SAR Speckle Filtering

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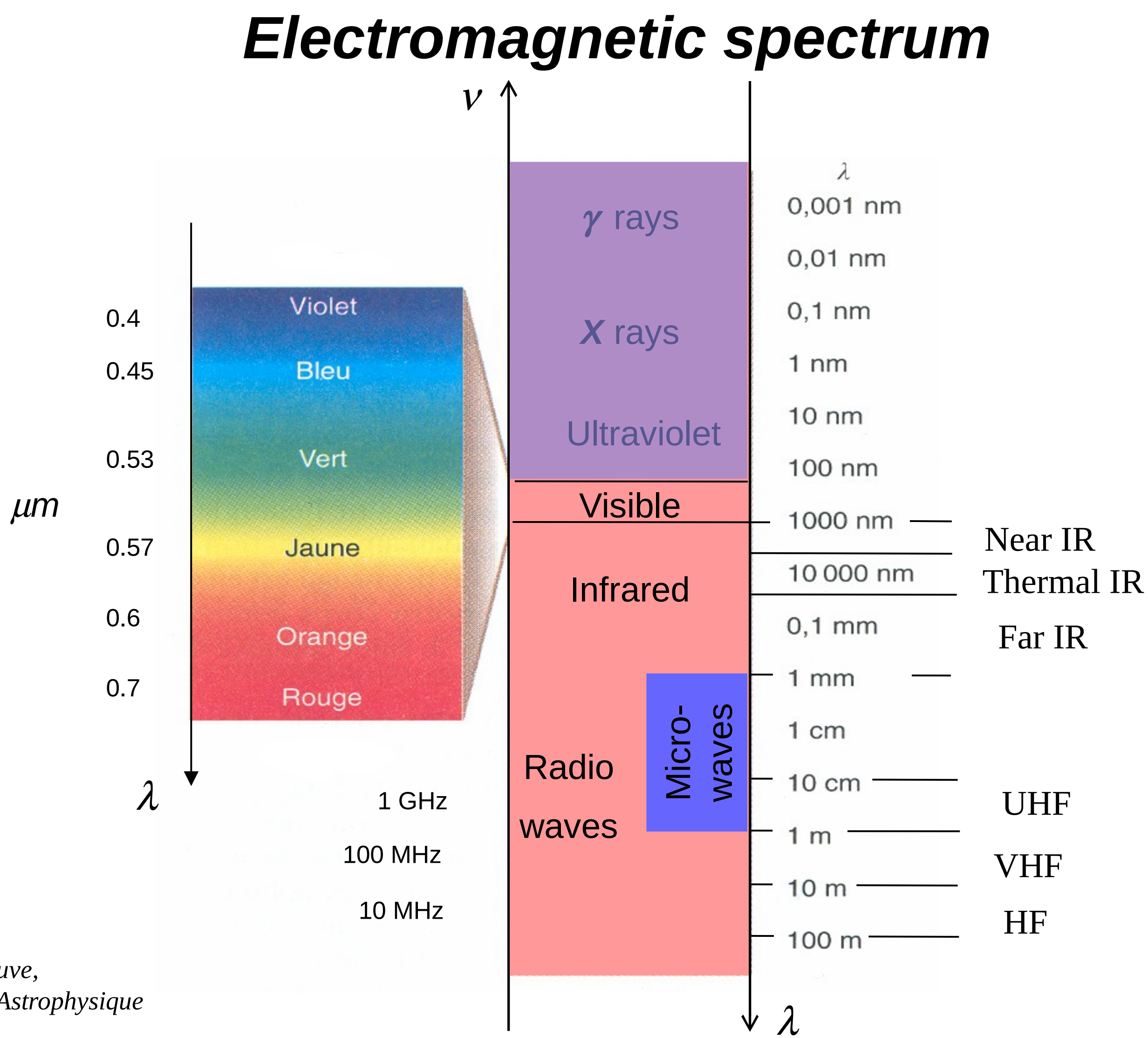
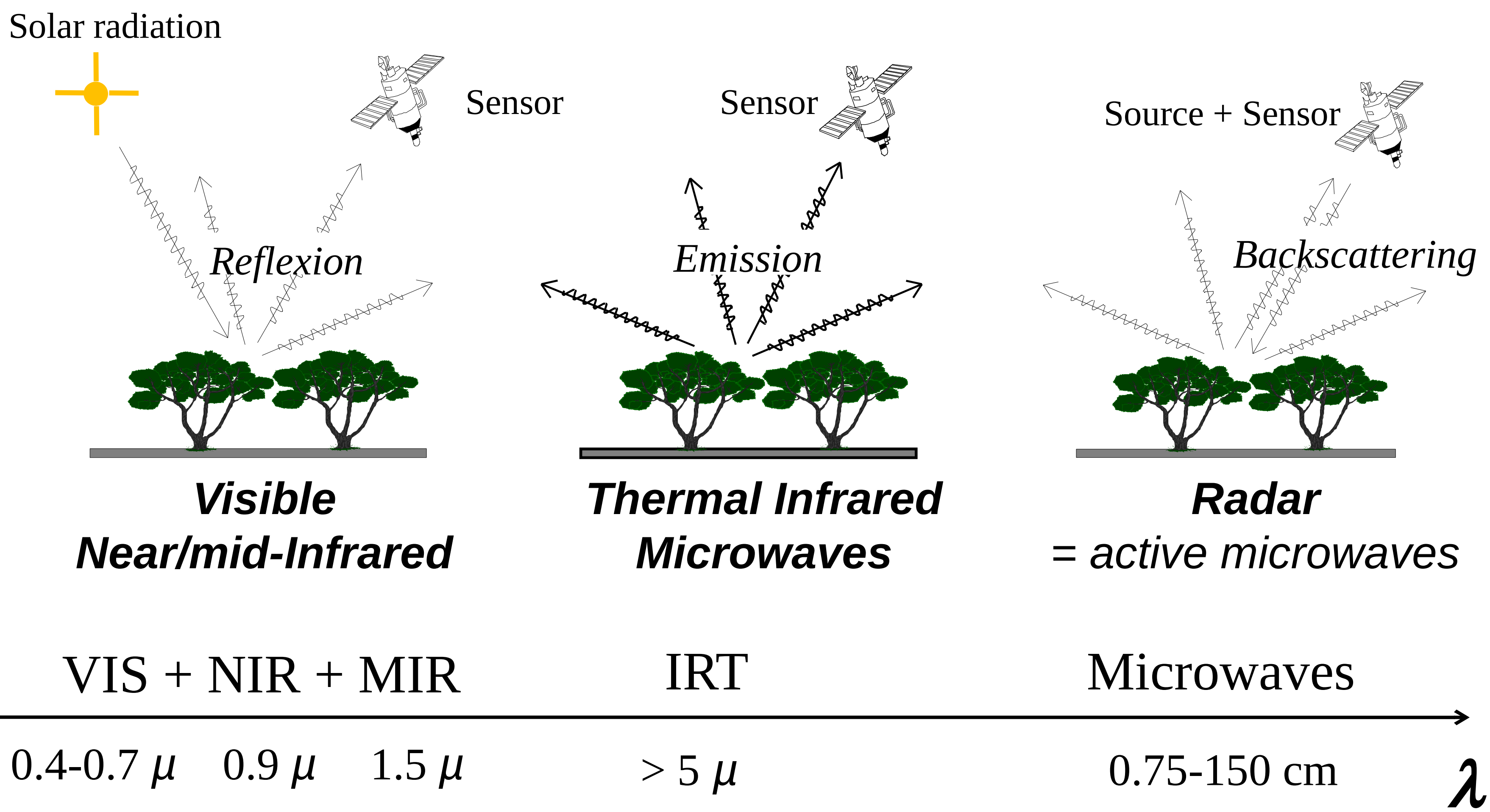
Electromagnetic coherent wave



