

# Cloud based spatio-temporal analysis of change in sequences of Sentinel images

Allan A. Nielsen<sup>1</sup>, Morton J. Canty<sup>2</sup>, Henning Skriver<sup>1</sup>,  
Knut Conradsen<sup>1</sup>

<sup>1</sup>Technical University of Denmark

<sup>2</sup>Research Center Jülich, Germany

ESA Big Data from Space, Munich, Germany, 19-21 Feb 2019



# Outline

- Optical data, bi-temporal change detection and normalization.

# Outline

- Optical data, bi-temporal change detection and normalization.
- Radar data, PolSAR, multi-temporal change detection, visualization.



# Outline

- Optical data, bi-temporal change detection and normalization.
- Radar data, PolSAR, multi-temporal change detection, visualization.
- Computer implementations, including cloud.

# Outline

- Optical data, bi-temporal change detection and normalization.
- Radar data, PolSAR, multi-temporal change detection, visualization.
- Computer implementations, including cloud.
- Ongoing work, here on latest developments (no time to go into optical part).

# Optical data

- $m$  dimensional  $\mathbf{X}$  at  $t_1$  and  $\mathbf{Y}$  at  $t_2$  with reflected or emitted EM signal.

# Optical data

- $m$  dimensional  $\mathbf{X}$  at  $t_1$  and  $\mathbf{Y}$  at  $t_2$  with reflected or emitted EM signal.
- Wavelengths  $\lambda$  typically VIS (400-700 nm), NIR, SWIR and TIR (3-15  $\mu\text{m}$ , typically 10-12  $\mu\text{m}$ ).

# Optical data

- $m$  dimensional  $\mathbf{X}$  at  $t_1$  and  $\mathbf{Y}$  at  $t_2$  with reflected or emitted EM signal.
- Wavelengths  $\lambda$  typically VIS (400-700 nm), NIR, SWIR and TIR (3-15  $\mu\text{m}$ , typically 10-12  $\mu\text{m}$ ).
- Space- or airborne imaging instruments.

# Optical data

- $m$  dimensional  $\mathbf{X}$  at  $t_1$  and  $\mathbf{Y}$  at  $t_2$  with reflected or emitted EM signal.
- Wavelengths  $\lambda$  typically VIS (400-700 nm), NIR, SWIR and TIR (3-15  $\mu\text{m}$ , typically 10-12  $\mu\text{m}$ ).
- Space- or airborne imaging instruments.
- Detect change in graytone images ( $m = 1$ ): after normalization subtract,  $\mathbf{X} - \mathbf{Y}$ . Zero is no-change, large positive and large negative values are change.

# Optical data

- Idea to detect change in bitemporal multispectral images  $\mathbf{X}$  and  $\mathbf{Y}$  with  $m$  spectral bands: after normalization, do bandwise subtractions  $\mathbf{X} - \mathbf{Y}$  and maybe concentrate change information, e.g.,  $\mathbf{v}^T(\mathbf{X} - \mathbf{Y})$  by PCA or SVD.

# Optical data

- Idea to detect change in bitemporal multispectral images  $\mathbf{X}$  and  $\mathbf{Y}$  with  $m$  spectral bands: after normalization, do bandwise subtractions  $\mathbf{X} - \mathbf{Y}$  and maybe concentrate change information, e.g.,  $\mathbf{v}^T(\mathbf{X} - \mathbf{Y})$  by PCA or SVD.
- Better idea: (no normalization) do CCA followed by pairwise subtractions of CVs and maybe concentrate change information (MAD method). CCA orders the image bands according to similarity (correlation) rather than spectral wavelength. The differences between corresponding pairs of canonical variates are termed the MAD variates.

# Optical data

- Idea to detect change in bitemporal multispectral images  $\mathbf{X}$  and  $\mathbf{Y}$  with  $m$  spectral bands: after normalization, do bandwise subtractions  $\mathbf{X} - \mathbf{Y}$  and maybe concentrate change information, e.g.,  $\mathbf{v}^T(\mathbf{X} - \mathbf{Y})$  by PCA or SVD.
- Better idea: (no normalization) do CCA followed by pairwise subtractions of CVs and maybe concentrate change information (MAD method). CCA orders the image bands according to similarity (correlation) rather than spectral wavelength. The differences between corresponding pairs of canonical variates are termed the MAD variates.
- Specifically, a MAD variate  $Z$  is

$$Z = \mathbf{a}^T \mathbf{X} - \mathbf{b}^T \mathbf{Y}$$

where  $\mathbf{a}$  and  $\mathbf{b}$  are the eigenvectors from the CCA.



# Optical data

- Thus  $\mathbf{a}^T \mathbf{X}$  is a canonical variate for  $t_1$  and  $\mathbf{b}^T \mathbf{Y}$  is a canonical variate for  $t_2$ . We have  $m$  uncorrelated canonical variates (CVs) with mean value zero and variance one from both time points, the correlation between corresponding pairs of CVs is  $\rho$  (termed the canonical correlation which is maximized in CCA), and we have  $m$  uncorrelated MAD variates with variance  $2(1 - \rho)$ .

# Optical data

- Thus  $\mathbf{a}^T \mathbf{X}$  is a canonical variate for  $t_1$  and  $\mathbf{b}^T \mathbf{Y}$  is a canonical variate for  $t_2$ . We have  $m$  uncorrelated canonical variates (CVs) with mean value zero and variance one from both time points, the correlation between corresponding pairs of CVs is  $\rho$  (termed the canonical correlation which is maximized in CCA), and we have  $m$  uncorrelated MAD variates with variance  $2(1 - \rho)$ .
- Even better: iterate CCA to obtain an increasingly better background of no-change against which to detect change.

# Optical data

- In each iteration the values of each image pixel  $j$  in  $\mathbf{X}$  and  $\mathbf{Y}$  are weighted by  $w_j$  which is the current estimate of the no-change probability and the image statistics (mean and covariance matrices) are re-sampled.

# Optical data

- In each iteration the values of each image pixel  $j$  in  $\mathbf{X}$  and  $\mathbf{Y}$  are weighted by  $w_j$  which is the current estimate of the no-change probability and the image statistics (mean and covariance matrices) are re-sampled.
- Since the MAD variates for the no-change observations are approximately Gaussian and uncorrelated, the sum of their squared values (after normalization to unit variance)

$$C^2 = \sum_{i=1}^m \frac{Z_i^2}{2(1 - \rho_i)}$$

will ideally follow a chi squared distribution with  $m$  degrees of freedom,  $C^2 \sim \chi^2(m)$ .



# Optical data

- The probability of finding a smaller value of  $C^2$  is approximated by ( $c^2$  is the actually observed value of  $C^2$ )

$$P\{C^2 \leq c^2\} \simeq P\{\chi^2(m) \leq c^2\}.$$

# Optical data

- The probability of finding a smaller value of  $C^2$  is approximated by ( $c^2$  is the actually observed value of  $C^2$ )

$$P\{C^2 \leq c^2\} \simeq P\{\chi^2(m) \leq c^2\}.$$

- Hence the no-change probability used as weight  $w_j$  in the iterations is

$$w_j = 1 - P\{\chi^2(m) \leq c^2\}.$$

# Optical data

- The probability of finding a smaller value of  $C^2$  is approximated by ( $c^2$  is the actually observed value of  $C^2$ )

$$P\{C^2 \leq c^2\} \simeq P\{\chi^2(m) \leq c^2\}.$$

- Hence the no-change probability used as weight  $w_j$  in the iterations is

$$w_j = 1 - P\{\chi^2(m) \leq c^2\}.$$

- Iterations continue until the canonical correlations stop changing (or a maximum number of iterations is reached).



# Optical data

- The probability of finding a smaller value of  $C^2$  is approximated by ( $c^2$  is the actually observed value of  $C^2$ )

$$P\{C^2 \leq c^2\} \simeq P\{\chi^2(m) \leq c^2\}.$$

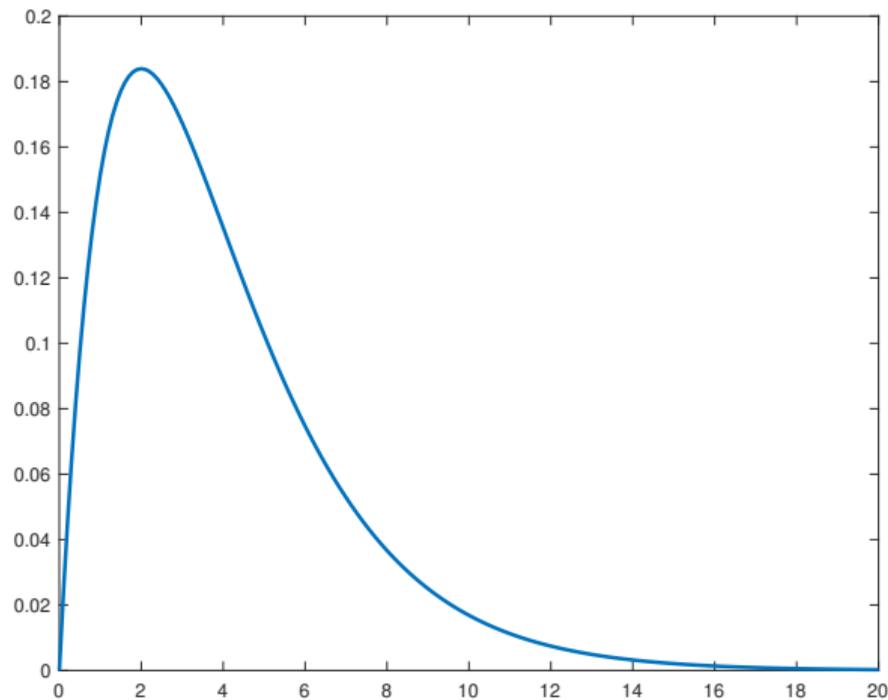
- Hence the no-change probability used as weight  $w_j$  in the iterations is

$$w_j = 1 - P\{\chi^2(m) \leq c^2\}.$$

- Iterations continue until the canonical correlations stop changing (or a maximum number of iterations is reached).
- Orthogonality of the CVs/MADs: discrimination between types of change.



# $\chi^2$ distribution



$\chi^2$  distribution with 4 degrees of freedom.

# S-2, 4 Apr and 7 July 2017, forest fire, GEE

Google Earth Engine

Search places and datasets...

Code Docs Assets

Filter scripts... NEW

Owner (1)  
users/AllanANIelsen/default

Writer  
No accessible repositories.

Reader  
No accessible repositories.

Examples

Link a1f9a4a55783c0e958941e56f150594c

Imports (1 entry)  
var image: Image users/mortcanty/imad/imad\_coimbra1 (5 bands)

```

1 Map.centerObject(image,10);
2 Map.addLayer(image.select('MAD1','MAD3','MAD4'),{min:[-5], max:[5]},'MAD
3

```

Inspector Console Tasks

Use print(...) to write to this console.

Layers

Google

5 km

imagery © Report a map

DTU

# S-2, 20 and 30 Aug 2017, hurricane Harvey, GEE

Google Earth Engine

Search places and datasets...

