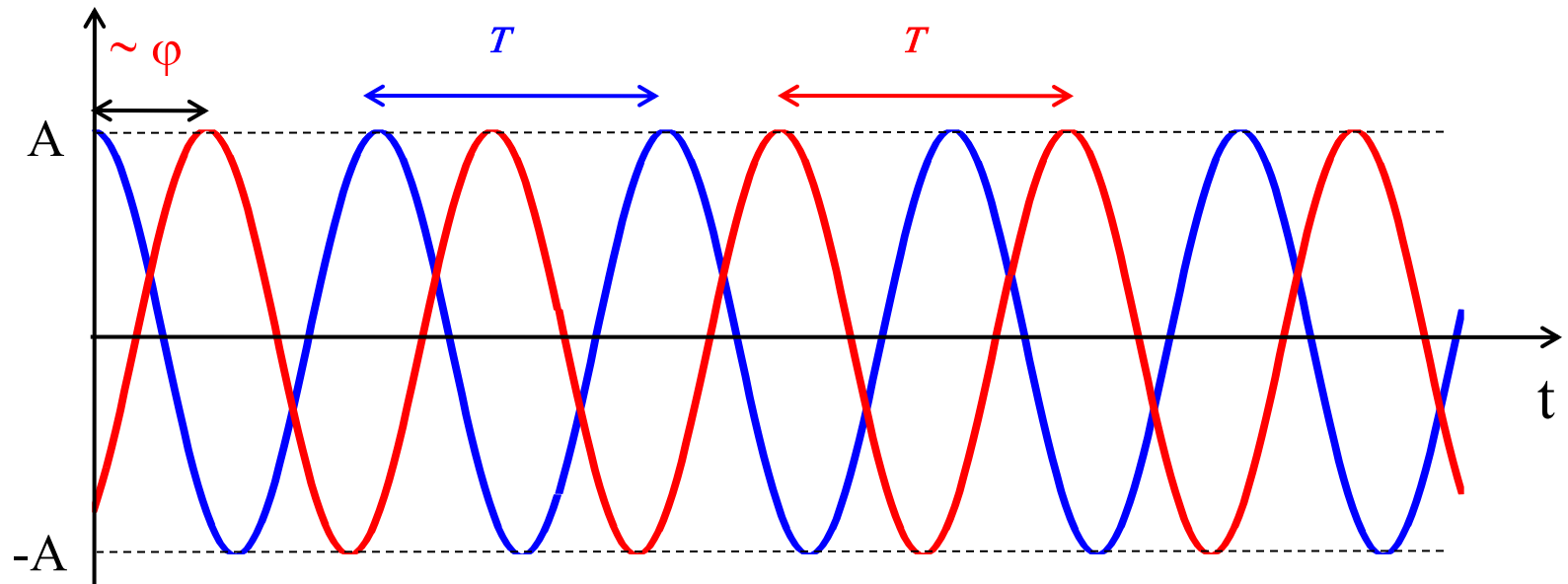


# OUTLINE

- I. Radar imaging - Spatial resolution
- II. Polarization - Polarimetry
- III. Radar response sensitivity
- IV. Relief effects
- V. **Speckle and Filtering**

# Coherent wave: temporal behaviour



$$y(t) = A \cos\left(\frac{2\pi}{T} t\right)$$

$$T = \frac{1}{f_0}$$

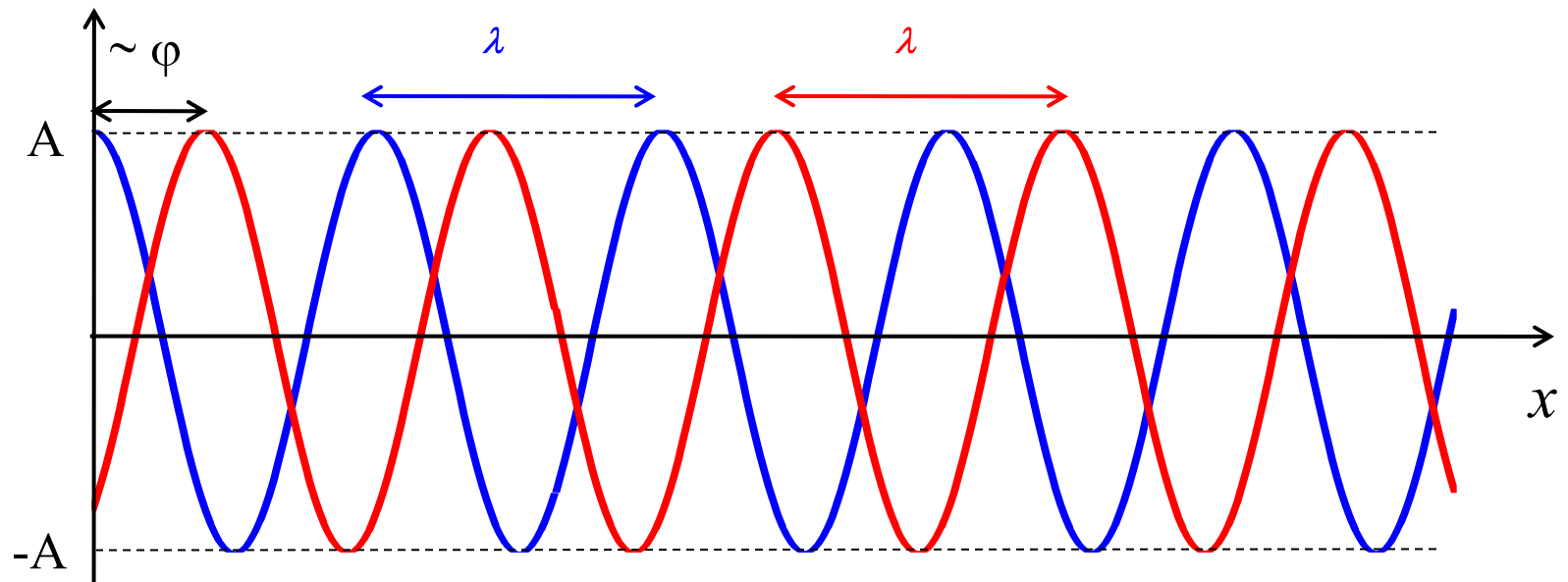
$$y(t) = A \cos\left(\frac{2\pi}{T} t - \varphi\right)$$

$A$ : amplitude

$T$ : Temporal period

$\varphi$ : dephasage

# Coherent wave: spatial behaviour



$$y(x) = A \cos\left(\frac{2\pi}{\lambda} x\right)$$

$$\lambda = cT = \frac{c}{f_0}$$

$$y(x) = A \cos\left(\frac{2\pi}{\lambda} x - \phi\right)$$

$A$ : amplitude

$\lambda$ : spatial period = wavelength

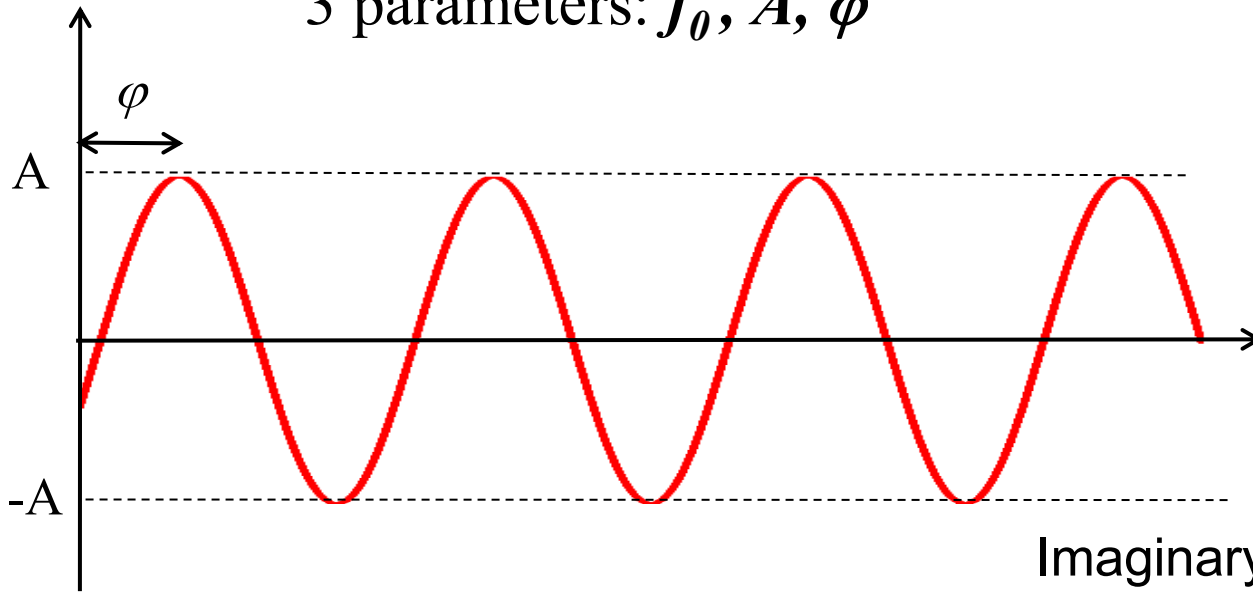
$\phi$ : dephasage

## *Coherent wave*

3 parameters:  $f_0, A, \varphi$

$$y = A \cos\left(\frac{2\pi}{T} t + \frac{2\pi}{\lambda} x + \varphi\right)$$

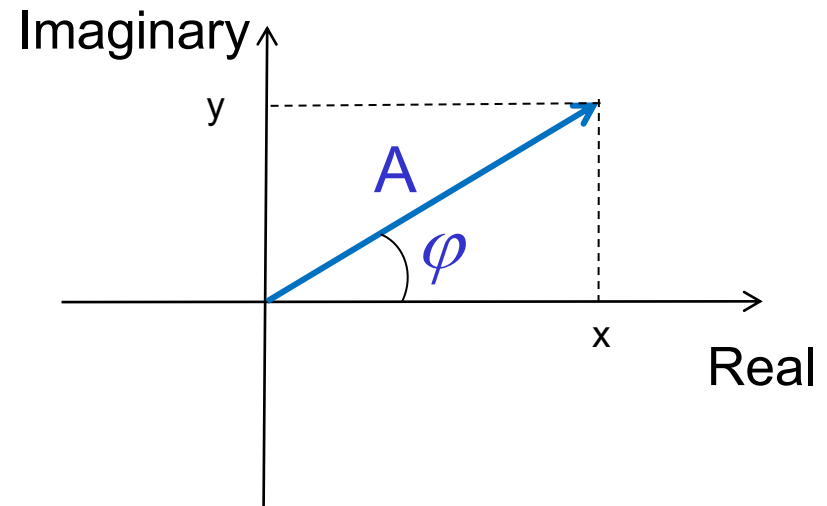
$$\lambda = cT = \frac{c}{f_0}$$



For given frequency  $f_0$  (or  $\lambda$ ) (system)

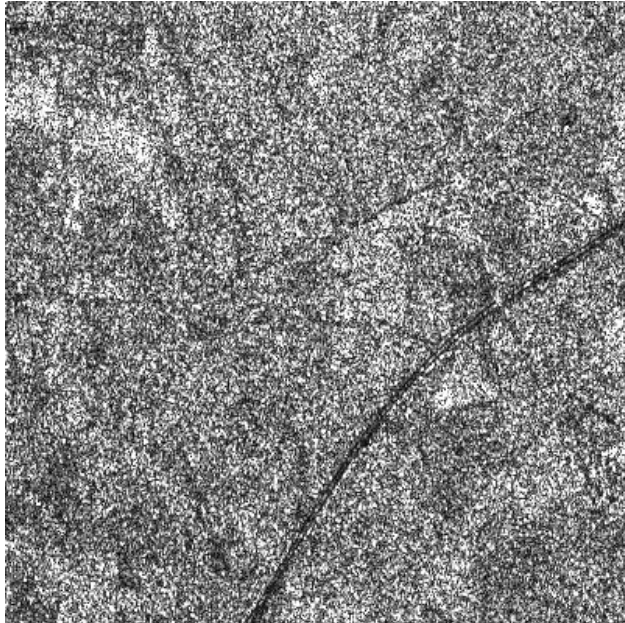
backscattered echo

characterized by  $A$  and  $\varphi$

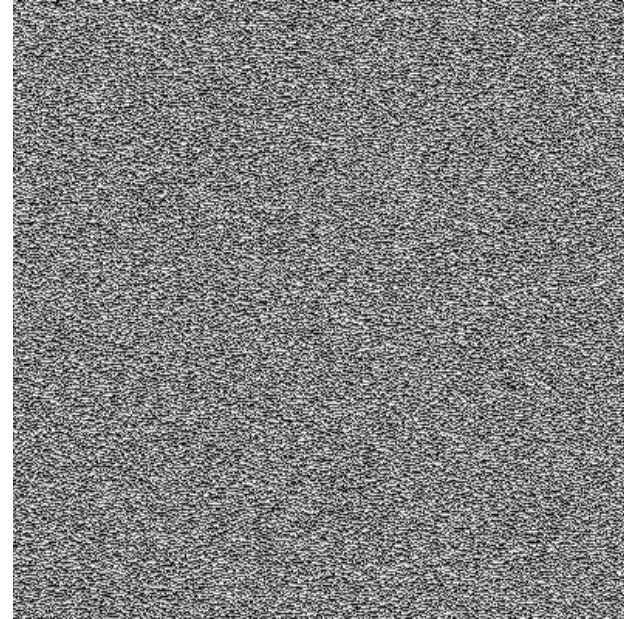


complex number:  $x + jy = A e^{j\varphi} = A \cos(\varphi)$

# RADAR DATA = COMPLEX DATA



Amplitude image



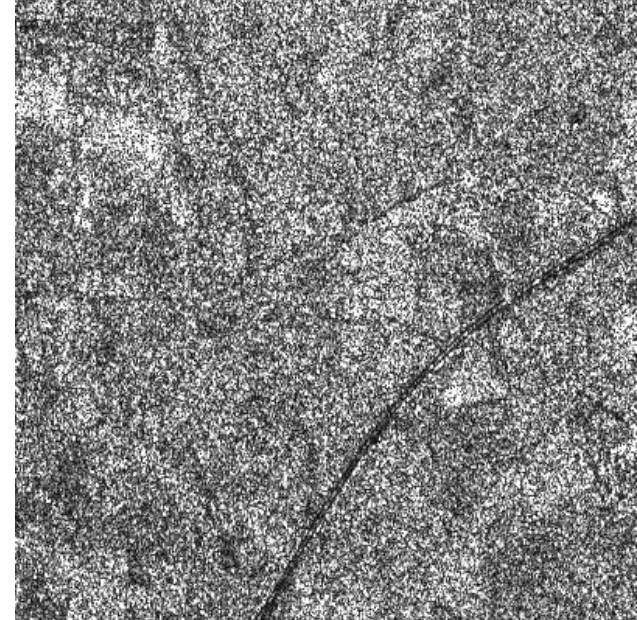
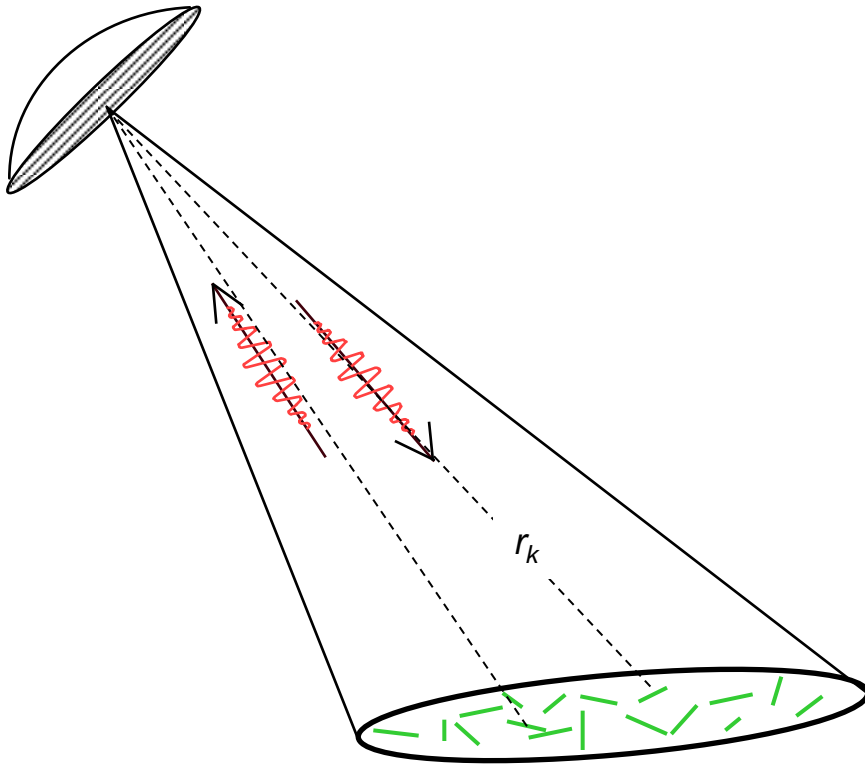
Phase image

SLC product: Single Look **Complex** product

$$\text{complex number: } x + jy = A e^{j\varphi} = A \cos(\varphi)$$

# Speckle Origin

Coherent Wave  $A \cos(\omega_0 t - k r + \psi)$



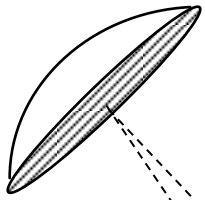
Homogeneous scene :

N elementary scatterers  $a_k, \varphi_k$   
*randomly oriented*

$$\varphi_k = \psi_k + \frac{4\pi r_k}{\lambda}$$



# Case of two scatterers



$$r_2 = r_1 + \Delta r$$

$$r_1$$

$$\Delta r$$

Scatterer 1:  $A \cos(\omega_o t - \varphi_1)$

Scatterer 2:  $A \cos(\omega_o t - \varphi_2)$

$$\varphi_2 = \psi + \frac{4\pi r_2}{\lambda} = \psi + \frac{4\pi (r_1 + \Delta r)}{\lambda} = \varphi_1 + \frac{4\pi \Delta r}{\lambda}$$

$$\varphi_1 = \psi + \frac{4\pi r_1}{\lambda}$$

$$\varphi_2 = \varphi_1 + \frac{4\pi \Delta r}{\lambda}$$

$$\Delta r = \frac{\lambda}{2} \Rightarrow \frac{4\pi}{\lambda} \Delta r = 2\pi \quad \text{et} \quad \varphi_2 = \varphi_1 + 2\pi$$

$$\Delta r = \frac{\lambda}{4} \Rightarrow \frac{4\pi}{\lambda} \Delta r = \pi \quad \text{et} \quad \varphi_2 = \varphi_1 + \pi$$