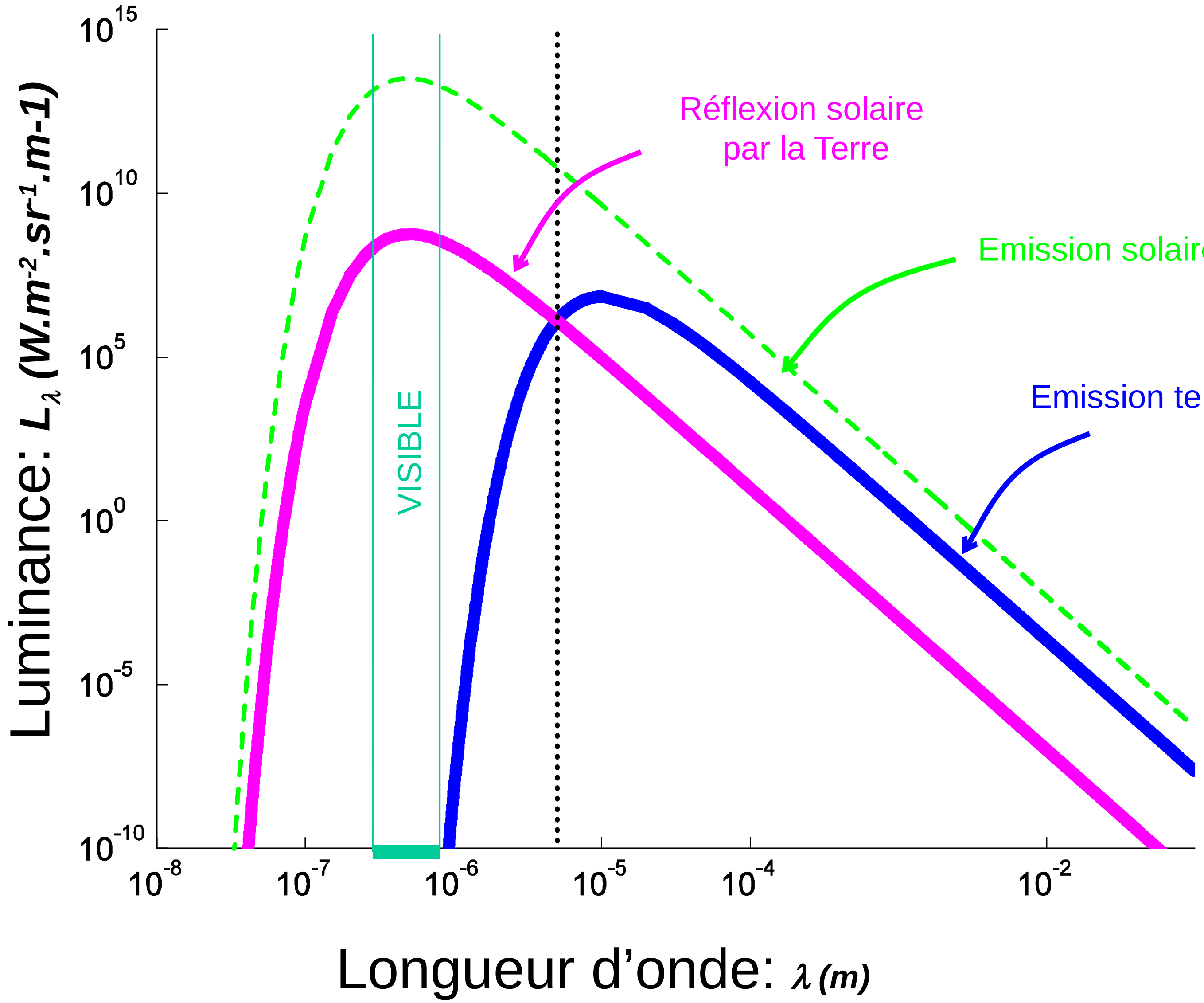
From *Seguin & Villeneuve, Astromnomie et Astrophysique*

