OUTLINE

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

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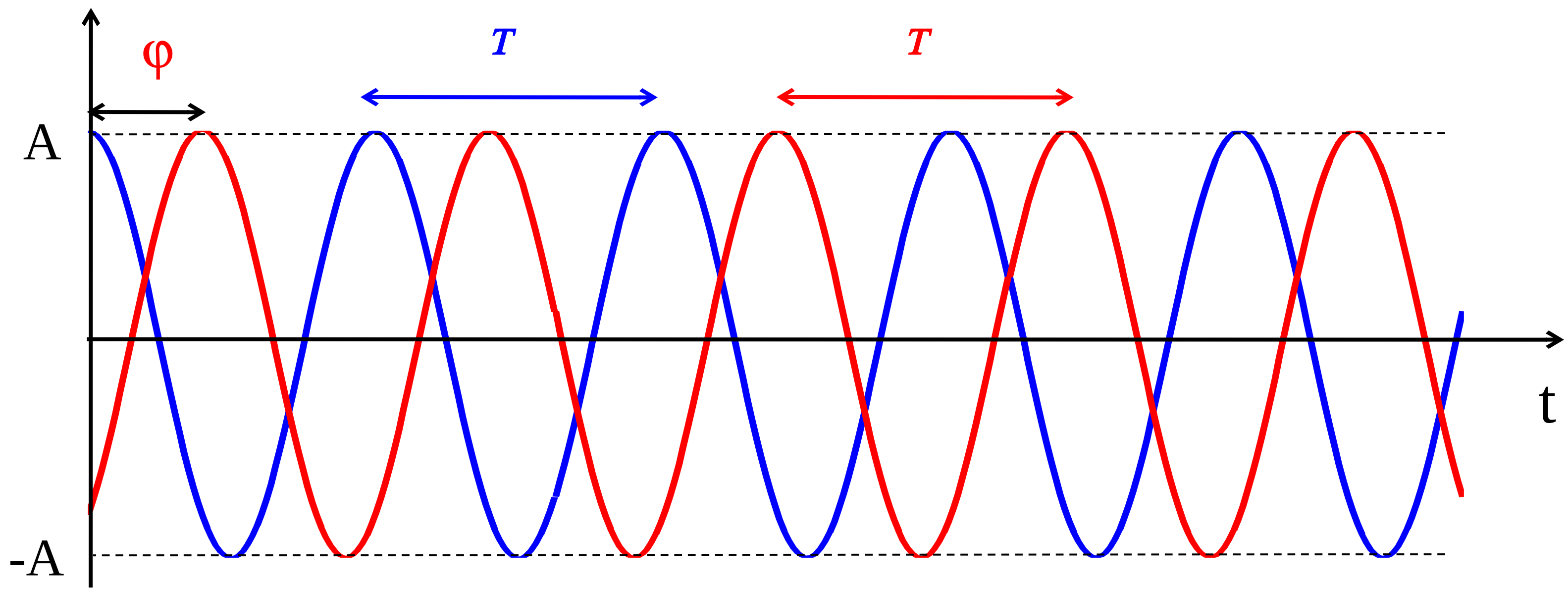
Coherente wave: temporal behaviour



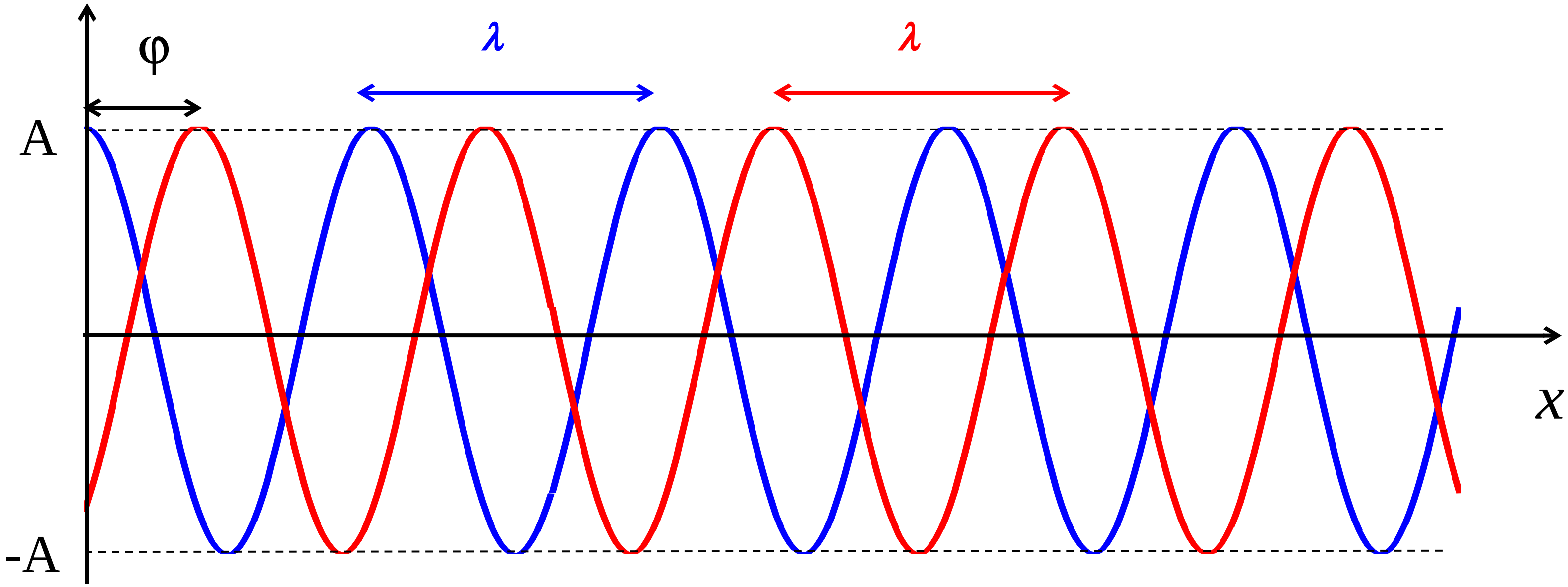
$$y(t) = A\cos\left(\frac{2\pi}{T}t\right)$$

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

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

A: amplitude
T: Temporal period
φ: dephasage

Coherent wave: spatial behabiour



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

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

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

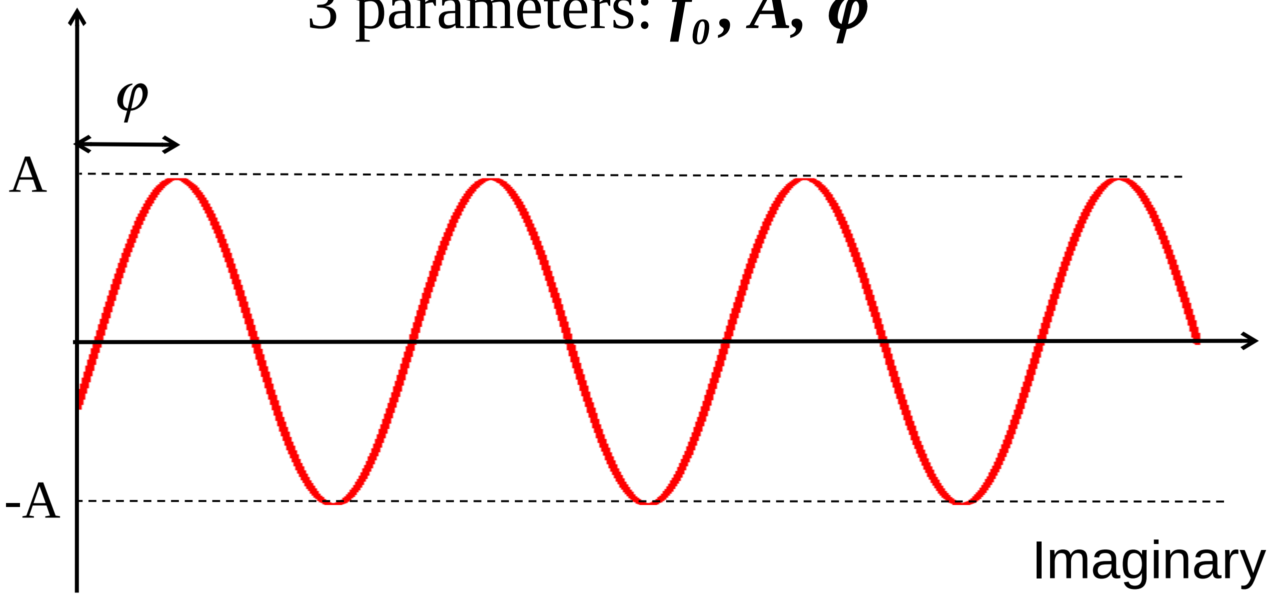
A: amplitude
λ: spatial period = wavelength
φ: dephasage

Coherent wave

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

3 parameters: f_0, A, φ

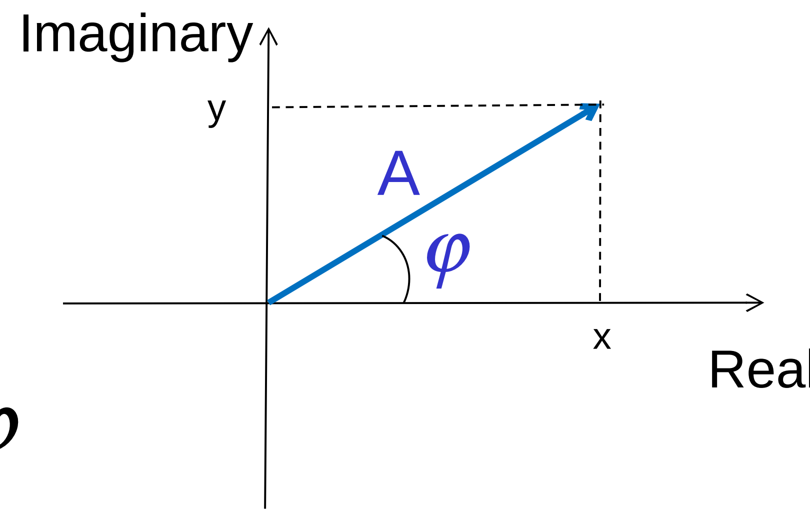
$$\lambda = cT = \frac{c}{f_0}$$



For given frequency f_0 (or λ) (system)

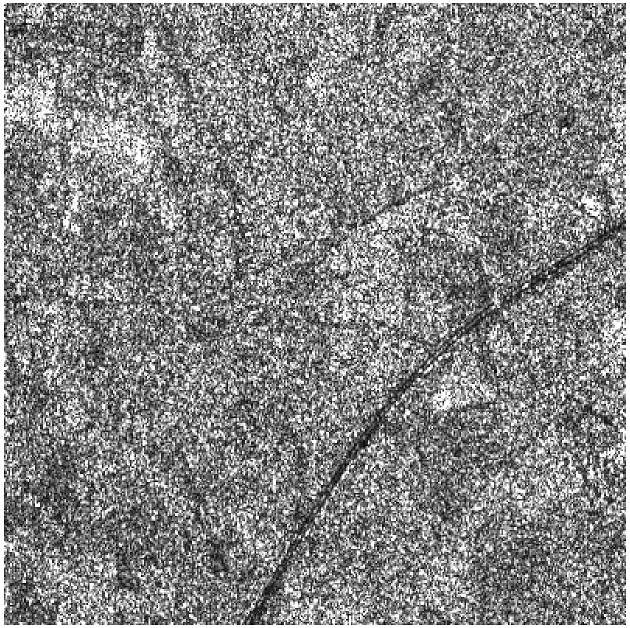
backscattered echo

characterized by A and φ

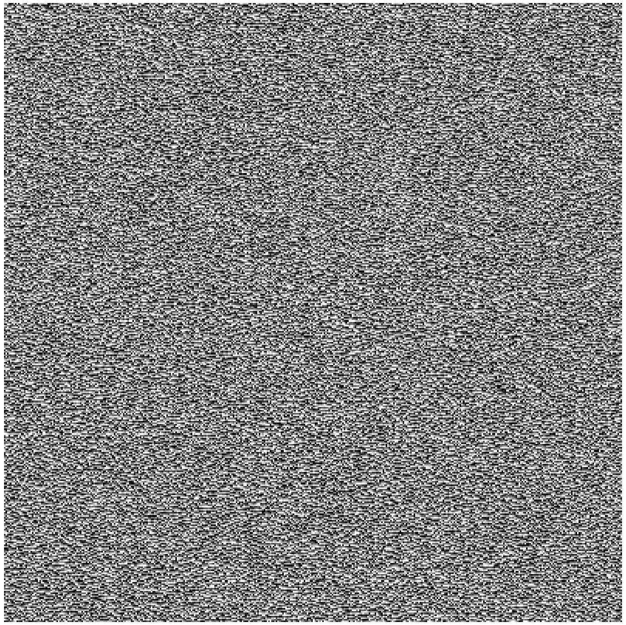


complex number: $x + j\,y = A\,e^{j\varphi} = A\,cos(\varphi)$

RADAR DATA = COMPLEX DATA



Amplitude image



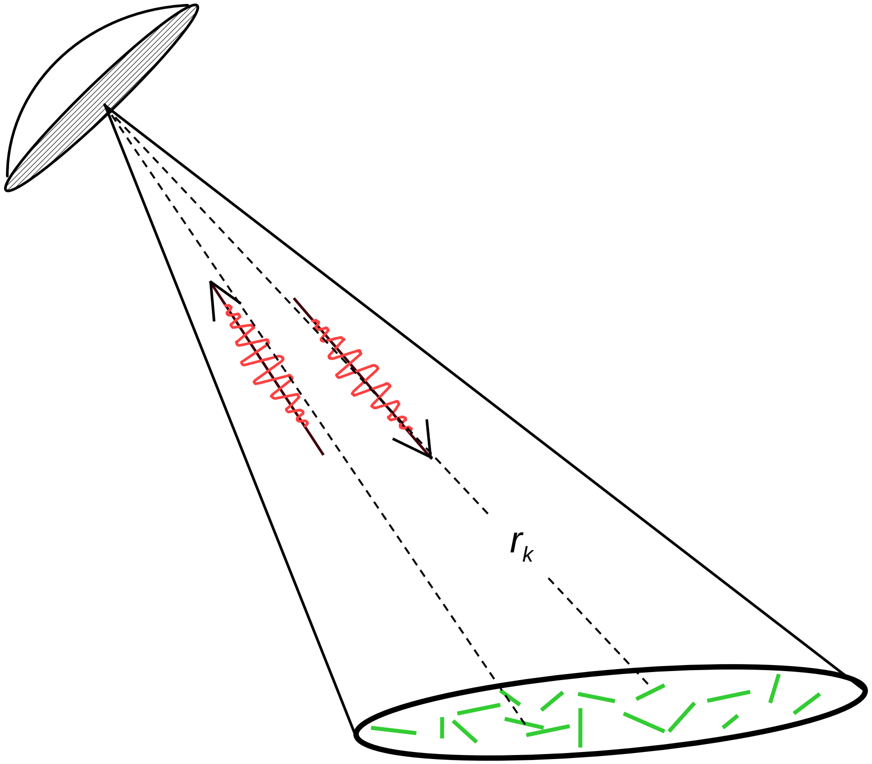
Phase image

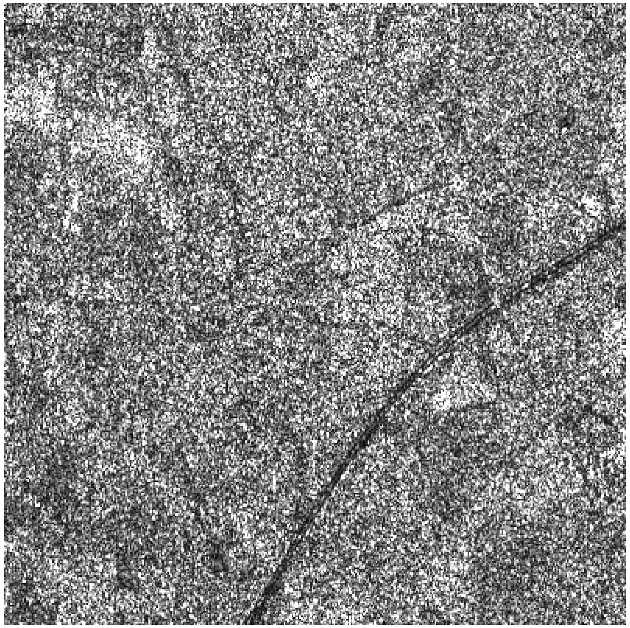
SLC product: Single Look **Complex** product

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

Speckle Origin

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





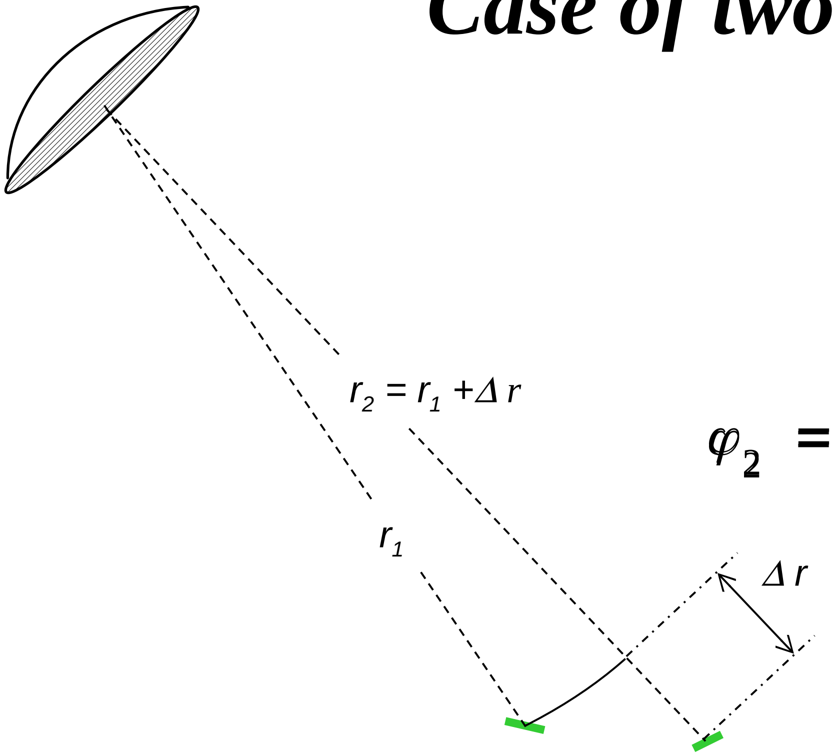
Homogeneous scene :