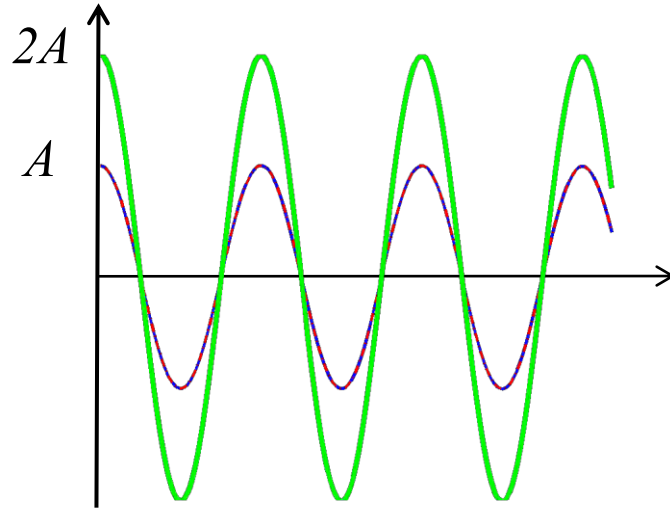
$$\Delta r = \frac{3\lambda}{8} \Rightarrow \frac{4\pi}{\lambda} \Delta r = \frac{3\pi}{2} \quad \text{et} \quad \varphi_2 = \varphi_1 + \frac{3\pi}{2}$$

## *2 coherent waves sum*

$$y(t) = A \cos\left(\frac{2\pi}{T}t - \frac{4\pi}{\lambda}r_1 + \varphi\right) + A \cos\left(\frac{2\pi}{T}t - \frac{4\pi}{\lambda}r_2 + \varphi\right)$$

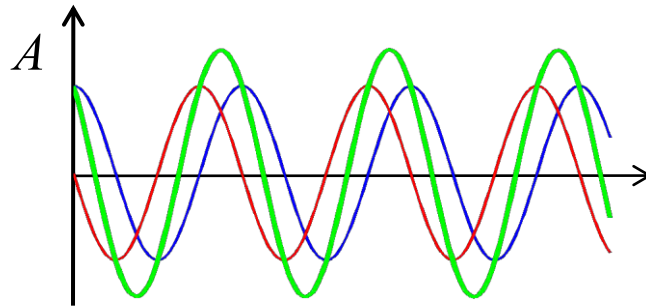
$$r_2 = r_1 + \frac{\lambda}{2}$$

$$\varphi_2 = \varphi_1 + 2\pi$$



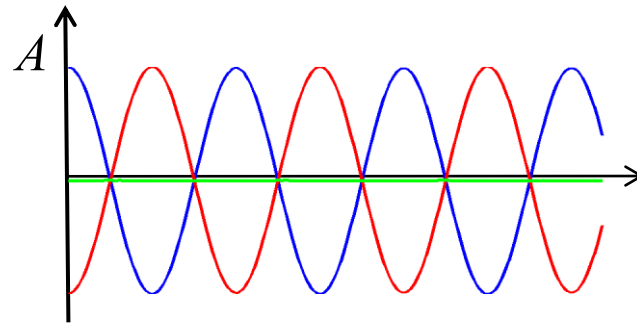
$$r_2 = r_1 + \frac{3\lambda}{8}$$

$$\varphi_2 = \varphi_1 + \frac{3\pi}{2}$$



$$r_2 = r_1 + \frac{\lambda}{4}$$

$$\varphi_2 = \varphi_1 + \pi$$



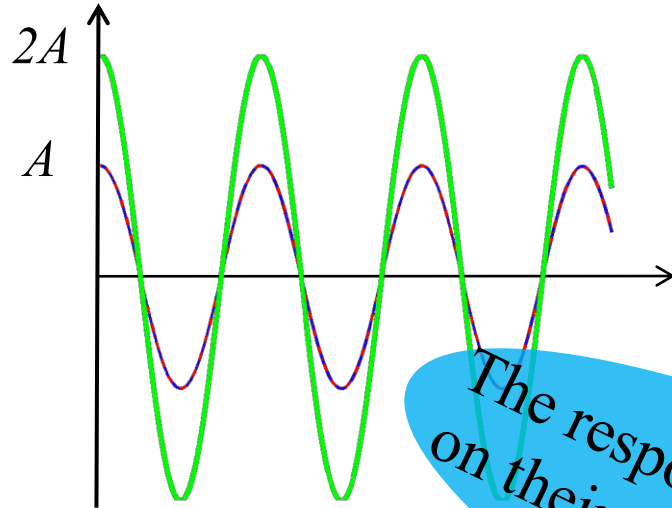


## 2 coherent waves sum

$$y(t) = A \cos\left(\frac{2\pi}{T}t - \frac{4\pi}{\lambda}r_1 + \varphi\right) + A \cos\left(\frac{2\pi}{T}t - \frac{4\pi}{\lambda}r_2 + \varphi\right)$$

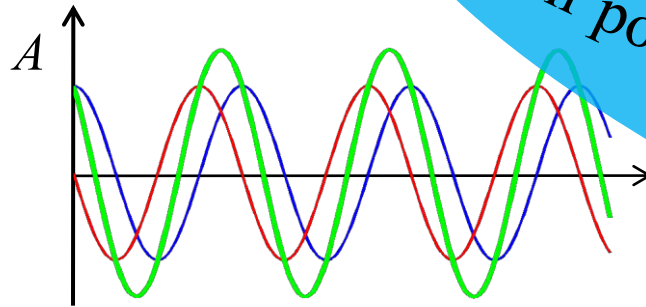
$$r_2 = r_1 + \frac{\lambda}{2}$$

$$\varphi_2 = \varphi_1 + 2\pi$$



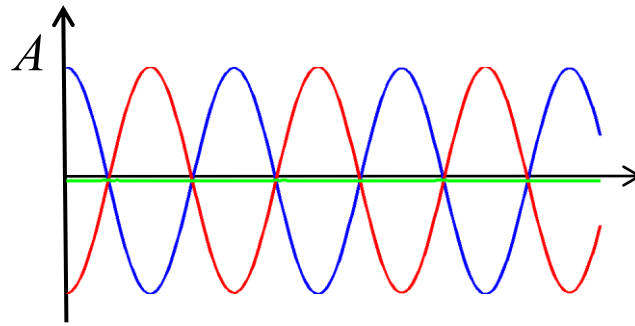
$$r_2 = r_1 + \frac{3\lambda}{8}$$

$$\varphi_2 = \varphi_1 + \frac{3\pi}{2}$$



$$r_2 = r_1 + \frac{\lambda}{4}$$

$$\varphi_2 = \varphi_1 + \pi$$



The response of two scatterers depends on their position... relatively to  $\lambda$ !!!!