Radar Fundamentals

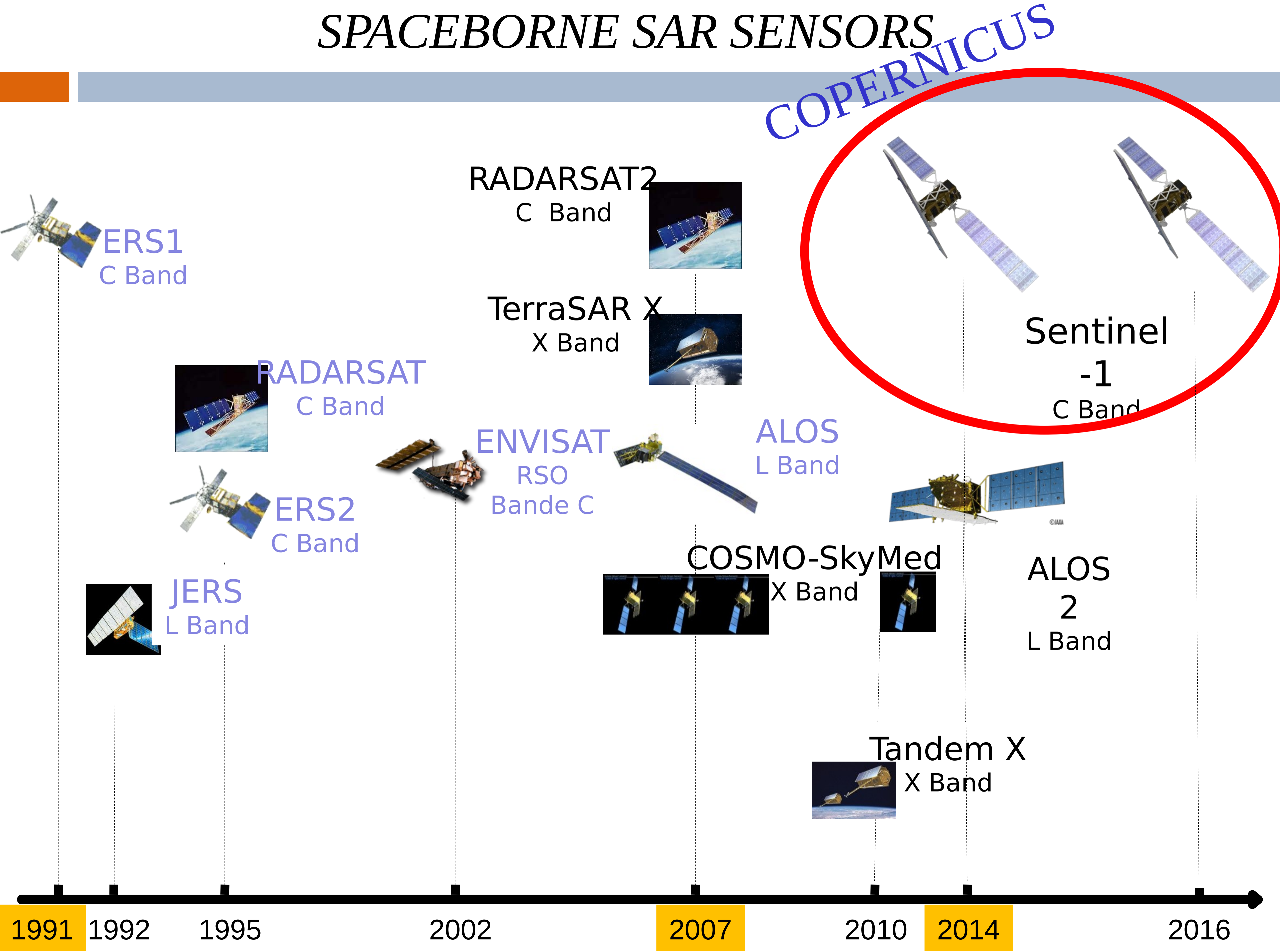
Remote Sensing observations mode



Le Rayonnement électromagnétique en provenance de la Terre



SPACEBORNE SAR SENSORS

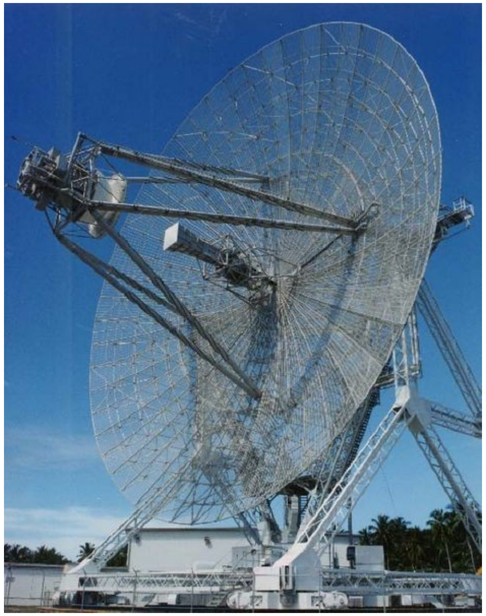


RADAR:

