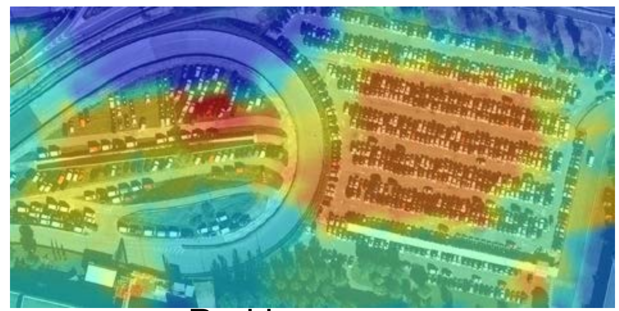
Data provided by DLR in the framework of the scientific project GEO0389

Temporal stability results

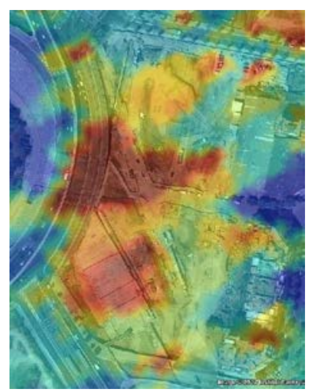
Detail of the geo-coded results over Barcelona, Spain



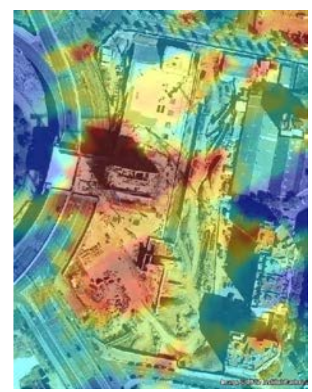
Trucks around industrial buildings



Parking areas

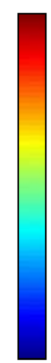


2010



2011

Larger changes detected are associated with human activities, construction and transportation, which change completely the geometry of the scene producing substantial variations in terms of the PolSAR response



$$\delta_p = -3\ dB$$

Google earth

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Department of Signal Theory and Communications

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

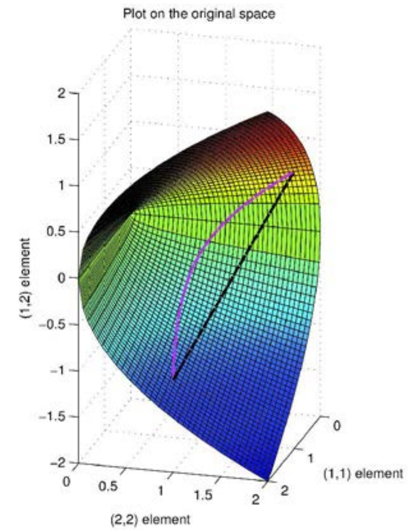
Diagonal: $$d_{dw}(A,B)=\left(\sum_{i=1}^{N}\left(\frac{Z_{A_{ii}}+Z_{B_{ii}}}{Z_{A_{ii}}Z_{B_{ii}}}\right)\right)\cdot(n_A+n_B)$$

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

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

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

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

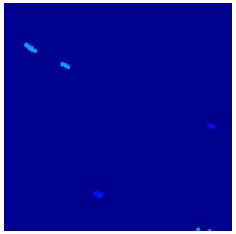


Vessel change detection

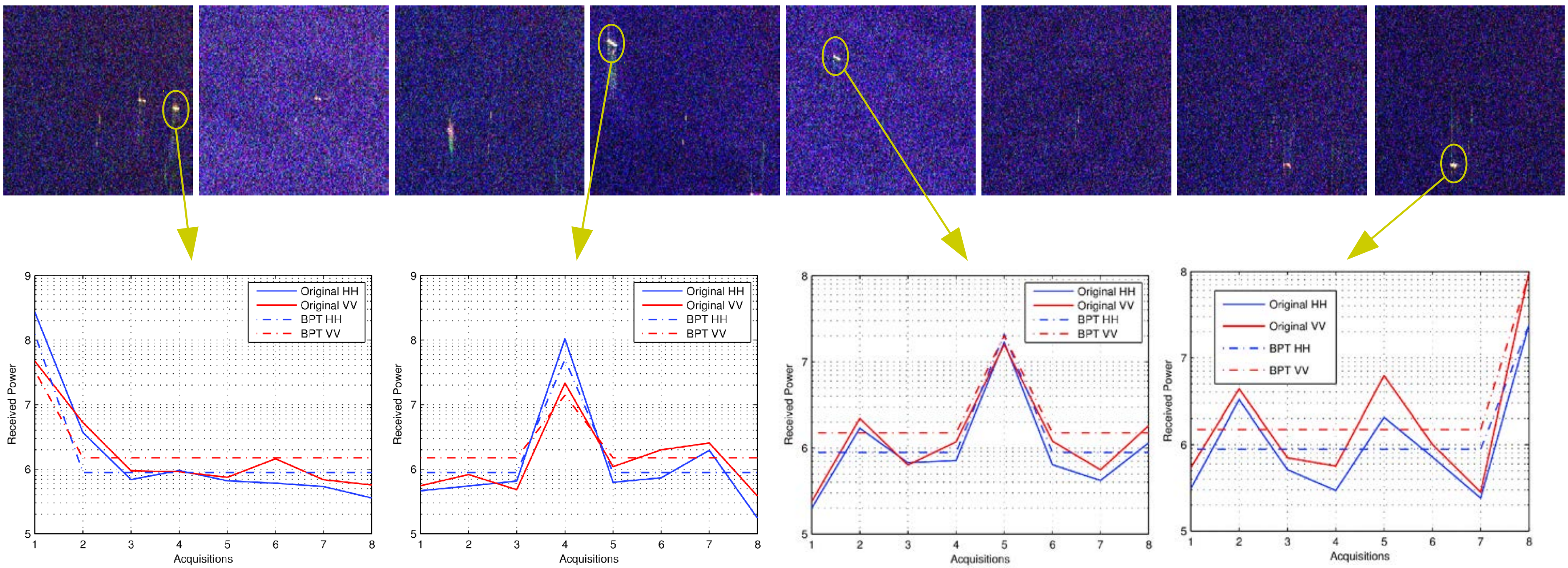
Detail of a 270 by 270 pixel sea area containing vessels