**Ideal Radar reflectivity image**



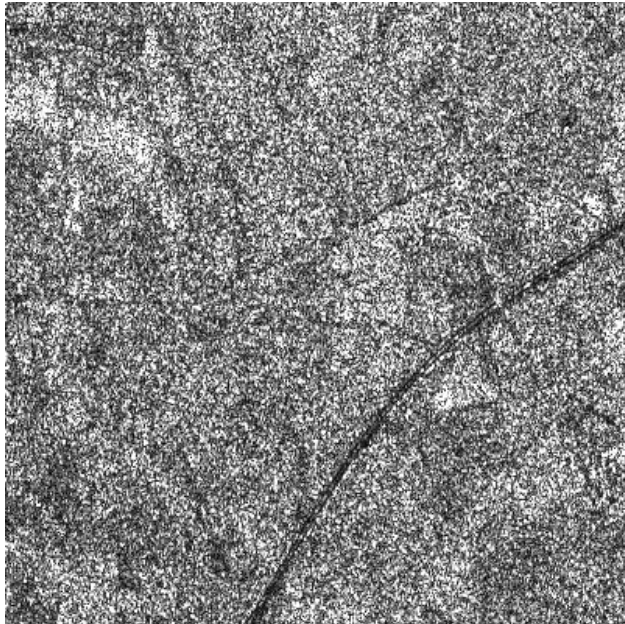
**Radar acquisition**





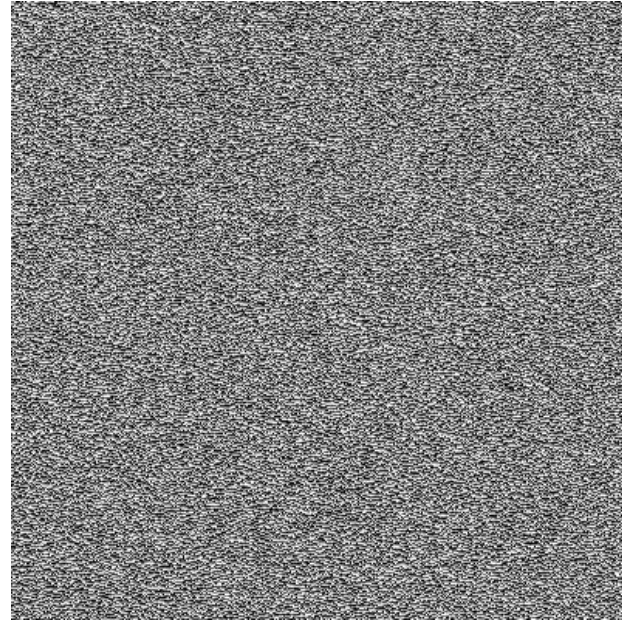
RADAR DATA = Amplitude + Phase DATA

$A$



Amplitude image

$\varphi$



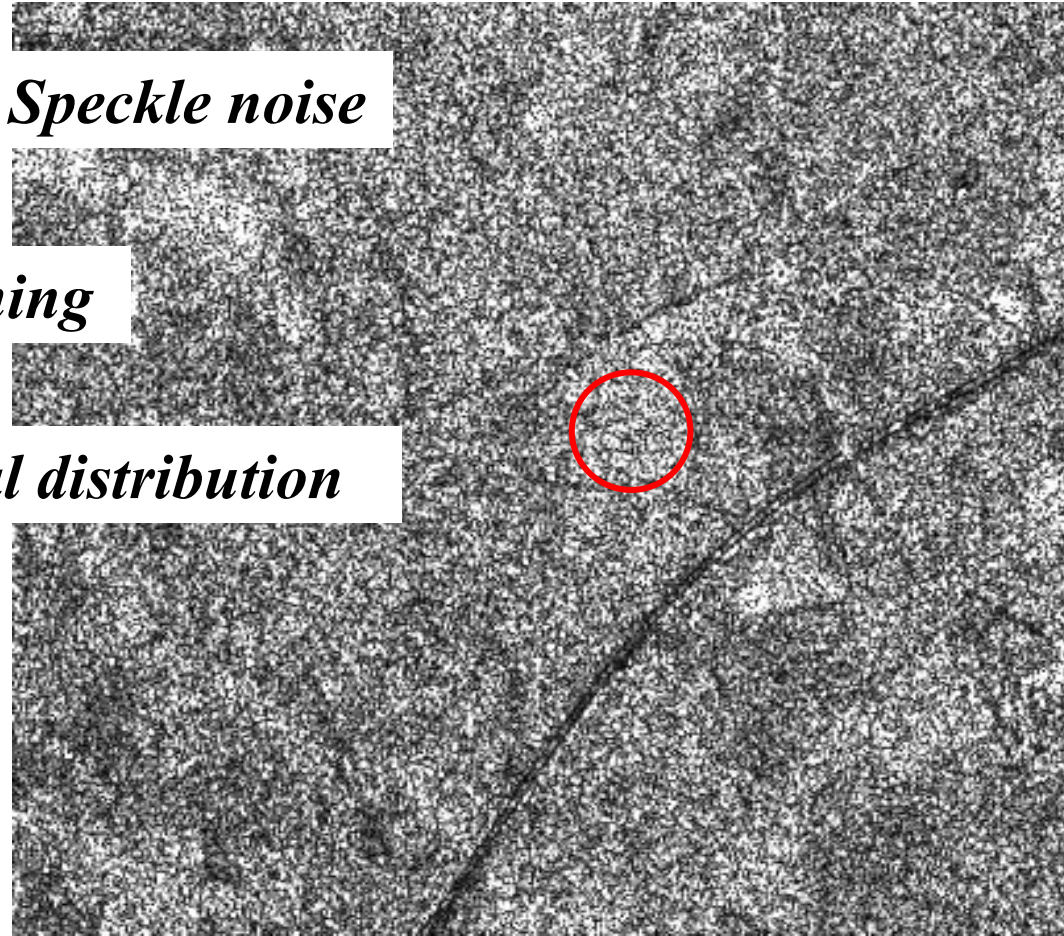
Phase image

SLC product

Coherent Imagery System → *Speckle noise*

*Single pixel value = no meaning*

Homogeneous are = *statistical distribution*



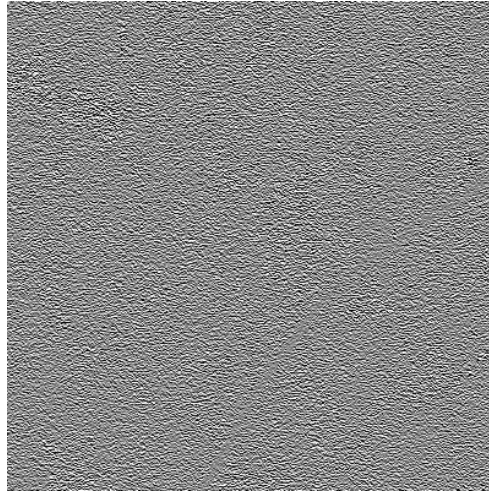


## *SLC Product*

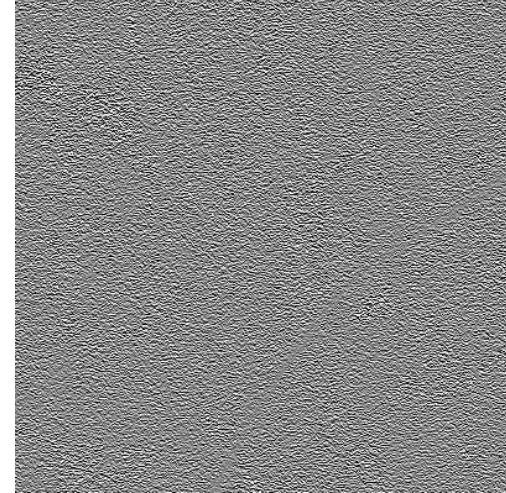
$$z = x + jy$$

$$= A e^{j\varphi}$$

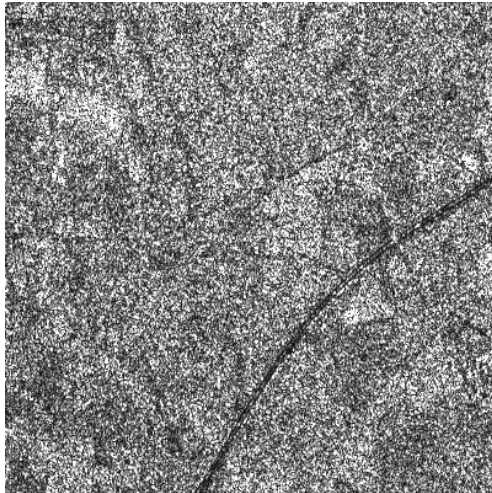
Real part:  $x$



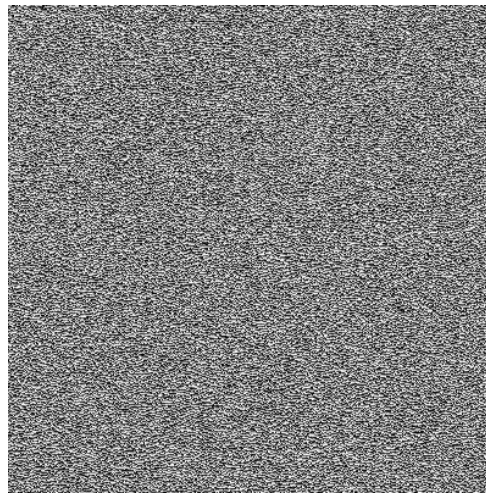
Imaginary part:  $y$



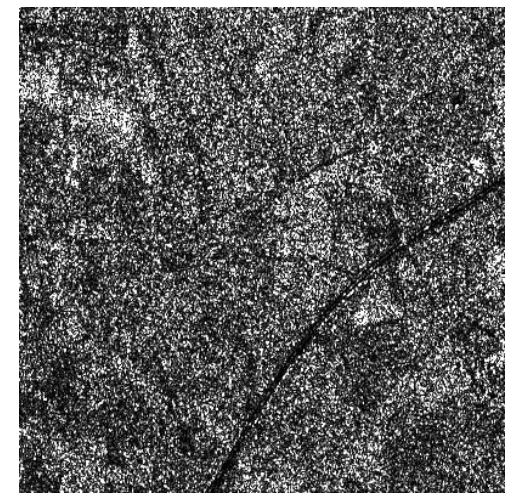
Amplitude  $A$



Phase  $\varphi$



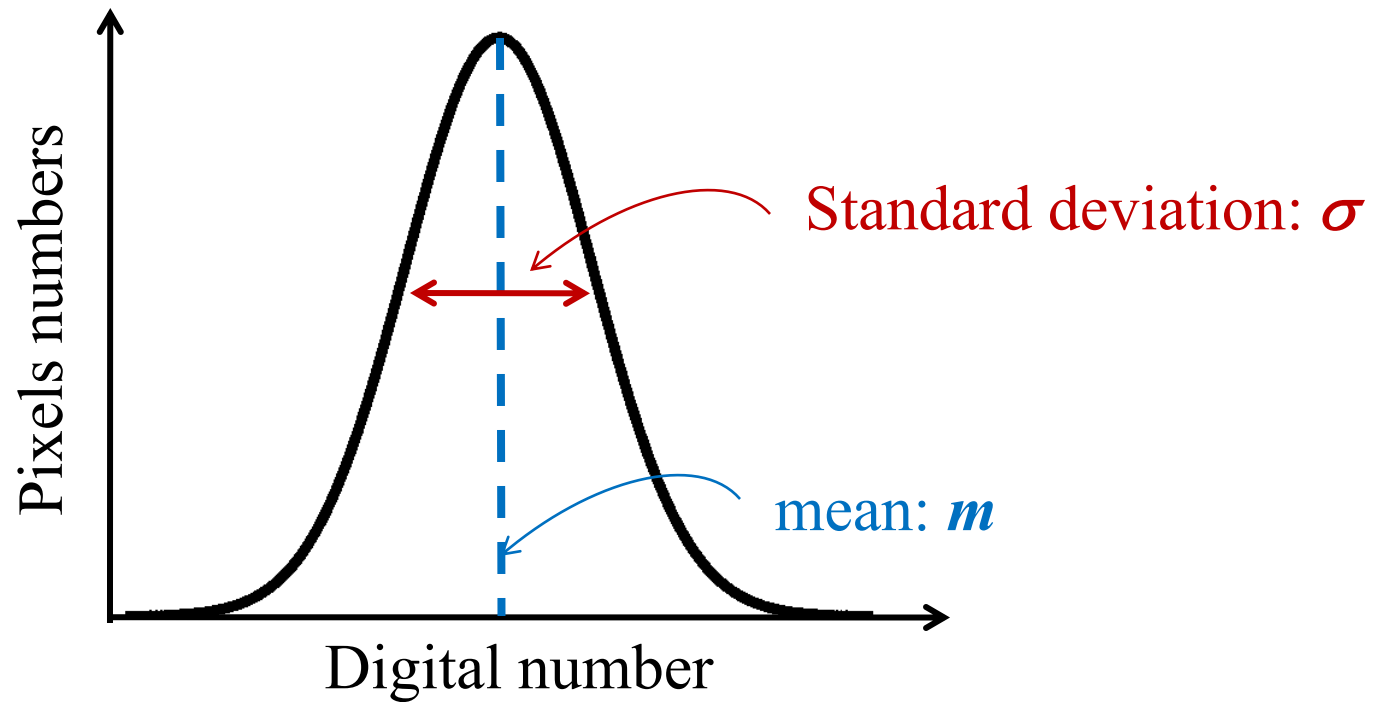
Intensity  $I$



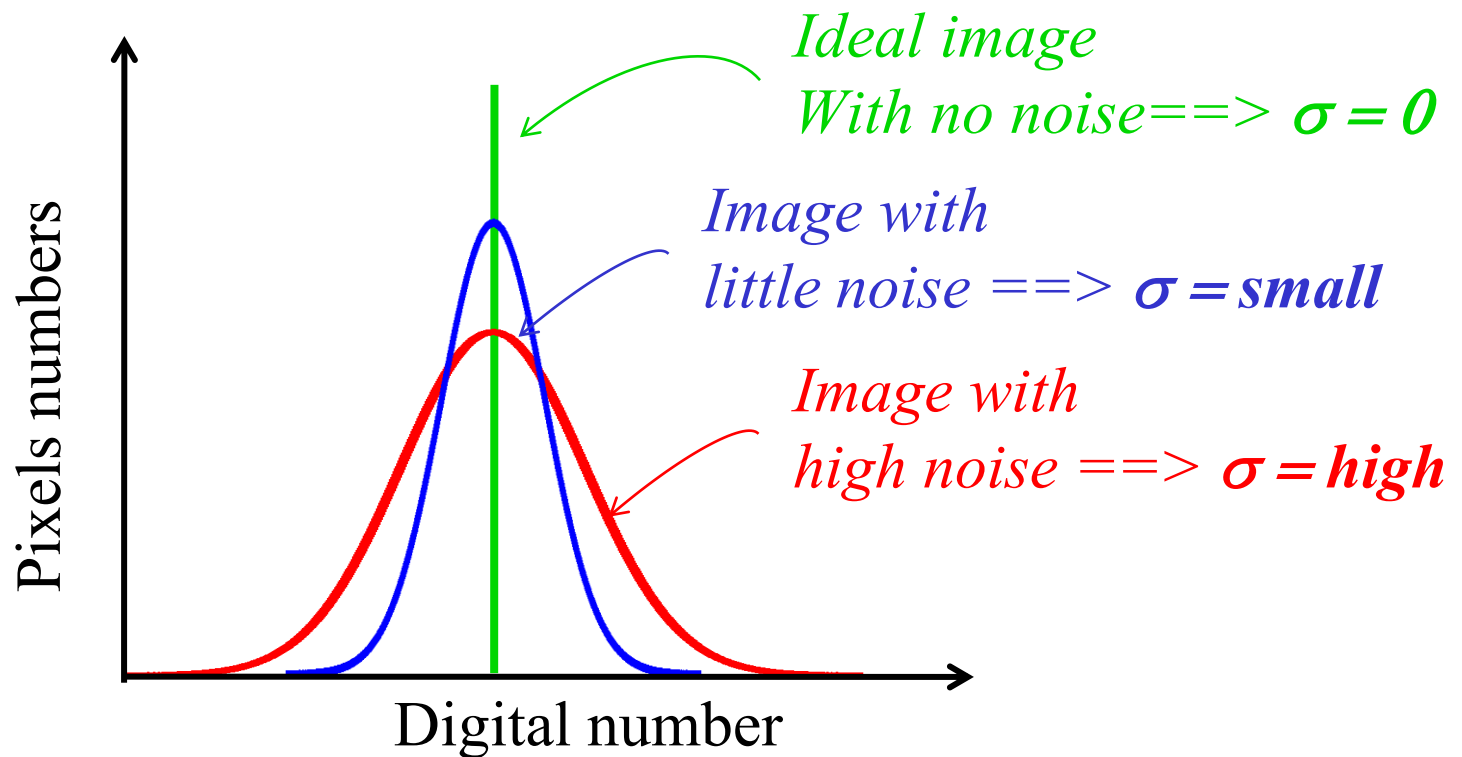
$\varphi$  image no useful except for interferometry

$A$  or  $I$  image similar to optical image

## *Reminder: Histogram*



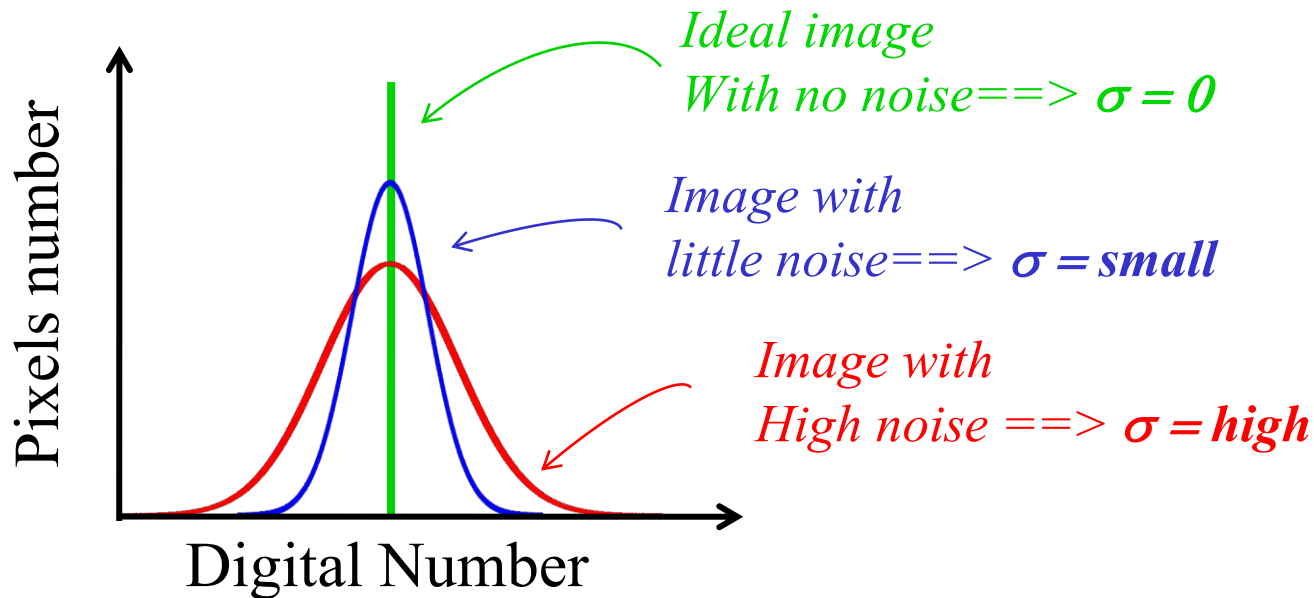
## *Histogram over an homogeneous area*





# *Goal of radar image filtering:*

Histogram over an homogeneous area



***Decrease the standard deviation  $\sigma$  (noise)  
without modify the mean  $m$  ( $\approx$  radar reflectivity)***











© Camille Pissaro

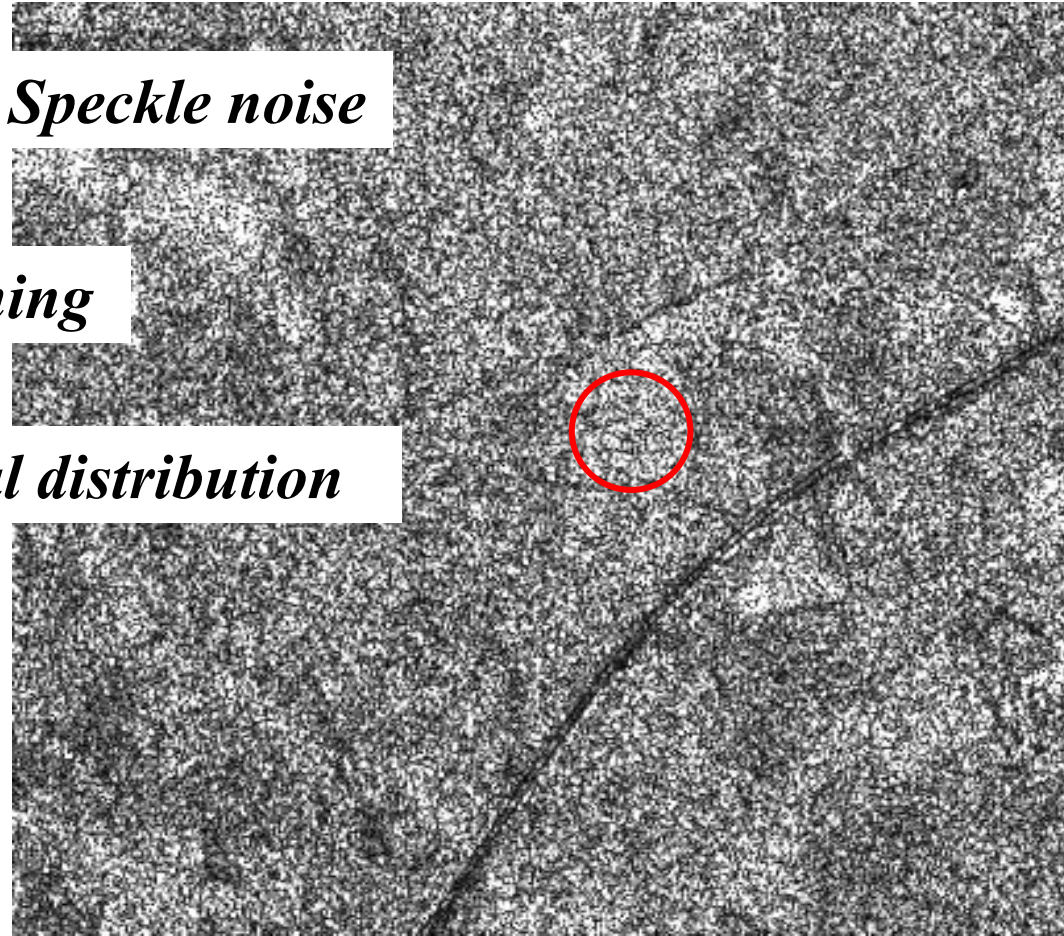
A distant vision allows to blur the pointillist effect  
and see the homogeneous areas

→ The *average process* effect!!!  
Reduces the noise (standard deviation)  
doesn't change the average radiometry (mean)

Coherent Imagery System → *Speckle noise*

*Single pixel value = no meaning*

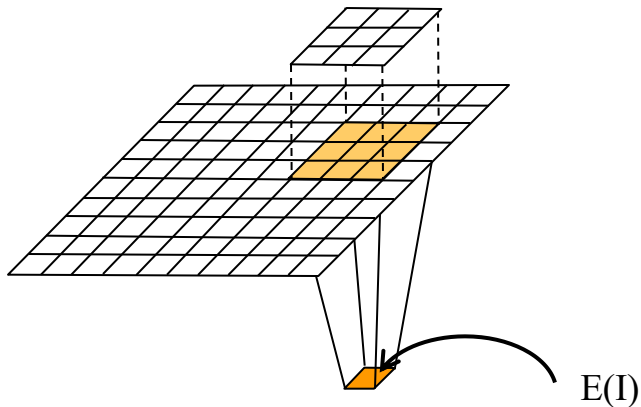
Homogeneous are = *statistical distribution*