Link b19e906e713448c862e512ccc8595b24

Imports (1 entry)

- var image: Image users/mortcanty/imad/simonton1 (18 bands)

```

1 Map.centerObject(image,12);
2 Map.addLayer(image.select('B2','B3','B4',{min:[0,0,0],max:[2000]}),'IM1 RGB');
3 Map.addLayer(image.select('B2_1','B3_1','B4_1',{min:[0,0,0],max:[2000]}),'IM2 RGB');
4 Map.addLayer(image.select('Ch12',{min:0,max:5000}),'Ch12');
5

```

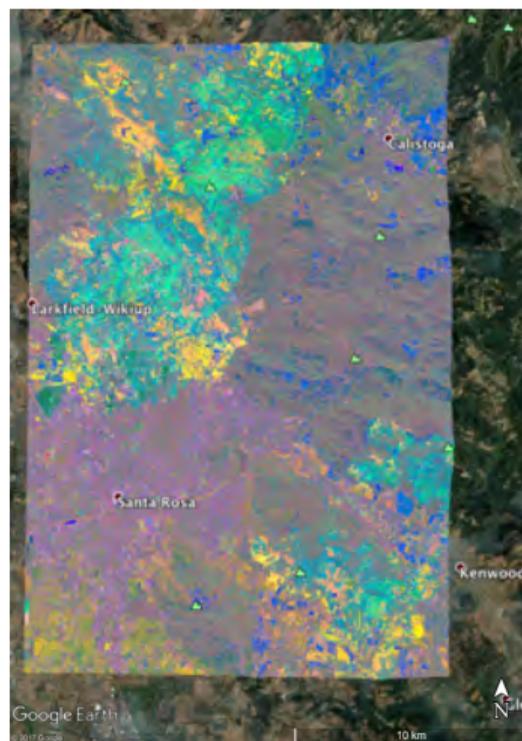
Inspector Console Task

Use print(...) to write to this console.

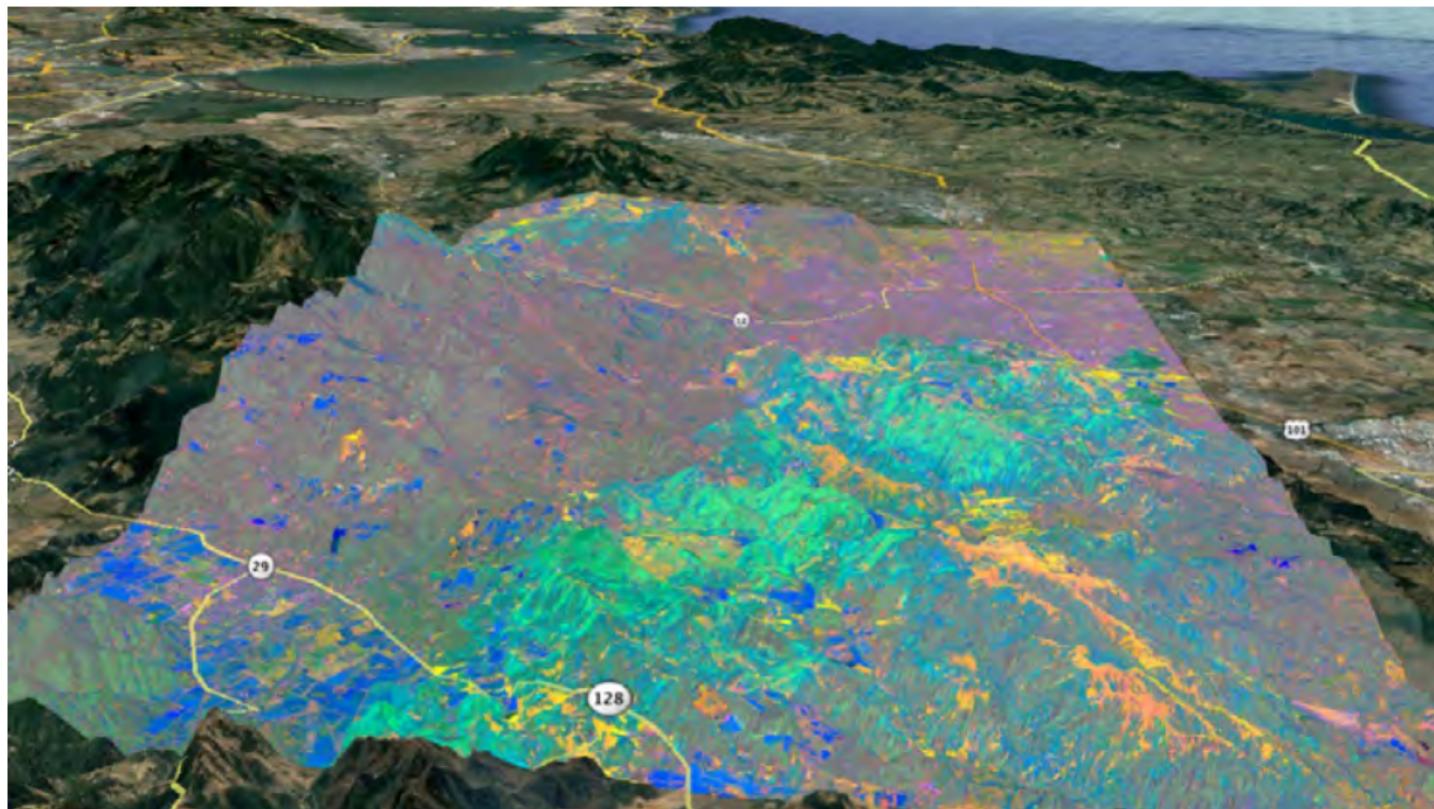
Layers

2 km

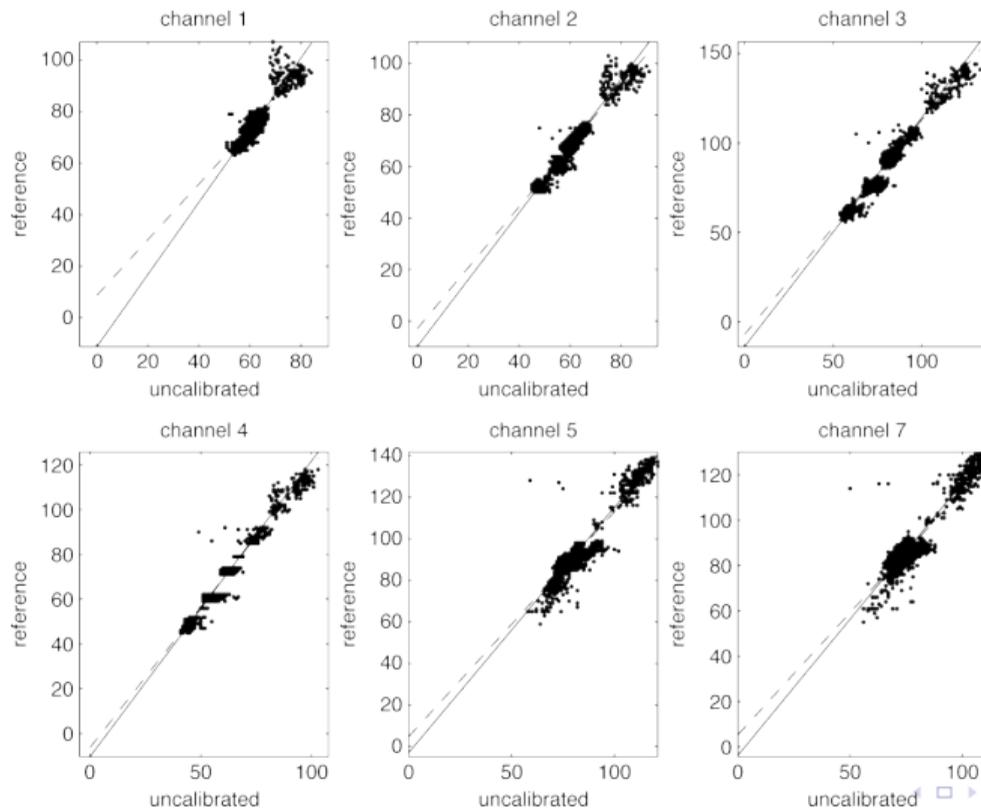
# S-2, 5 Oct and 1 Nov, Tubbs Fire, GEE



# S-2, 5 Oct and 1 Nov, Tubbs Fire, GEE



# Landsat TM, normalization



# Polarimetric SAR data

- Space- or airborne imaging synthetic aperture radar, SAR.  $\lambda$  typically 3-100 cm (all-weather, day-and-night capability).

# Polarimetric SAR data

- Space- or airborne imaging synthetic aperture radar, SAR.  $\lambda$  typically 3-100 cm (all-weather, day-and-night capability).
- PolSAR: transmit and receive horizontally and vertically:  $S_{hh}$ ,  $S_{hv}$ ,  $S_{vh}$ ,  $S_{vv}$ .

# Polarimetric SAR data

- Space- or airborne imaging synthetic aperture radar, SAR.  $\lambda$  typically 3-100 cm (all-weather, day-and-night capability).
- PolSAR: transmit and receive horizontally and vertically:  $S_{hh}$ ,  $S_{hv}$ ,  $S_{vh}$ ,  $S_{vv}$ .
- Reciprocity:  $S_{hv} = S_{vh}$ :  $\mathbf{s} = [S_{hh} \ S_{hv} \ S_{vv}]^T$ .

# Polarimetric SAR data

- Space- or airborne imaging synthetic aperture radar, SAR.  $\lambda$  typically 3-100 cm (all-weather, day-and-night capability).
- PolSAR: transmit and receive horizontally and vertically:  $S_{hh}$ ,  $S_{hv}$ ,  $S_{vh}$ ,  $S_{vv}$ .
- Reciprocity:  $S_{hv} = S_{vh}$ :  $\mathbf{s} = [S_{hh} \ S_{hv} \ S_{vv}]^T$ .
- Coherent pulses: speckle, multilooking.

# Polarimetric SAR data

- Space- or airborne imaging synthetic aperture radar, SAR.  $\lambda$  typically 3-100 cm (all-weather, day-and-night capability).
- PolSAR: transmit and receive horizontally and vertically:  $S_{hh}, S_{hv}, S_{vh}, S_{vv}$ .
- Reciprocity:  $S_{hv} = S_{vh}$ :  $\mathbf{s} = [S_{hh} \ S_{hv} \ S_{vv}]^T$ .
- Coherent pulses: speckle, multilooking.
- In the covariance matrix representation each pixel at each time point is a matrix  $\langle \mathbf{C} \rangle$ ;  $\langle \mathbf{C} \rangle \times \text{ENL} \sim$  complex Wishart for fully developed speckle

$$\begin{aligned} \langle \mathbf{C} \rangle_{full} &= \langle \mathbf{s} \mathbf{s}^H \rangle \\ &= \begin{bmatrix} \langle S_{hh} S_{hh}^* \rangle & \langle S_{hh} S_{hv}^* \rangle & \langle S_{hh} S_{vv}^* \rangle \\ \langle S_{hv} S_{hh}^* \rangle & \langle S_{hv} S_{hv}^* \rangle & \langle S_{hv} S_{vv}^* \rangle \\ \langle S_{vv} S_{hh}^* \rangle & \langle S_{vv} S_{hv}^* \rangle & \langle S_{vv} S_{vv}^* \rangle \end{bmatrix}. \end{aligned}$$



# Polarimetric SAR data

- Detect change in a series of  $k$  full/quad pol, multi-looked SAR data sets in the covariance representation.

# Polarimetric SAR data

- Detect change in a series of  $k$  full/quad pol, multi-looked SAR data sets in the covariance representation.
- Omnibus likelihood ratio test statistic  $Q$  for the equality of several variance-covariance matrices following the complex Wishart distribution;  $Q$  establishes if change occurs.

# Polarimetric SAR data

- Detect change in a series of  $k$  full/quad pol, multi-looked SAR data sets in the covariance representation.
- Omnibus likelihood ratio test statistic  $Q$  for the equality of several variance-covariance matrices following the complex Wishart distribution;  $Q$  establishes if change occurs.
- Associated  $p$ -value for  $Q$  under equality hypothesis.