N elementary scatterers a_k, φ_k

randomly oriented

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

Case of two scatterers



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

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

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

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

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

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

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

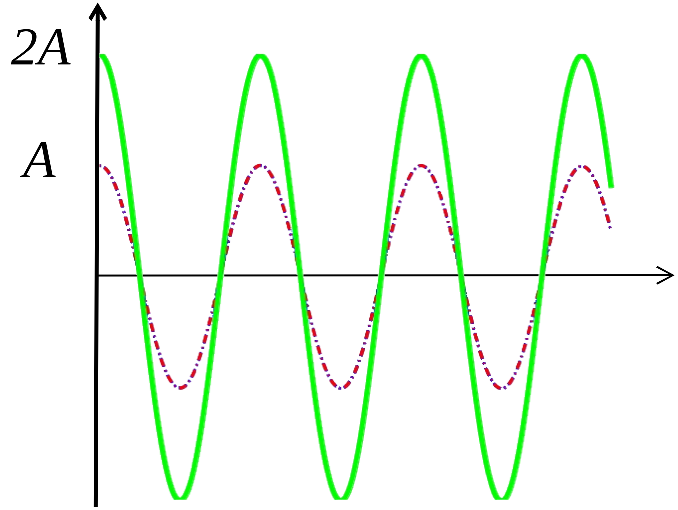
$$\Delta r = \frac{3\lambda}{8} \Rightarrow \frac{4\pi}{\lambda}\Delta r = \frac{3\pi}{2} \quad \text{et} \quad \varphi_2 = \varphi_1 + \frac{3\pi}{2}$$

2 coherent waves sum

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

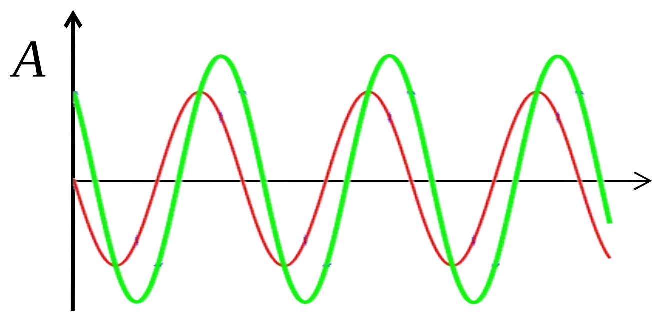
$$r_2 = r_1 + \frac{\lambda}{2}$$

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



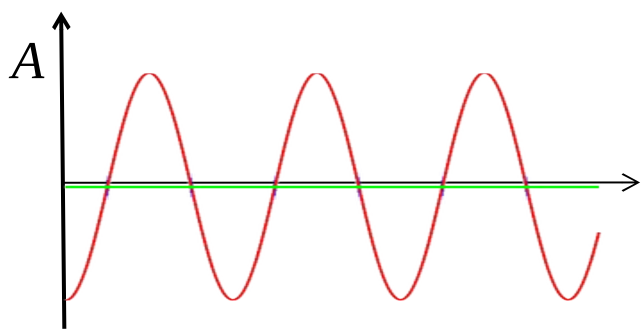
$$r_2 = r_1 + \frac{3\lambda}{8}$$

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



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

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

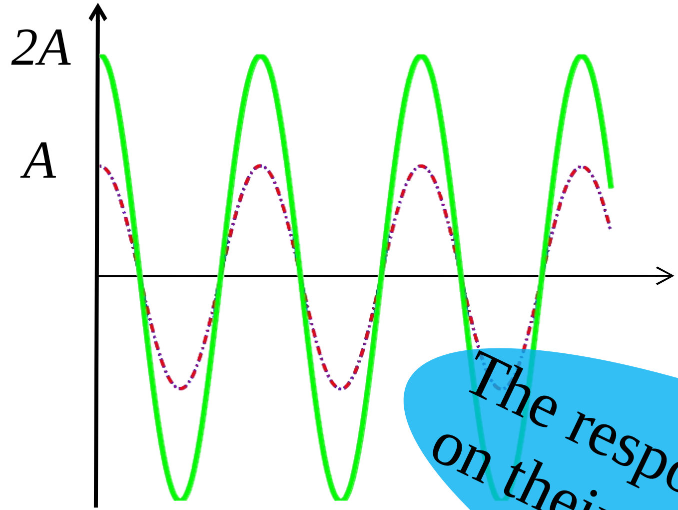


2 coherent waves sum

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

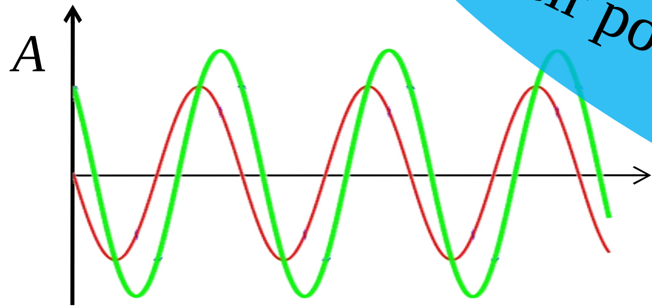
$$r_2 = r_1 + \frac{\lambda}{2}$$

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



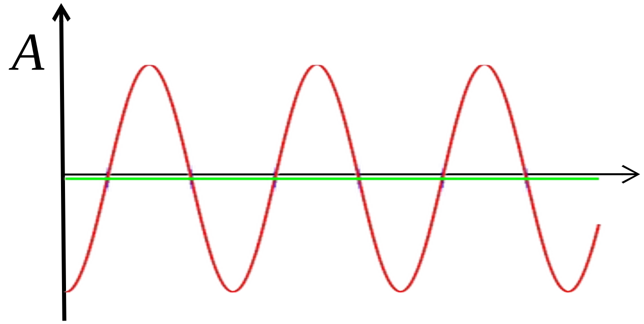
$$r_2 = r_1 + \frac{3\lambda}{8}$$

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



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

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



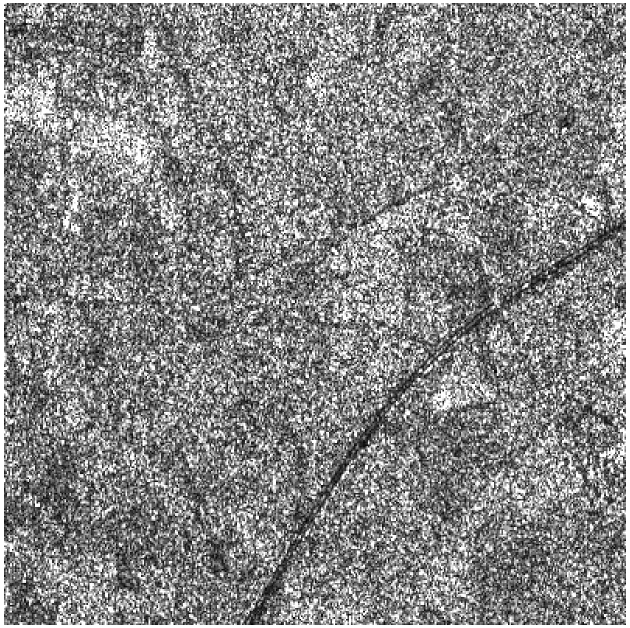
The response of two scatterers depends on their position… relatively to λ!!!!!

Ideal Radar reflectivity image

Radar acquisition

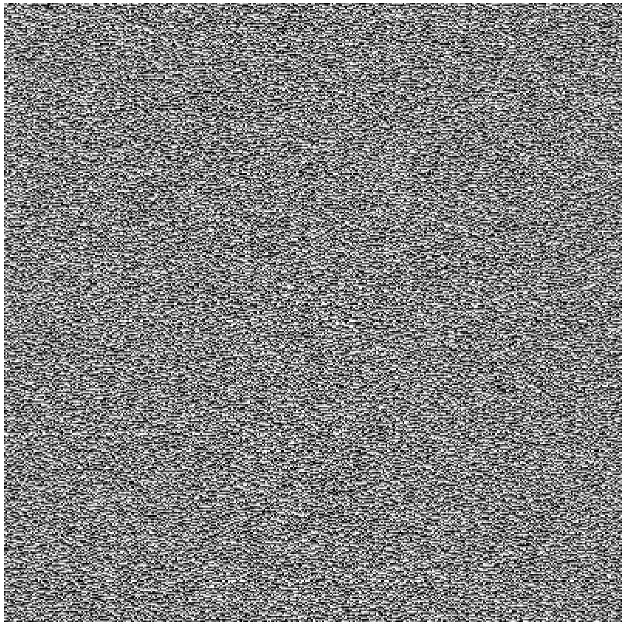
RADAR DATA = Amplitude + Phase DATA

A



Amplitude image

φ



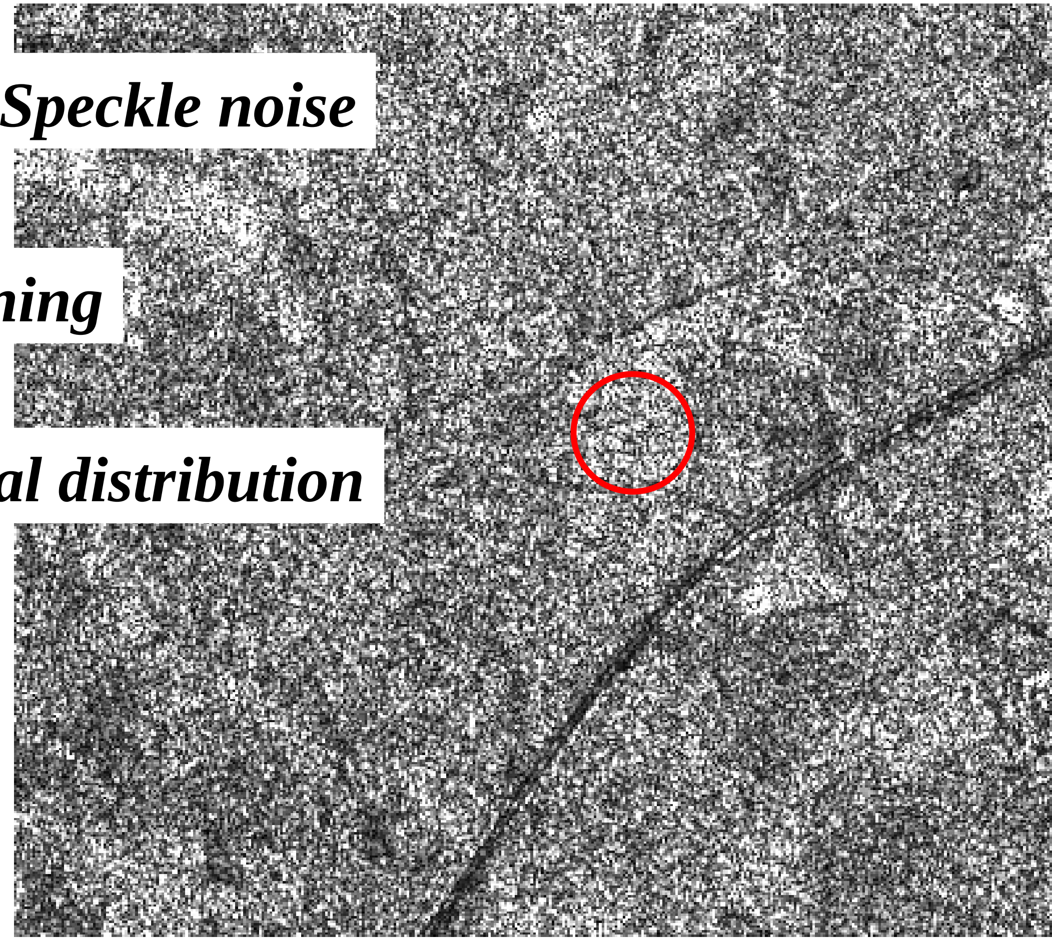
Phase image

SLC product

Coherent Imagery System ***Speckle noise***

Single pixel value = no meaning

Homogeneous are = ***statistical distribution***

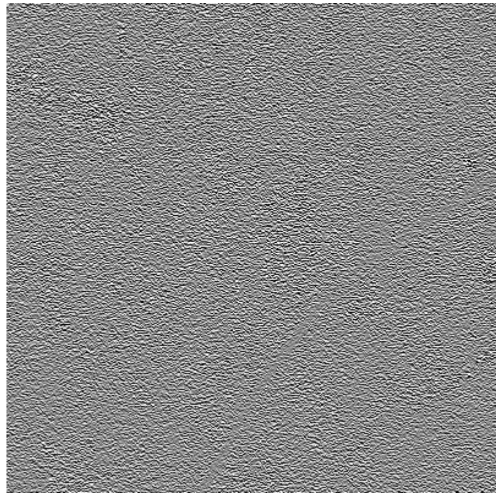


SLC Product

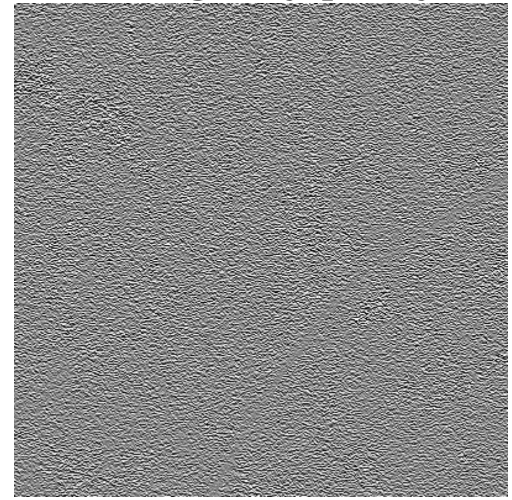
$$z = x + j\,y$$

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

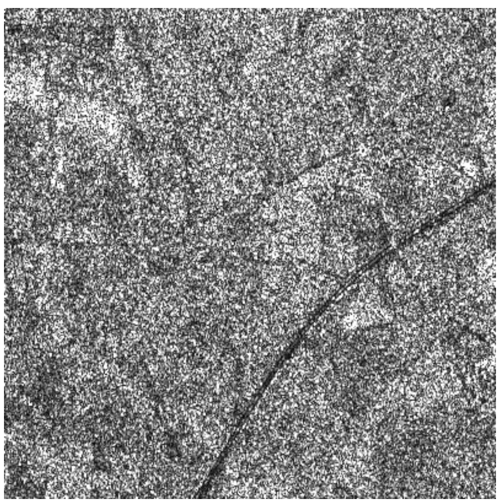
Real part: *x*



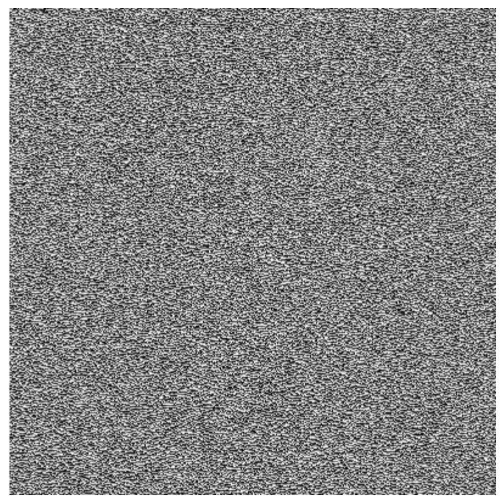
Imaginary part: *y*



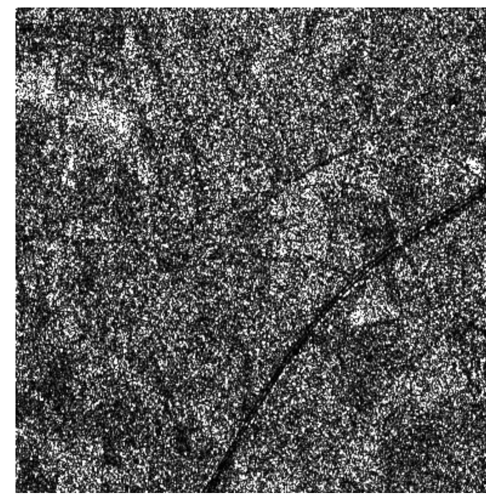
Amplitude *A*



Phase φ



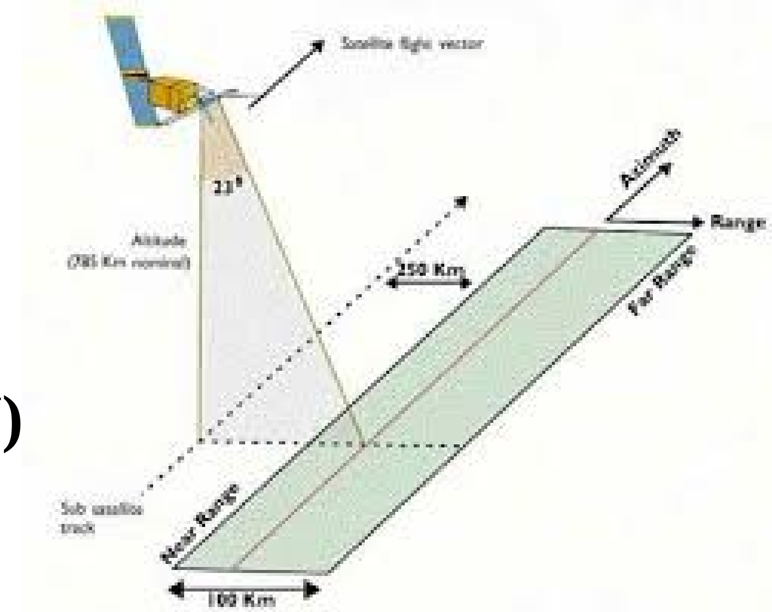
Intensity *I*



φ image no useful except for interferometry

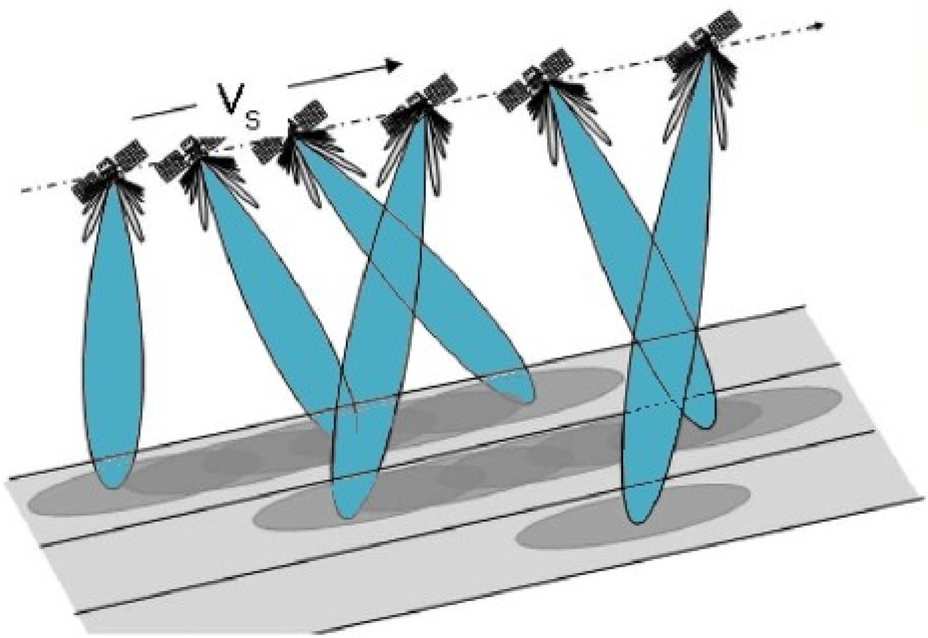
A or ***I*** image similar to optical image