RAdio **D**etection **A**nd **R**anging

Emition of emw

Reception backscattered echoes

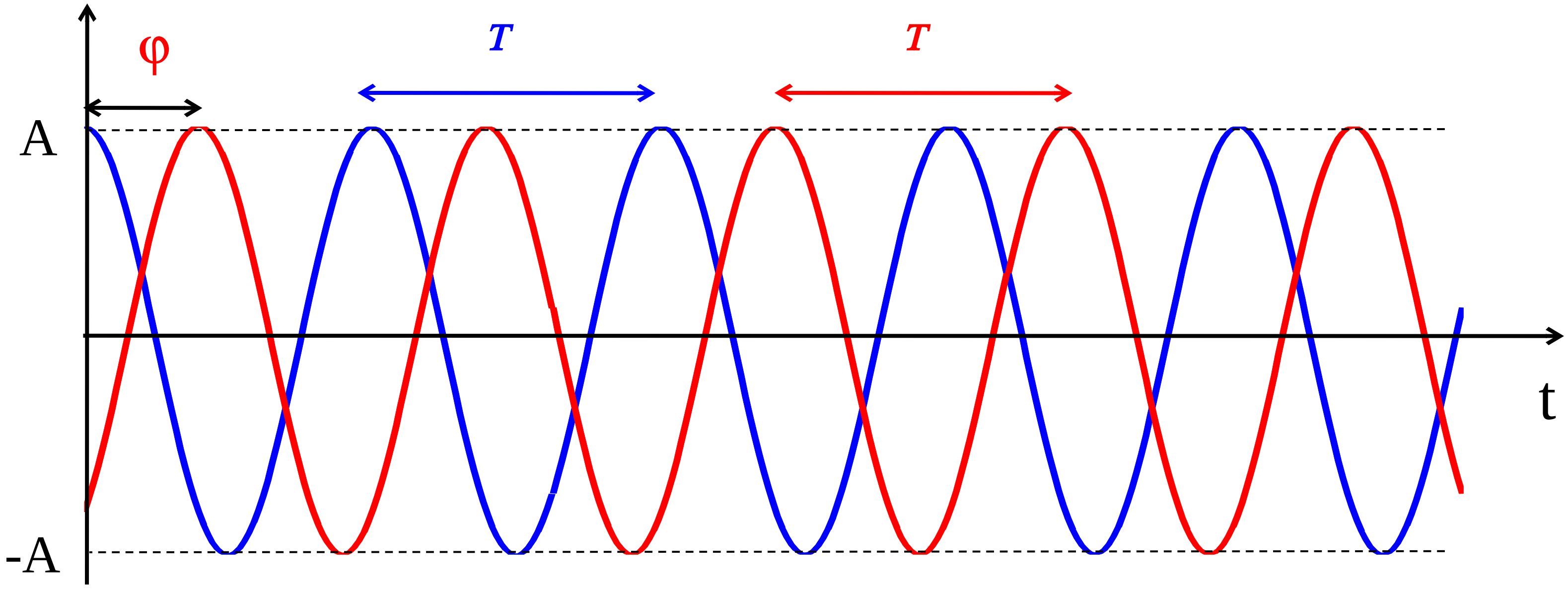


US Army

Road RADAR (© US police)

Imaging RADAR PALSAR (© NASDA)