# MULTILOOK OBTENTION

in spatial domain

*Sliding window: image \* window*

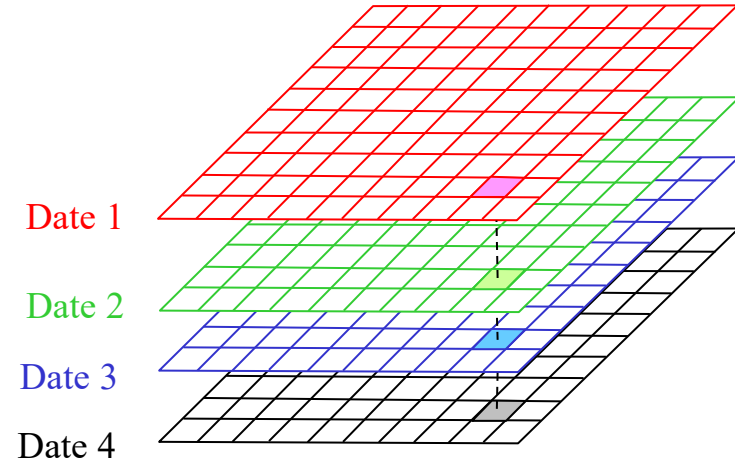


*9 looks if pixel sare not correlated*

Example: ERS data - PRI products :  $\cong$  3 looks

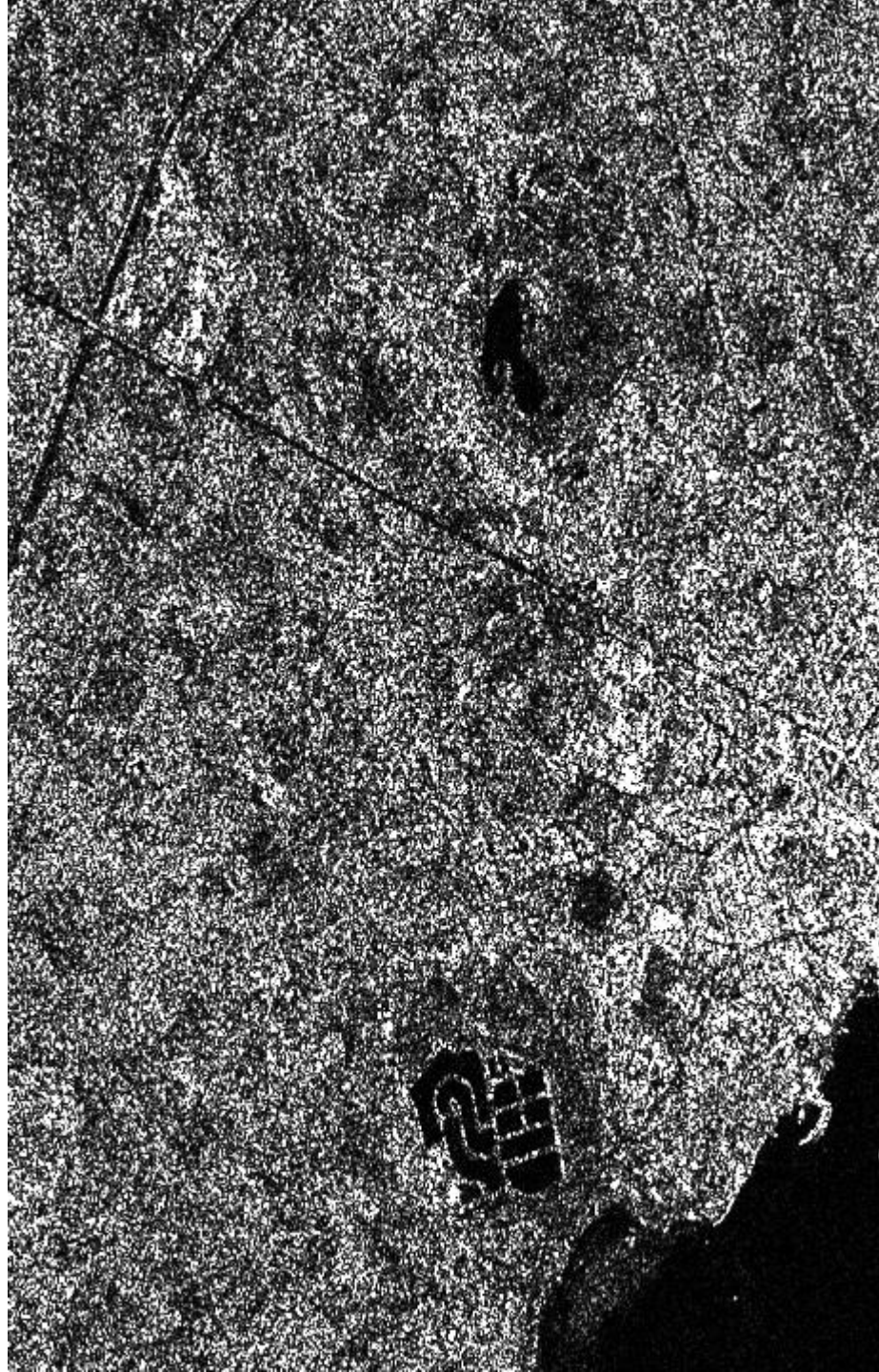
***Loss of spatial resolution***

in temporal domain



4 looks if surface  
has not changed

***Preservation of spatial res.  
Loss temporal information***



## *Intensity image*

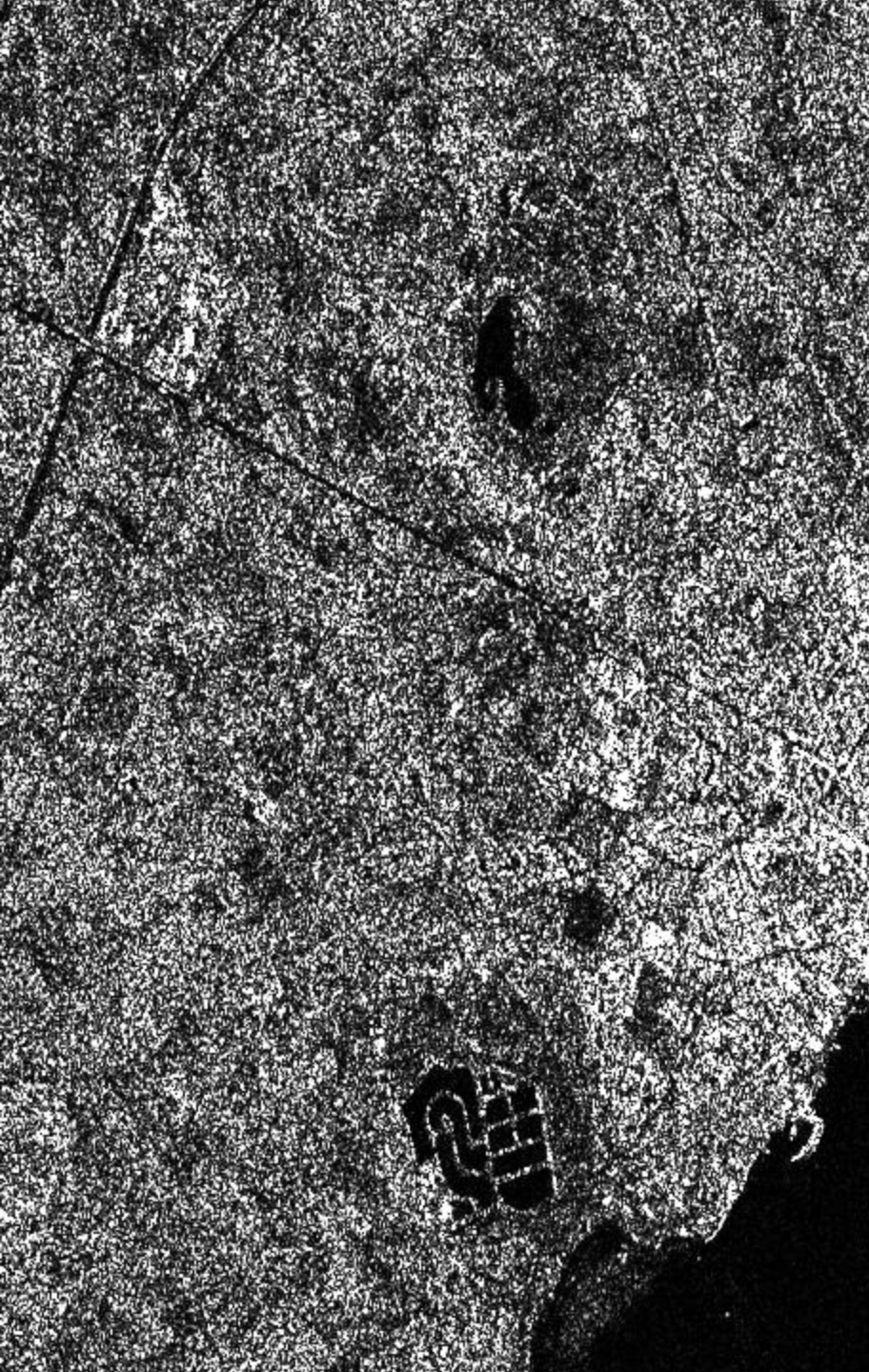
(from SLC product)

Sète - France: 21.06.2001

RADARSAT - FINE 1

INCIDENCE  $38^\circ$ , 4 x9 m

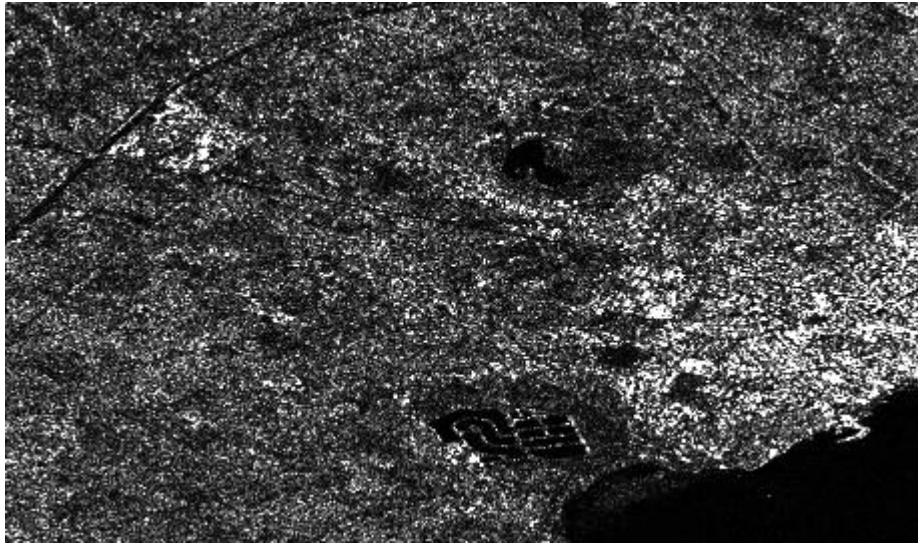






# *Spatial Multilook (=average) Processing*

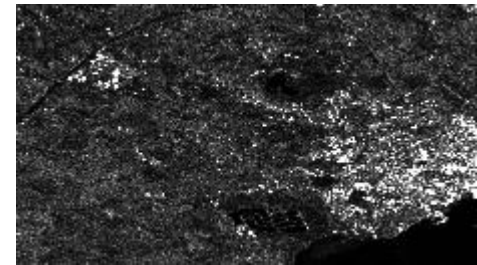
3x1 average window



< 3 Look

Sète - France: 21.06.2001

6x2 average window



< 12 Look

RADARSAT FINE 1  
INCIDENCE 38°, 9 x9 m

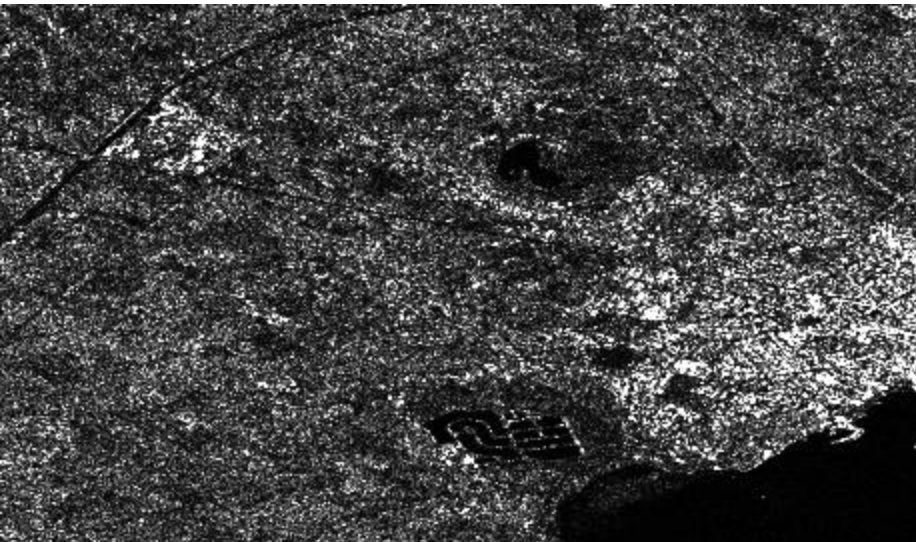
Due to pixels correlation!

# ***SPATIAL MULTILOOK PROCESSING***

Sète - France: 21.06.2001 - RADARSAT FINE 1 - INCIDENCE 38°, 9 x9 m

3x1 average window

< 3 Look



Due to pixels correlation!

6x2 average window

< 12 Look

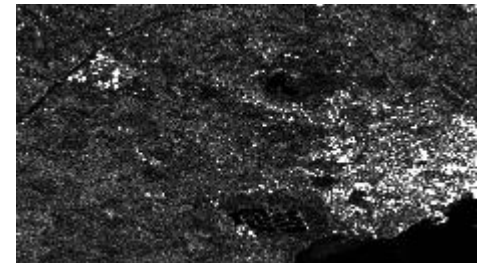
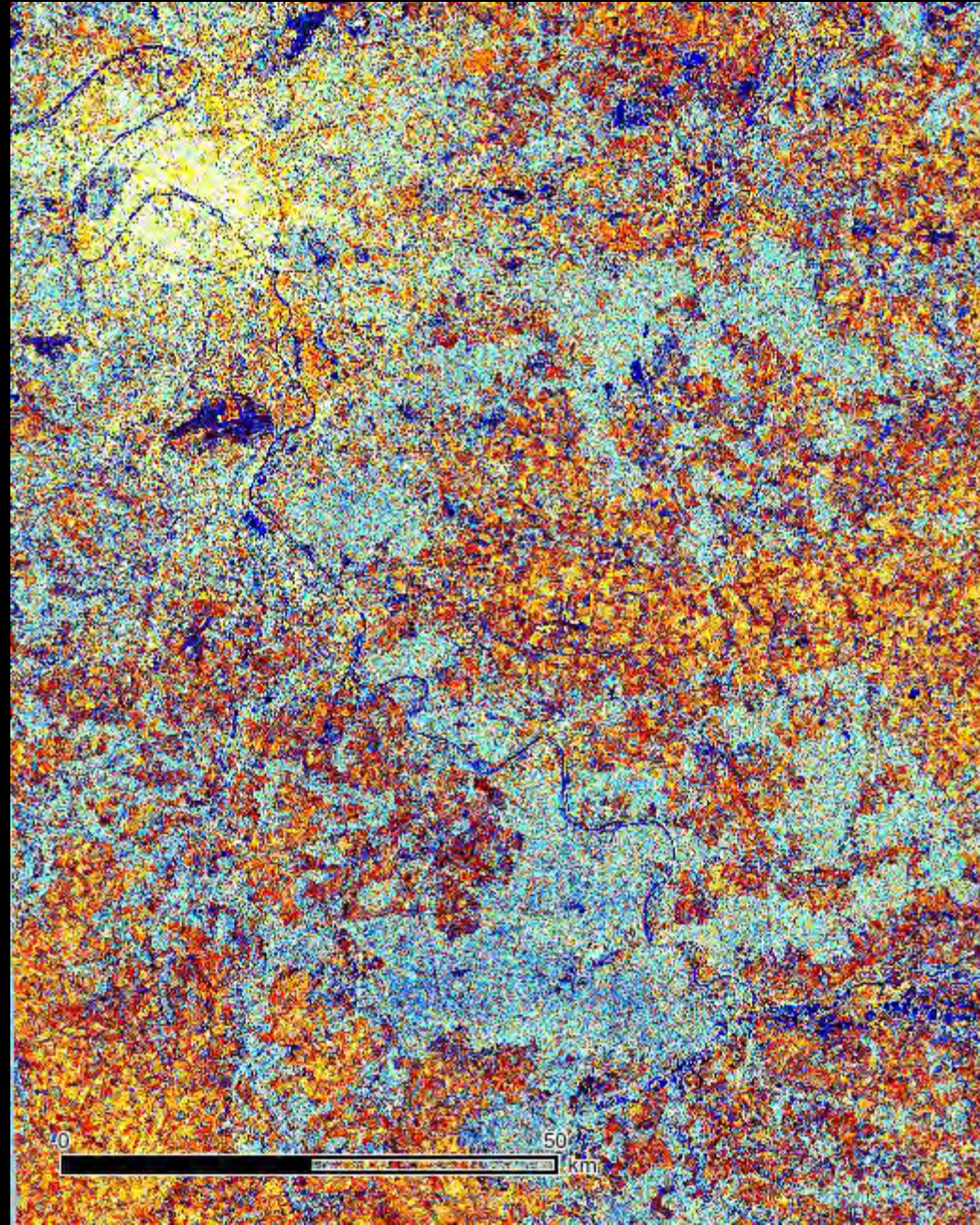


Photo aérienne ([www.géoportail.fr](http://www.géoportail.fr))



# Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015/03/02

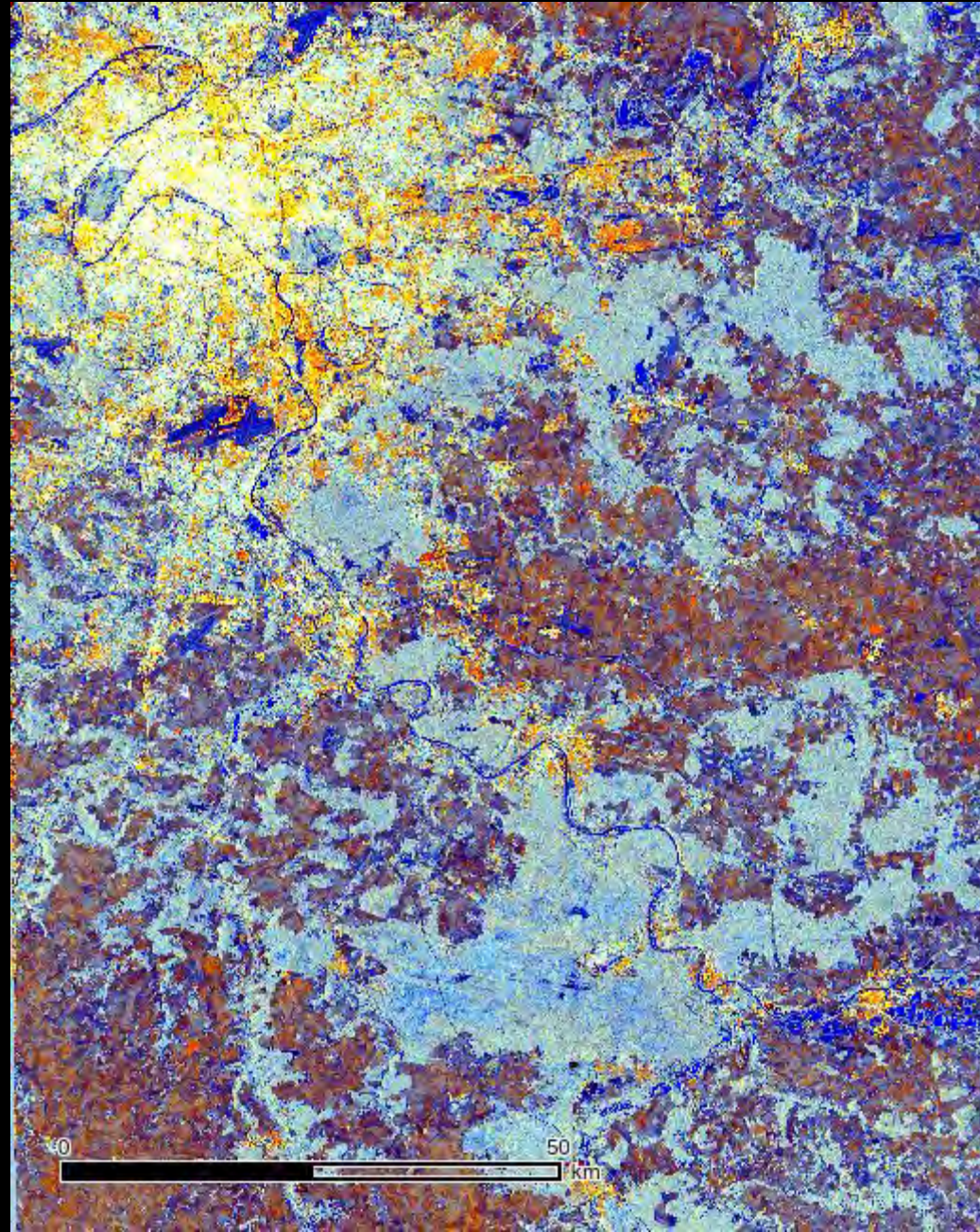
Parisian region



VV  
VH  
VH/VV



## Parisian region



VV  
VH  
VH/VV



GoogleEarth Image

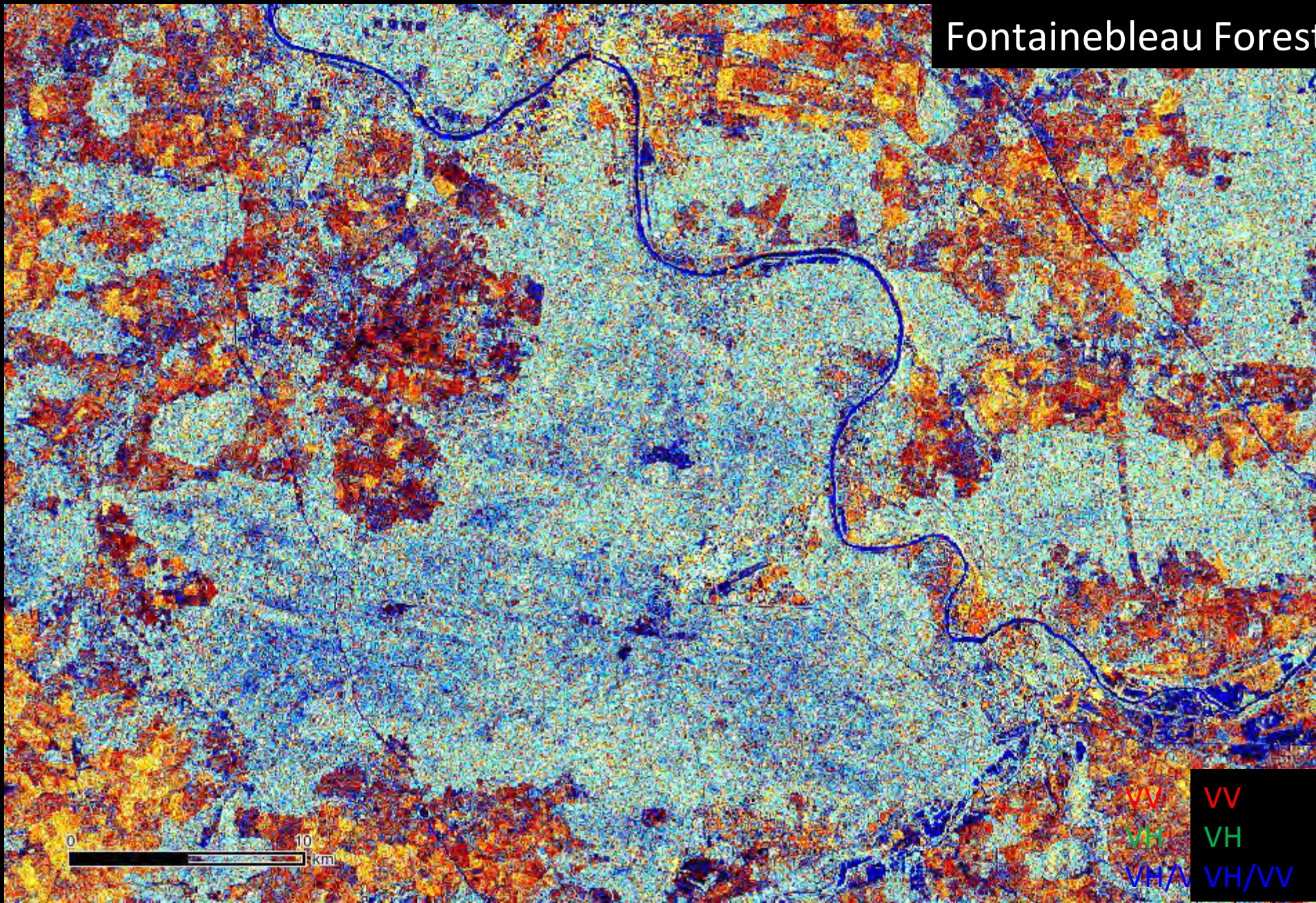
Parisian region





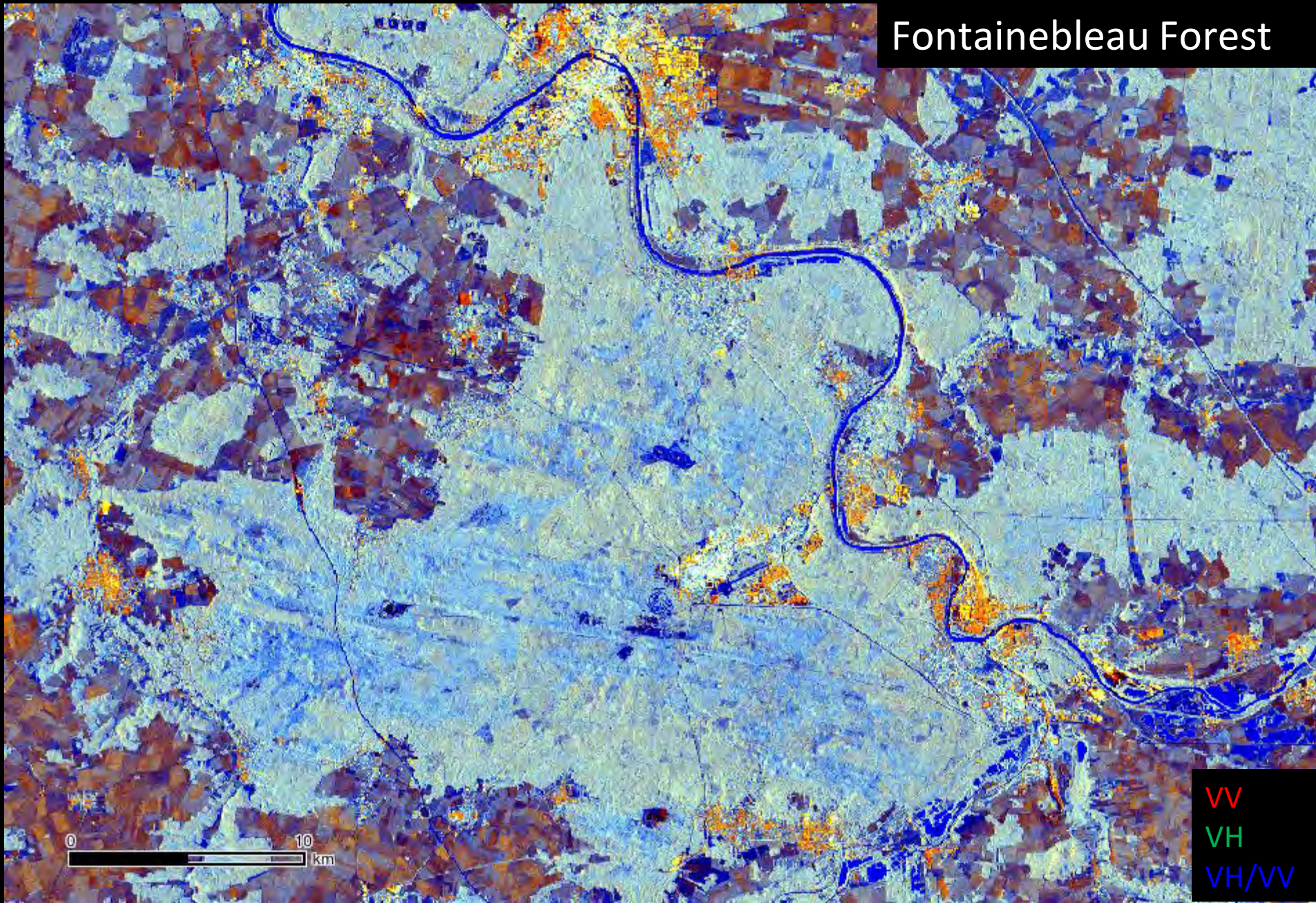
# Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015/03/02

Fontainebleau Forest





## Fontainebleau Forest





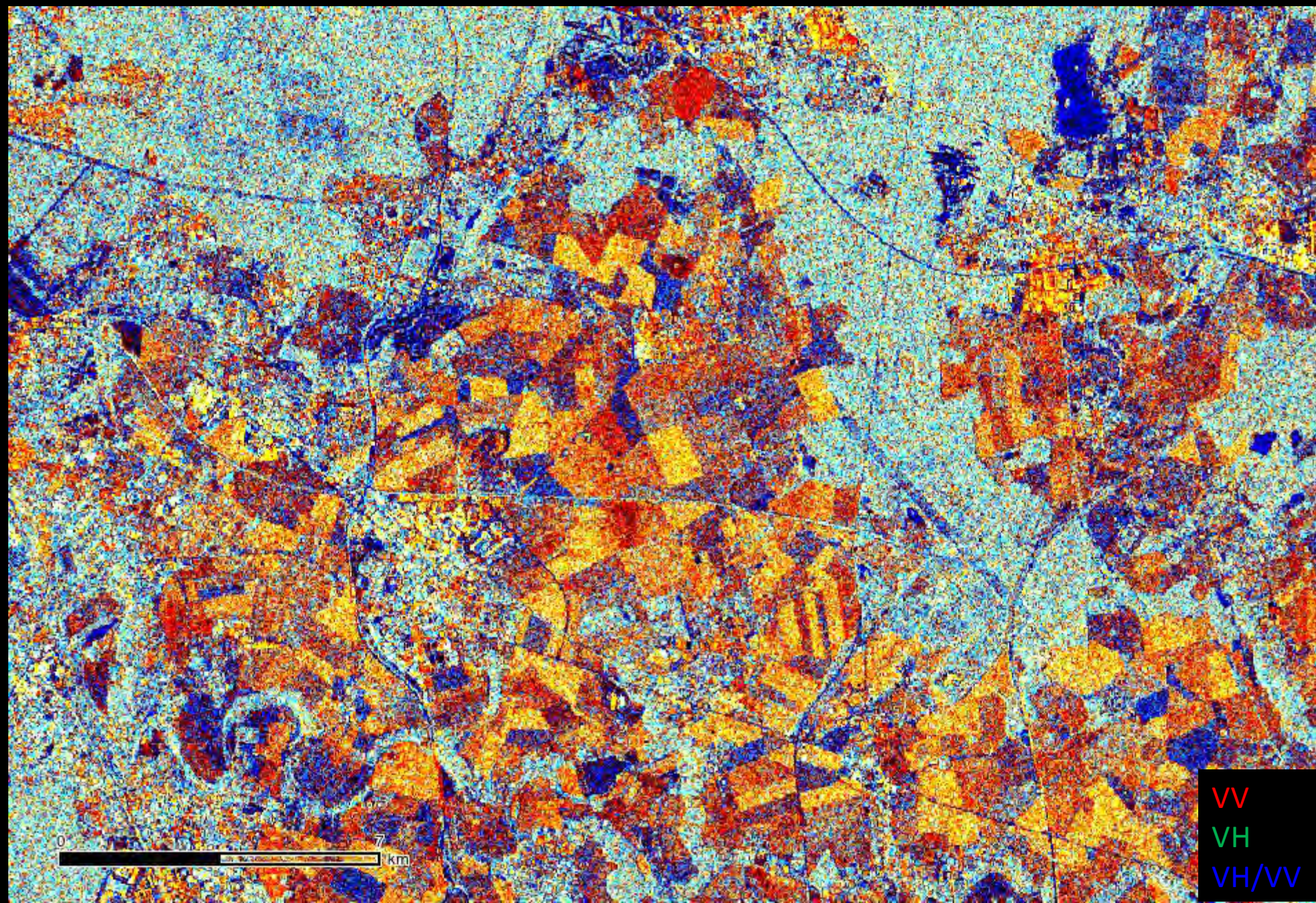
Fontainebleau Forest



0 10 km

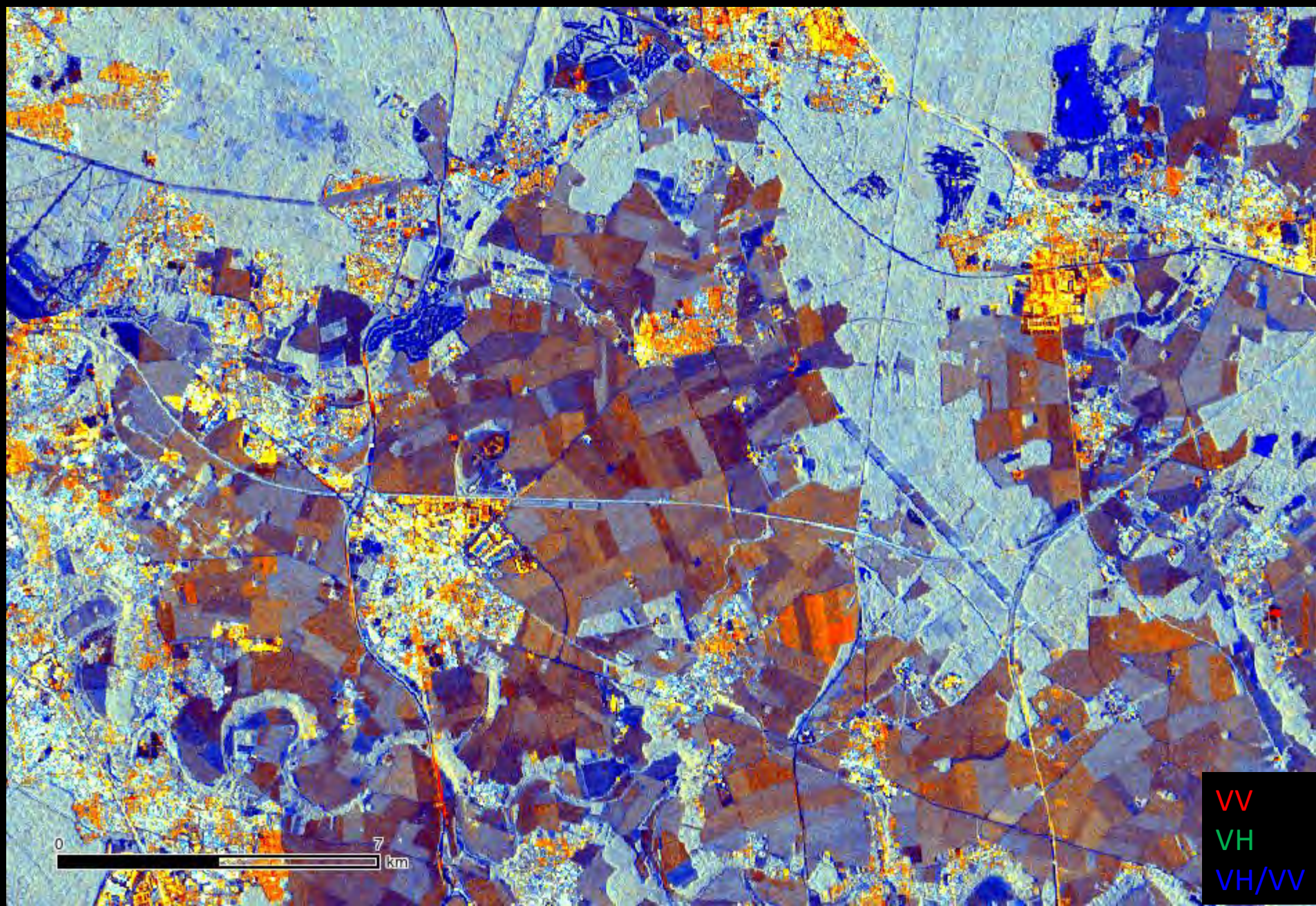


# Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015/03/02





Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average 2015/03/02 - 2017/01/26