SENTINEL-1 ACQUISITION MODES



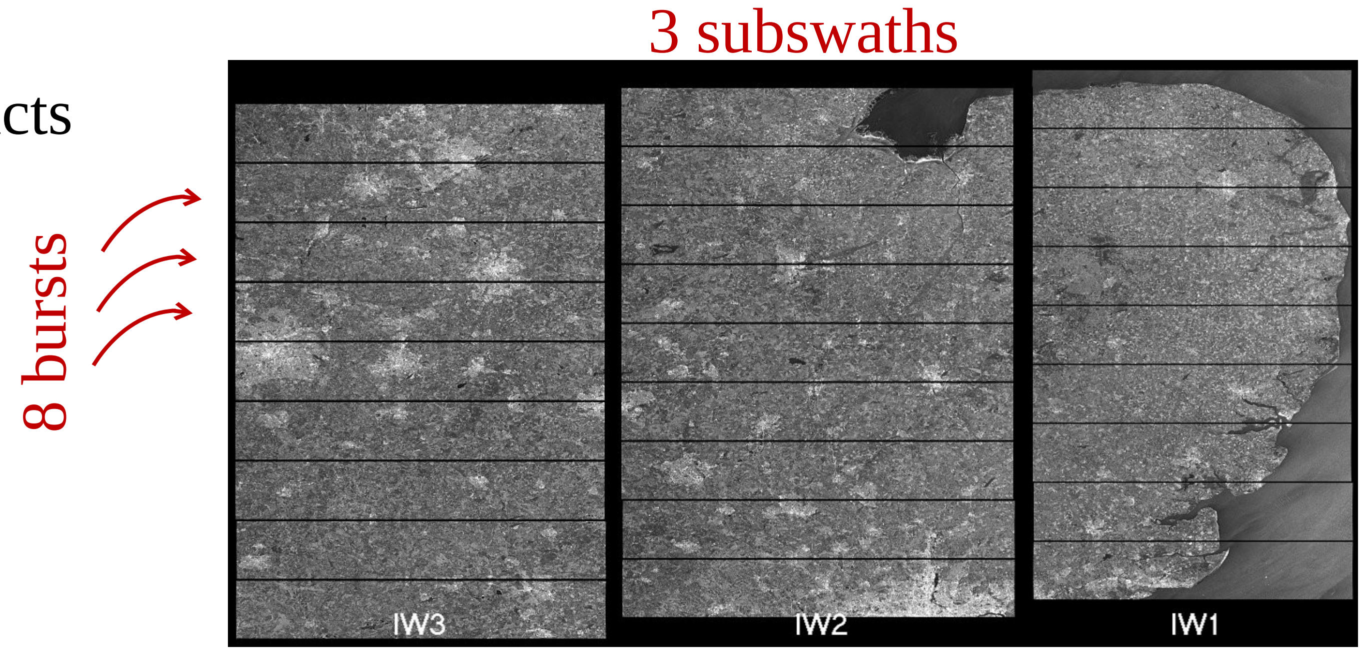
STRIPMAP

INTERFEROMETRICWIDE (IW)

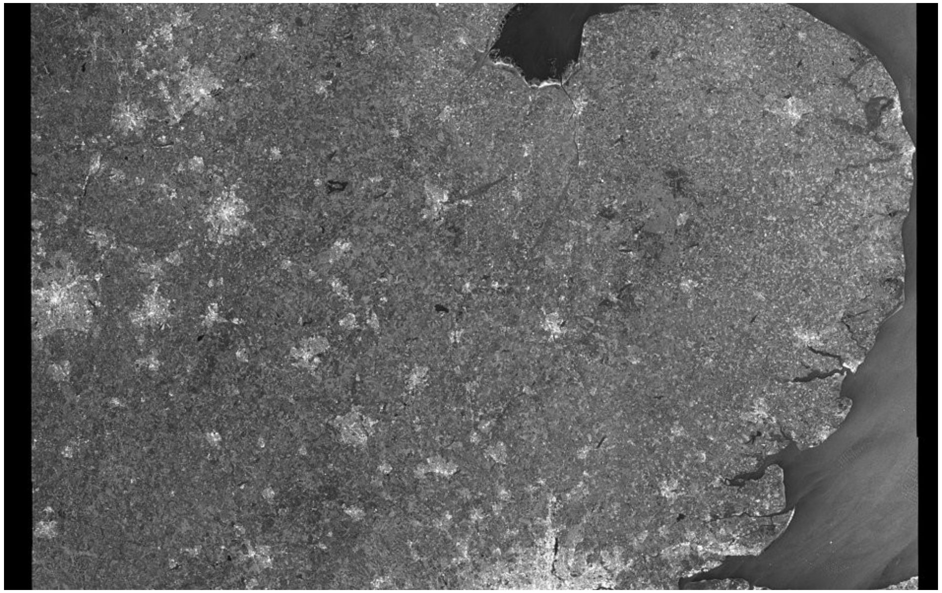


SENTINEL-1 INTERFEROMETRIC WIDE MODE

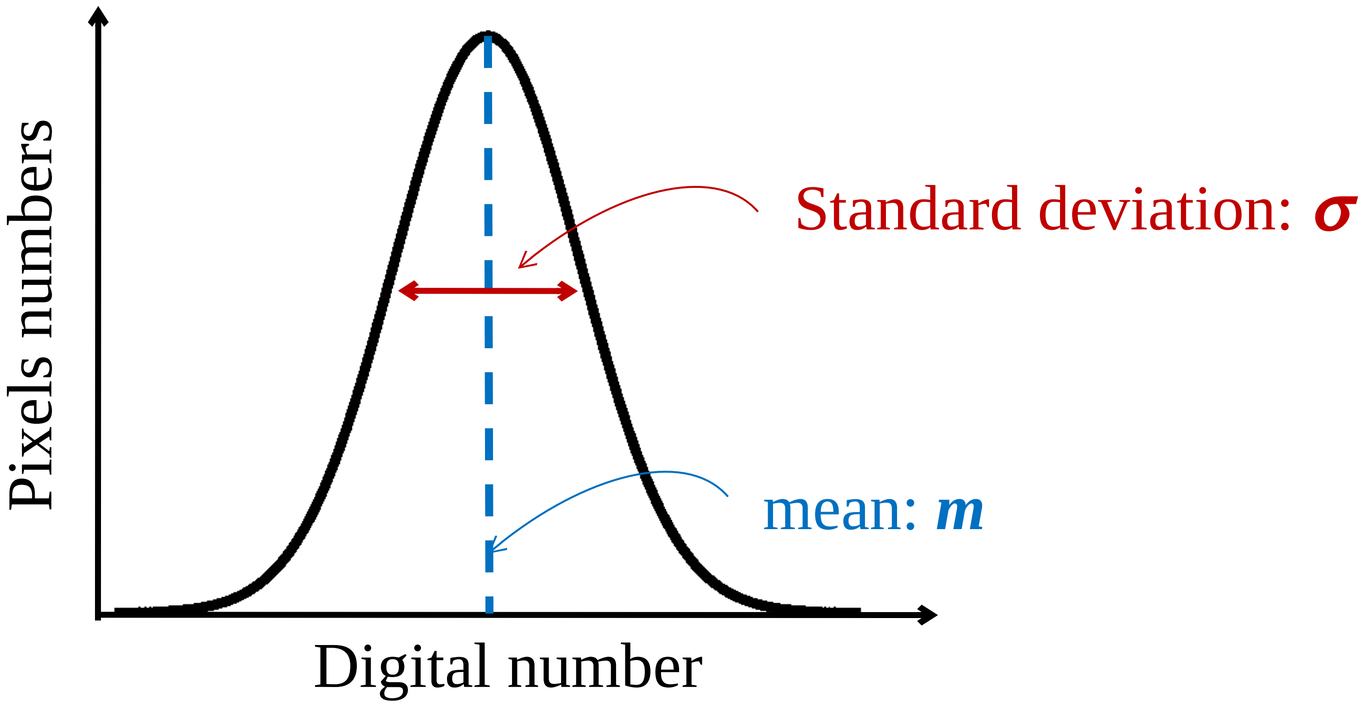
SLC products



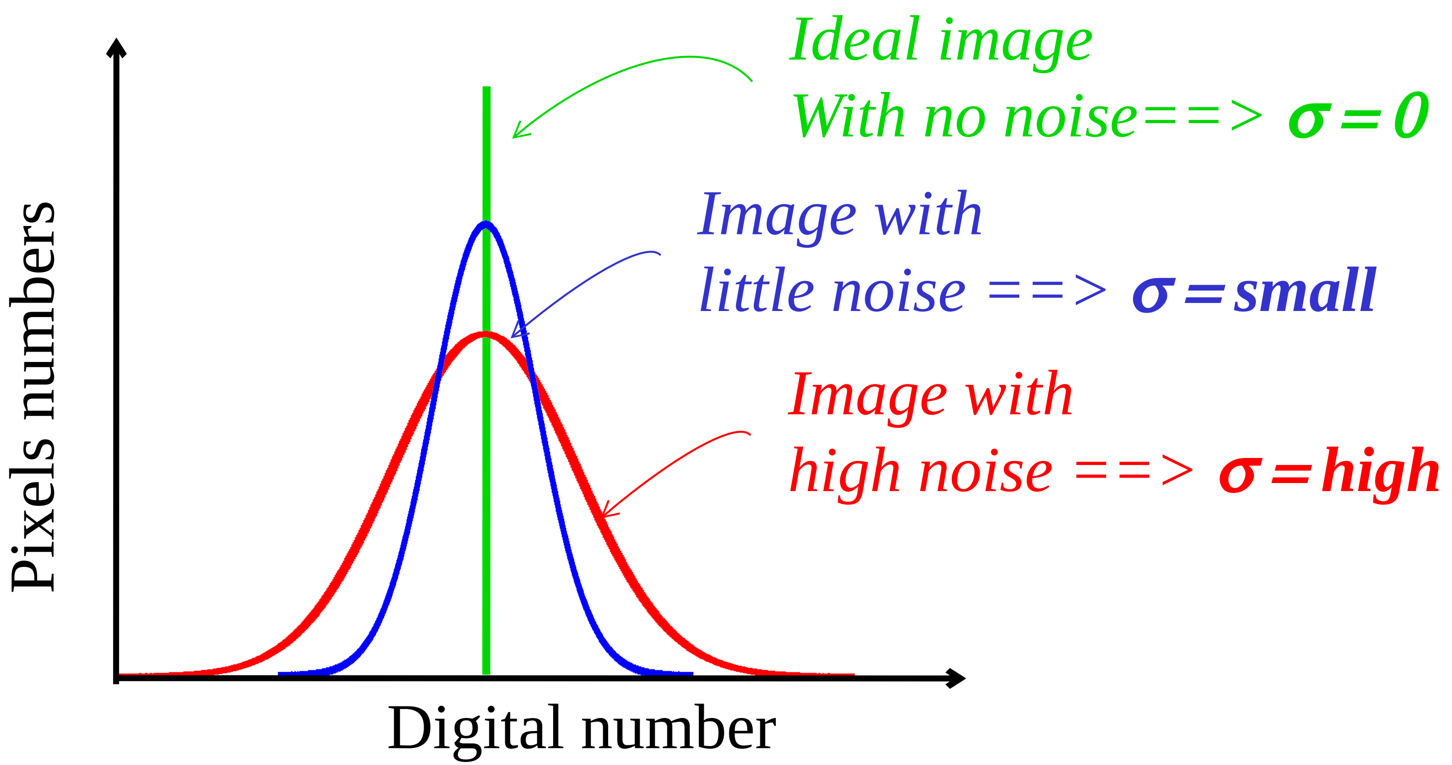
GRD products



Reminder: Histogram

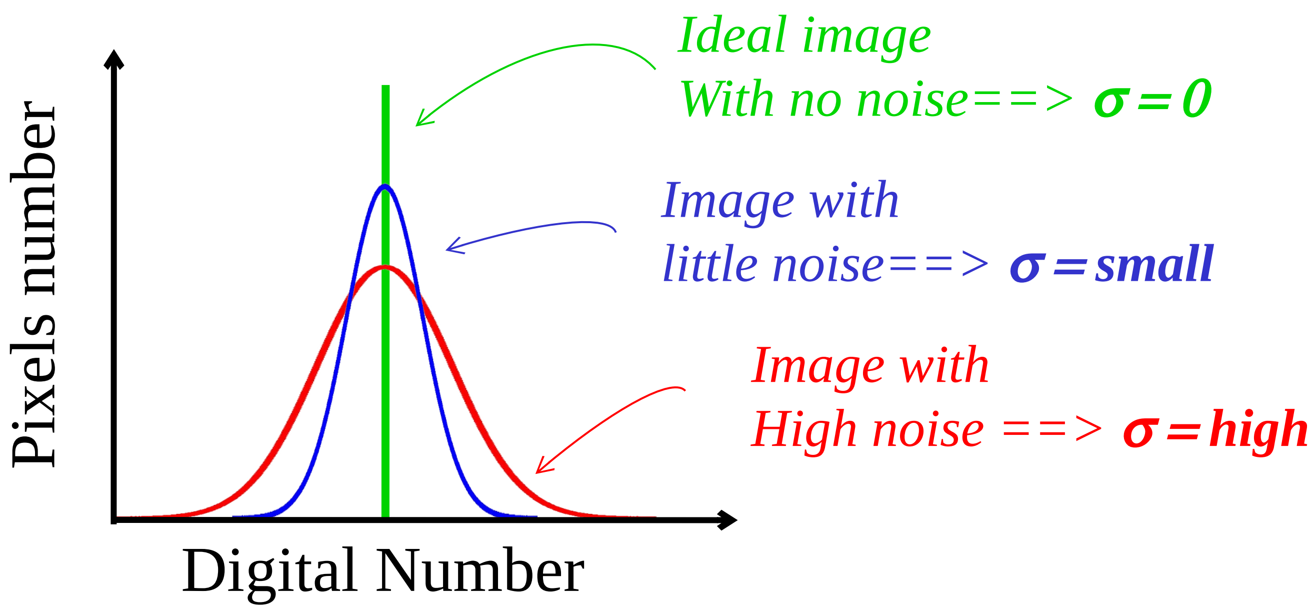


Histogram over an homogeneous area



Goal of radar image filtering:

Histogram over an homogeneous area



***Decrease the standard deviation σ** (noise)*
***without modify the mean m** (radar reflectivity)*

© Camille Pissaro

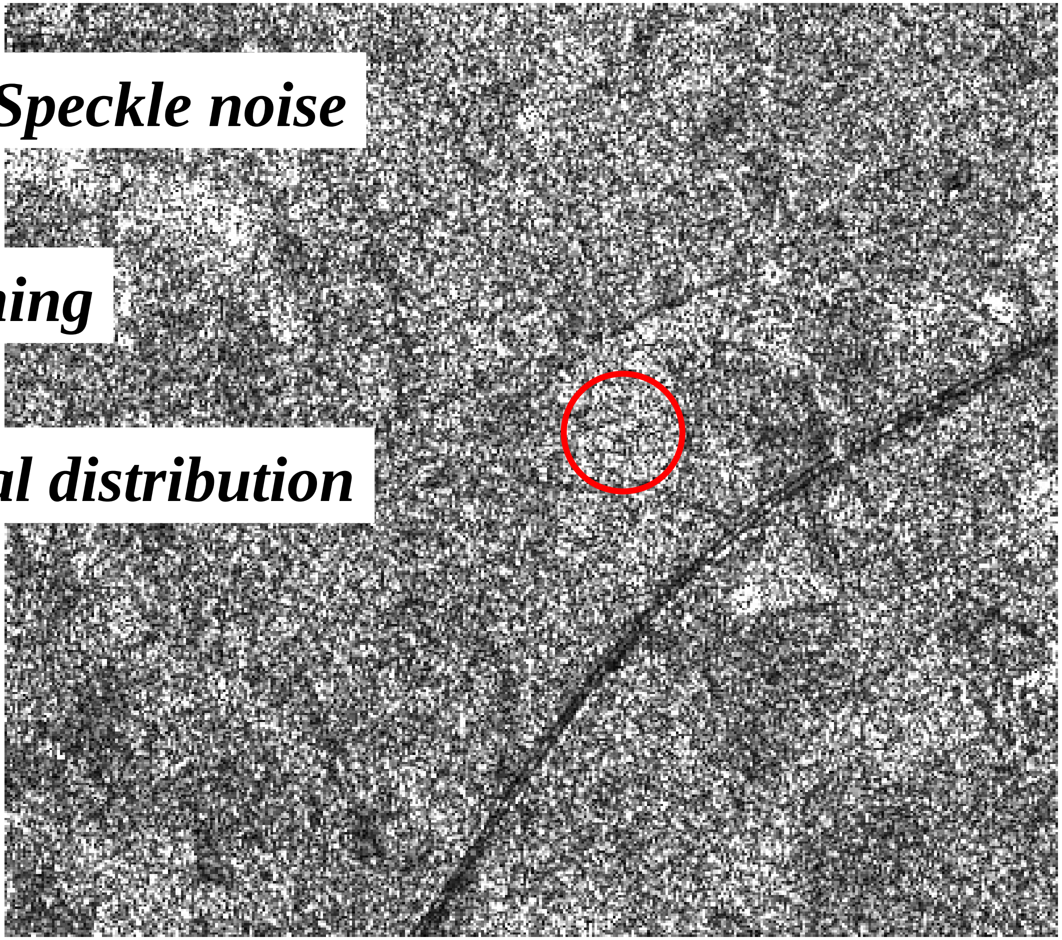
A distant vision allows to blur the pointillist effect
and see the homogeneous areas