# Polarimetric SAR data

- Detect change in a series of  $k$  full/quad pol, multi-looked SAR data sets in the covariance representation.
- Omnibus likelihood ratio test statistic  $Q$  for the equality of several variance-covariance matrices following the complex Wishart distribution;  $Q$  establishes if change occurs.
- Associated  $p$ -value for  $Q$  under equality hypothesis.
- Factorization of  $Q = \prod_2^k R_j$ ; if change occurs,  $R_j$  establishes when.

# Polarimetric SAR data

- Detect change in a series of  $k$  full/quad pol, multi-looked SAR data sets in the covariance representation.
- Omnibus likelihood ratio test statistic  $Q$  for the equality of several variance-covariance matrices following the complex Wishart distribution;  $Q$  establishes if change occurs.
- Associated  $p$ -value for  $Q$  under equality hypothesis.
- Factorization of  $Q = \prod_2^k R_j$ ; if change occurs,  $R_j$  establishes when.
- Associated  $p$ -value for  $R_j$ .



# Polarimetric SAR data, full

- $H_0$  : no change between all  $k$  time points ( $\boldsymbol{\Sigma}_1 = \boldsymbol{\Sigma}_2 = \dots = \boldsymbol{\Sigma}_k$ )

$$\ln Q = n \left\{ pk \ln k + \sum_{i=1}^k \ln |\mathbf{X}_i| - k \ln \left| \sum_{i=1}^k \mathbf{X}_i \right| \right\} \quad (1)$$

$p = 3$ ,  $\mathbf{X}_i = n \langle \mathbf{C} \rangle_{full}$ ,  $n$  is ENL, the equivalent number of looks, and  $|\cdot|$  denotes the determinant.<sup>1</sup>

<sup>1</sup>K. Conradsen, A. A. Nielsen, and H. Skriver (2016), Determining the points of change in time series of polarimetric SAR data. *IEEE Transactions on Geoscience and Remote Sensing* **54**(5), 3007-3024. <http://www.imm.dtu.dk/pubdb/p.php?6825>

# Polarimetric SAR data, full

- $H_0$  : no change between all  $k$  time points ( $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_k$ )

$$\ln Q = n \left\{ pk \ln k + \sum_{i=1}^k \ln |\mathbf{X}_i| - k \ln \left| \sum_{i=1}^k \mathbf{X}_i \right| \right\} \quad (1)$$

$p = 3$ ,  $\mathbf{X}_i = n \langle \mathbf{C} \rangle_{full}$ ,  $n$  is ENL, the equivalent number of looks, and  $|\cdot|$  denotes the determinant.<sup>1</sup>

- Under  $H_0$ ,  $-2 \ln Q \sim \chi^2((k-1)f)$  :  
 $P\{-2 \ln Q \leq z\} = P\{\chi^2((k-1)f) \leq z\}$ ,  $z = -2 \ln q_{obs}$ ,  $f = p^2 = 9$ .

<sup>1</sup>K. Conradsen, A. A. Nielsen, and H. Skriver (2016), Determining the points of change in time series of polarimetric SAR data. *IEEE Transactions on Geoscience and Remote Sensing* **54**(5), 3007-3024. <http://www.imm.dtu.dk/pubdb/p.php?6825>

# Polarimetric SAR data, full

- $H_0$  : no change between all  $k$  time points ( $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_k$ )

$$\ln Q = n \left\{ pk \ln k + \sum_{i=1}^k \ln |\mathbf{X}_i| - k \ln \left| \sum_{i=1}^k \mathbf{X}_i \right| \right\} \quad (1)$$

$p = 3$ ,  $\mathbf{X}_i = n \langle \mathbf{C} \rangle_{full}$ ,  $n$  is ENL, the equivalent number of looks, and  $|\cdot|$  denotes the determinant.<sup>1</sup>

- Under  $H_0$ ,  $-2 \ln Q \sim \chi^2((k-1)f)$  :  
 $P\{-2 \ln Q \leq z\} = P\{\chi^2((k-1)f) \leq z\}$ ,  $z = -2 \ln q_{obs}$ ,  $f = p^2 = 9$ .
- Better approximation for  $P\{-2\rho \ln Q \leq z\}$  ( $\rho$  is auxiliary variable).

<sup>1</sup>K. Conradsen, A. A. Nielsen, and H. Skriver (2016), Determining the points of change in time series of polarimetric SAR data. *IEEE Transactions on Geoscience and Remote Sensing* **54**(5), 3007-3024. <http://www.imm.dtu.dk/pubdb/p.php?6825>

# Polarimetric SAR data, full

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\Sigma_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\Sigma_1 = \Sigma_2 = \dots = \Sigma_{j-1}$ ,  $\Sigma_j = \Sigma_1$

$$\ln R_j = n\{p(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (2)$$

# Polarimetric SAR data, full

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\mathbf{\Sigma}_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_{j-1}$ ,  $\mathbf{\Sigma}_j = \mathbf{\Sigma}_1$

$$\ln R_j = n\{p(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (2)$$

- Under  $H_{0,j}$ ,  $-2 \ln R_j \sim \chi^2(f)$ :  
 $P\{-2 \ln R_j \leq z_j\} = P\{\chi^2(f) \leq z_j\}$ ,  $z_j = -2 \ln r_{j,\text{obs}}$ ,  $f = p^2 = 9$ .

# Polarimetric SAR data, full

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\mathbf{\Sigma}_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_{j-1}$ ,  $\mathbf{\Sigma}_j = \mathbf{\Sigma}_1$

$$\ln R_j = n\{\rho(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (2)$$

- Under  $H_{0,j}$ ,  $-2 \ln R_j \sim \chi^2(f)$ :  
 $P\{-2 \ln R_j \leq z_j\} = P\{\chi^2(f) \leq z_j\}$ ,  $z_j = -2 \ln r_{j,\text{obs}}$ ,  $f = p^2 = 9$ .
- Better approximation for  $P\{-2\rho_j \ln R_j \leq z_j\}$  ( $\rho_j$  are auxiliary variables).

# Polarimetric SAR data, full

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\mathbf{\Sigma}_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_{j-1}$ ,  $\mathbf{\Sigma}_j = \mathbf{\Sigma}_1$

$$\ln R_j = n\{p(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (2)$$

- Under  $H_{0,j}$ ,  $-2 \ln R_j \sim \chi^2(f)$ :  
 $P\{-2 \ln R_j \leq z_j\} = P\{\chi^2(f) \leq z_j\}$ ,  $z_j = -2 \ln r_{j,\text{obs}}$ ,  $f = p^2 = 9$ .
- Better approximation for  $P\{-2\rho_j \ln R_j \leq z_j\}$  ( $\rho_j$  are auxiliary variables).
- $R_j$  constitute a factorization  $Q = \prod_{j=2}^k R_j$  or

$$\ln Q = \sum_{i=2}^k \ln R_i. \quad (3)$$



# Polarimetric SAR data, dual

- For dual polarimetry, we have for example  $\langle \mathbf{C} \rangle$ ;  $\langle \mathbf{C} \rangle \times \text{ENL} \sim$  complex Wishart for fully developed speckle

$$\langle \mathbf{C} \rangle_{dual} = \begin{bmatrix} \langle S_{vv} S_{vv}^* \rangle & \langle S_{vv} S_{vh}^* \rangle \\ \langle S_{vh} S_{vv}^* \rangle & \langle S_{vh} S_{vh}^* \rangle \end{bmatrix}.$$

# Polarimetric SAR data, dual

- For dual polarimetry, we have for example  $\langle \mathbf{C} \rangle$ ;  $\langle \mathbf{C} \rangle \times \text{ENL} \sim$  complex Wishart for fully developed speckle

$$\langle \mathbf{C} \rangle_{dual} = \begin{bmatrix} \langle S_{vv} S_{vv}^* \rangle & \langle S_{vv} S_{vh}^* \rangle \\ \langle S_{vh} S_{vv}^* \rangle & \langle S_{vh} S_{vh}^* \rangle \end{bmatrix}.$$

- We may think of VV/VH data as the diagonal elements only

$$\langle \mathbf{C} \rangle_{dual,diag} = \begin{bmatrix} \langle S_{vv} S_{vv}^* \rangle & 0 \\ 0 & \langle S_{vh} S_{vh}^* \rangle \end{bmatrix};$$

$\langle \mathbf{C} \rangle \times \text{ENL}$  not complex Wishart but the two (1 by 1) “blocks” on the diagonal are,  $\langle S_{vv} S_{vv}^* \rangle$  is 1 by 1,  $p_1 = 1$ , and  $\langle S_{vh} S_{vh}^* \rangle$  is 1 by 1,  $p_2 = 1$ .



# Polarimetric SAR data, dual

- $H_0$  : no change between all  $k$  time points ( $\boldsymbol{\Sigma}_1 = \boldsymbol{\Sigma}_2 = \dots = \boldsymbol{\Sigma}_k$ )

$$\ln Q = n \left\{ pk \ln k + \sum_{i=1}^k \ln |\mathbf{X}_i| - k \ln \left| \sum_{i=1}^k \mathbf{X}_i \right| \right\} \quad (4)$$

$p = p_1 + p_2 = 2$ ,  $\mathbf{X}_i = n \langle \mathbf{C} \rangle_{dual,diag}$ ,  $n$  is ENL, the equivalent number of looks, and  $|\cdot|$  denotes the determinant.

# Polarimetric SAR data, dual

- $H_0$  : no change between all  $k$  time points ( $\boldsymbol{\Sigma}_1 = \boldsymbol{\Sigma}_2 = \dots = \boldsymbol{\Sigma}_k$ )

$$\ln Q = n \left\{ pk \ln k + \sum_{i=1}^k \ln |\mathbf{X}_i| - k \ln \left| \sum_{i=1}^k \mathbf{X}_i \right| \right\} \quad (4)$$

$p = p_1 + p_2 = 2$ ,  $\mathbf{X}_i = n \langle \mathbf{C} \rangle_{dual,diag}$ ,  $n$  is ENL, the equivalent number of looks, and  $|\cdot|$  denotes the determinant.

- Under  $H_0$ ,  $-2 \ln Q \sim \chi^2((k-1)f)$  :  
 $P\{-2 \ln Q \leq z\} = P\{\chi^2((k-1)f) \leq z\}$ ,  $z = -2 \ln q_{obs}$ ,  $f = p_1^2 + p_2^2 = 2$ .

# Polarimetric SAR data, dual

- $H_0$  : no change between all  $k$  time points ( $\boldsymbol{\Sigma}_1 = \boldsymbol{\Sigma}_2 = \dots = \boldsymbol{\Sigma}_k$ )

$$\ln Q = n \left\{ pk \ln k + \sum_{i=1}^k \ln |\mathbf{X}_i| - k \ln \left| \sum_{i=1}^k \mathbf{X}_i \right| \right\} \quad (4)$$

$p = p_1 + p_2 = 2$ ,  $\mathbf{X}_i = n \langle \mathbf{C} \rangle_{dual,diag}$ ,  $n$  is ENL, the equivalent number of looks, and  $|\cdot|$  denotes the determinant.

- Under  $H_0$ ,  $-2 \ln Q \sim \chi^2((k-1)f)$  :  
 $P\{-2 \ln Q \leq z\} = P\{\chi^2((k-1)f) \leq z\}$ ,  $z = -2 \ln q_{obs}$ ,  $f = p_1^2 + p_2^2 = 2$ .
- (Better approximation for  $P\{-2\rho \ln Q \leq z\}$  ( $\rho$  is auxiliary variable)).