Coherente wave: temporal behaviour



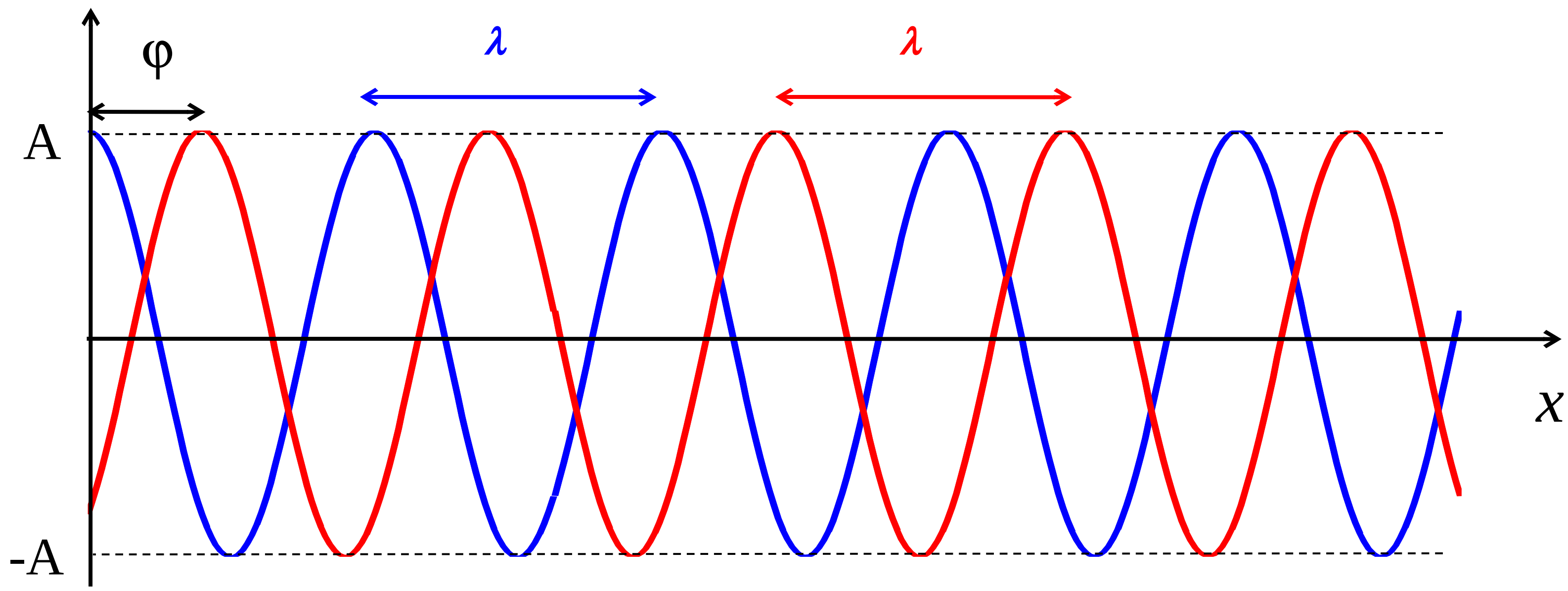
$$y(t) = A\cos\left(\frac{2\pi}{T}t\right)$$