➔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

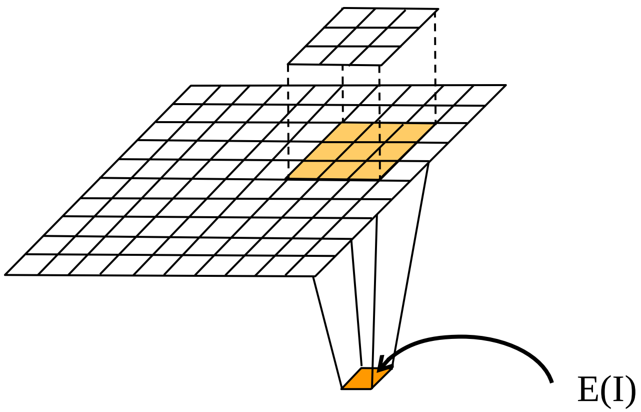
Homogeneous are = ***statistical distribution***



MULTILOOK OBTENTION

in spatial domain

*Sliding window: image * window*

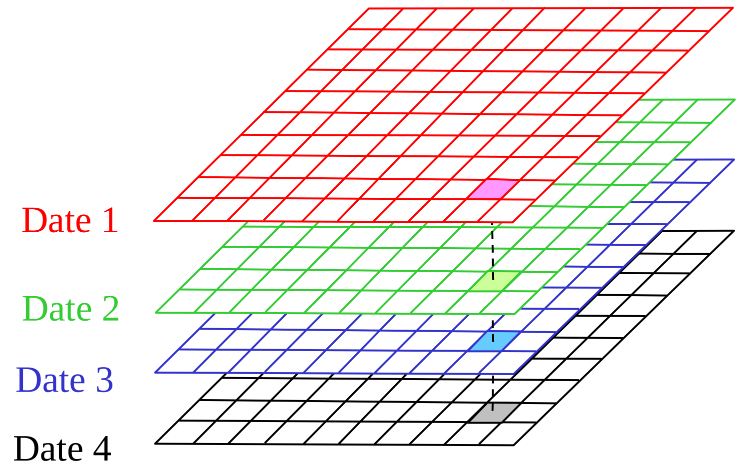


9 looks if pixel sare not correlated

Example: ERS data - PRI products : 3 looks

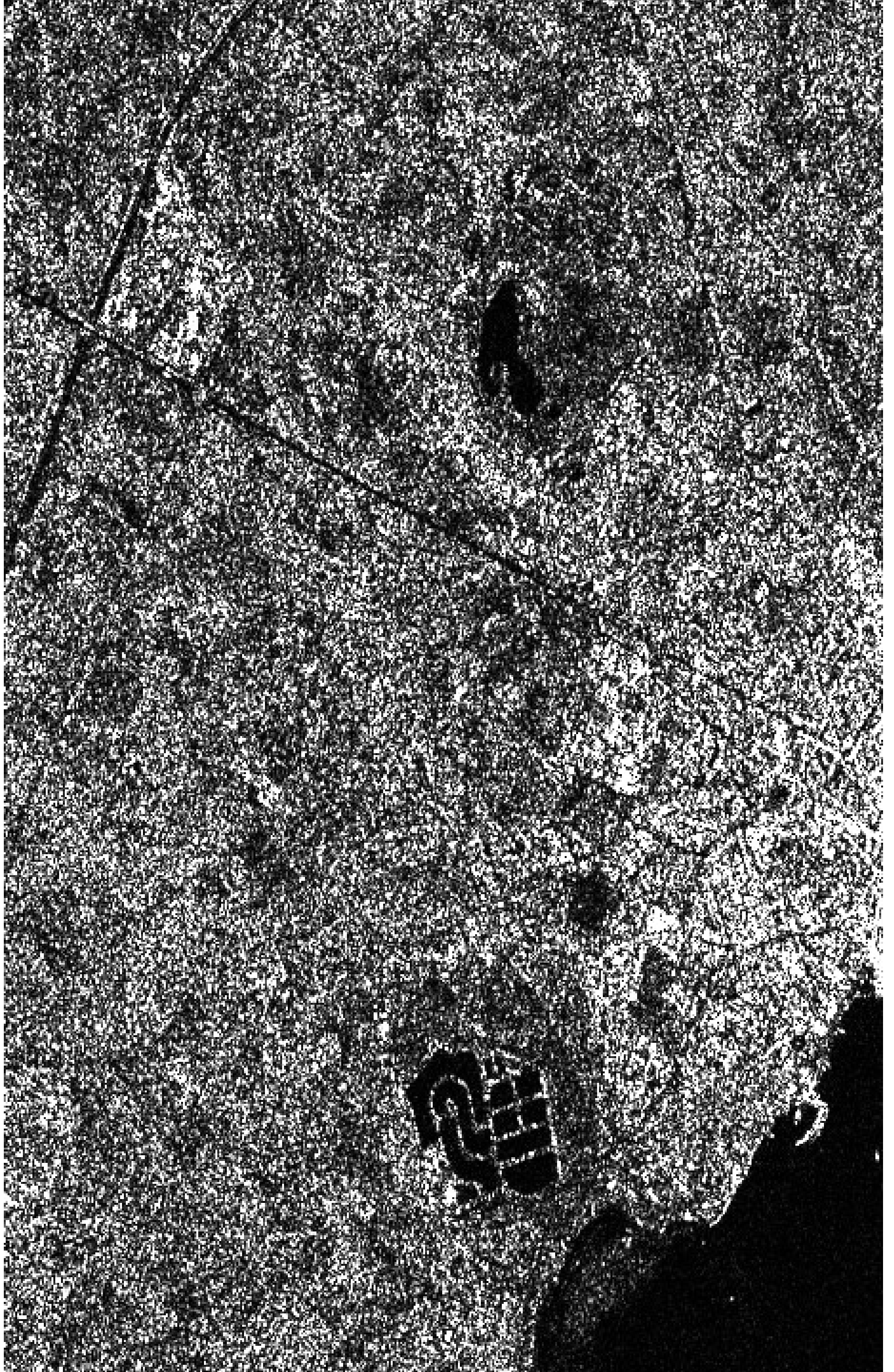
Loss of spatial resolution

in temporal domain



4 looks if surface has not changed

Preservation of spatial res.
Loss temporal information

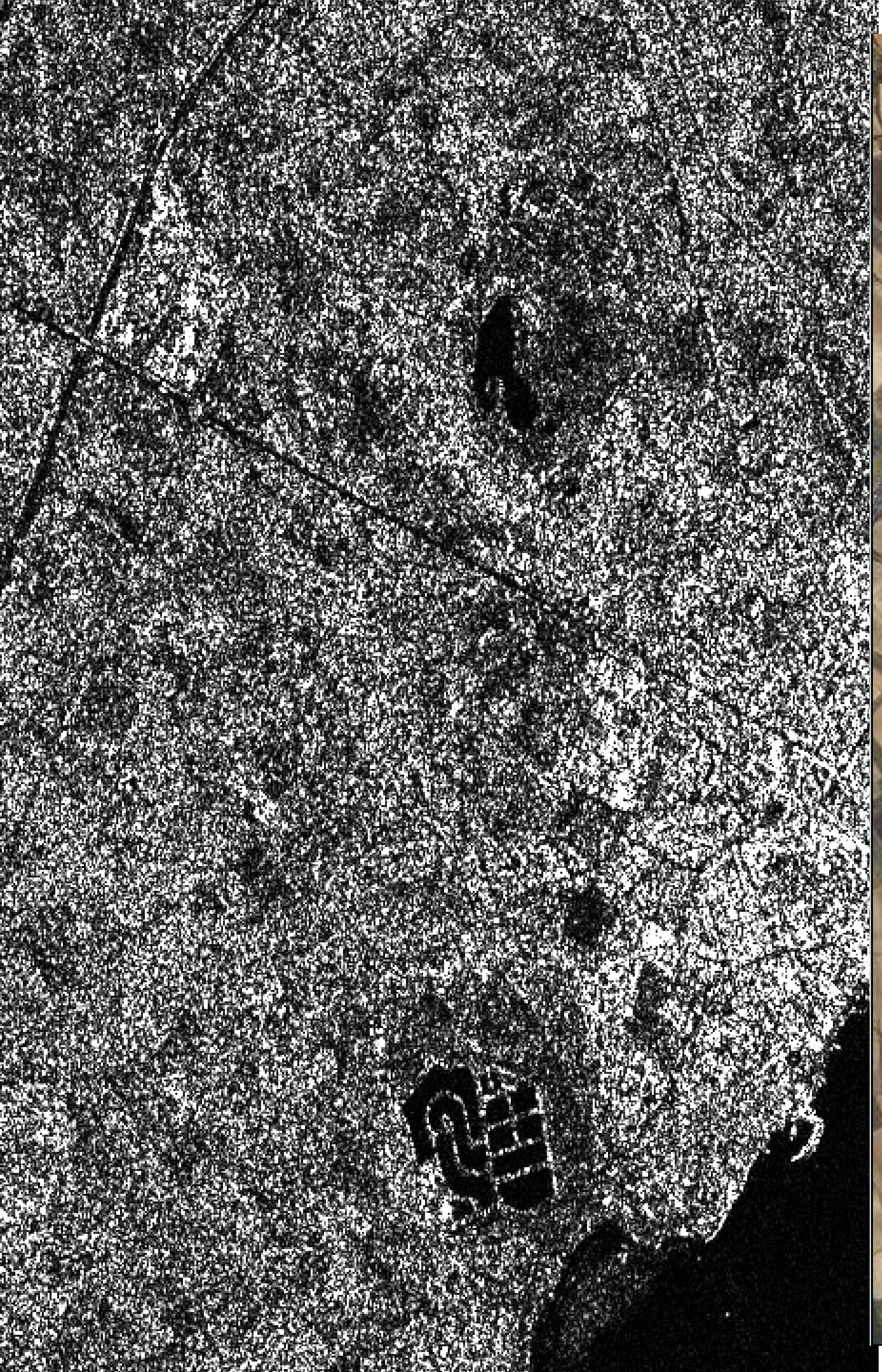


Intensity image

(from SLC product)

Sète - France: 21.06.2001

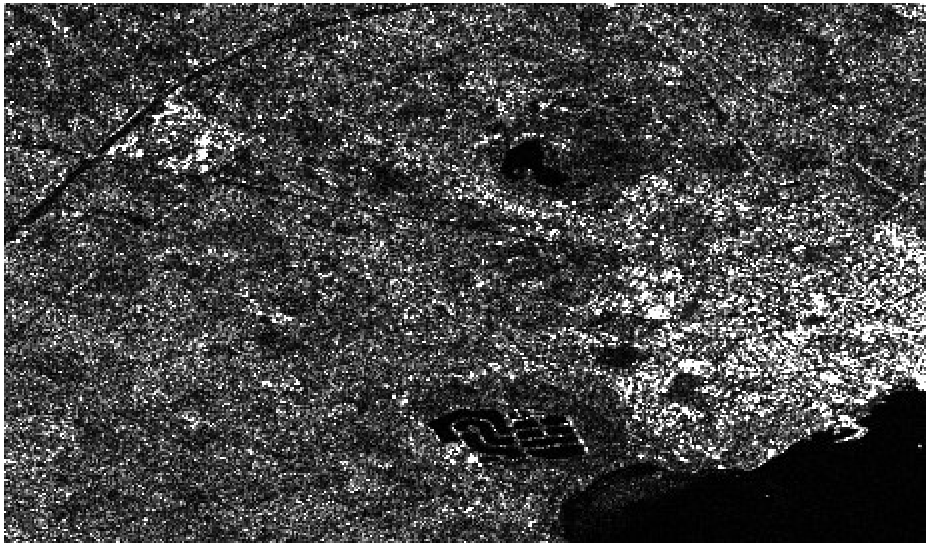
RADARSAT - FINE 1
INCIDENCE 38°, 4 x9 m

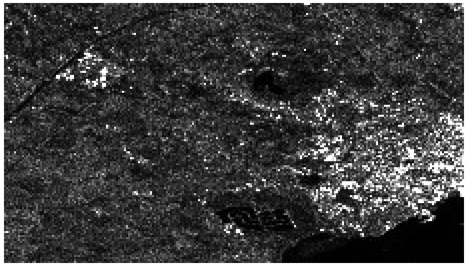


Spatial Multilook (=average) Processing

3x1 average window

6x2 average window





< 3 Look

Due to pixels correlation!

< 12 Look

Sète - France: 21.06.2001

RADARSAT FINE 1
INCIDENCE 38°, 9 x9 m

SPATIAL MULTILOOK PROCESSING

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

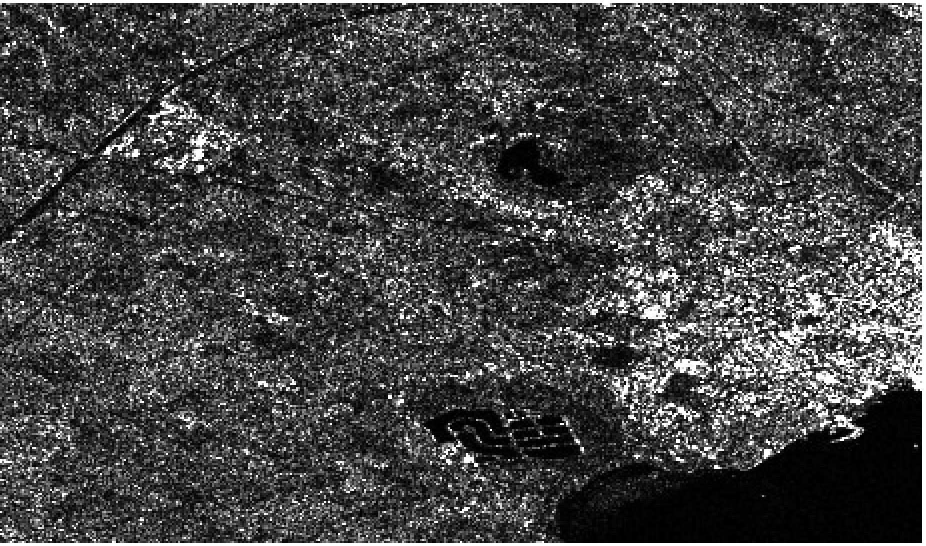
3x1 average window

< 3 Look

Due to pixels correlation!

6x2 average window

< 12 Look



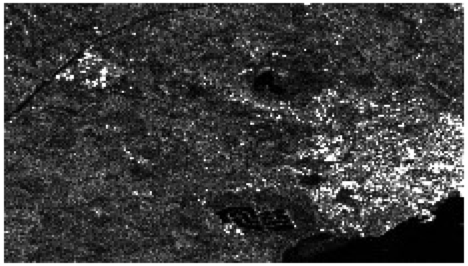
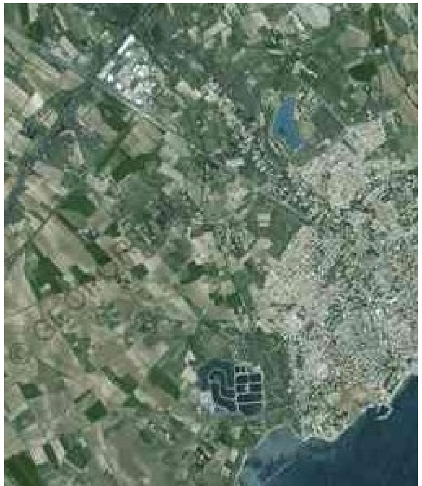
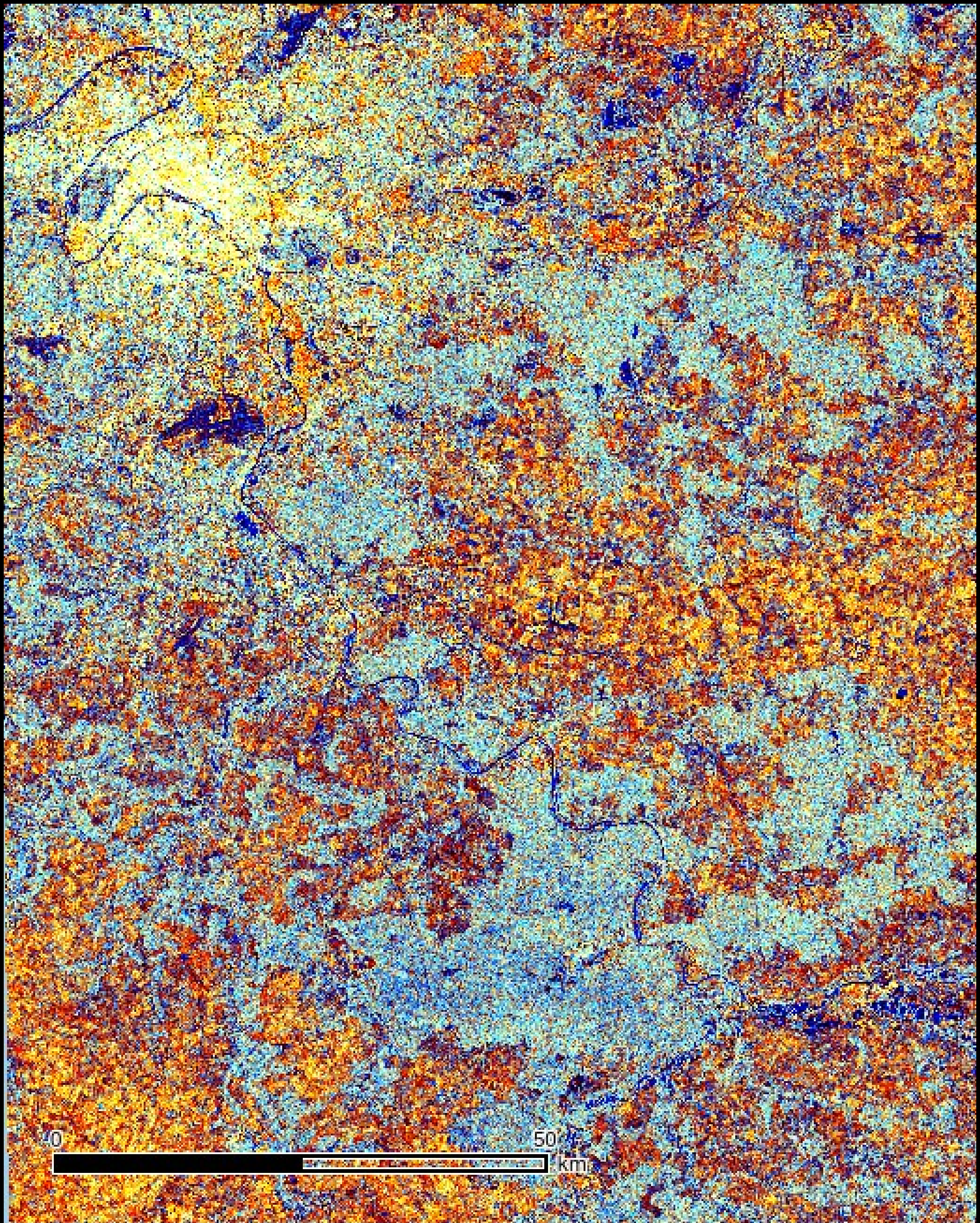