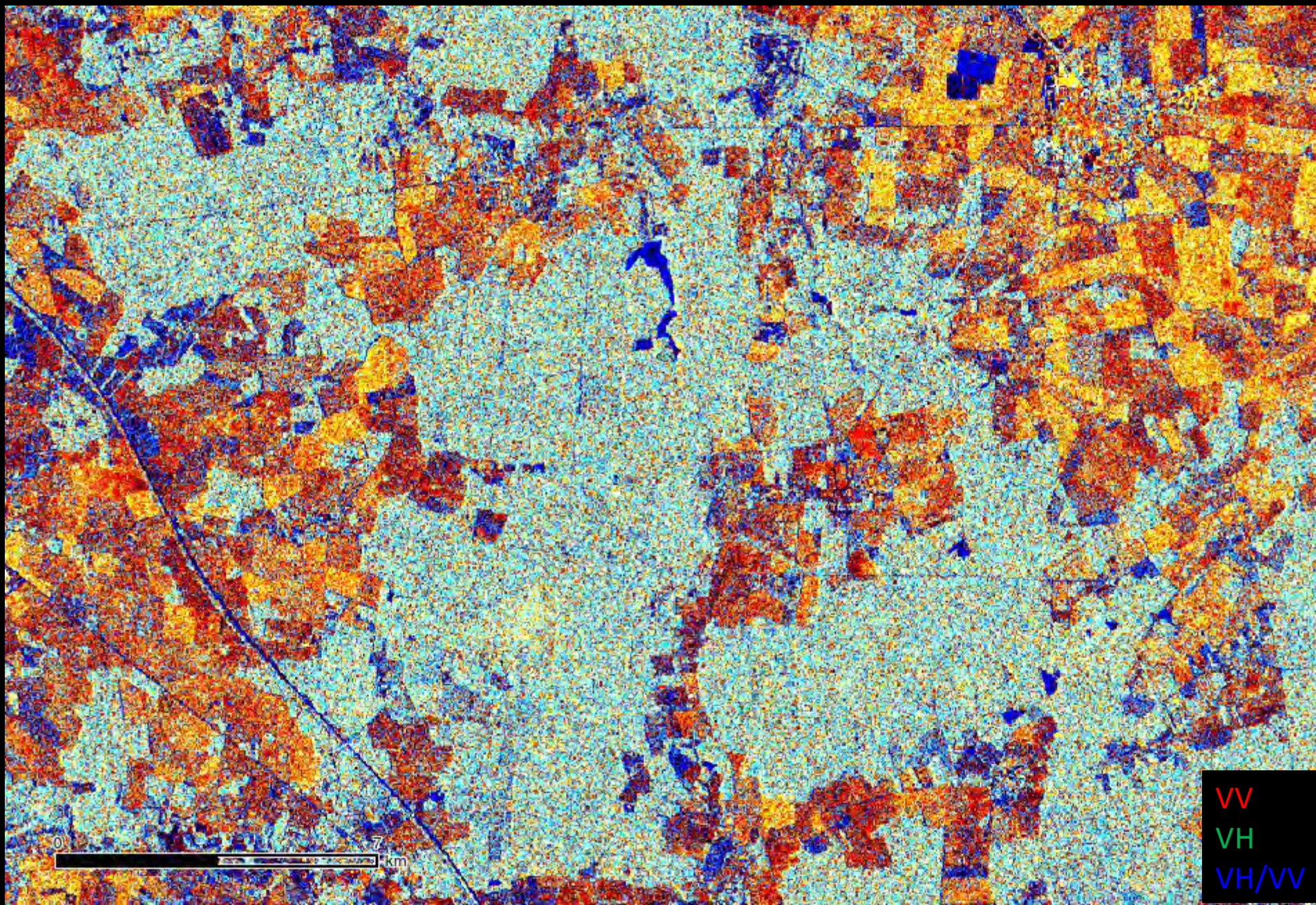




0 7 km

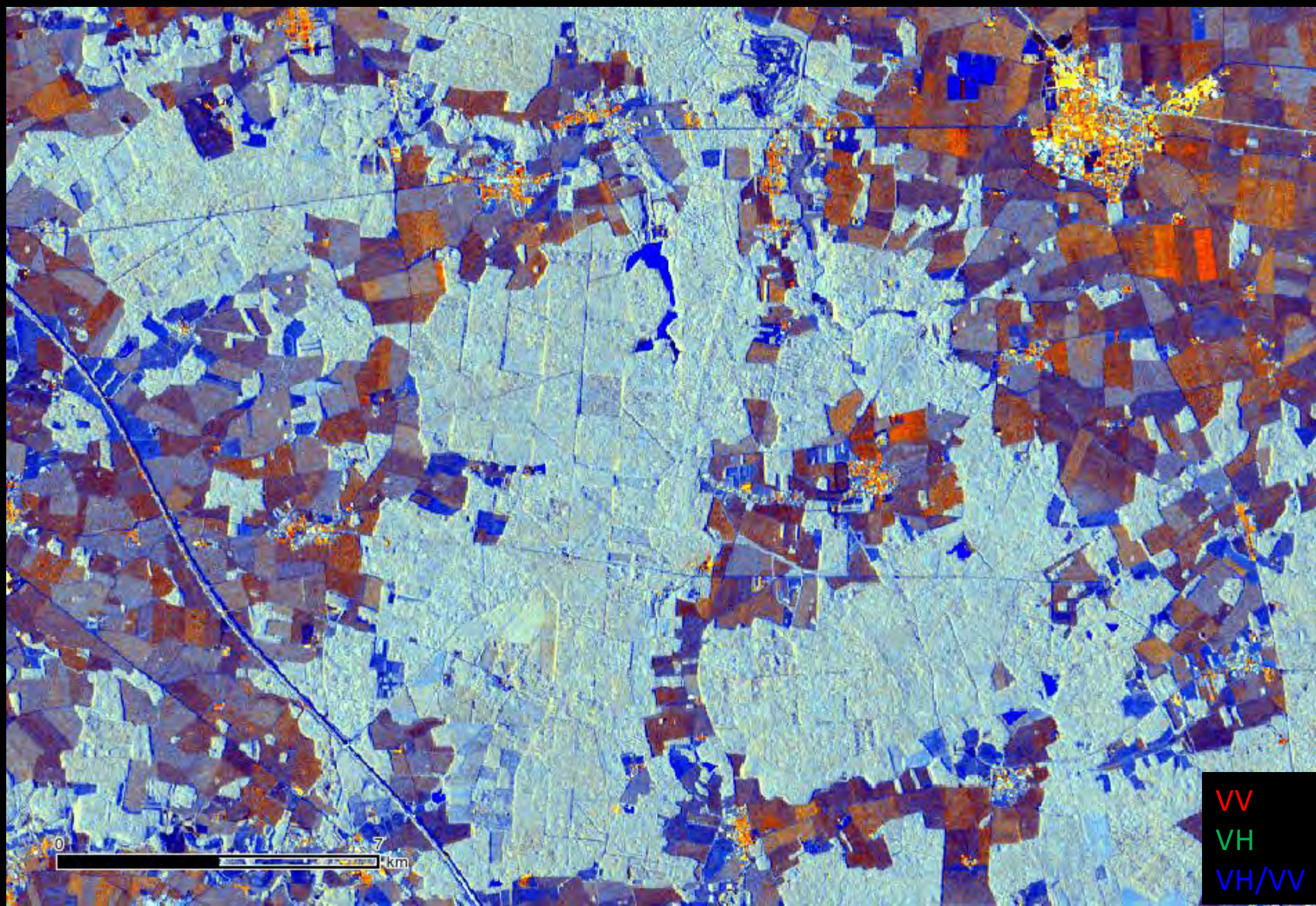


# Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015/03/02

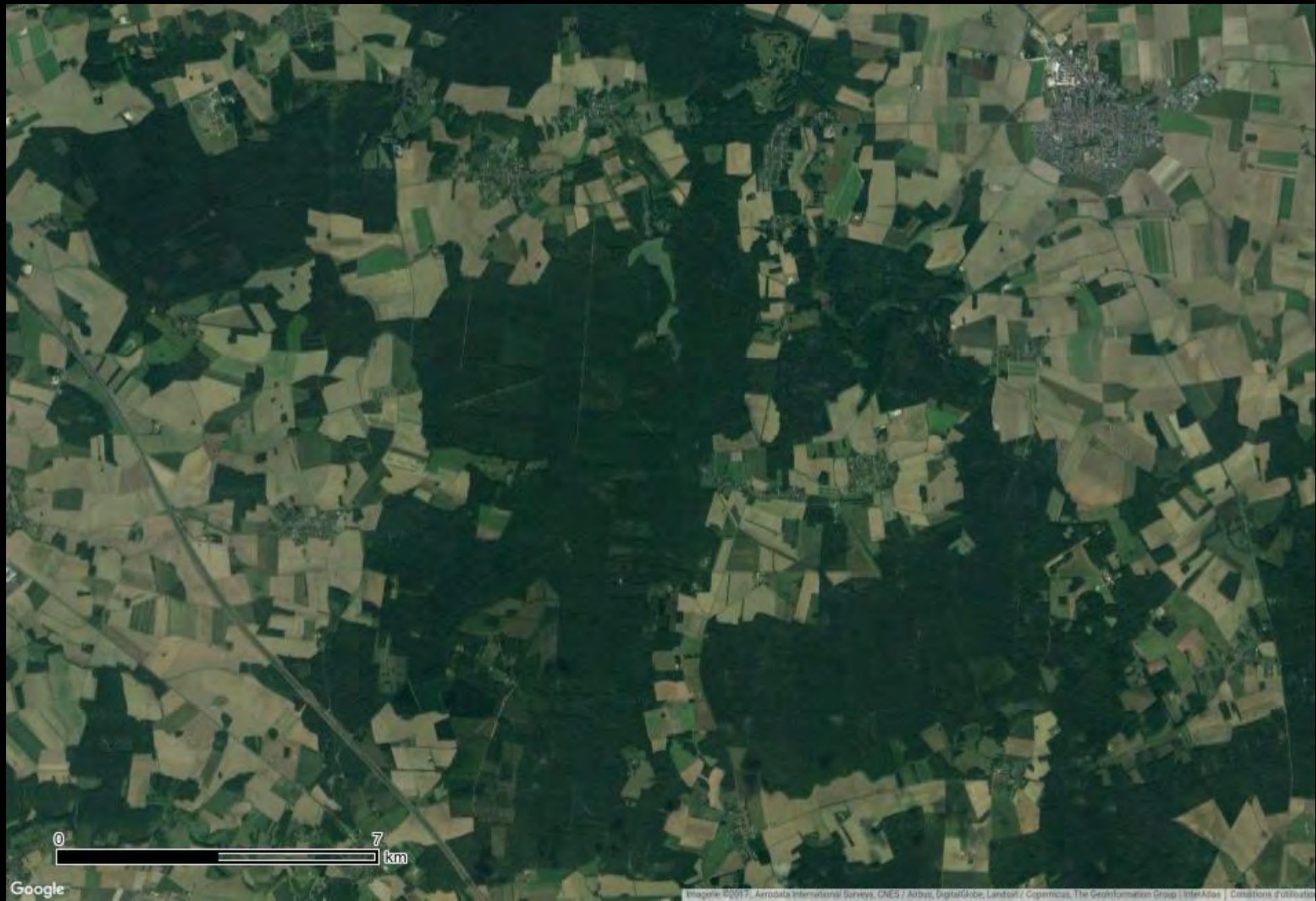




Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average 2015/03/02 - 2017/01/26



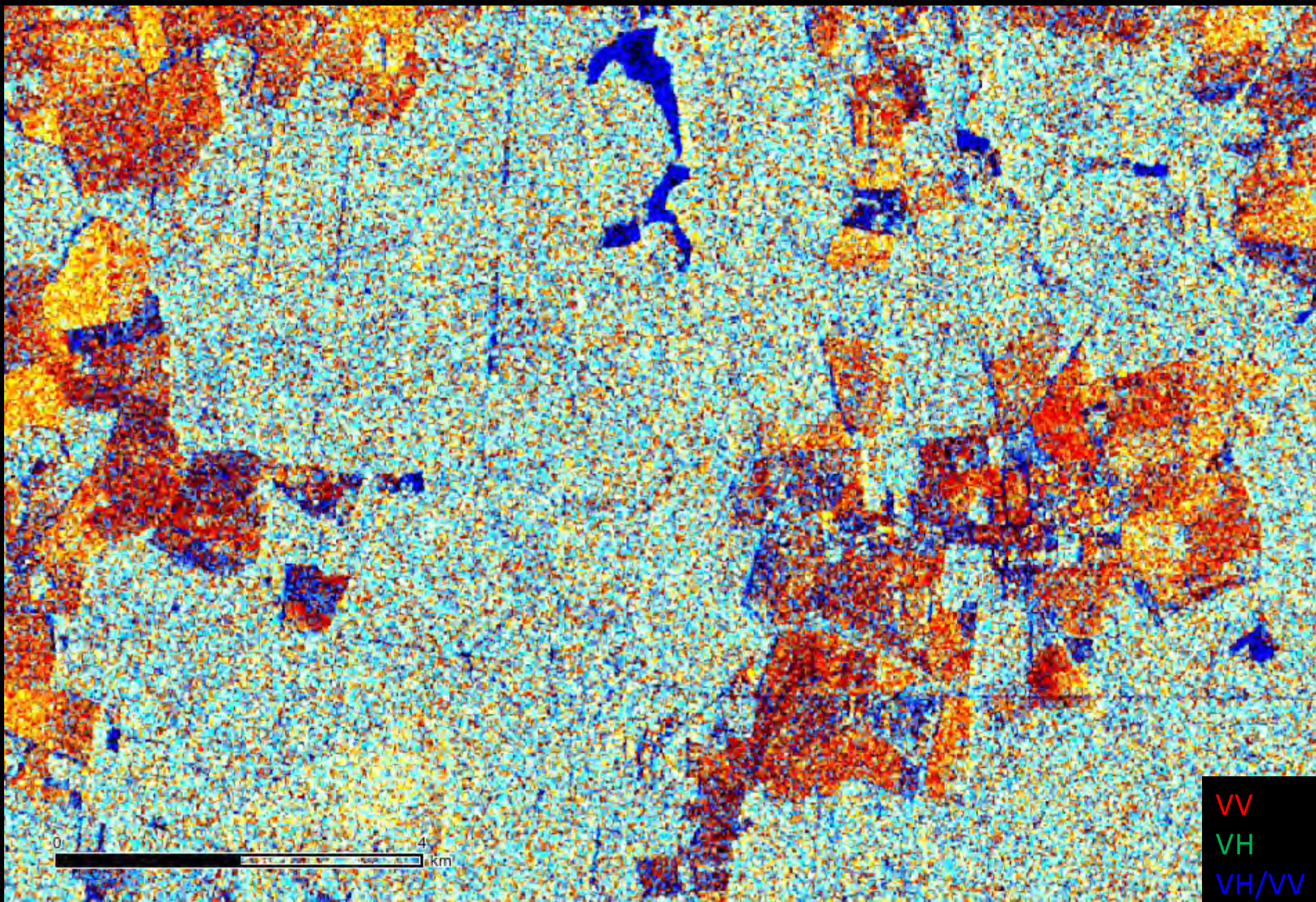




0 7 km

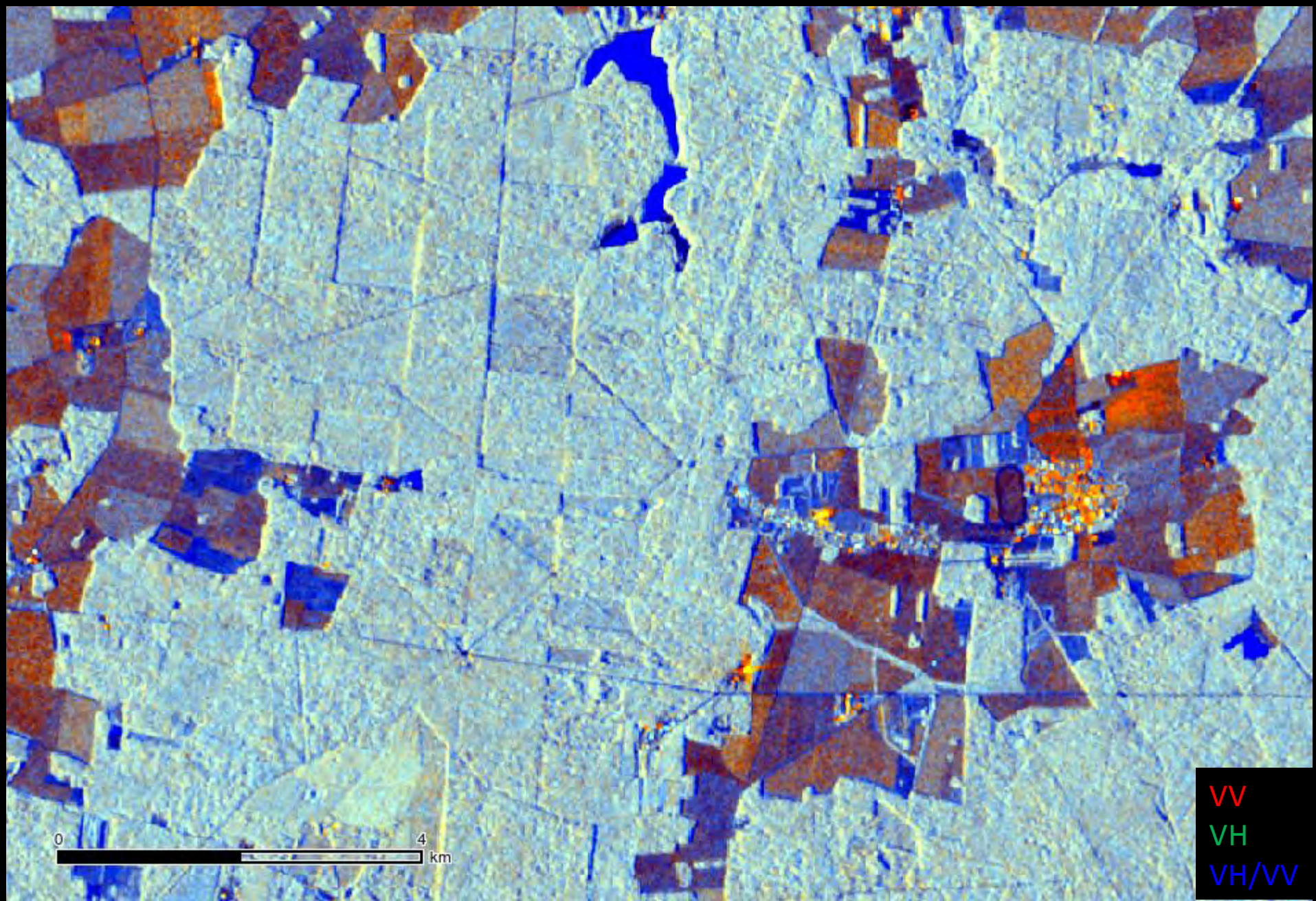


# Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015/03/02





# Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average 2015/03/02 - 2017/01/26