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

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

A: amplitude
T: Temporal period
φ: dephasage

Coherent wave: spatial behabiour



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

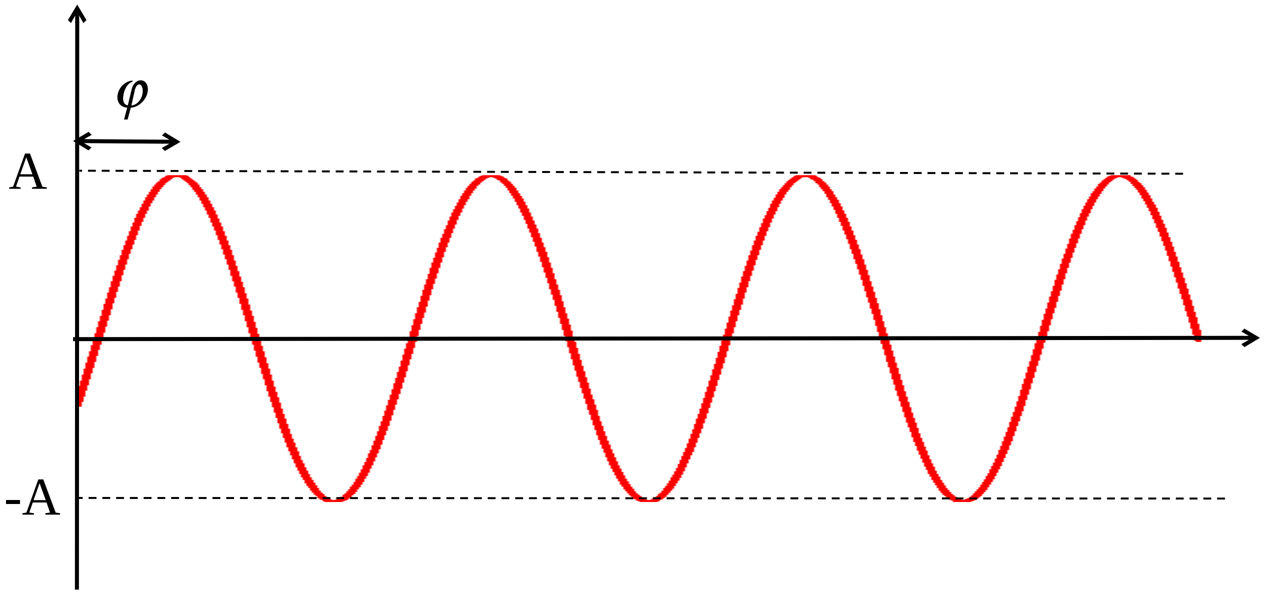
$$\lambda = cT = \frac{c}{f_0}$$

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

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

Coherent wave

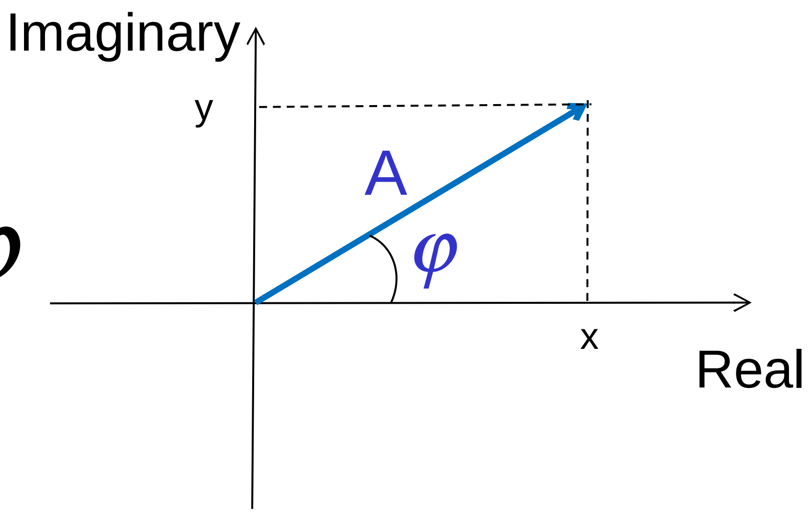
$$y = A\cos\left(\frac{2\pi}{T}t + \frac{2\pi}{\lambda}x + \varphi\right)$$



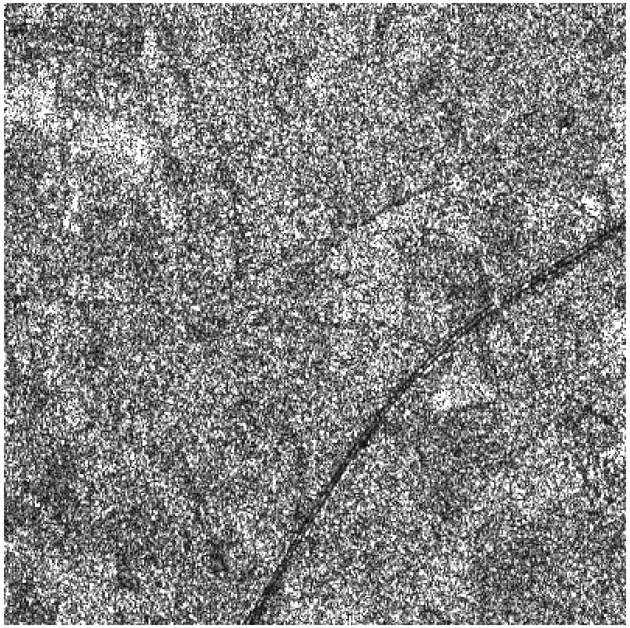
$$\lambda = cT = \frac{c}{f_0}$$

For given frequency f_0 (or λ)