Photo aérienne (www.géoportail.fr)



Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

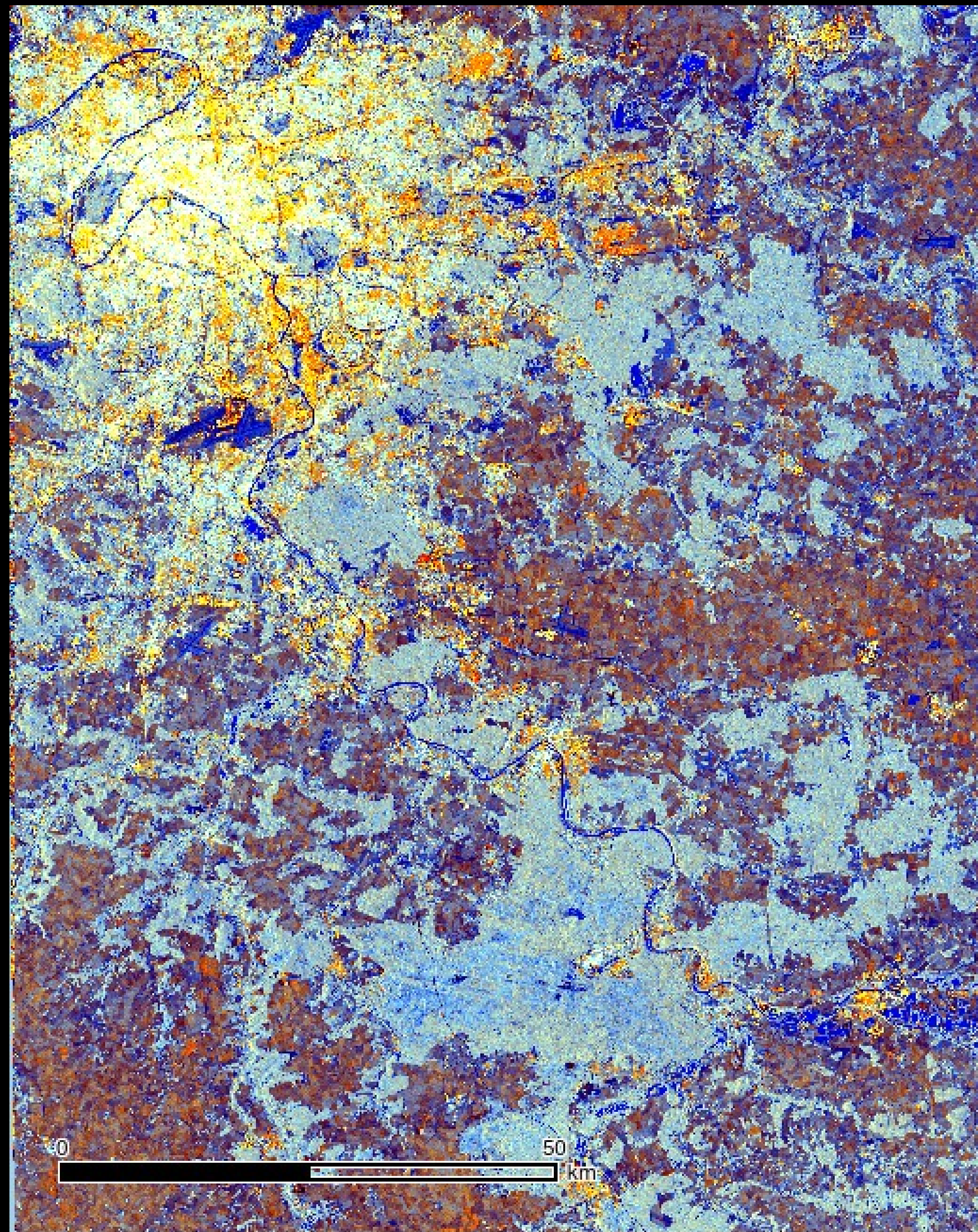
Parisian region



VV
VH
VH/VV

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

Parisian region

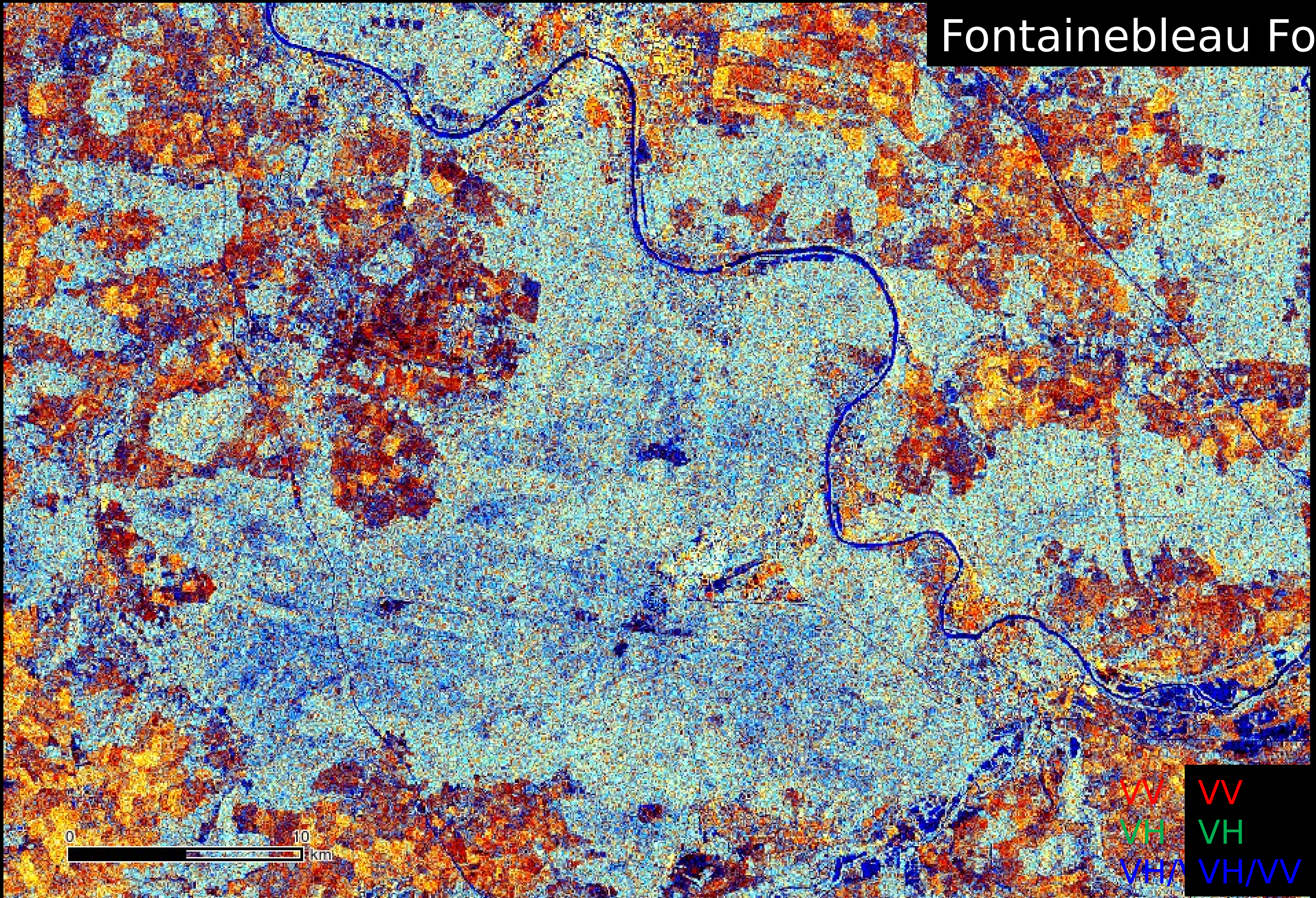


VV
VH
VH/VV

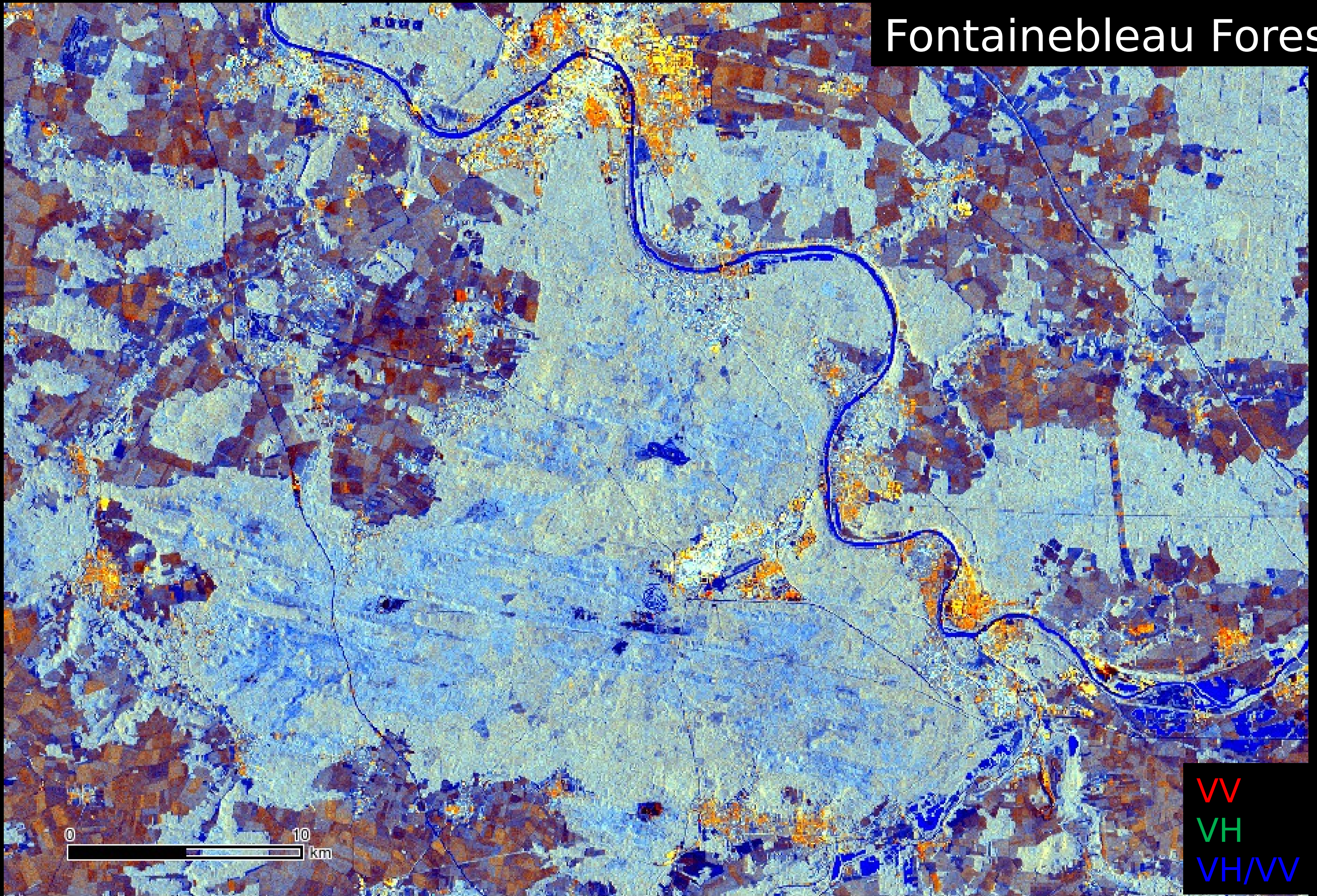
GoogleEarth Image

Parisian region

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015



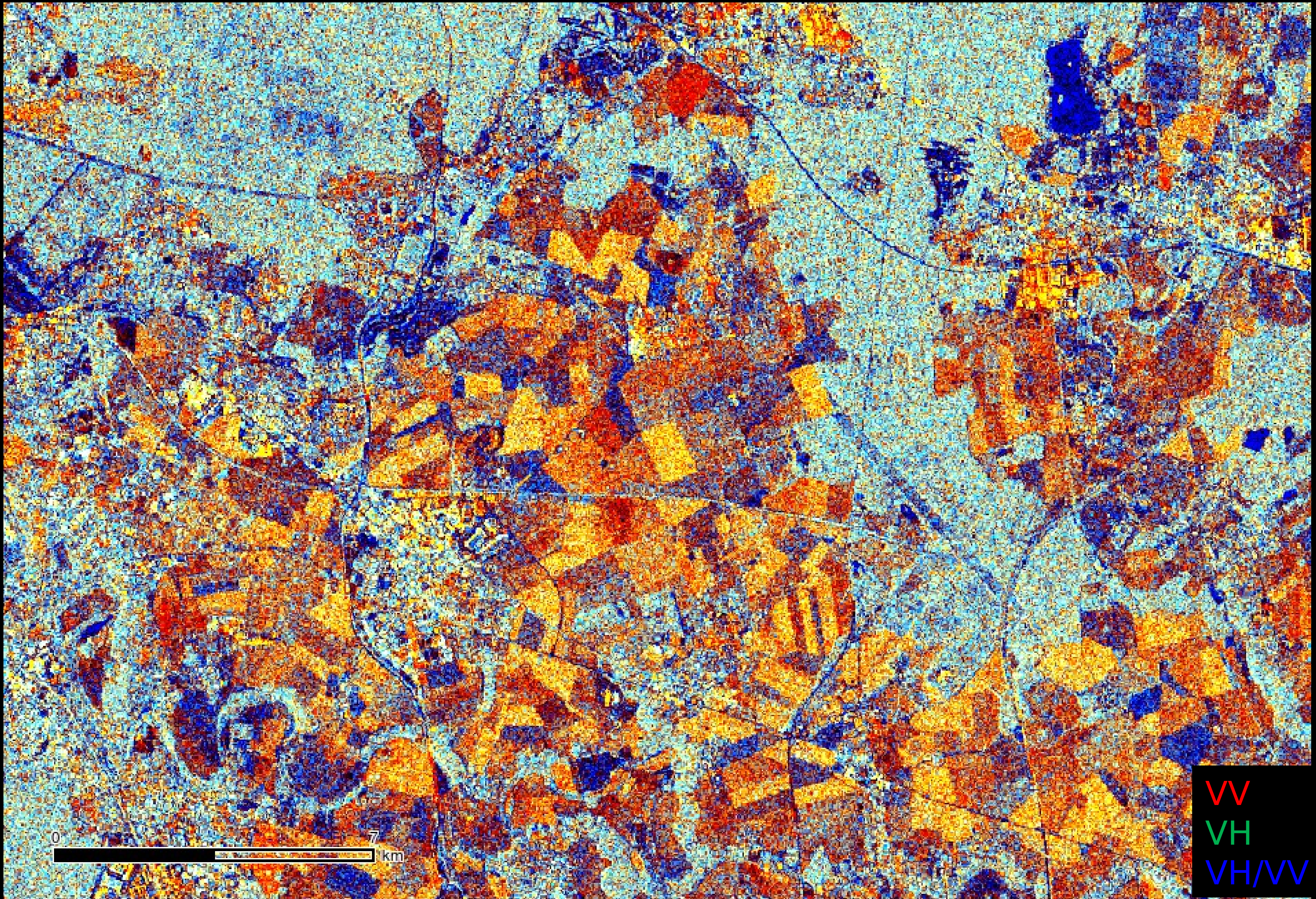
Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average
2015/03/02 - 2017/01/26