# Polarimetric SAR data, dual

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\Sigma_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\Sigma_1 = \Sigma_2 = \dots = \Sigma_{j-1}$ ,  $\Sigma_j = \Sigma_1$

$$\ln R_j = n\{p(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (5)$$

# Polarimetric SAR data, dual

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\mathbf{\Sigma}_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_{j-1}$ ,  $\mathbf{\Sigma}_j = \mathbf{\Sigma}_1$

$$\ln R_j = n\{p(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (5)$$

- Under  $H_{0,j}$ ,  $-2 \ln R_j \sim \chi^2(f)$ :  
 $P\{-2 \ln R_j \leq z_j\} = P\{\chi^2(f) \leq z_j\}$ ,  $z_j = -2 \ln r_{j,obs}$ ,  $f = p_1^2 + p_2^2 = 2$ .

# Polarimetric SAR data, dual

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\mathbf{\Sigma}_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_{j-1}$ ,  $\mathbf{\Sigma}_j = \mathbf{\Sigma}_1$

$$\ln R_j = n\{\rho(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (5)$$

- Under  $H_{0,j}$ ,  $-2 \ln R_j \sim \chi^2(f)$ :  
 $P\{-2 \ln R_j \leq z_j\} = P\{\chi^2(f) \leq z_j\}$ ,  $z_j = -2 \ln r_{j,obs}$ ,  $f = p_1^2 + p_2^2 = 2$ .
- (Better approximation for  $P\{-2\rho_j \ln R_j \leq z\}$  ( $\rho_j$  are auxiliary variables)).

# Polarimetric SAR data, dual

- If there is change (we reject  $H_0$ ), to find when, test whether the first  $j$  ( $1 < j \leq k$ ) complex variance-covariance matrices  $\mathbf{\Sigma}_i$  are equal, i.e.,  $H_{0,j}$ : given that  $\mathbf{\Sigma}_1 = \mathbf{\Sigma}_2 = \dots = \mathbf{\Sigma}_{j-1}$ ,  $\mathbf{\Sigma}_j = \mathbf{\Sigma}_1$

$$\ln R_j = n\{p(j \ln j - (j-1) \ln(j-1)) + (j-1) \ln \left| \sum_{i=1}^{j-1} \mathbf{X}_i \right| + \ln |\mathbf{X}_j| - j \ln \left| \sum_{i=1}^j \mathbf{X}_i \right|\}. \quad (5)$$

- Under  $H_{0,j}$ ,  $-2 \ln R_j \sim \chi^2(f)$ :  
 $P\{-2 \ln R_j \leq z_j\} = P\{\chi^2(f) \leq z_j\}$ ,  $z_j = -2 \ln r_{j,obs}$ ,  $f = p_1^2 + p_2^2 = 2$ .
- (Better approximation for  $P\{-2\rho_j \ln R_j \leq z\}$  ( $\rho_j$  are auxiliary variables)).
- $R_j$  constitute a factorization  $Q = \prod_{j=2}^k R_j$  or

$$\ln Q = \sum_{i=2}^k \ln R_i. \quad (6)$$



# Change Structure

Illustration of the change structure for each pixel/patch from seven time points.

	$t_1 = \dots = t_7$	$t_2 = \dots = t_7$	$t_3 = \dots = t_7$	$t_4 = \dots = t_7$	$t_5 = t_6 = t_7$	$t_6 = t_7$
Omnibus	$Q^{(1)}$	$Q^{(2)}$	$Q^{(3)}$	$Q^{(4)}$	$Q^{(5)}$	$Q^{(6)}$
$t_1 = t_2$	$R_2^{(1)}$					
$t_2 = t_3$	$R_3^{(1)}$	$R_2^{(2)}$				
$t_3 = t_4$	$R_4^{(1)}$	$R_3^{(2)}$	$R_2^{(3)}$			
$t_4 = t_5$	$R_5^{(1)}$	$R_4^{(2)}$	$R_3^{(3)}$	$R_2^{(4)}$		
$t_5 = t_6$	$R_6^{(1)}$	$R_5^{(2)}$	$R_4^{(3)}$	$R_3^{(4)}$	$R_2^{(5)}$	
$t_6 = t_7$	$R_7^{(1)}$	$R_6^{(2)}$	$R_5^{(3)}$	$R_4^{(4)}$	$R_3^{(5)}$	$R_2^{(6)}$

# Change Structure

Example of the change structure for each pixel from seven time points.

	$t_1 = \dots = t_7$	$t_2 = \dots = t_7$	$t_3 = \dots = t_7$	$t_4 = \dots = t_7$	$t_5 = t_6 = t_7$	$t_6 = t_7$
Omnibus	$Q^{(1)}$	$Q^{(2)}$	$Q^{(3)}$	$Q^{(4)}$	$Q^{(5)}$	$Q^{(6)}$
$t_1 = t_2$	$R_2^{(1)}$					
$t_2 = t_3$	$R_3^{(1)}$	$R_2^{(2)}$				
$t_3 = t_4$	$R_4^{(1)}$	$R_3^{(2)}$	$R_2^{(3)}$			
$t_4 = t_5$	$R_5^{(1)}$	$R_4^{(2)}$	$R_3^{(3)}$	$R_2^{(4)}$		
$t_5 = t_6$	$R_6^{(1)}$	$R_5^{(2)}$	$R_4^{(3)}$	$R_3^{(4)}$	$R_2^{(5)}$	
$t_6 = t_7$	$R_7^{(1)}$	$R_6^{(2)}$	$R_5^{(3)}$	$R_4^{(4)}$	$R_3^{(5)}$	$R_2^{(6)}$



# Change Structure

Example of the change structure for each pixel from seven time points.

	$t_1 = \dots = t_7$	$t_2 = \dots = t_7$	$t_3 = \dots = t_7$	$t_4 = \dots = t_7$	$t_5 = t_6 = t_7$	$t_6 = t_7$
Omnibus	$Q^{(1)}$			$Q^{(4)}$		
$t_1 = t_2$	$R_2^{(1)}$					
$t_2 = t_3$	$R_3^{(1)}$					
$t_3 = t_4$	$R_4^{(1)}$					
$t_4 = t_5$				$R_2^{(4)}$		
$t_5 = t_6$				$R_3^{(4)}$		
$t_6 = t_7$						$R_2^{(6)}$



# Change Structure

Example of the change structure for each pixel from seven time points (may skip  $Q^{(\ell)}$ ).

	$t_1 = \dots = t_7$	$t_4 = \dots = t_7$	$t_6 = t_7$
Omnibus	$Q^{(1)}$	$Q^{(4)}$	
$t_1 = t_2$	$R_2^{(1)}$		
$t_2 = t_3$	$R_3^{(1)}$		
$t_3 = t_4$	$R_4^{(1)}$		
$t_4 = t_5$		$R_2^{(4)}$	
$t_5 = t_6$		$R_3^{(4)}$	
$t_6 = t_7$			$R_2^{(6)}$

# Change Structure

$R_2^{(\ell)}$  are the consecutive pair-wise test statistics.

	$t_1 = \dots = t_7$	$t_2 = \dots = t_7$	$t_3 = \dots = t_7$	$t_4 = \dots = t_7$	$t_5 = t_6 = t_7$	$t_6 = t_7$
Omnibus	$Q^{(1)}$	$Q^{(2)}$	$Q^{(3)}$	$Q^{(4)}$	$Q^{(5)}$	$Q^{(6)}$
$t_1 = t_2$	$R_2^{(1)}$					
$t_2 = t_3$	$R_3^{(1)}$	$R_2^{(2)}$				
$t_3 = t_4$	$R_4^{(1)}$	$R_3^{(2)}$	$R_2^{(3)}$			
$t_4 = t_5$	$R_5^{(1)}$	$R_4^{(2)}$	$R_3^{(3)}$	$R_2^{(4)}$		
$t_5 = t_6$	$R_6^{(1)}$	$R_5^{(2)}$	$R_4^{(3)}$	$R_3^{(4)}$	$R_2^{(5)}$	
$t_6 = t_7$	$R_7^{(1)}$	$R_6^{(2)}$	$R_5^{(3)}$	$R_4^{(4)}$	$R_3^{(5)}$	$R_2^{(6)}$

# Data Sentinel-1

- S-1 data acquired in instrument Interferometric Wide Swath (IW) mode, are Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox<sup>2</sup> to generate a calibrated, ortho-corrected product.

---

<sup>2</sup><https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-1> 

# Data Sentinel-1

- S-1 data acquired in instrument Interferometric Wide Swath (IW) mode, are Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox<sup>2</sup> to generate a calibrated, ortho-corrected product.
- Includes thermal noise removal, radiometric calibration, and terrain correction using Shuttle Radar Topography Mission 30 m (SRTM 30) data.

---

<sup>2</sup><https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-1> 

# Data Sentinel-1

- S-1 data acquired in instrument Interferometric Wide Swath (IW) mode, are Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox<sup>2</sup> to generate a calibrated, ortho-corrected product.
- Includes thermal noise removal, radiometric calibration, and terrain correction using Shuttle Radar Topography Mission 30 m (SRTM 30) data.
- Used to include saturating the data (quoting GEE): “Values are then clamped to the 1st and 99th percentile to preserve the dynamic range against anomalous outliers, and quantized to 16 bits.” GEE is re-ingesting the entire S-1 series in floats.

---

<sup>2</sup><https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-1> 

# Data Sentinel-1

- S-1 data acquired in instrument Interferometric Wide Swath (IW) mode, are Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox<sup>2</sup> to generate a calibrated, ortho-corrected product.
- Includes thermal noise removal, radiometric calibration, and terrain correction using Shuttle Radar Topography Mission 30 m (SRTM 30) data.
- Used to include saturating the data (quoting GEE): “Values are then clamped to the 1st and 99th percentile to preserve the dynamic range against anomalous outliers, and quantized to 16 bits.” GEE is re-ingesting the entire S-1 series in floats.
- The spatial resolution is (range by azimuth) 20 m by 22 m and the pixel spacing is 10 m.

---

<sup>2</sup><https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-1> 

# Data Sentinel-1

- S-1 data acquired in instrument Interferometric Wide Swath (IW) mode, are Ground Range Detected (GRD) scenes, processed using the Sentinel-1 Toolbox<sup>2</sup> to generate a calibrated, ortho-corrected product.
- Includes thermal noise removal, radiometric calibration, and terrain correction using Shuttle Radar Topography Mission 30 m (SRTM 30) data.
- Used to include saturating the data (quoting GEE): “Values are then clamped to the 1st and 99th percentile to preserve the dynamic range against anomalous outliers, and quantized to 16 bits.” GEE is re-ingesting the entire S-1 series in floats.
- The spatial resolution is (range by azimuth) 20 m by 22 m and the pixel spacing is 10 m.
- The IW data are multi-looked, the number of looks is 5 by 1 and the equivalent number of looks is 4.4 (was 4.9?). VV, VH, covariance matrix representation, diagonal only.

---

<sup>2</sup><https://sentinel.esa.int/web/sentinel/toolboxes/sentinel-1> 

# Data Sentinel-1

- Sentinel-1 dual polarization C-band SAR instrument (here VV/VH, multi-look, covariance representation, diagonal only – from Google Earth Engine, GEE<sup>3</sup>).

---

<sup>3</sup><https://earthengine.google.com> and  
<https://developers.google.com/earth-engine>



# Data Sentinel-1

- Sentinel-1 dual polarization C-band SAR instrument (here VV/VH, multi-look, covariance representation, diagonal only – from Google Earth Engine, GEE<sup>3</sup>).
- 17 scenes (all ascending node and all with relative orbit number 15), international airport in Frankfurt, Germany (made especially by GEE for our experiments).