- Original Pauli images (Flevoland dataset)
  Acquisition number: $|S_{hh}+S_{vv}|$, $|S_{hv}+S_{vh}|$, $|S_{hh}-S_{vv}|$

- Changes detected



1 2 3 4 5 6 7 8



ML 3x3 has been applied over plots

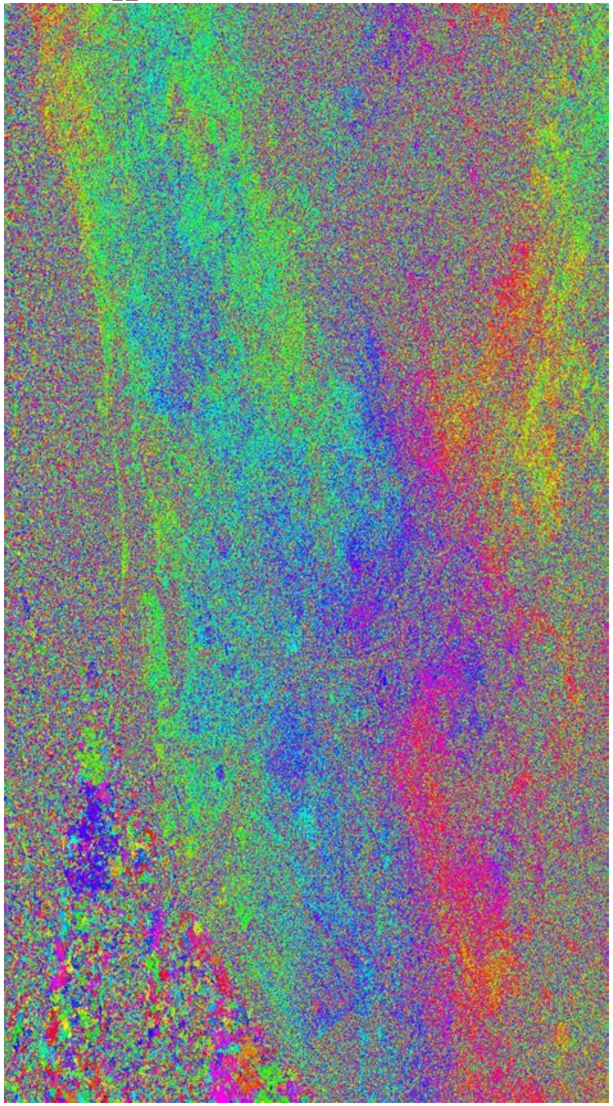
$$d_{dw},\ \delta_p = -1\,dB$$

- The sea area is filtered as one region in the temporal dimension but small details as the vessels are preserved

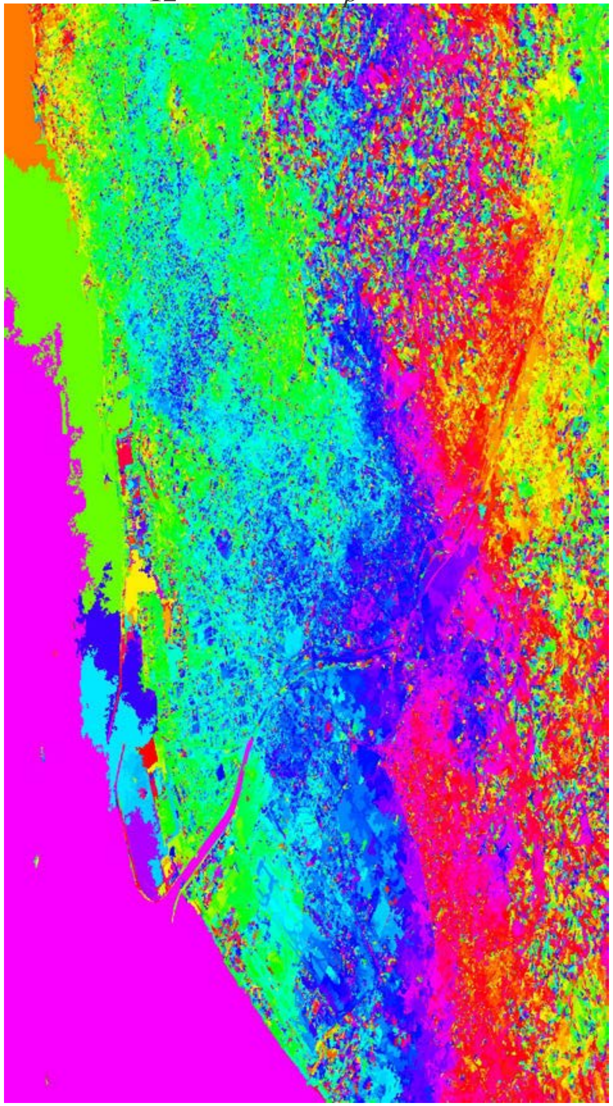
Interferometric info preservation (TE BPT)

BPT phase

$\Omega_{12}(1,1)$ original phase



$\Omega_{12}(1,1), \delta_p = 0\text{dB}$



$\Omega_{12}(1,1), \delta_p = 2\text{dB}$