GoogleEarth Image

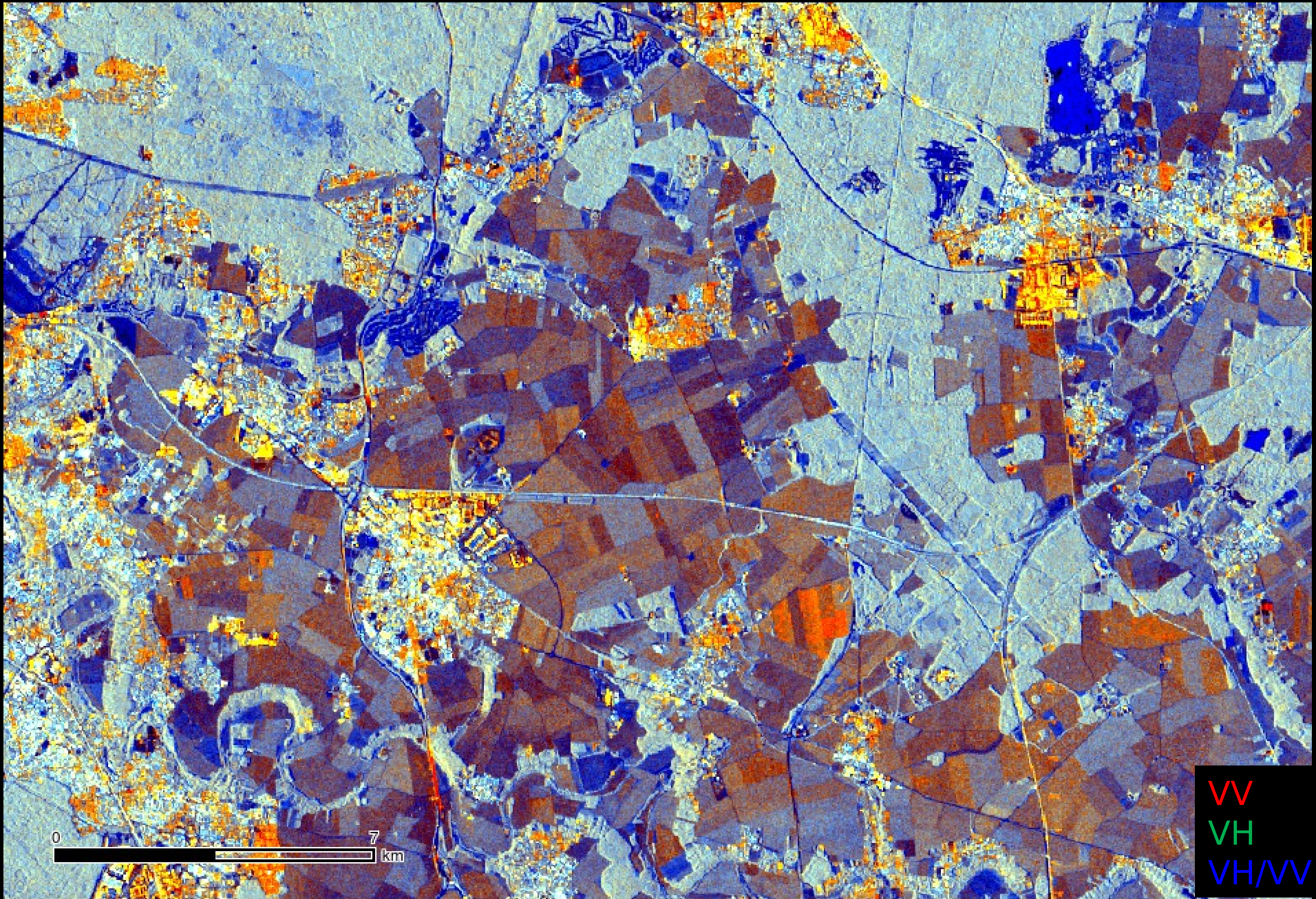
Fontainebleau Fores

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015



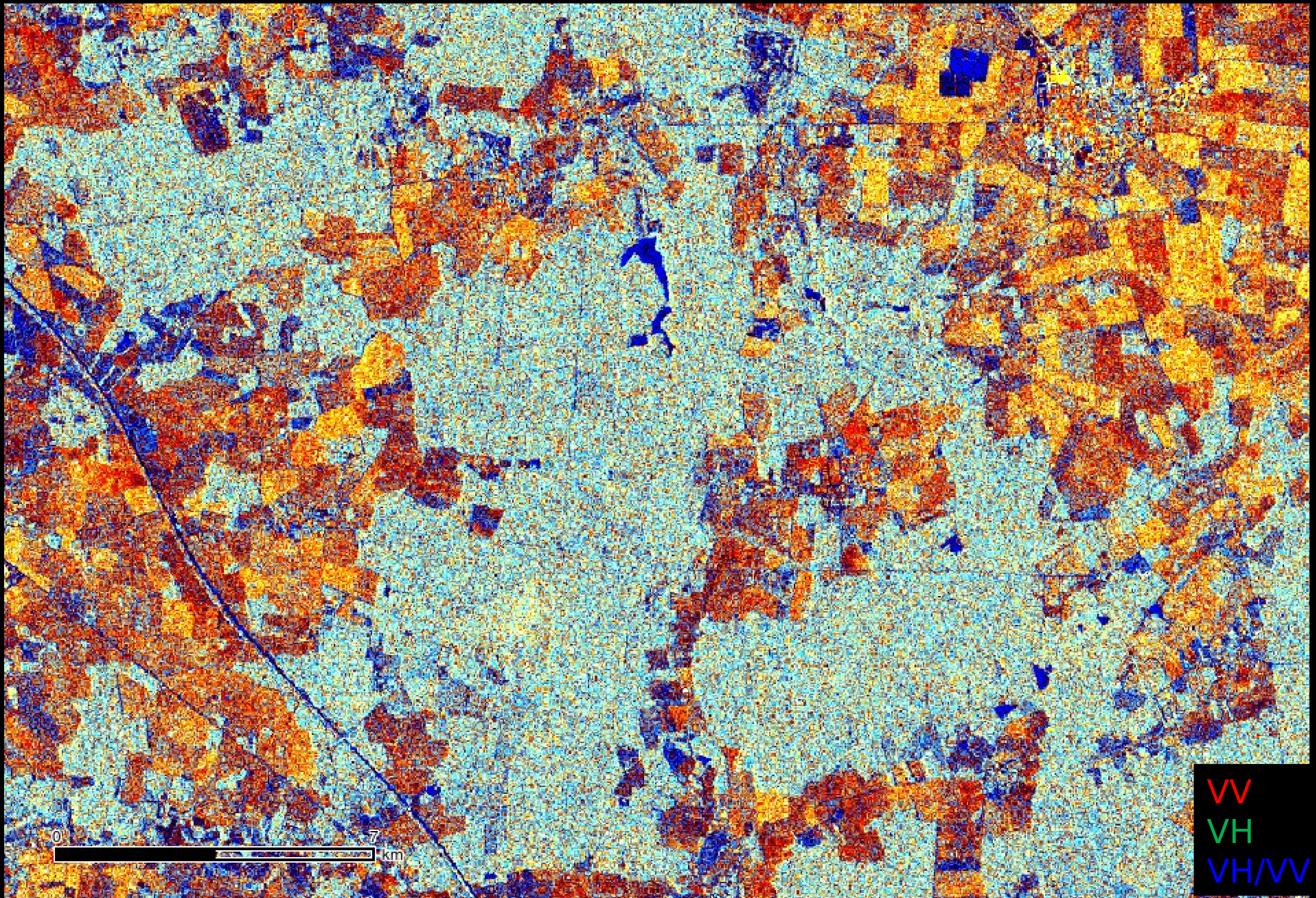
Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average