---

<sup>3</sup><https://earthengine.google.com> and  
<https://developers.google.com/earth-engine>

# Data Sentinel-1

- Sentinel-1 dual polarization C-band SAR instrument (here VV/VH, multi-look, covariance representation, diagonal only – from Google Earth Engine, GEE<sup>3</sup>).
- 17 scenes (all ascending node and all with relative orbit number 15), international airport in Frankfurt, Germany (made especially by GEE for our experiments).
- Acquisition dates are from 5 Mar till 31 Oct 2016.

---

<sup>3</sup><https://earthengine.google.com> and  
<https://developers.google.com/earth-engine>

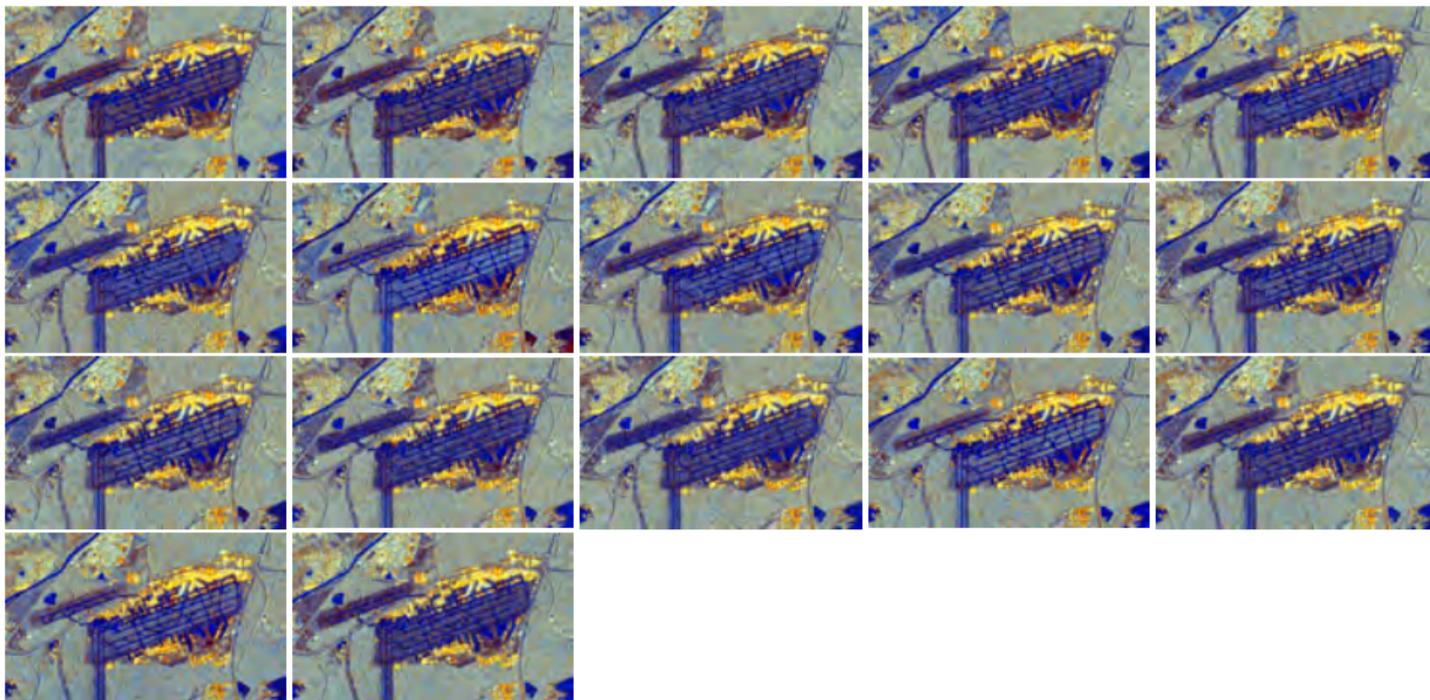
# Data Sentinel-1

- Sentinel-1 dual polarization C-band SAR instrument (here VV/VH, multi-look, covariance representation, diagonal only – from Google Earth Engine, GEE<sup>3</sup>).
- 17 scenes (all ascending node and all with relative orbit number 15), international airport in Frankfurt, Germany (made especially by GEE for our experiments).
- Acquisition dates are from 5 Mar till 31 Oct 2016.
- Will show different ways of visualizing change (not all ways are necessarily informative in all applications).

---

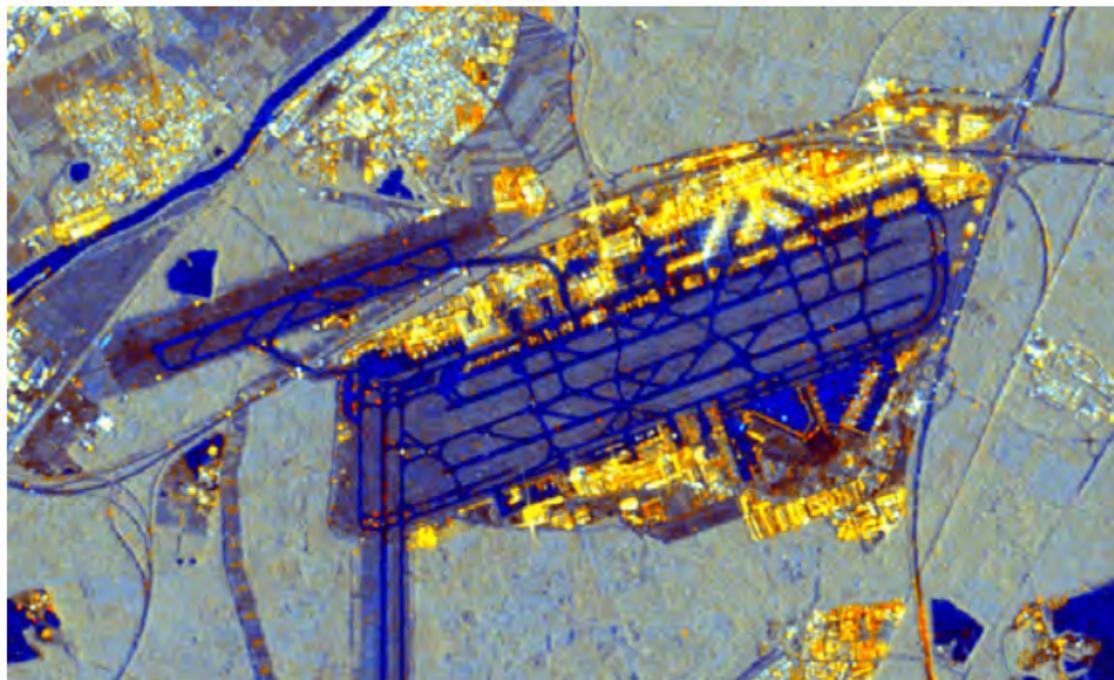
<sup>3</sup><https://earthengine.google.com> and  
<https://developers.google.com/earth-engine>

# Data Sentinel-1



RGB image of Sentinel-1 C-band multi-temporal data, VV as R, VH as G and VH/VV as B, 5 Mar to 31 Oct 2016 as R, 10 m pixels, 6 km north-south and 10 km east-west.

# Data Sentinel-1, temporally de-speckled



RGB image of temporal mean of all 17 Sentinel-1 C-band VV as R, VH as G and VH/VV as B, 10 m pixels, 6 km north-south and 10 km east-west.

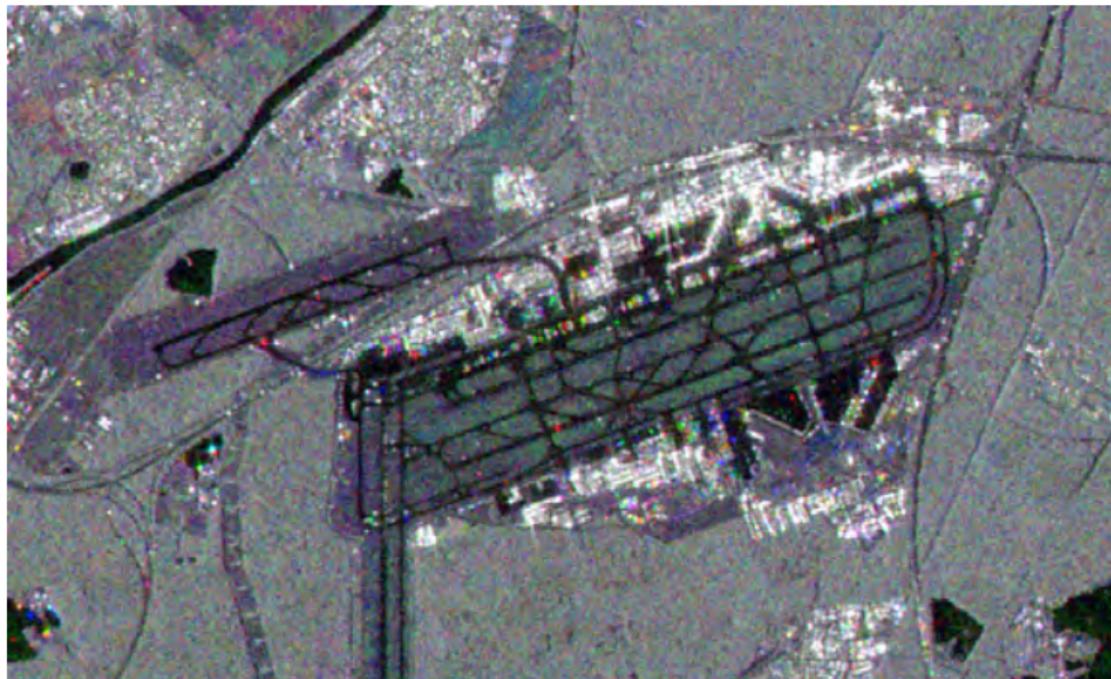
# Data Sentinel-2



RGB image of Sentinel-2 MSI band 8 (near-infrared as R), band 4 (red as G), and band 3 (green as B), 10 m pixels, 6 km north-south and 10 km east-west, Frankfurt Airport, Germany, acquired on 12 Sep 2016.



# Data Sentinel-1



RGB image of Sentinel-1 C-band multi-temporal VV data, 5 Mar 2016 as B, 15 Jul 2016 as G, and 31 Oct 2016 as R, 10 m pixels, 6 km north-south and 10 km east-west.  $-24 \text{ dB} \rightarrow 6 \text{ dB}$ .