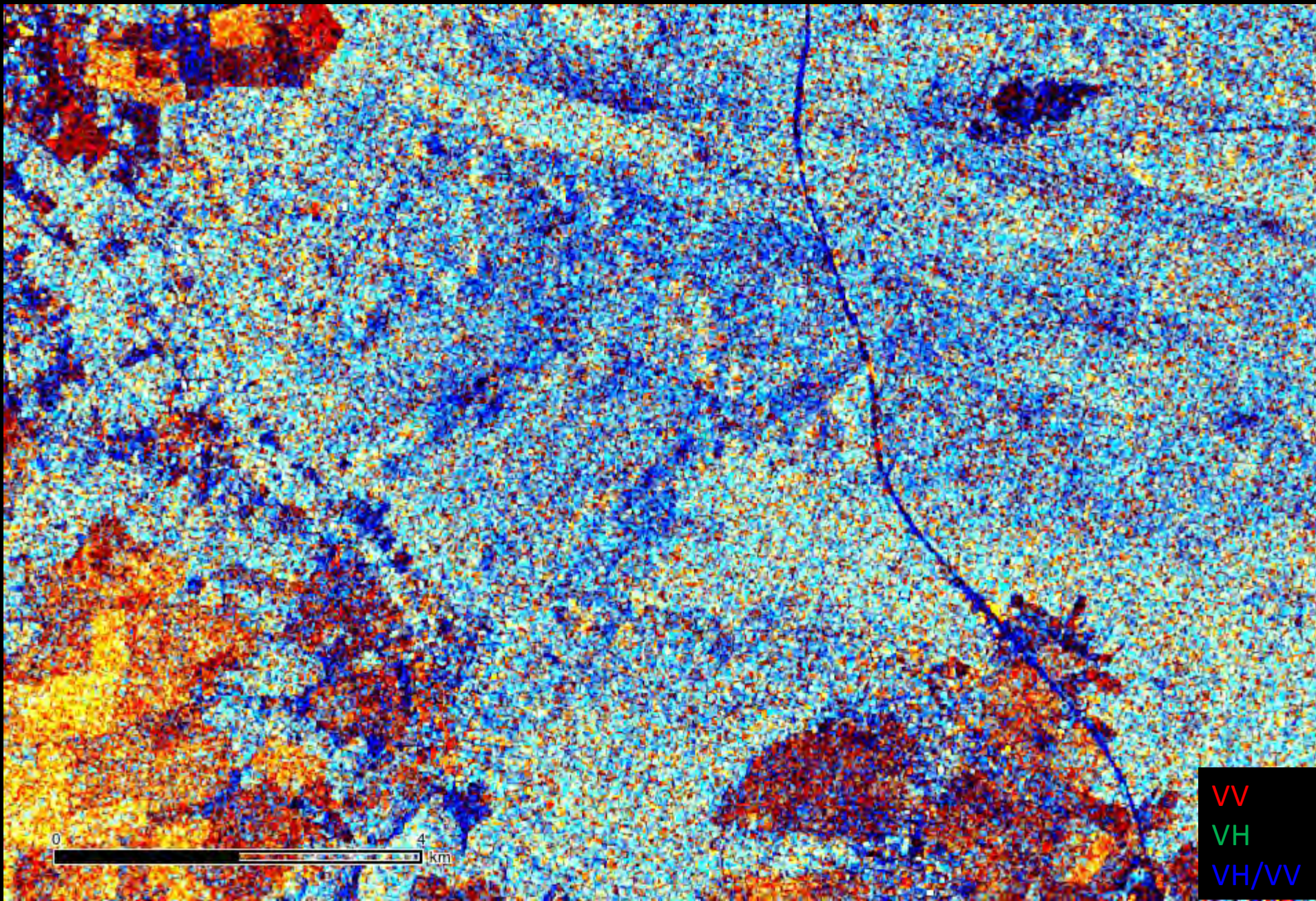




0 4 km

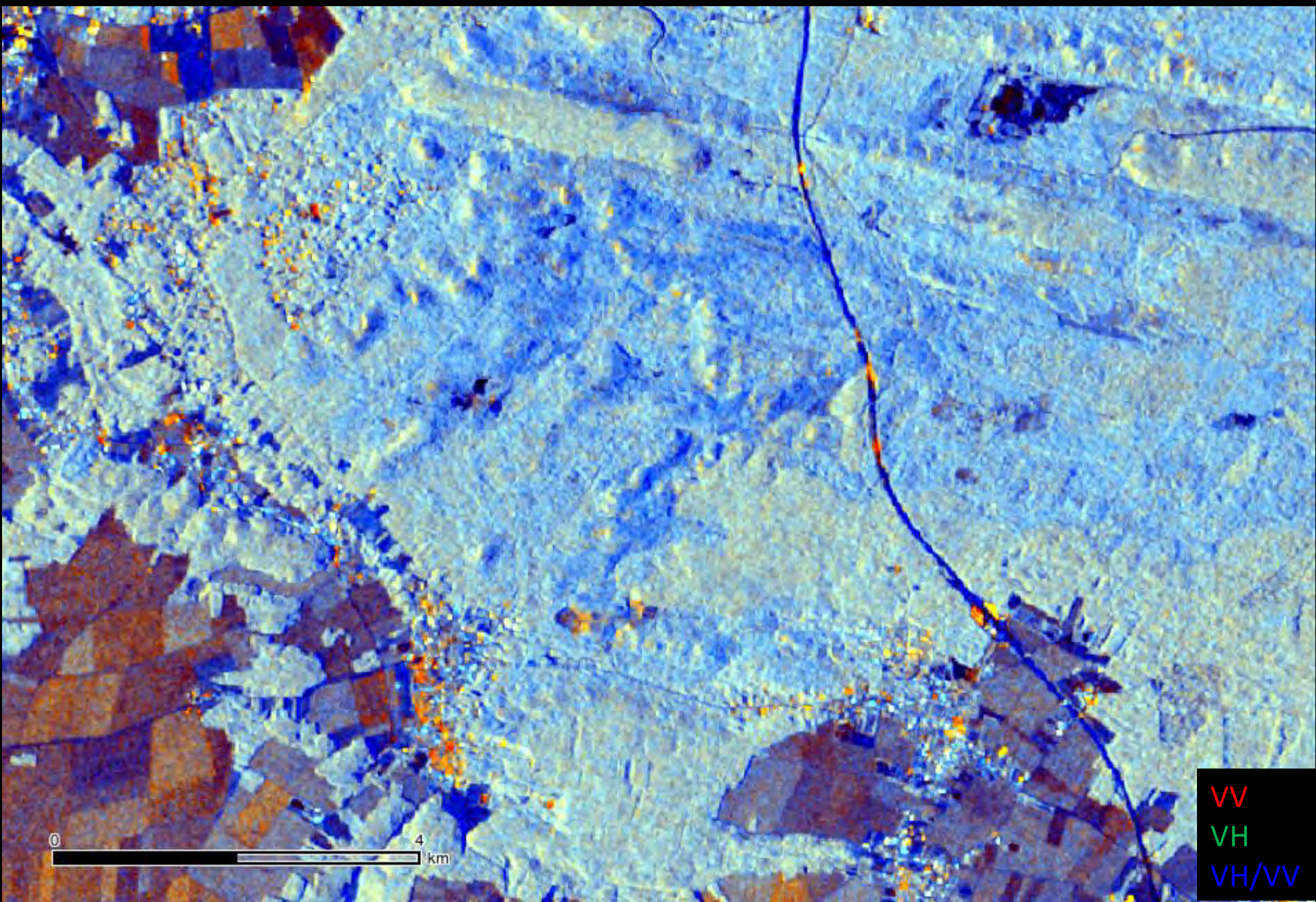


# Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015/03/02

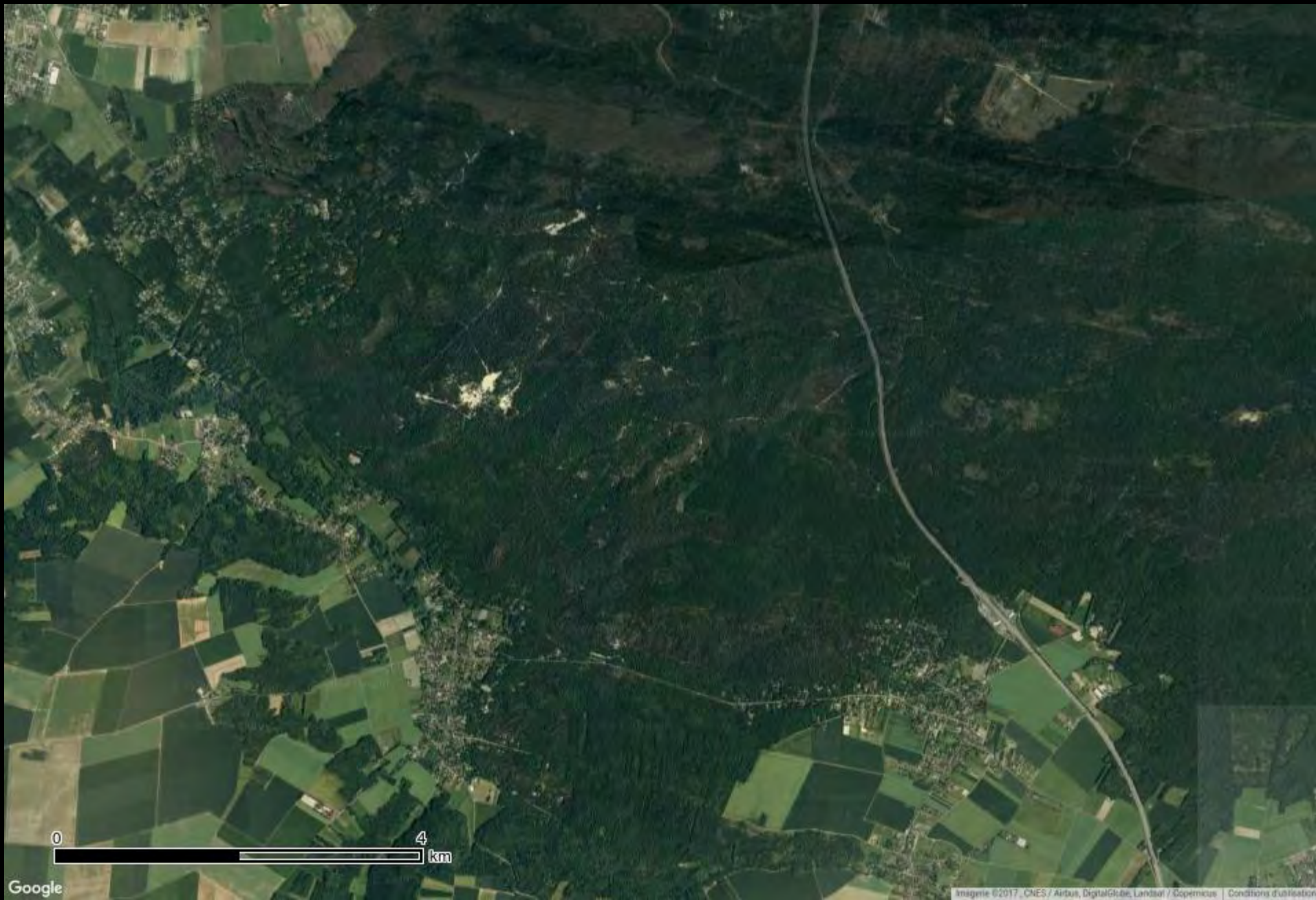




# Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average 2015/03/02 - 2017/01/26







# Speckle “*fully developped*” (Goodman hypothesis)

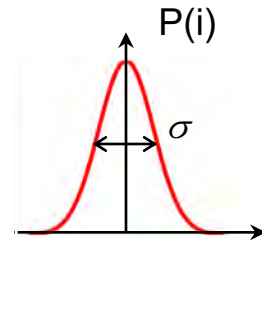
Valid for natural surfaces

Homogeneous  
areas

- A lot of scatterer:  $N$  is big
- Ampl. and phase of scatterer ‘ $k$ ’ are independant regard to  $N-1$  others
- Each scatterer amplitude and phase are independant
- $a_k$  are identically distributed ( $E(a)$ ,  $E(a^2)$ )
- $\varphi_k$  are uniformly distributed over  $[-\pi, \pi]$

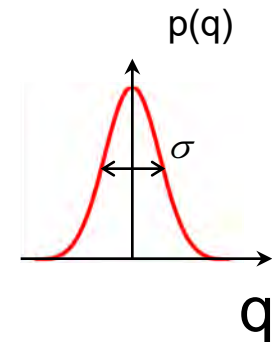
$\Rightarrow z = i + j \cdot q$  is normally distributed  
 $i$  and  $q$  are independent

$$p_i(i / \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\left(\frac{-i^2}{2\sigma^2}\right)}$$



$$E(i) = E(q) = 0$$

$$E(i^2) = E(q^2) = \sigma^2 = N \frac{E(a^2)}{2}$$



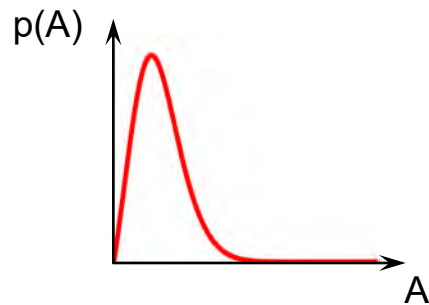


Homogeneous  
areas

Amplitude:  $A$

$$p_A(A/\sigma) = \frac{A}{\sigma^2} \exp\left(\frac{-A^2}{2\sigma^2}\right)$$

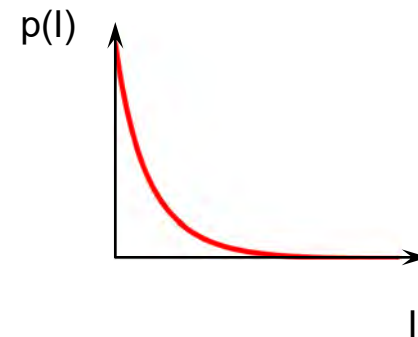
$$E(A) = \sigma \sqrt{\frac{\pi}{2}}, \quad E(A^2) = 2\sigma^2$$



Intensity:  $I$

$$p_I(I/\sigma) = \frac{1}{2\sigma^2} \exp\left(\frac{-I}{2\sigma^2}\right)$$

$$E(I) = 2\sigma^2 = R, \quad E(I^2) = 8\sigma^4 = 2R^2$$



Radar reflectivity:  $R \cong \sigma^2$

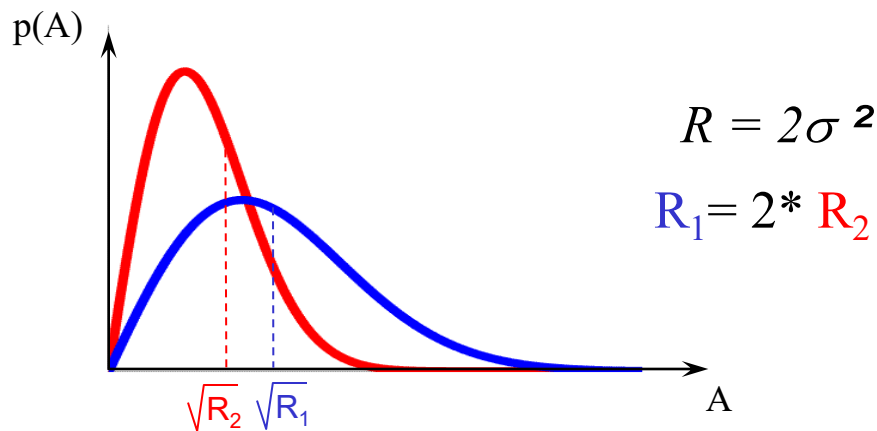
$$E(I) = E(i^2 + q^2) = 2\sigma^2 = R$$

Homogeneous  
areas

Amplitude:  $A$

$$p_A(A/\sigma) = \frac{A}{\sigma^2} \exp\left(\frac{-A^2}{2\sigma^2}\right)$$

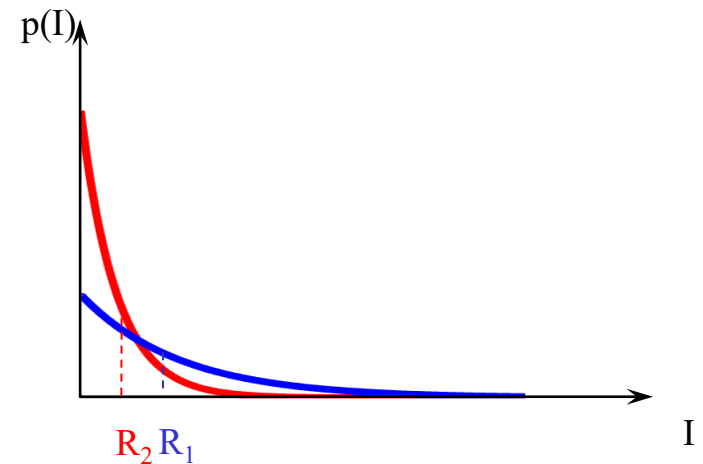
$$E(A) = \sigma \sqrt{\frac{\pi}{2}}, \quad E(A^2) = 2\sigma^2$$



Intensity:  $I$

$$p_I(I/\sigma) = \frac{1}{2\sigma^2} \exp\left(\frac{-I}{2\sigma^2}\right)$$

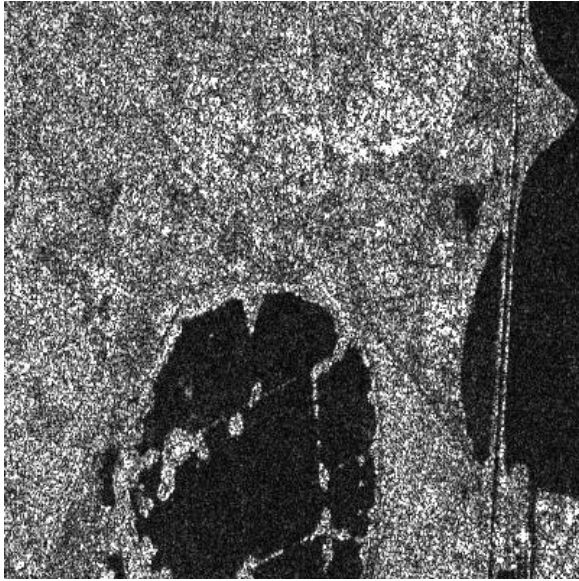
$$E(I) = 2\sigma^2, \quad E(I^2) = 8\sigma^4$$



The higher is  $R$ , the more data are spread over



# Speckle: multiplicative noise



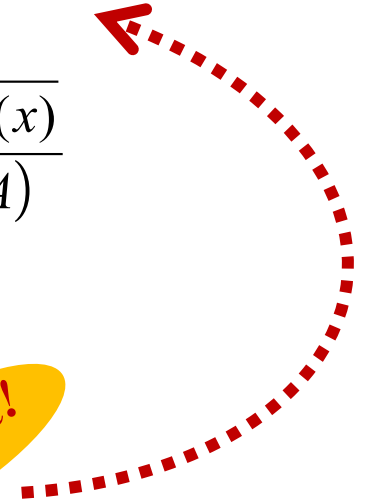
RADARSAT - Mode Fine 1

Variation coefficient:  $C_v = \frac{\sqrt{\text{var}(x)}}{E(A)}$

$$C_A = \frac{\sqrt{\text{var}(A)}}{E(A)} = \sqrt{\frac{4}{\pi} - 1} \approx 0.5227$$

$$C_I = \frac{\sqrt{\text{var}(I)}}{E(I)} = 1$$

**constant!**



multilook data

$$y = \frac{1}{N}(x_1 + x_2 + \dots + x_L) \Rightarrow \begin{cases} \text{var}(y) = \frac{\text{var}(X)}{N} \\ E(y) = E(x) \end{cases}$$

**L: Look number**

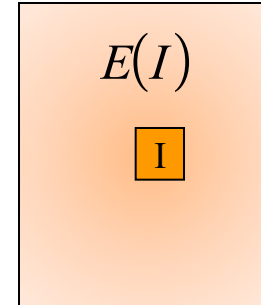
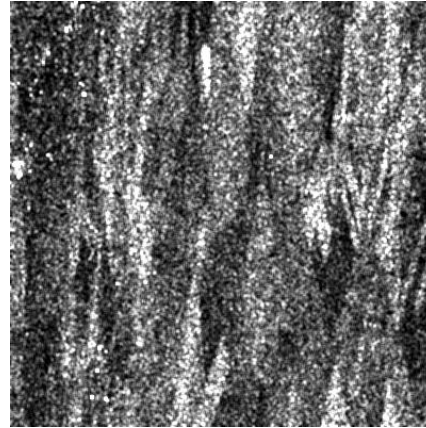
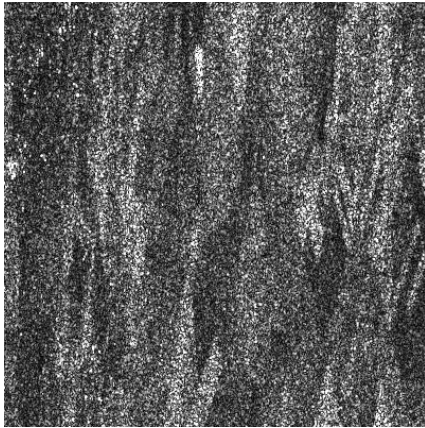
$$C_{ML} = \frac{C_{1L}}{\sqrt{N}} \Leftrightarrow N = \left( \frac{C_{1L}}{C_{ML}} \right)^2$$

with  $C_{1L} = \begin{cases} 1 & \text{for intensity data} \\ 0.5227 & \text{for amplitude data} \end{cases}$

and  $C_{ML}$  estimated over an homogeneous area

*Goal: estimate  $R \cong \sigma^2$*

Most simple: Box Filtering:  $I \longleftrightarrow E(I)$



Advantages: simple + best estimation (*MMSE*) over homogeneous area

Inconvenients: Details lost, fuzzy introduction

Other classical filters: (median, Sigma, math. morph.....): WORST!