2015/03/02 - 2017/01/26



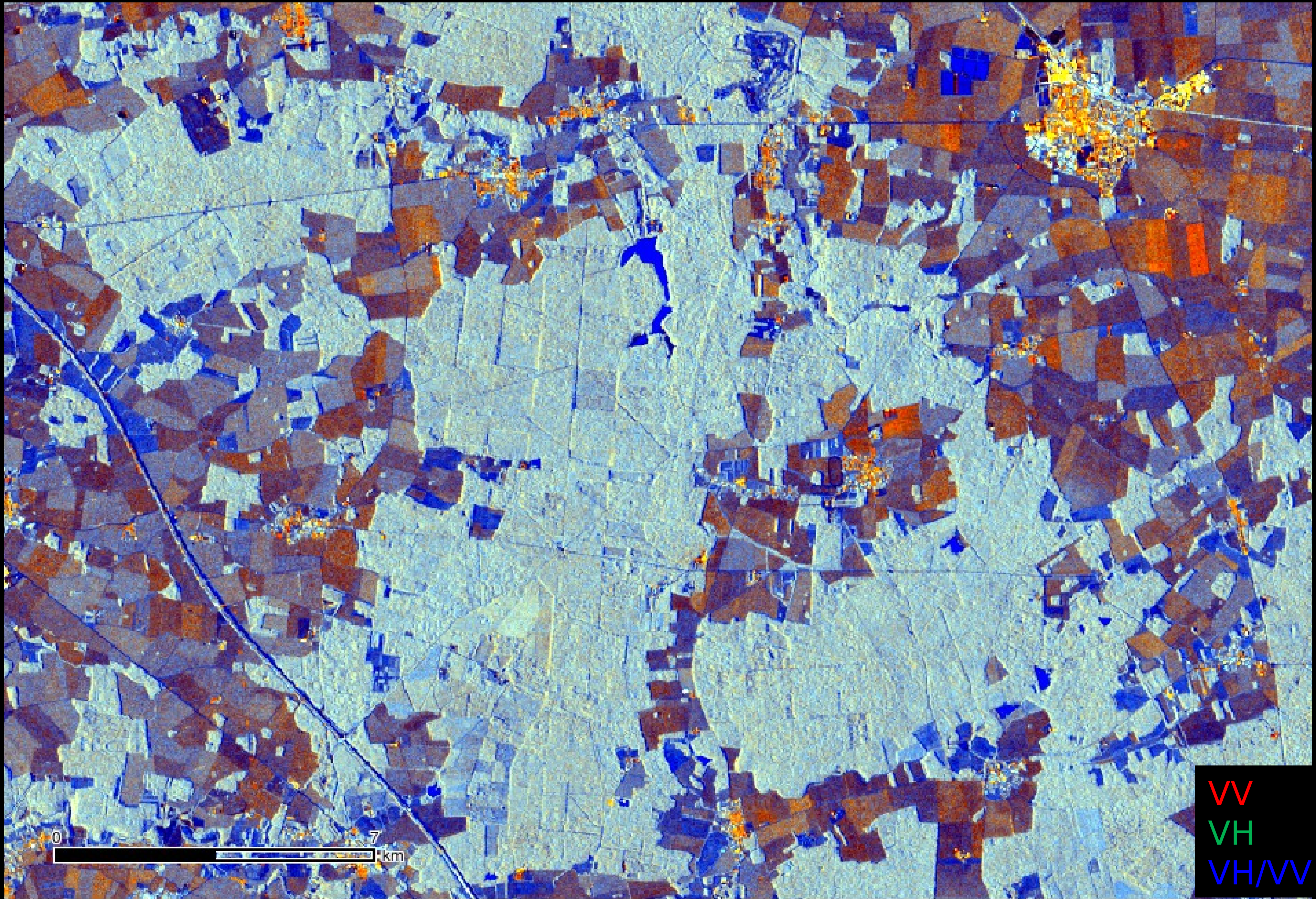
GoogleEarth Image

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

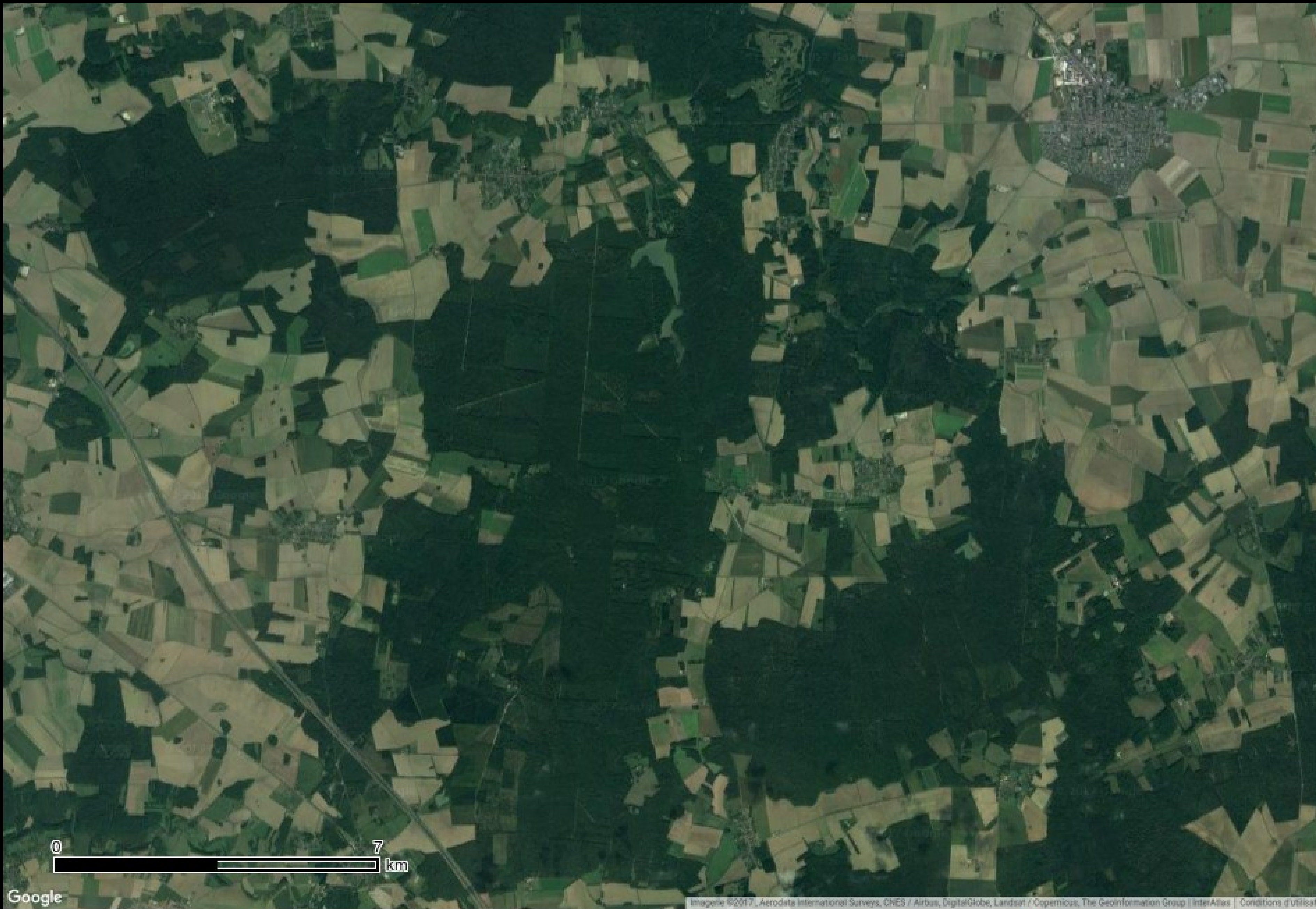


Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average

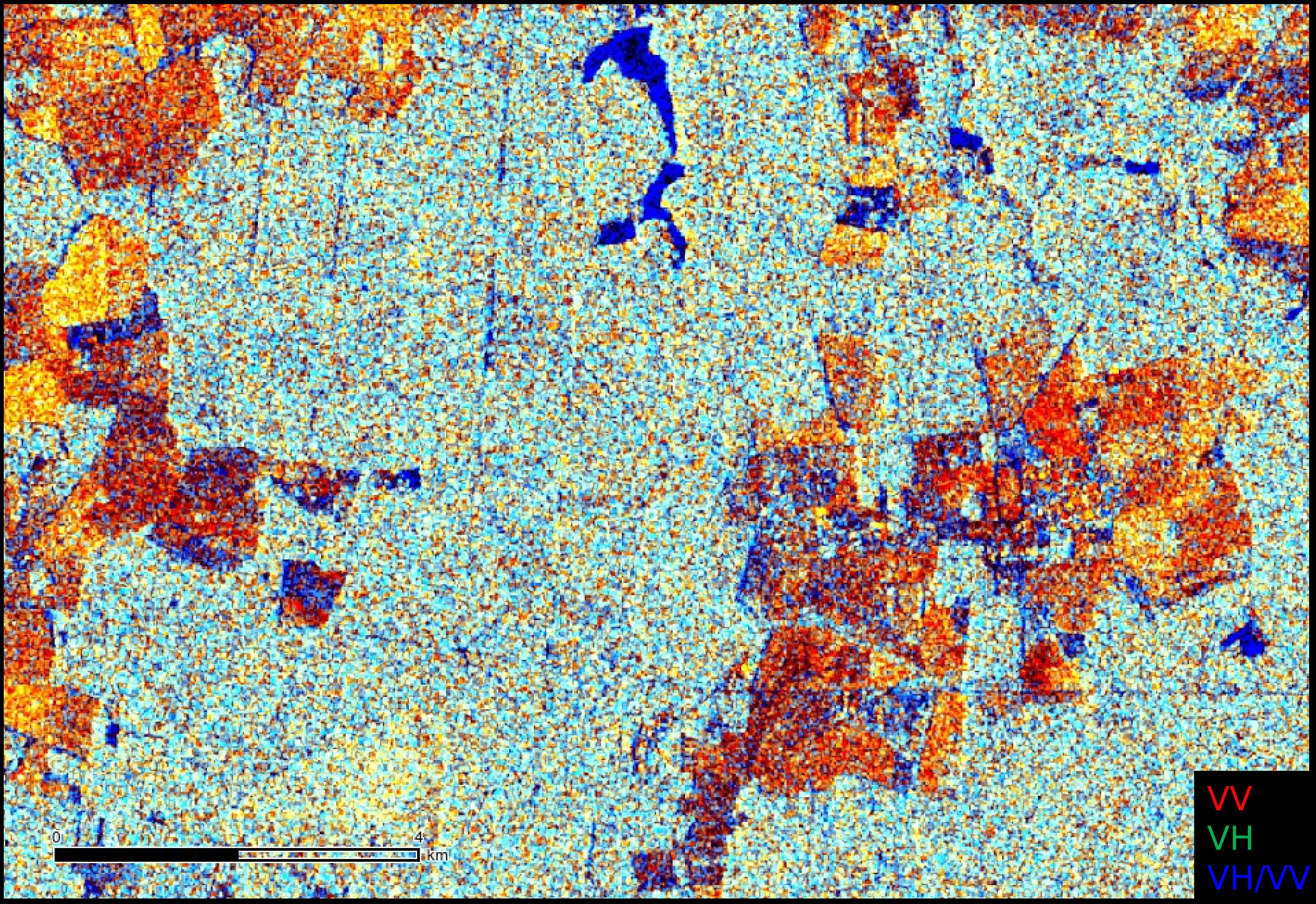
2015/03/02 - 2017/01/26



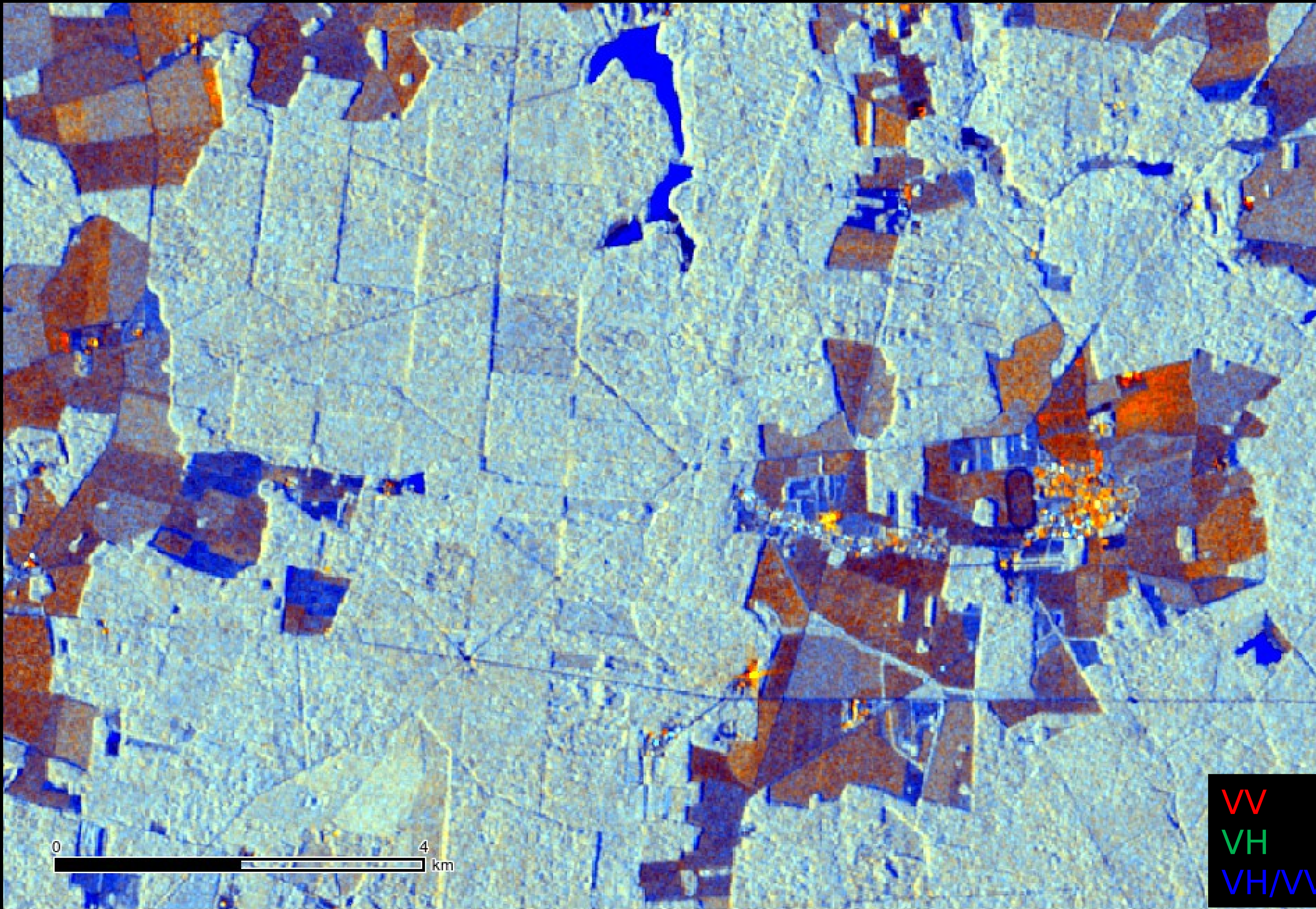
GoogleEarth Image



Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

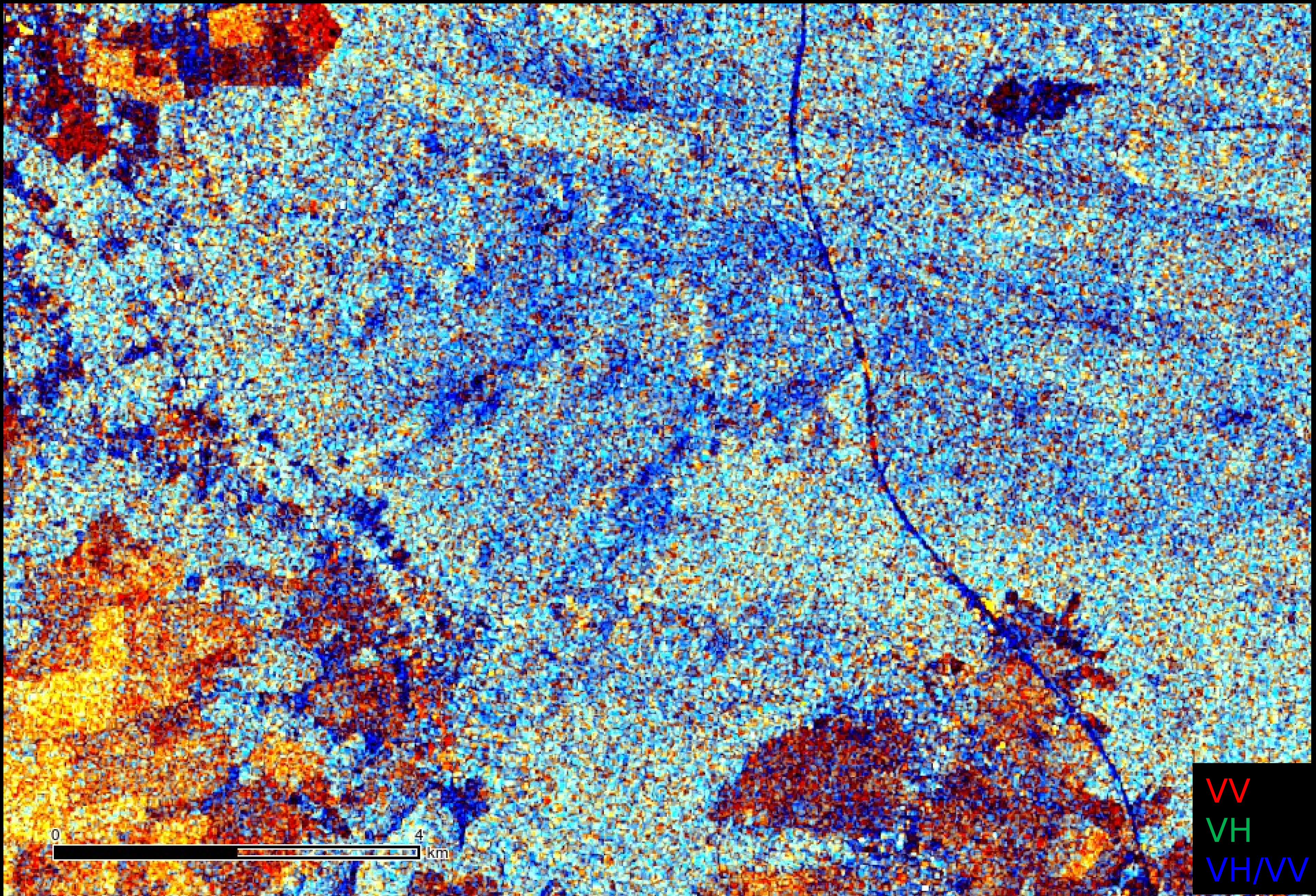


Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average
2015/03/02 - 2017/01/26



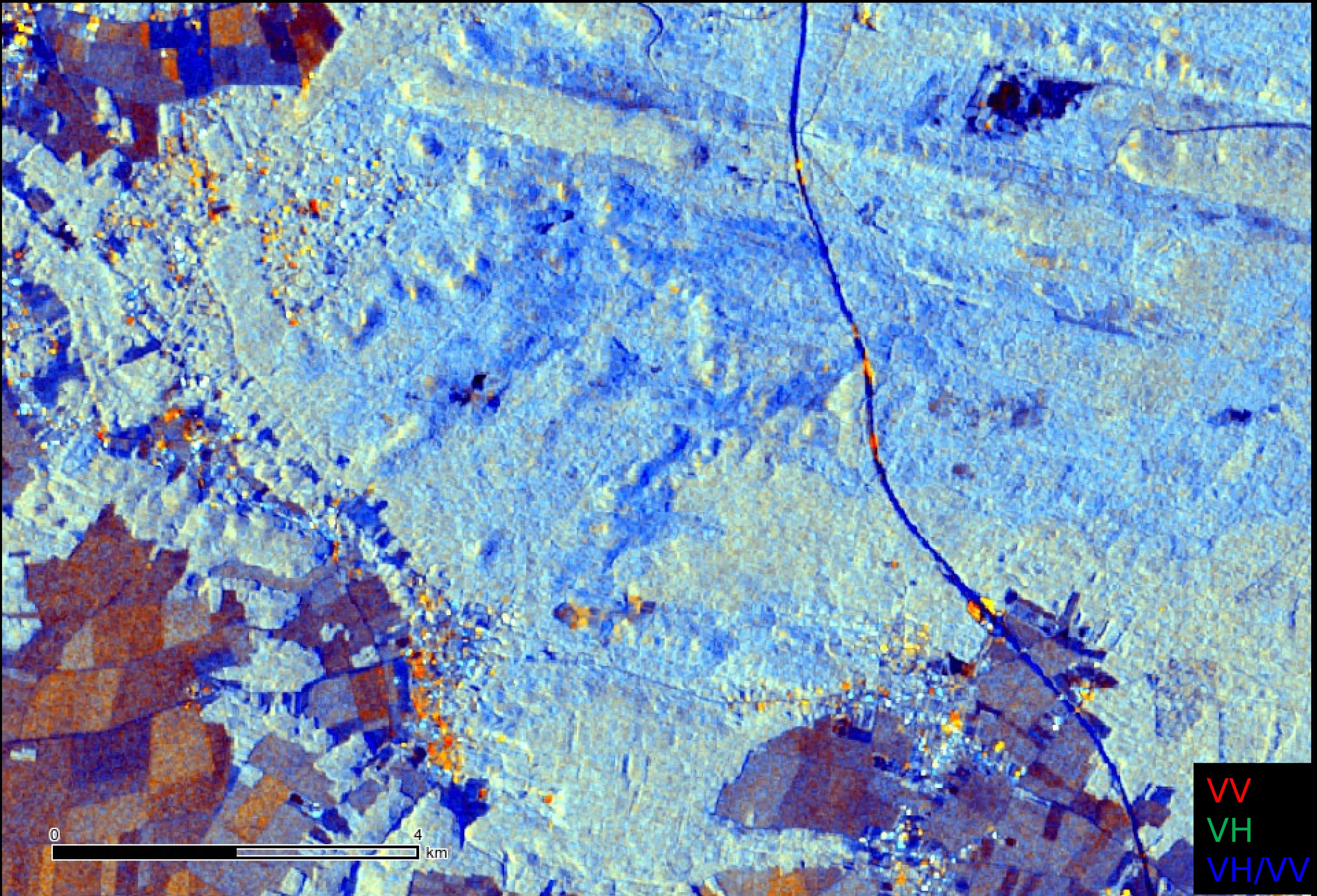
GoogleEarth Image

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015



Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average

2015/03/02 - 2017/01/26



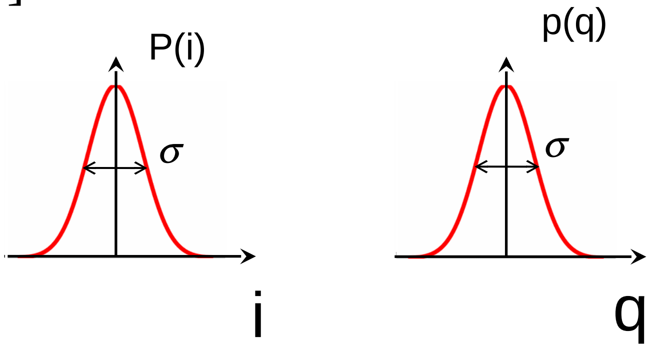
GoogleEarth Image

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(a²))
- φ_k are uniformly distributed over $[-\pi,\pi]$



==> z=i + j . 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

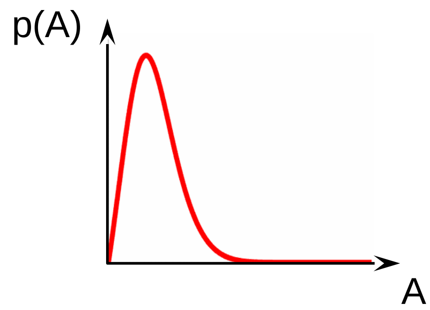
$$p_A(A/\sigma) = \frac{A}{\sigma^2}\exp\left(\frac{-A^2}{2\sigma^2}\right)$$

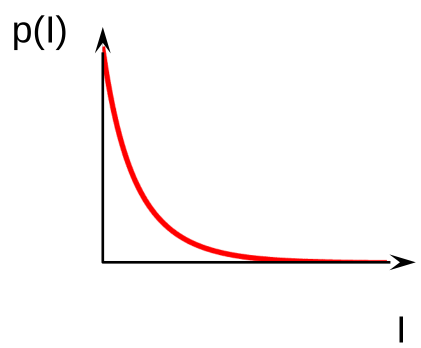
$$E(A) = \sigma\sqrt{\frac{\pi}{2}}, \quad E(A^2) = 2\sigma^2$$

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: $R \propto \sigma^\circ$

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

Homogeneous areas

Amplitude: *A*

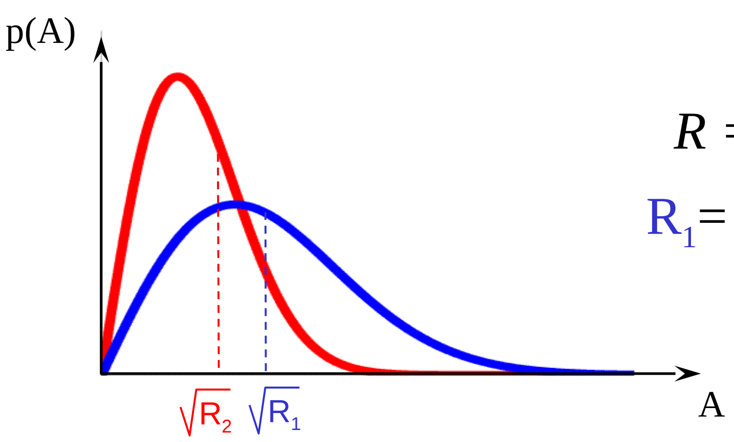
$$p_A(A/\sigma) = \frac{A}{\sigma^2}\exp\left(\frac{-A^2}{2\sigma^2}\right)$$

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

Intensity: *I*

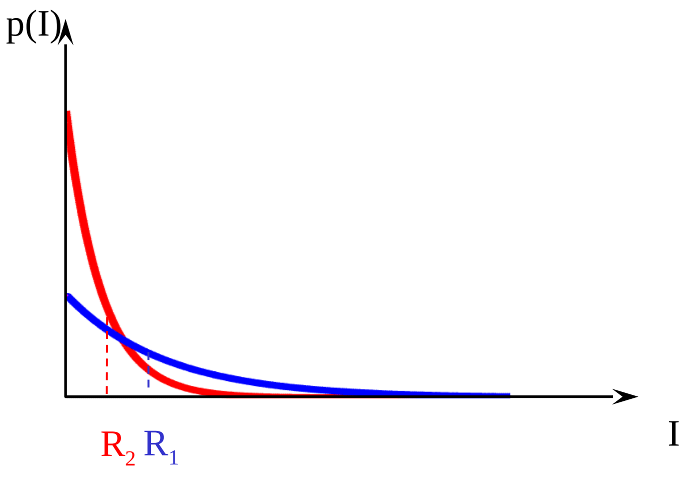
$$p_I(I/\sigma) = \frac{1}{2\sigma^2}\exp\left(\frac{-I}{2\sigma^2}\right)$$

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



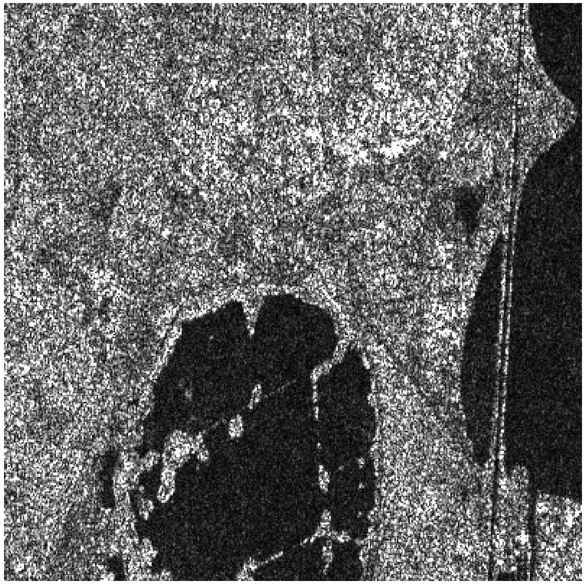
$R = 2\sigma^2$

$R_1 = 2 * R_2$



The higher is R, the more data are spread over

Speckle: multiplicative noise



RADARSAT - Mode Fine 1

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

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

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

constant!

multilook data

$$y = \frac{1}{N}\left(x_1 + x_2 + \ldots + x_L\right) \Rightarrow \begin{cases} var(y) = \dfrac{var(X)}{N} \\ E(y) = E(x) \end{cases}$$

L: Look number

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

with

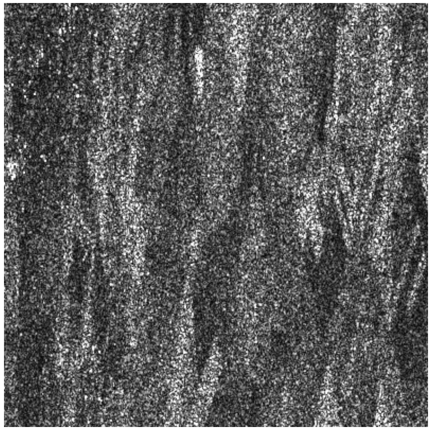
for intensity data

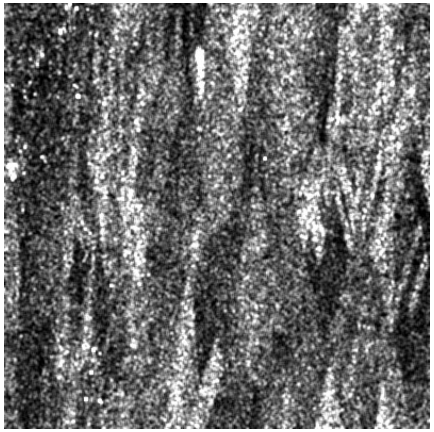
for amplitude data

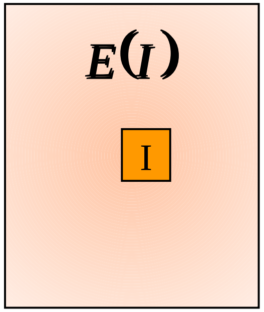
and C_{ML} estimated over an homogeneous area

Goal: estimate R $\overset{\times}{\times\circ}$ σ°

Most simple: Box Filtering: I ⟷ E(I)







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

Inconvenients: Details lost, fuzzy introduction

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

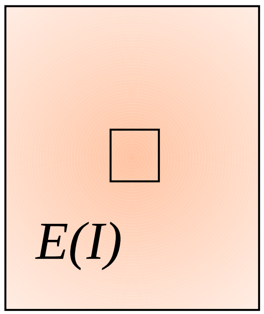
==> Need to introduce specific filters taken into account speckle statistics

Neighbourhood size depends on local scene characteristics
==> ***Adaptive filters***