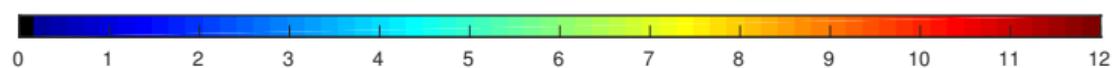
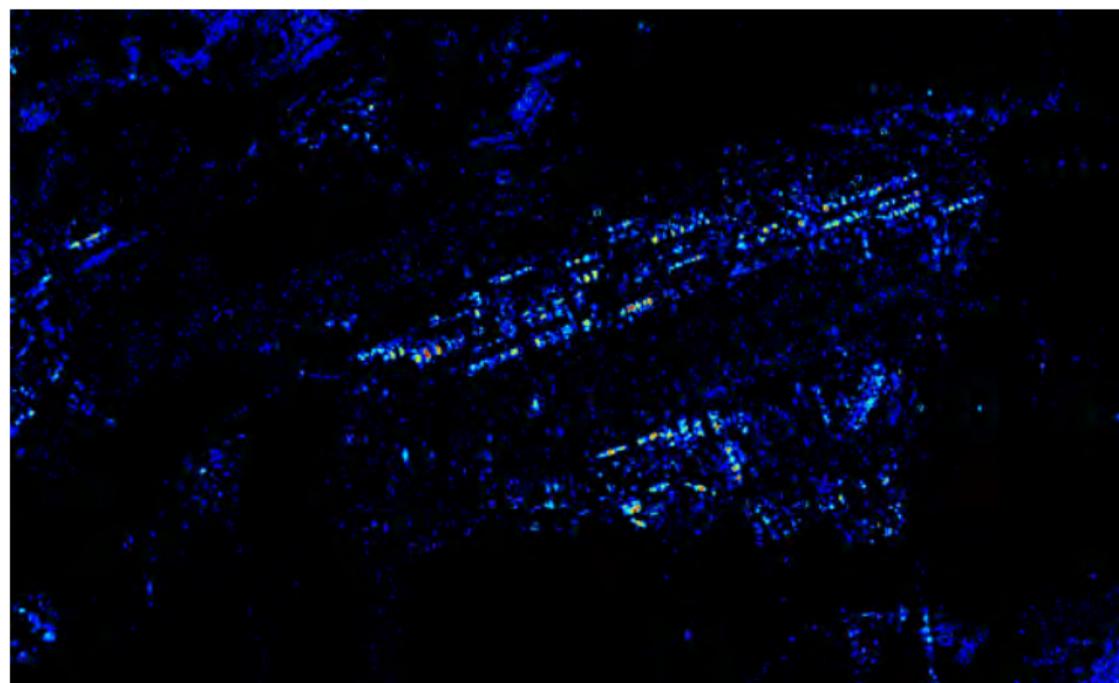


# Results, test statistic

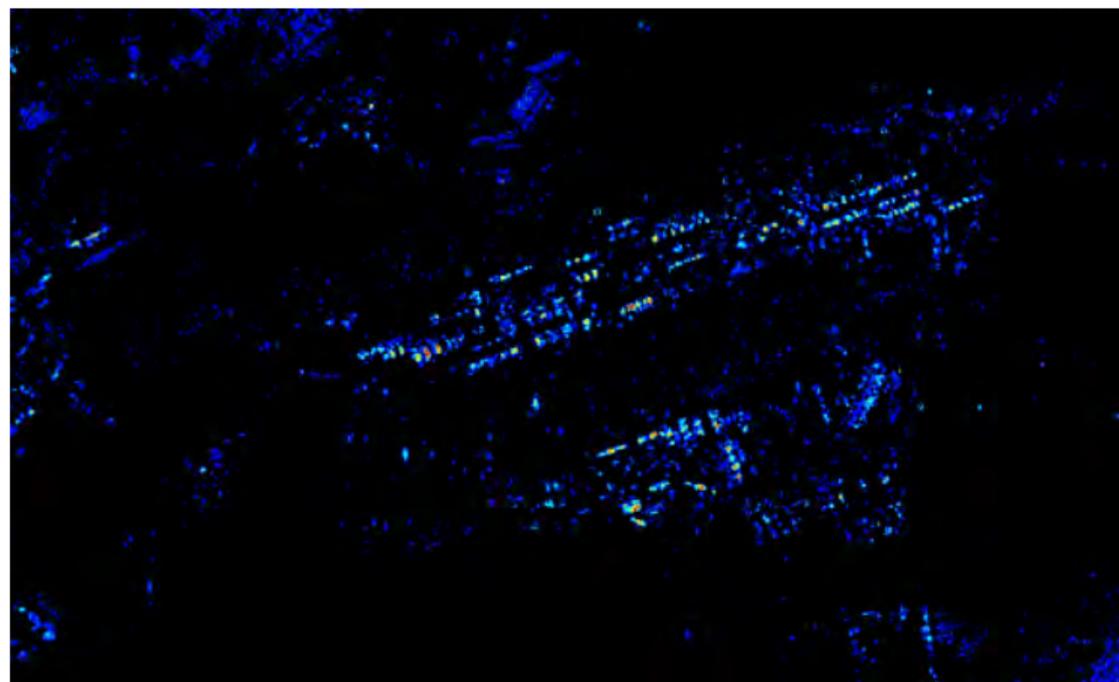


$-2 \ln Q$  omnibus change detector for Sentinel-1 C-band VV/VH dual polarization data, diagonal only, stretched linearly between 0 and 300.

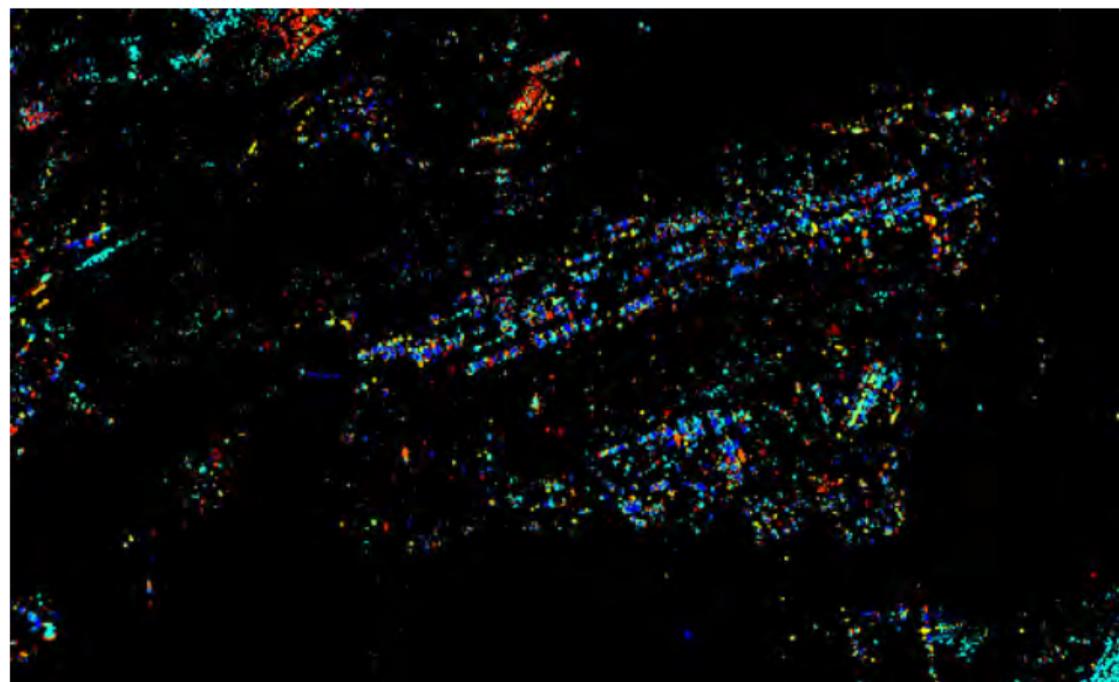
# Results, number of changes, $R_j$ only