*==> Need to introduce specific filters taken into account speckle statistics*

Neighbourhood size depends on local scene characteristics

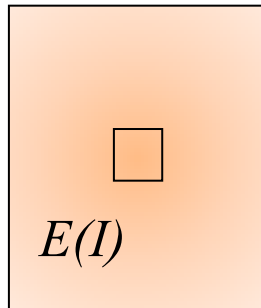
*==> Adaptive filters*



# Adaptative Filters

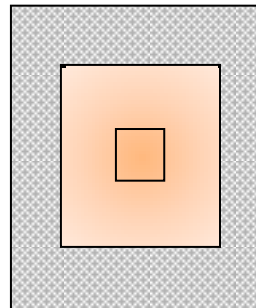
*Goal: adapt the size of the neighbourhood before average*

Homogeneous area



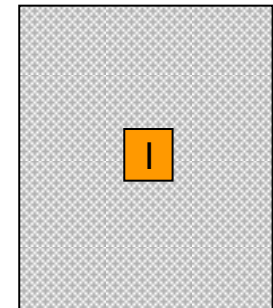
Average over the whole neighbourhood

Heterogeneous area



Reduce the neighbourhood size

Very Heterogeneous area



Keep the central pixel value (no averaging)

□ necessary to discriminate homogeneity of local neighborhood

Coefficient of variation:

$$c_v = \frac{1}{\sqrt{N}} \quad \left( \text{or } \frac{0.5227}{\sqrt{N}} \right) \quad \text{over } \textit{homogeneous area}$$
$$C_v \geq \frac{1}{\sqrt{N}} \quad \left( \text{or } \frac{0.5227}{\sqrt{N}} \right) \quad \text{over } \textit{heterogeneous area}$$

# Kuan and Lee Filters

$$\hat{R} = E(I) + a(I - E(I)) \quad \text{with } a = \begin{cases} 0 & \text{over homogeneous area} \\ 1 & \text{over heterogeneous area} \end{cases}$$

**Kuan:**  $a = \frac{c_I^2 - 1/N}{c_I^2 (1 + 1/N)}$

$N$ : looks number

$$c_{v\_speckle}^2 = 1/N$$

*estimated preliminary over an homogeneous area*

**Lee:**  $a = \frac{c_I^2 - 1/N}{c_I^2}$

$c_I$ : coefficient of variation  
of the local neighbourhood

$N < 3 \implies \text{Lee} < \text{Kuan}$

$N \geq 3 \implies \text{Lee} \approx \text{Kuan}$



# Frost Filter

*Weghting of the neighbour pixels relative to its distance*

$$\hat{R}(d) = I(d) * m(d) \text{ with } m(d) = K_1 c_l e^{-K_2 c_l d}$$

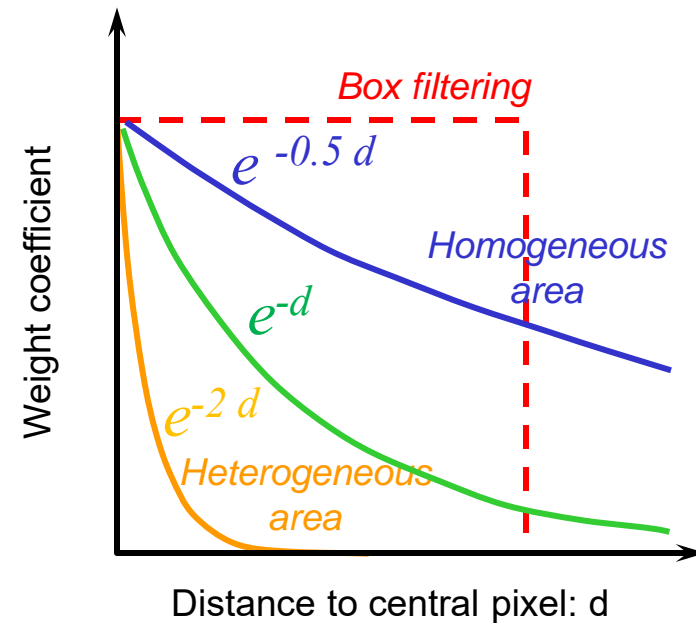
(MMSE criteria)

d: distance to central pixel

$K_1$  and  $K_2$  set for the whole image

homogeneous area:  $c_l$  low

heterogeneous area:  $c_l$  high



## ***MAP (Maximum a posteriori) Filters***

Maximize Bayesian criteria:  $p(R / I) = \frac{p(I / R) \cdot p(R)}{p(I)}$

Hypothesis on  $p(R)$ :  $\Gamma$  law

$$\Rightarrow \hat{R} = \frac{E(I)(\alpha - L - 1) + \sqrt{E^2(I)(\alpha - L - 1)^2 + 4\alpha L I E(I)}}{2\alpha}$$

homogeneous area:  $\alpha$  high  $\Rightarrow \hat{R} = E(I)$   $\alpha = K / c_I^2$

$\left. \begin{array}{l} p(R): \Gamma \text{ law} \\ p(I/R): \Gamma \text{ law} \end{array} \right\} \text{ MAP filter = Gamma-Gamma filter}$





Radar image – 1 Look  
(N=1)





Boxcar 9x9



Lee Filter 9x9

$c_{v\_ref} = 1$





Lee Filter 9x9

$c_{v\_ref} = 0.7$



Lee Filter 9x9

$c_{v\_ref} = 1.1$





## Spatial filtering tools test (1/4)



**Radarsat image**  
Over-sampled fine mode (SGX)  
(Aerial base of 'Salon de Provence')  
Resolution (Single Look complex)  
(range x azi.) (m) : **6.0 x 8.9**

Pixel spacing  
(range x azi.) (m) : **3.125 x 3.125**





## Spatial filtering tools test (2/4)

→ Frost filter test



Original image



Filtered image

- **Frost** filter application (analysis window size **9 x 9**)  
Over-sampled Radarsat fine mode (SGX)  
'Salon de Provence' : aerial base extract



## Spatial filtering tools test (3/4)

→ Comparison of different adaptive filters



Original image



average 7x7



Frost 7x7



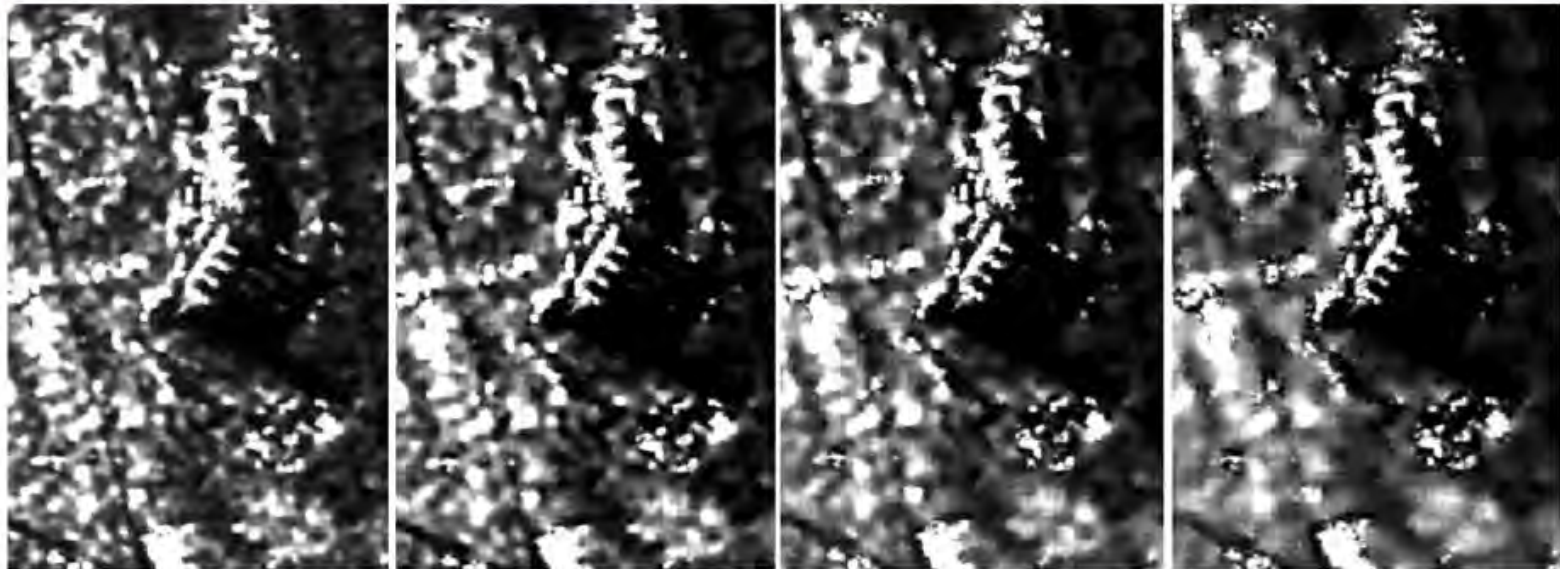
Gamma-Gamma  
MAP 7x7

*Radarsat 1 extract, fine mode,  
'Salon de Provence'*

*Simple average computed from  
the numerical values of neighbor pixels*

## Spatial filtering tools test (4/4)

→ influence of the analysis window size



window 7x7

window 9x9

window 11x11

window 15x15

*Test of a Gamma-Gamma Map filter over square analysis windows of variable size*

*Extract Radarsat 1 Fine mode 'Salon de Provence'*



## Spatial filtering : toward more sophisticated procedures



Original image



Filtered image  
(@ Touzi, CCRS, Canada)

- Contour detection,  
linear structures detection  
punctual target detection  
(analysis window of  
adaptive shape)
- Multi-scale analysis
- Integration of the  
non-stationary property  
of the radar signature



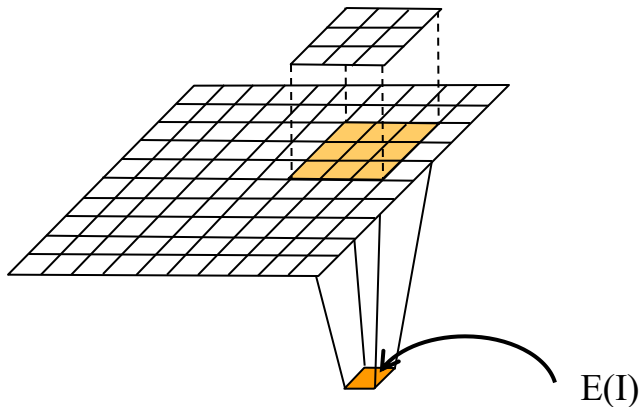
*Extract image :  
SETHI C band,  
VV polarization :  
3m resolution  
Eiffel tower, Paris*

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# MULTILOOK OBTENTION

in spatial domain

*Sliding window: image \* window*

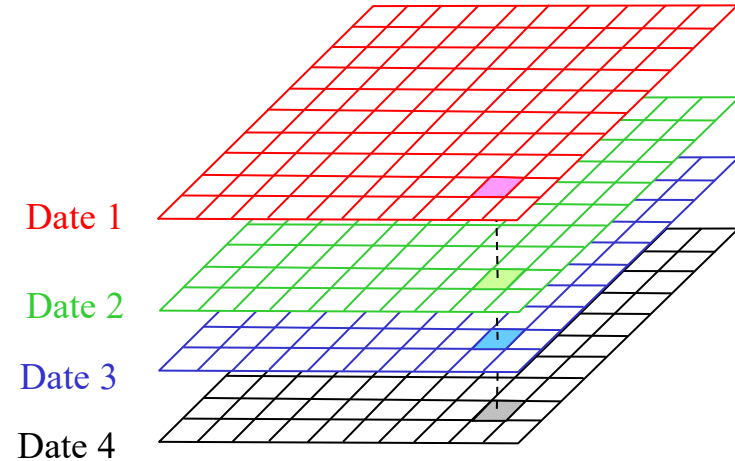


*9 looks if pixel sare not correlated*

Example: ERS data - PRI products :  $\cong$  3 looks

***Loss of spatial resolution***

in temporal domain



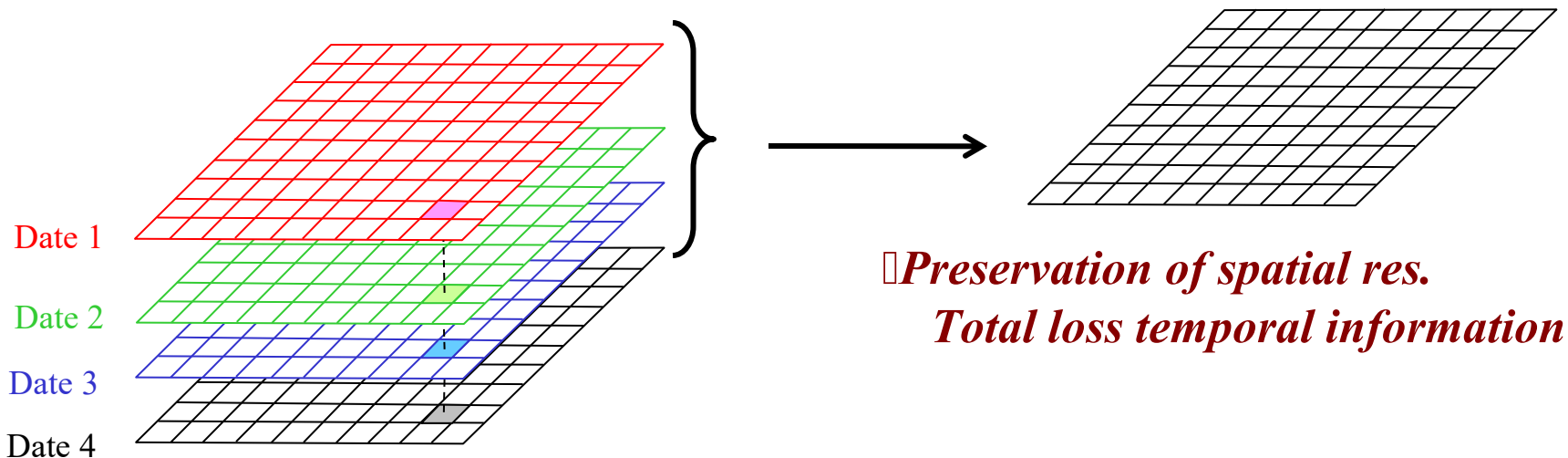
4 looks if surface  
has not changed

***Preservation of spatial res.  
Loss temporal information***

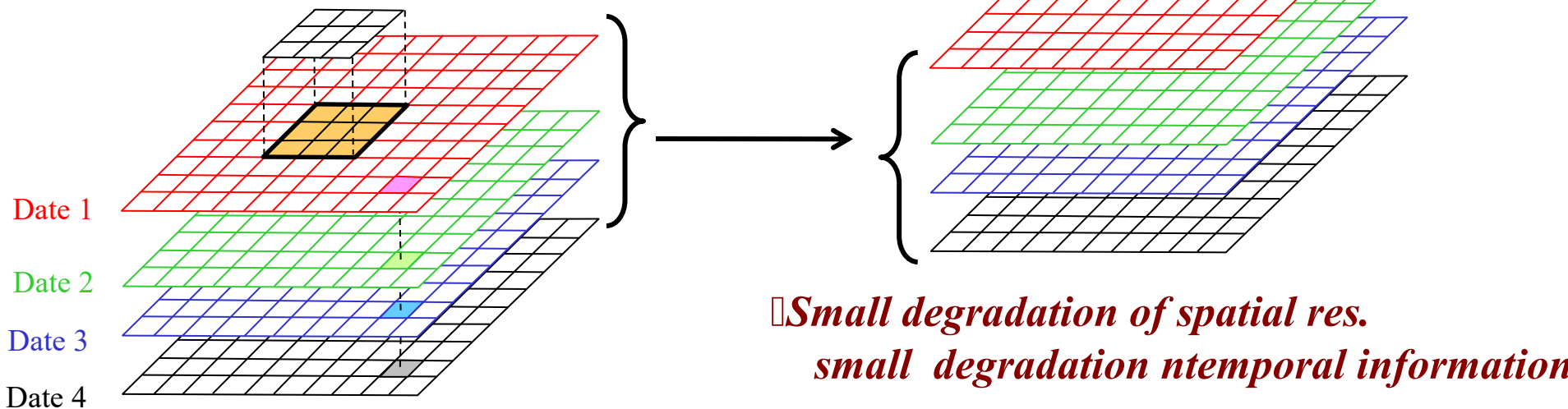


# *Spatio-temporal Filter (Sentinel-1)*

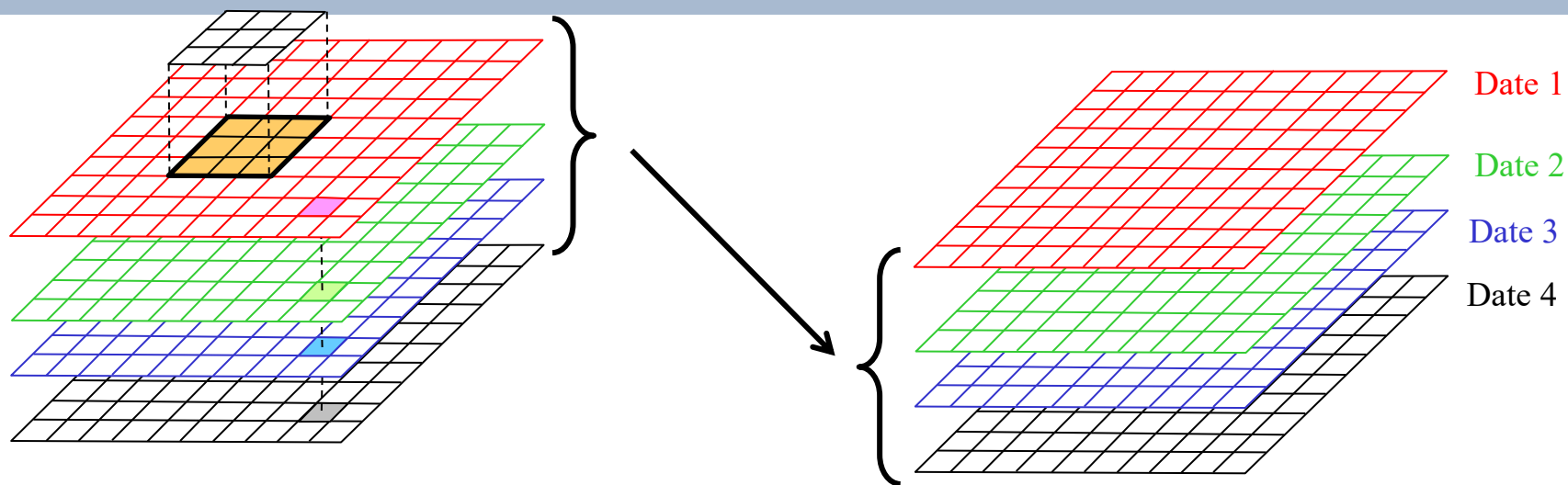
*temporal domain*



*Spatio-temporal domain*



# Spatio-temporal Filter (Sentinel-1)



**Date k:**

□ *Small degradation spatial resolution*  
*Small degradation temporal resolution*

$$J_k = \langle I_k \rangle \cdot \frac{1}{N} \sum_{t=1}^N \frac{I_t}{\langle I_t \rangle}$$

temporal average

Same for all dates  
for a given pixel

N: acquisitions number (different dates)

$J_k$ : pixel value of the output (filtered) image

$I_k$ : pixel value of acquisition k

$\langle I_k \rangle$ : spatial average over a local neighbor. around  $I_k$



# TAKE HOME MESSAGE- 1

- Radar images: coherent waves ( $A, \varphi$ ):  $\implies$  ***SPECKLE***
- ***SLC products***: (*Single Look Products*:  $A, \varphi$ )
  - $\varphi$  image: (*not useful except for interferometry*)
  - use of  $A$  (or  $I = A^2$ ) image, similar to optical image
- Speckle  $\implies$   $A$  or  $I$  value of a single pixel: no meaning!
  - $\implies$  *main drawback for classification algorithms*
    - $\square$  *need to apply a speckle filter*
- ***Sentinel-1 GRD Products (Ground Range Detected)***
  - Multilook products (5 looks)*
    - (*pixel size:  $10 * 10m^2$  - spatial resolution:  $\approx 20 \times 20 m^2$* )
  - $\square$  *still need to reduce the speckle for classification algorithms*

# TAKE HOME MESSAGE - 2

- Best processing for speckle reduction: *pixels AVERAGE*  
(i.e. *multilooking creation*)

*Single acquisition: local average* (loss spatial resolution)

*Temporal serie:*

*temporal average* (loss temporal information)

*spatio temporal filter* (better preservation of spatio-temp. info)

- *Adaptative* filters (Lee, Frost, Kuan,...):  $E(I)$

*homogeneous* areas: average over *all the neighbourhood*

*heterogeneous* areas: average over *smallest neighbourhood*