Adaptative Filters

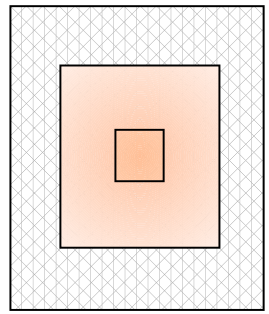
Goal: adapt the size of the neighbourhood before average

Homogeneous area



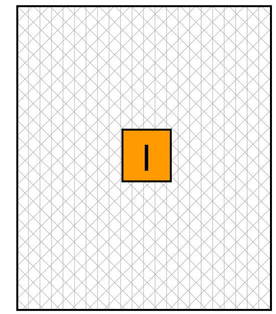
Average over the whole neighbourhood

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:

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

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

Kuan and Lee Filters

$$\hat{R} = E(I) + a\left(I - E(I)\right)$$

with $a = \begin{cases} 0 & \textit{over homogeneous area} \\ 1 & \textit{over heterogeneous area} \end{cases}$

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

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 ==> Lee < Kuan

N 3 ==> Lee   Kuan

Frost Filter

Weghting of the neighbour pixels relative to its distance

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

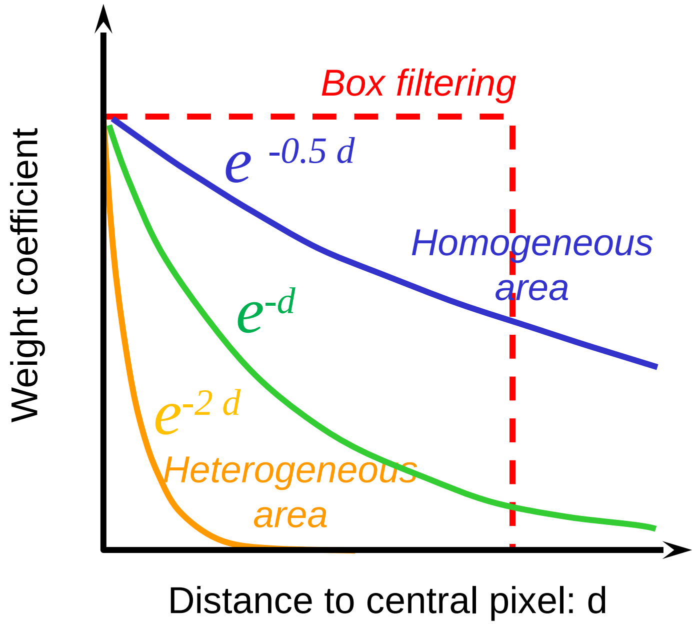
(MMSE criteria)

d: distance to central pixel

K_1 and K_2 set for the whole image

homogeneous area: c_I low

heterogeneous area: c_I high



MAP (Maximum a posteriori) Filters

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

Hypothesis on *p(R):* Γ law

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

$$\alpha = K / c_I^2$$

homogeneous area: α high ==> $\hat{R} = E(I)$

p(R): Γ *law*
p(I/R): Γ *law*

MAP filter = Gamma-Gamma filter

Radar image – 1 Look
(N=1)

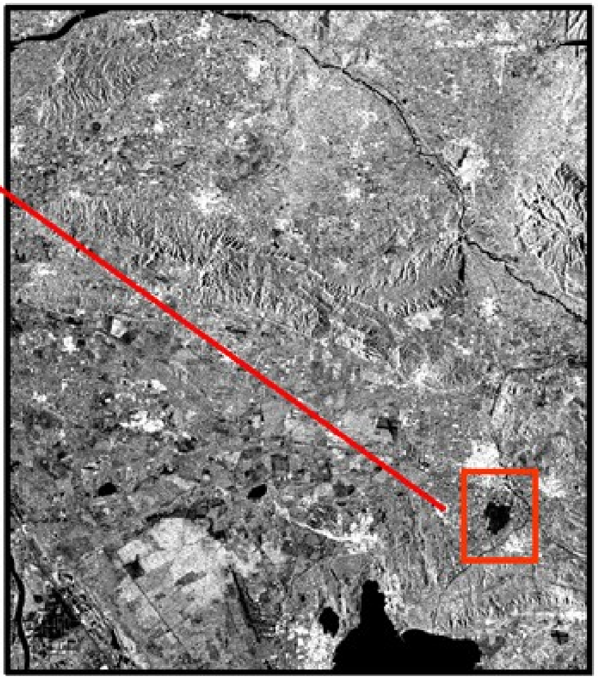

Boxcar 9x9


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

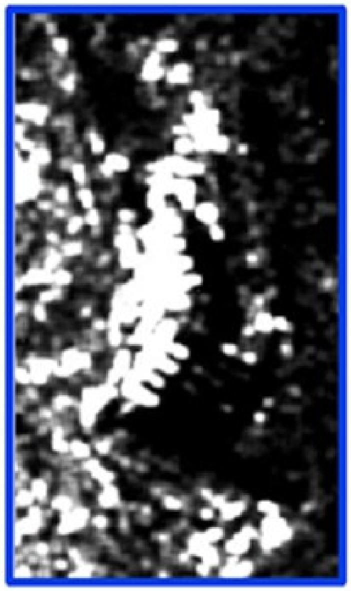

Filtered image

• 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

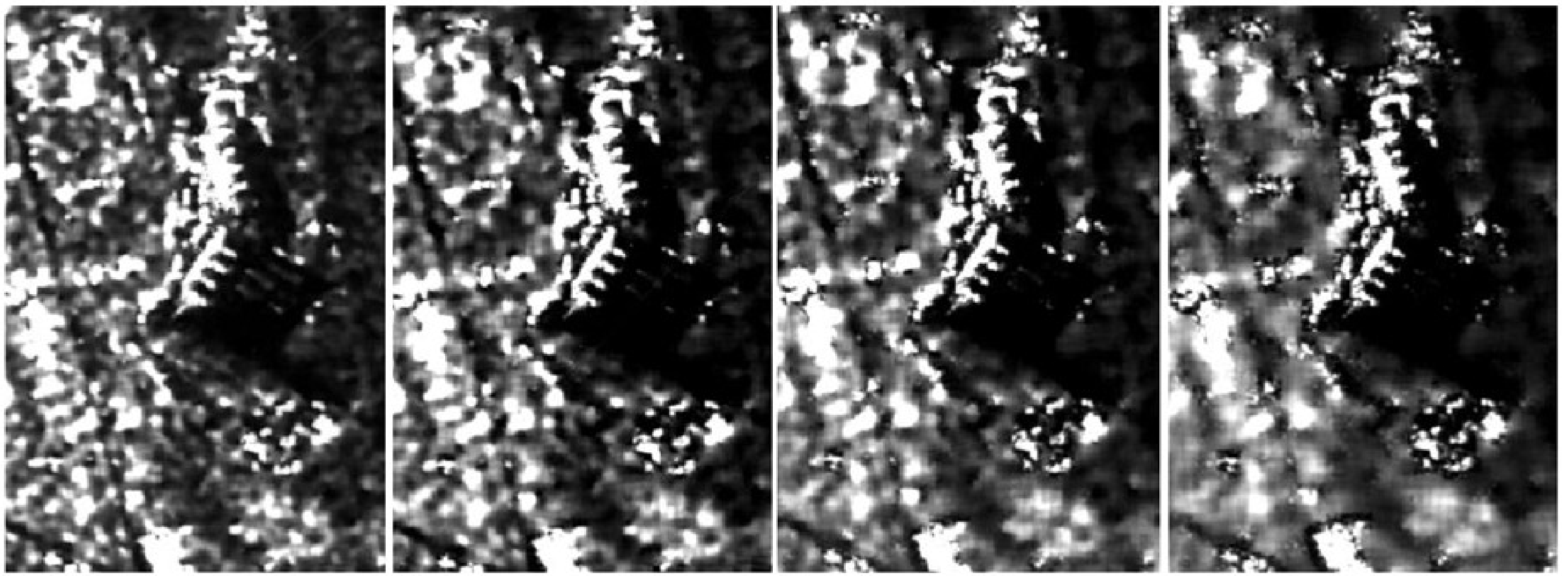
Gamma-Gamma
MAP 7x7

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)

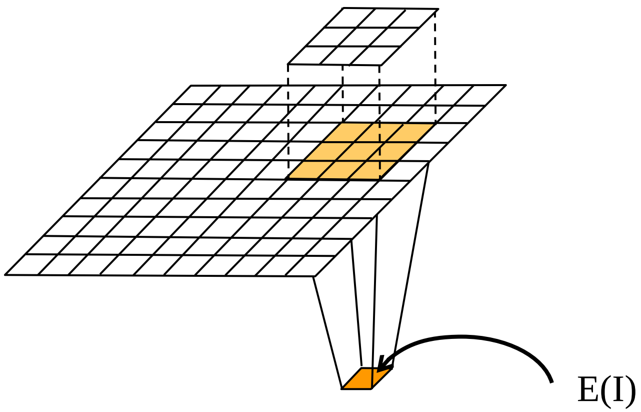
- **Contour** detection, linear structures detection, punctual target detection (analysis window of adaptive shape)
- Multi-scale analysis
- Integration of the non-stationary property of the radar signature

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

MULTILOOK OBTENTION

in spatial domain

*Sliding window: image * window*

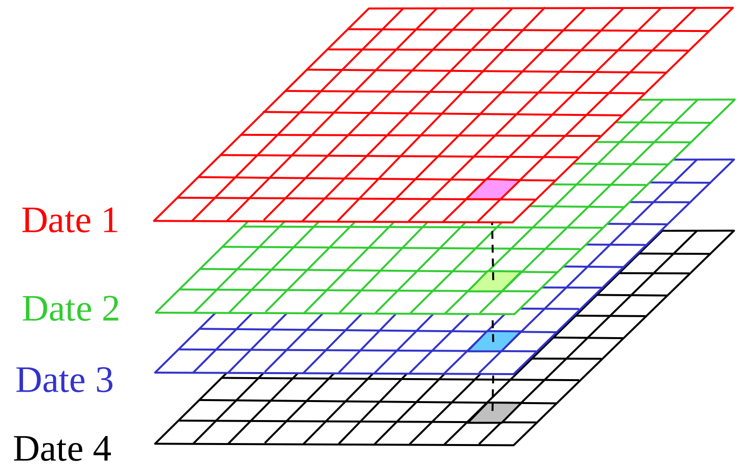


9 looks if pixel sare not correlated

Example: ERS data - PRI products : 3 looks

Loss of spatial resolution

in temporal domain

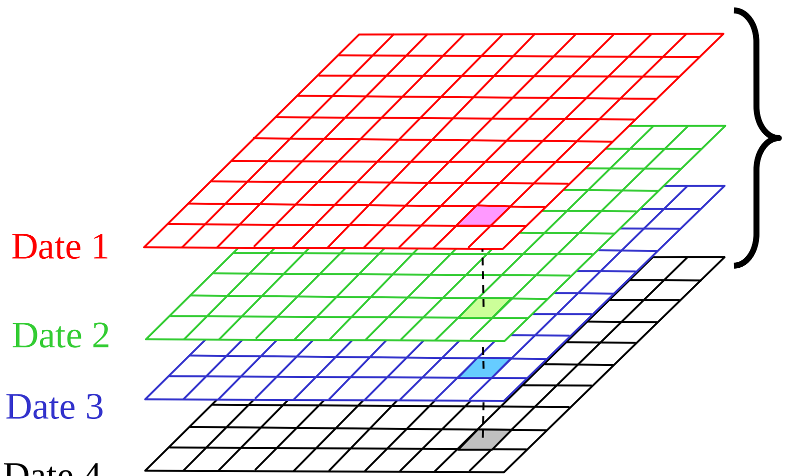


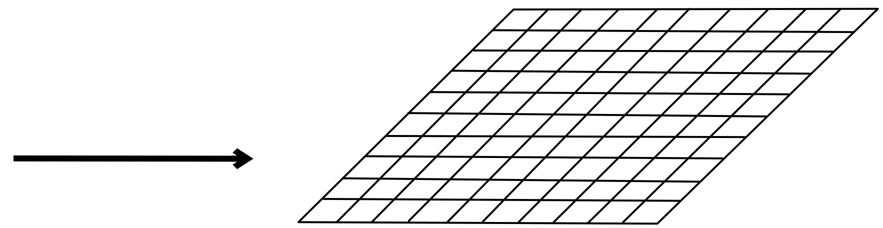
4 looks if surface
has not changed

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

Spatio-temporal Filter (Sentinel-1)

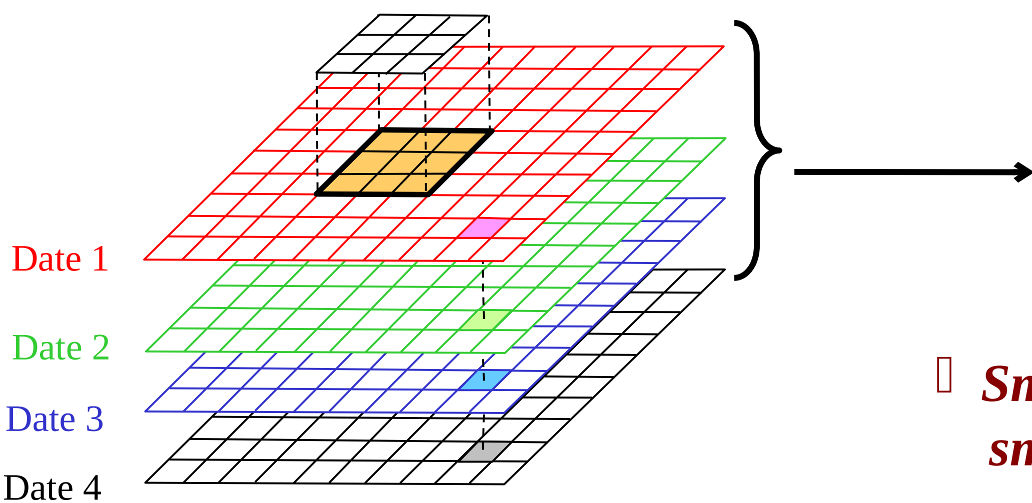
temporal domain

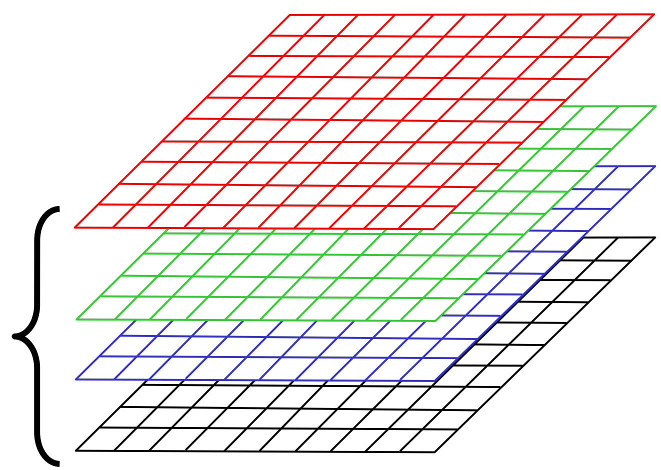




- ***Preservation of spatial res.***
  Total loss temporal information

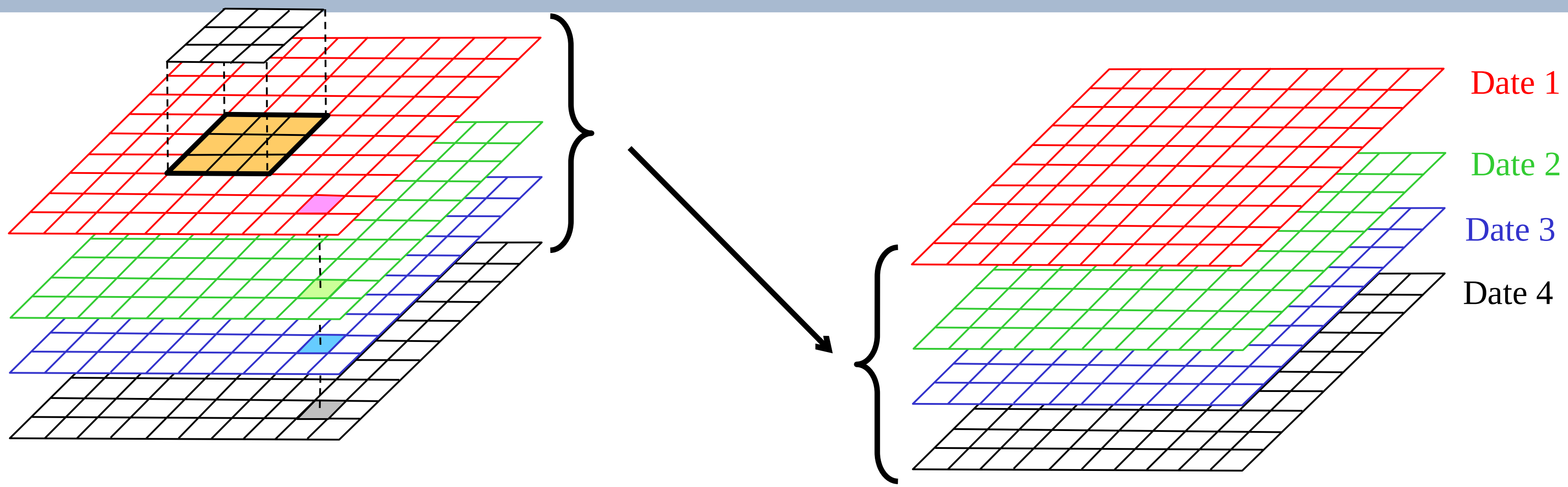
Spatio-temporal domain





- ***Small degradation of spatial res.***
  small degradation ntemporal information

Spatio-temporal Filter (Sentinel-1)



- ***Small degradation spatial resolution***
  Small degradation temporal resolution

Date k:

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

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

$< I_k >$: spatial average over a local neighbor. around I_k

Quegan & Yu, IEEE TGRS 2011

TAKE HOME MESSAGE- 1

- Radar images: coherent waves *(A, φ)*: ==> ***SPECKLE***
- ***SLC products:*** *(Single Look Products: A, φ)*

  φ image: *(not useful except for interferometry)*

  use of ***A*** (or ***I = A²***) image, similar to optical image

- Speckle ==> ***A*** or ***I*** value of a single pixel: no meaning!

  ==> ***main drawback for classification algorithms***

  need to apply a speckle filter

- ***Sentinel-1 GRD Products (Ground Range Detected)***

  Multilook products (5 looks)

  (pixel size: 10 * 10m² - spatial resolution: ≈ 20 x 20 m²)

  steel 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***

  heteregeneous areas: average over ***smallest neighbourhood***