# Results, number of changes, $Q$ and $R_j$



# Results, first change



0

1

2

3

4

5

6

7

8

9

10

11

12

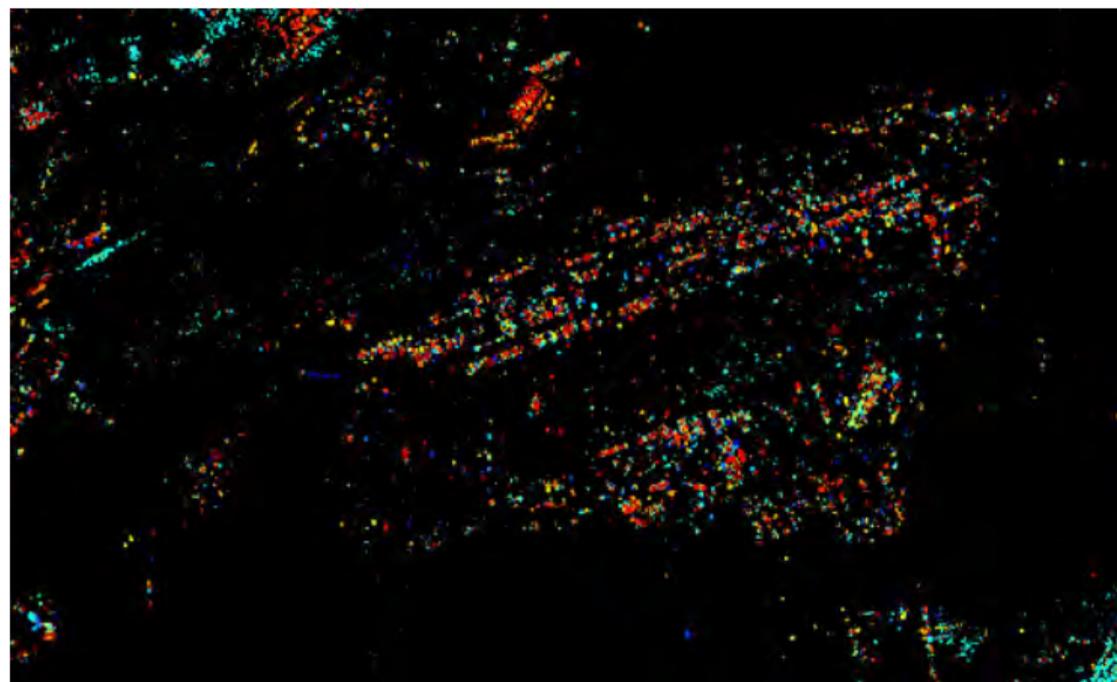
13

14

15

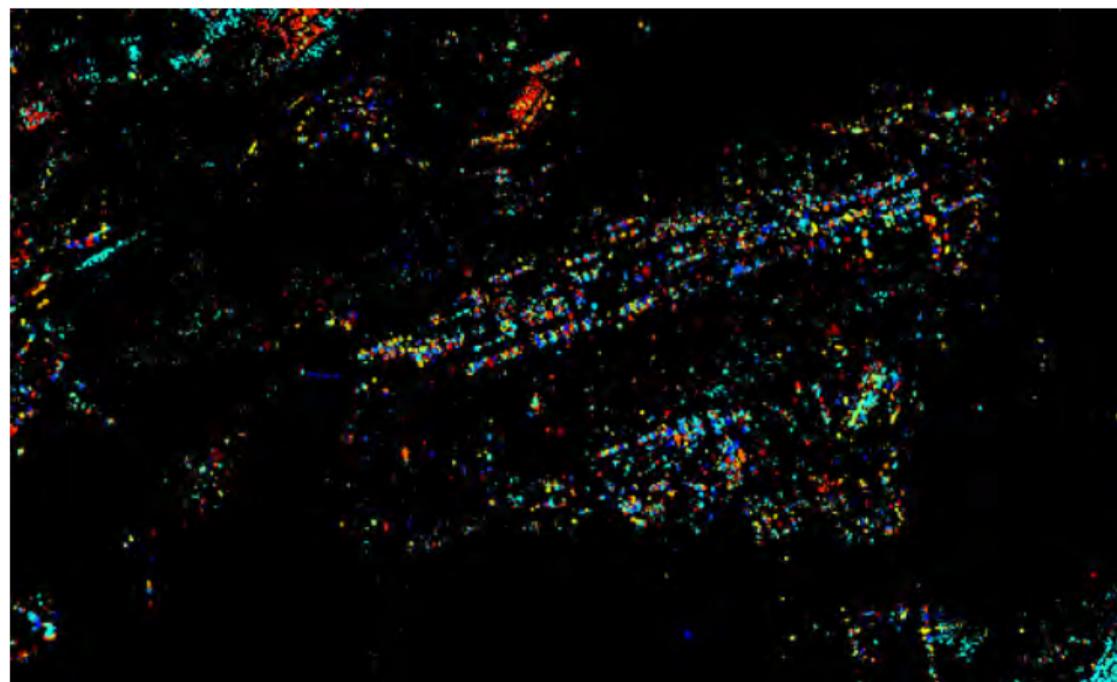
16

# Results, last change

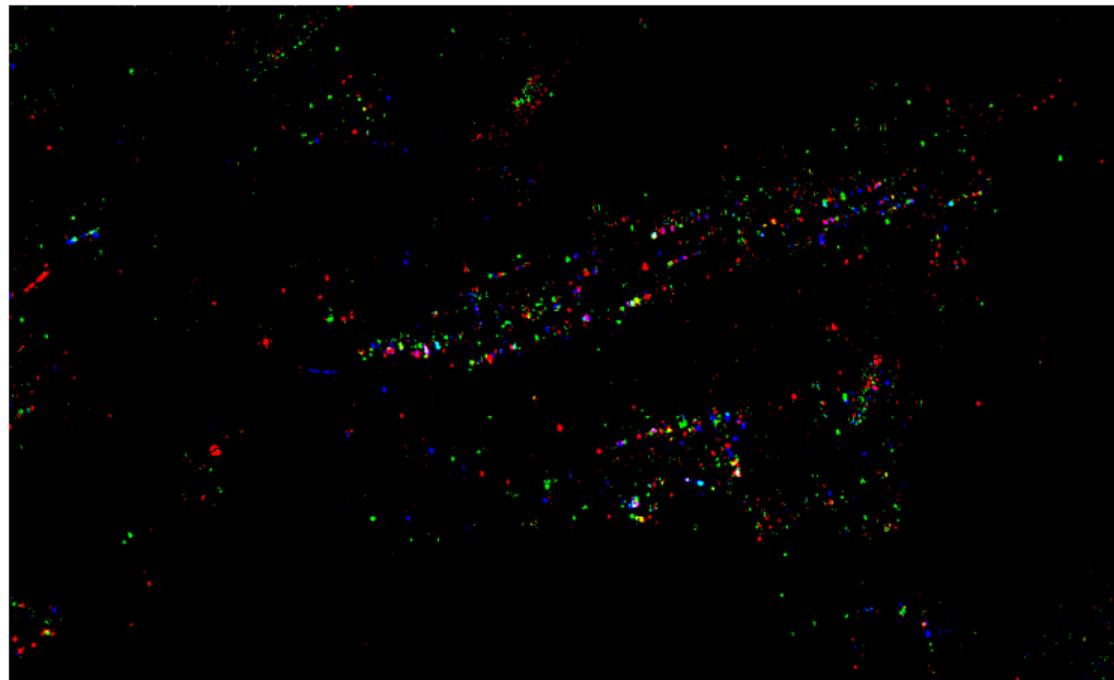


0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

# Results, maximum change



# Results, RGB example

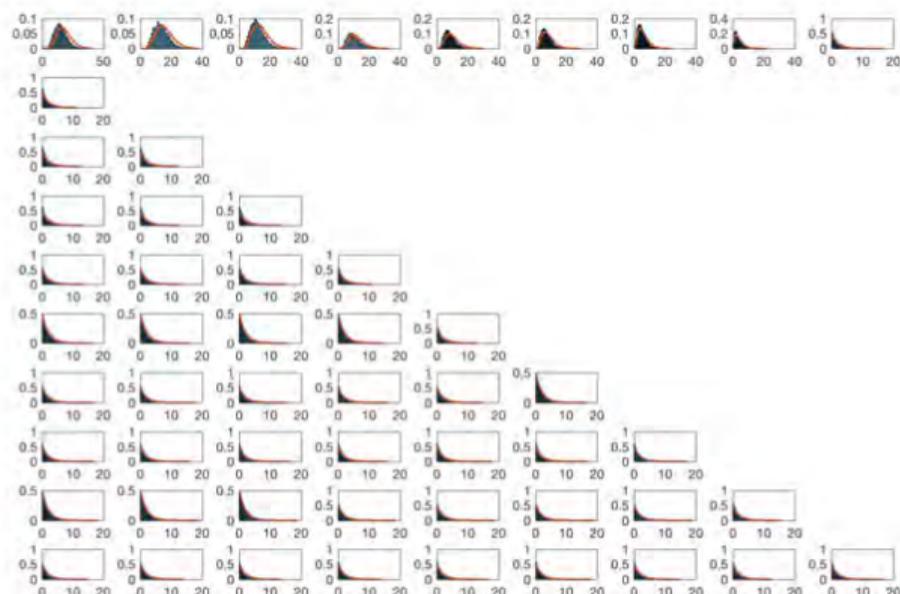


Change after 5 Mar 2016 is B, 15 Jul 2016 is G, and 19 Oct 2016 is R, 10 m pixels, 6 km north-south and 10 km east-west.

# Results, RGB example in GE

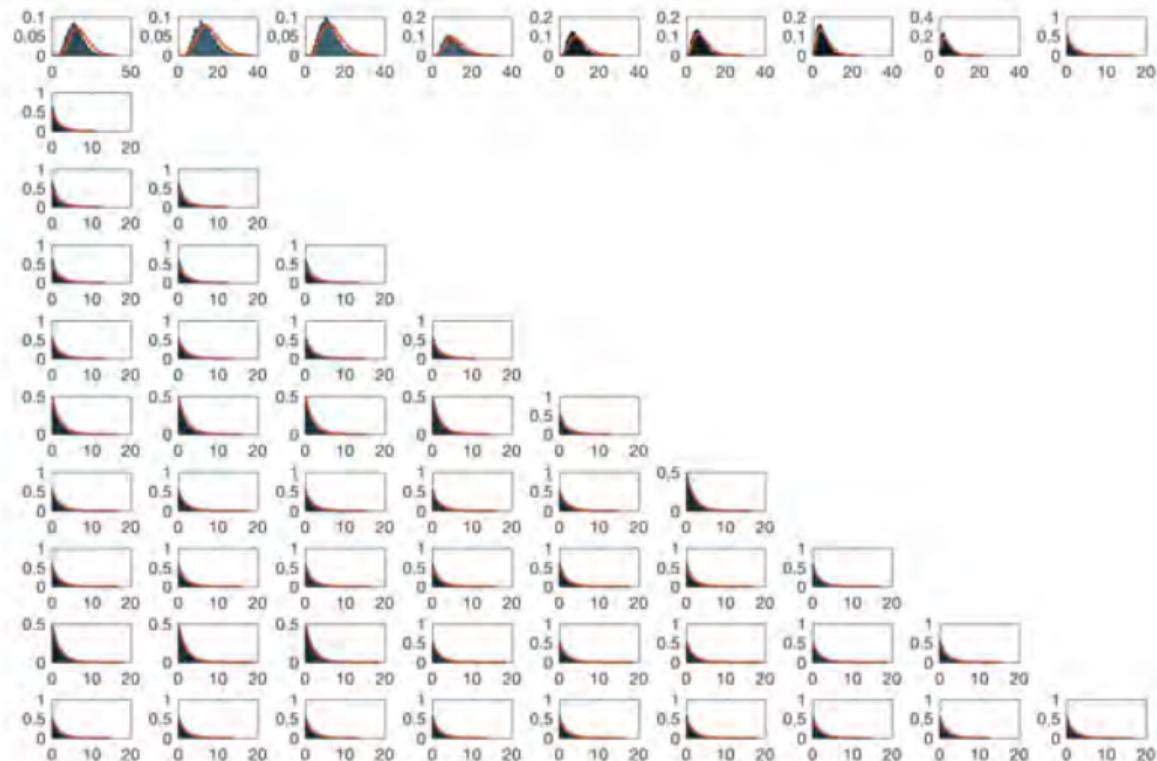


# Results, first 10 time points only



Histograms for an analysis of omnibus change for the first ten time points of the Sentinel-1 data (5 Mar through 27 Jul) along with the theoretical distributions for a no-change wooded area (top of image). For the  $-2 \ln Q$  (top row plots) the numbers of degrees of freedom are 18, 16, ..., 2, respectively. For all the  $-2 \ln R_j$  (the remaining rows) the number of degrees of freedom is 2. Judged visually this illustrates a satisfactory fit between sample histograms and theoretical distributions for the test statistics in a no-change region. > < < < < <

# Results, first 10 of 19 time points



# S-1, 28 scenes Apr–Dec 2016, port activity, GEE

Google Earth Engine

Search places and datasets...

Code Docs Assets

Link 5b543ad81805801d4c86a499bf4171a8 Get Link Save Run Reset

Imports (1 entry)

```

1 var image: Image users/mortcanty/omnibus/tripoli (30 bands)
2 var max = image.bandNames().length().subtract(3).getInfo();
3 var jet = ['black', 'blue', 'cyan', 'yellow', 'red'];
4 var vis = {min:0, max:max, palette:jet};
5 Map.centerObject(image,11);
6 function zcut(e) {
7   e = ee.Dictionary(e);
8   var point = ee.Geometry.Point([e.get('lon'),e.get('lat')]);
9   var bmap = image.select(image.bandNames().slice(3));
10  var bandChart = ui.Chart.image.region(

```

Inspector Console Tasks

Use print(...) to write to this console.

0 27

Layers

Tripoli طرابلس

Google

DTU

# S-1, 19 scenes May–Oct 2016, agricultural activity, GEE

The screenshot displays the Google Earth Engine (GEE) web interface. At the top, there is a search bar and navigation tabs for 'Code', 'Docs', and 'Assets'. The 'Code' tab is active, showing a JavaScript script for processing Sentinel-1 imagery. The script defines a color palette (jet) and a function to calculate the z-cut of the image. Below the code editor, a 'Layers' panel shows a visualization of the processed data, overlaid on a satellite image of a rural landscape. A color scale legend indicates values from 0 to 18, with a rainbow color gradient. The 'Layers' panel also includes a 'Layers' button and a '5 km' scale bar.

```

1 var max = image.bandNames().length().subtract(3).getIn
2 var jet = ['black','blue','cyan','yellow','red'];
3 var vis = {min:0, max:max, palette:jet};
4 Map.centerObject(image);
5 function zcut(e) {
6   e = ee.Dictionary(e);
7   var point = ee.Geometry.Point([e.get('lon'),e.g

```

# S-1, 19 scenes Apr–Oct 2017, hurricane Maria (20 Sep), GEE

The screenshot displays the Google Earth Engine (GEE) interface. The top navigation bar includes 'Code', 'Docs', and 'Assets'. The left sidebar shows a project structure under 'Owner (1)' with folders for 'users/AllanANIelsen/default', 'omnibus', 'omnibus\_run', 'omnibus\_view', and 'utilities'. The main code editor shows the following code:

```

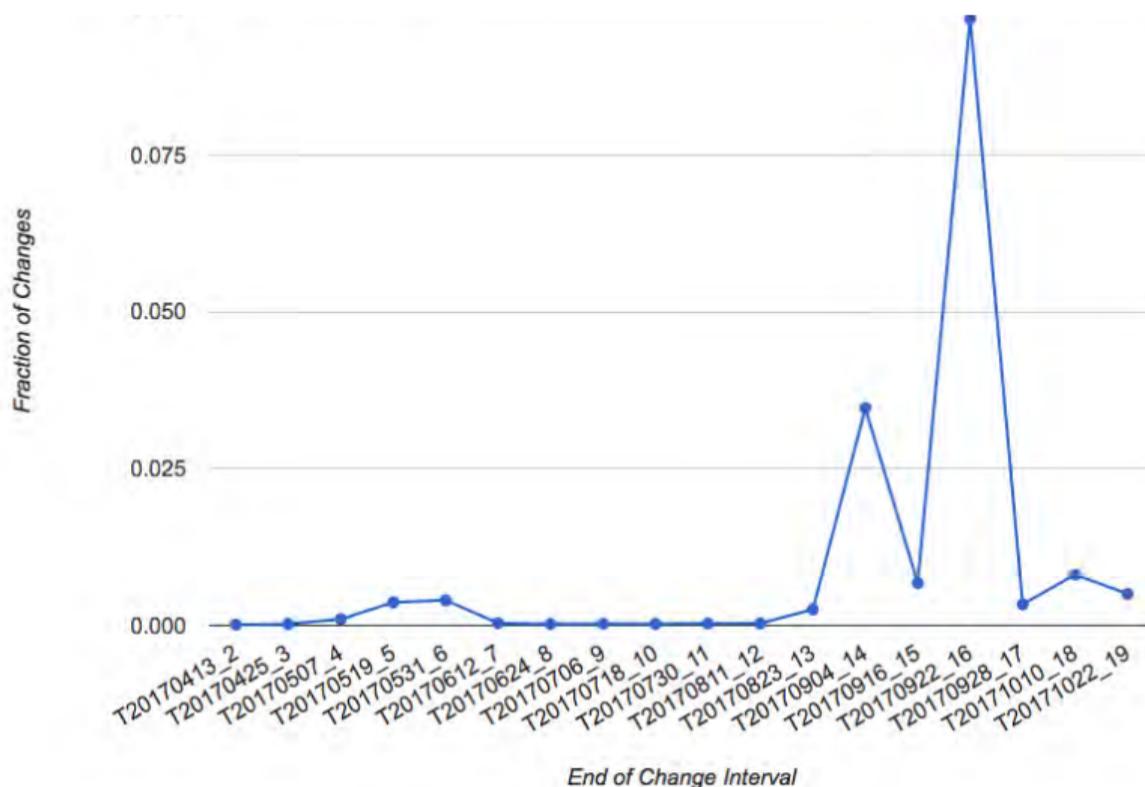
1 // *****
2 // Viewer for Exported Sequential Omnibus Change Maps
3 // *****
4 var util = require('users/mortcanty/changedetection:utilities');
5
6
7 var max = image.bandNames().length().subtract(3).getInfo()
8 var jet = ['black', 'blue', 'cyan', 'yellow', 'red'];
9 var vis = {min:0, max:max, palette:jet};
10

```

The right sidebar contains the 'Inspector' and 'Console' tabs. The 'Inspector' shows a 'Polygon, 5 vertices' with a 'ROI Change Profile' graph. The graph plots 'ROI of Change' (y-axis, 0.050 to 0.100) against a horizontal axis. A blue line with a peak at 0.100 is visible. The 'Console' tab shows the message: 'Use print(...) to write to this console.'

The main map area shows a satellite view of a coastal region. A 'Geometry Imports' box is visible in the top left. A color scale legend is centered, ranging from 0 (black) to 18 (red), with intermediate colors (blue, cyan, yellow). The map shows a large area of change detection, with a significant portion colored in red and yellow, indicating high change. A 'Layers' box is in the top right. The bottom of the map shows a 'Google' logo, a '5 km' scale bar, and a 'Report a map error' link.

# S-1, 19 scenes Apr–Oct 2017, hurricane Maria (20 Sep), GEE



# Software

- Matlab, lots of possibilities for small datasets, including automatic generation of tables, histogram/distribution plots, and visualizations<sup>4</sup>.

---

<sup>4</sup><https://people.compute.dtu.dk/alan>

<sup>5</sup><https://hub.docker.com/u/mort>

<sup>6</sup><http://mortcanty.github.io/SARDocker>

<sup>7</sup><http://mortcanty.github.io/src/tutorialsar.html>

<sup>8</sup><https://github.com/mortcanty/earthengine>



# Software

- Matlab, lots of possibilities for small datasets, including automatic generation of tables, histogram/distribution plots, and visualizations<sup>4</sup>.
- Matlab, line-by-line implementation for SAR.

---

<sup>4</sup><https://people.compute.dtu.dk/alan>

<sup>5</sup><https://hub.docker.com/u/mort>

<sup>6</sup><http://mortcanty.github.io/SARDocker>

<sup>7</sup><http://mortcanty.github.io/src/tutorialsar.html>

<sup>8</sup><https://github.com/mortcanty/earthengine>



# Software

- Matlab, lots of possibilities for small datasets, including automatic generation of tables, histogram/distribution plots, and visualizations<sup>4</sup>.
- Matlab, line-by-line implementation for SAR.
- Python (IPython and Docker)<sup>5,6,7</sup>.

---

<sup>4</sup><https://people.compute.dtu.dk/alan>

<sup>5</sup><https://hub.docker.com/u/mort>

<sup>6</sup><http://mortcanty.github.io/SARDocker>

<sup>7</sup><http://mortcanty.github.io/src/tutorialsar.html>

<sup>8</sup><https://github.com/mortcanty/earthengine>



# Software

- Matlab, lots of possibilities for small datasets, including automatic generation of tables, histogram/distribution plots, and visualizations<sup>4</sup>.
- Matlab, line-by-line implementation for SAR.
- Python (IPython and Docker)<sup>5,6,7</sup>.
- Google Earth Engine (GEE) on open-source repository Github<sup>8</sup>. Client-side programs run in a local Docker container serving a simple Flask web application. Docker engine plus browser needed (and authentication to GEE), nothing else.

---

<sup>4</sup><https://people.compute.dtu.dk/alan>

<sup>5</sup><https://hub.docker.com/u/mort>

<sup>6</sup><http://mortcanty.github.io/SARDocker>

<sup>7</sup><http://mortcanty.github.io/src/tutorialsar.html>

<sup>8</sup><https://github.com/mortcanty/earthengine>



# Software on GEE

- JavaScript code<sup>9</sup> to run the IR-MAD and the omnibus methods directly in the GEE code editor/playground. Omnibus code also generates MP4 movie showing where and when change occurred.

---

<sup>9</sup><http://fwenvi-idl.blogspot.de/>

<sup>10</sup><http://www.imm.dtu.dk/pubdb/p.php?7024>

<sup>11</sup><http://www.imm.dtu.dk/pubdb/p.php?7027>

# Software on GEE

- JavaScript code<sup>9</sup> to run the IR-MAD and the omnibus methods directly in the GEE code editor/playground. Omnibus code also generates MP4 movie showing where and when change occurred.
- Morton J. Canty and Allan A. Nielsen. Spatio-temporal analysis of change with Sentinel imagery on the Google Earth Engine. *ESA Conference on Big Data from Space*, pp. 126-129, Toulouse, France, 28-30 Nov 2017<sup>10</sup>.

---

<sup>9</sup><http://fwenvi-idl.blogspot.de/>

<sup>10</sup><http://www.imm.dtu.dk/pubdb/p.php?7024>

<sup>11</sup><http://www.imm.dtu.dk/pubdb/p.php?7027>

# Software on GEE

- JavaScript code<sup>9</sup> to run the IR-MAD and the omnibus methods directly in the GEE code editor/playground. Omnibus code also generates MP4 movie showing where and when change occurred.
- Morton J. Canty and Allan A. Nielsen. Spatio-temporal analysis of change with Sentinel imagery on the Google Earth Engine. *ESA Conference on Big Data from Space*, pp. 126-129, Toulouse, France, 28-30 Nov 2017<sup>10</sup>.
- Allan A. Nielsen, Knut Conradsen, Henning Skriver and Mort Canty (2017). Visualization of and software for omnibus test based change detected in a time series of polarimetric SAR data<sup>11</sup>. *Canadian Journal of Remote Sensing* **43**(6), 582-592. DOI:10.1080/07038992.2017.1394182.

---

<sup>9</sup><http://fwenvi-idl.blogspot.de/>

<sup>10</sup><http://www.imm.dtu.dk/pubdb/p.php?7024>

<sup>11</sup><http://www.imm.dtu.dk/pubdb/p.php?7027>

# Recent Software

- Docker-based interface to the GEE for the Wishart omnibus algorithm<sup>12</sup> (flexible, via Jupyter notebook).

---

<sup>12</sup>[http:](http://fwenvi-idl.blogspot.com/2018/07/jupyter-notebook-interfacefor.html/)

[//fwenvi-idl.blogspot.com/2018/07/jupyter-notebook-interfacefor.html/](http://fwenvi-idl.blogspot.com/2018/07/jupyter-notebook-interfacefor.html/)

<sup>13</sup><https://www.databio.eu>

<sup>14</sup><https://github.com/BehnazP/DataBio/>

# Recent Software

- Docker-based interface to the GEE for the Wishart omnibus algorithm<sup>12</sup> (flexible, via Jupyter notebook).
- Computer implementation work within the Horizon 2020 project DataBio<sup>13</sup> DLV-732064 funded by the European Union: command-line and GUI executables<sup>14</sup> for Windows and Linux, version for small images which fit into memory and a line-by-line version for big data (BiDS 2019 poster #13, Dr Behnaz Pirzamanbein).

---

<sup>12</sup>[http:](http://fwenvi-idl.blogspot.com/2018/07/jupyter-notebook-interfacefor.html/)

[//fwenvi-idl.blogspot.com/2018/07/jupyter-notebook-interfacefor.html/](http://fwenvi-idl.blogspot.com/2018/07/jupyter-notebook-interfacefor.html/)

<sup>13</sup><https://www.databio.eu>

<sup>14</sup><https://github.com/BehnazP/DataBio/>



# Conclusions

- CCA based automatic change detection and automatic normalization in bitemporal multispectral optical data (Sentinel-2 MSI and Landsat TM).

# Conclusions

- CCA based automatic change detection and automatic normalization in bitemporal multispectral optical data (Sentinel-2 MSI and Landsat TM).
- Omnibus Wishart distribution based automatic change analysis in multitemporal polarimetric SAR data (Sentinel-1).

# Conclusions

- CCA based automatic change detection and automatic normalization in bitemporal multispectral optical data (Sentinel-2 MSI and Landsat TM).
- Omnibus Wishart distribution based automatic change analysis in multitemporal polarimetric SAR data (Sentinel-1).
- Computer implementations, including cloud versions.

# Conclusions

- CCA based automatic change detection and automatic normalization in bitemporal multispectral optical data (Sentinel-2 MSI and Landsat TM).
- Omnibus Wishart distribution based automatic change analysis in multitemporal polarimetric SAR data (Sentinel-1).
- Computer implementations, including cloud versions.
  - GEE gang very helpful (Noel Gorelick, Simon (Vsevolod) Ilyushchenko), implemented incomplete gamma function, re-ingest all S-1 data (store in floats rather than 2-byte int “clamped to the 1st and 99th percentile”).



# Conclusions

- CCA based automatic change detection and automatic normalization in bitemporal multispectral optical data (Sentinel-2 MSI and Landsat TM).
- Omnibus Wishart distribution based automatic change analysis in multitemporal polarimetric SAR data (Sentinel-1).
- Computer implementations, including cloud versions.
  - GEE gang very helpful (Noel Gorelick, Simon (Vsevolod) Ilyushchenko), implemented incomplete gamma function, re-ingest all S-1 data (store in floats rather than 2-byte int “clamped to the 1st and 99th percentile”).
- Use software, read and cite our (journal) papers.



# Cloud based spatio-temporal analysis of change in sequences of Sentinel images

Allan A. Nielsen<sup>1</sup>, Morton J. Canty<sup>2</sup>, Henning Skriver<sup>1</sup>,  
Knut Conradsen<sup>1</sup>

<sup>1</sup>Technical University of Denmark

<sup>2</sup>Research Center Jülich, Germany

ESA Big Data from Space, Munich, Germany, 19-21 Feb 2019