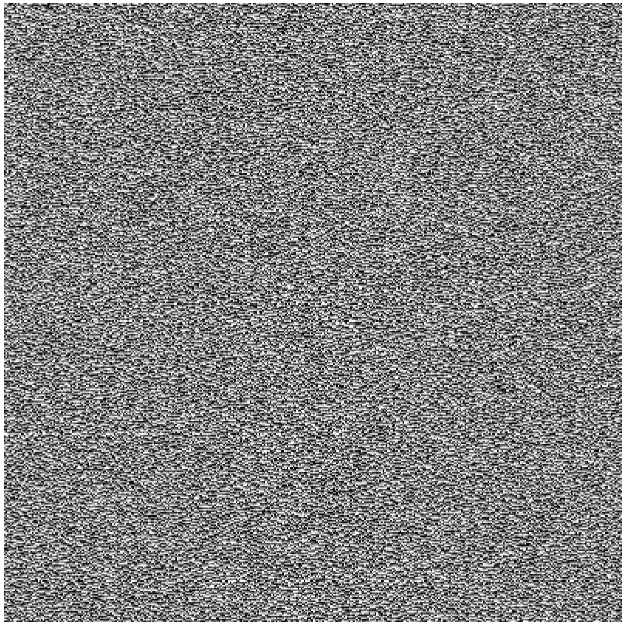
characterized by A and φ



RADAR DATA = COMPLEX DATA



Amplitude image

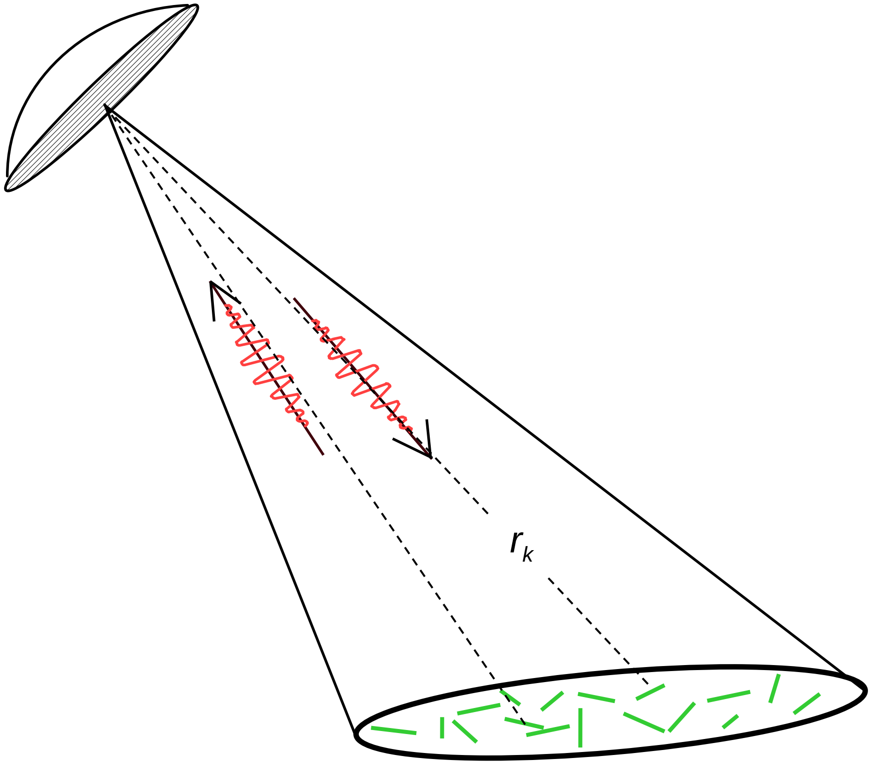


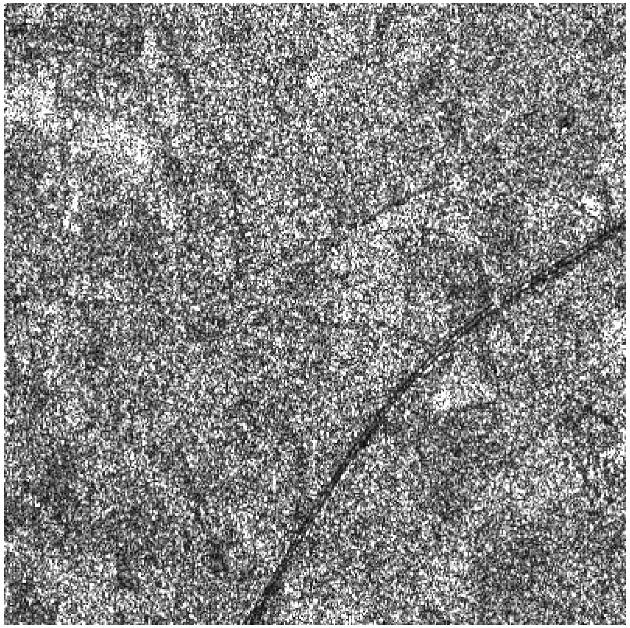
Phase image

RADARSAT - Fine 1
SLC product

Speckle Origin

Coherent Wave $E_0 \cos(\omega_O t - kr + \psi)$





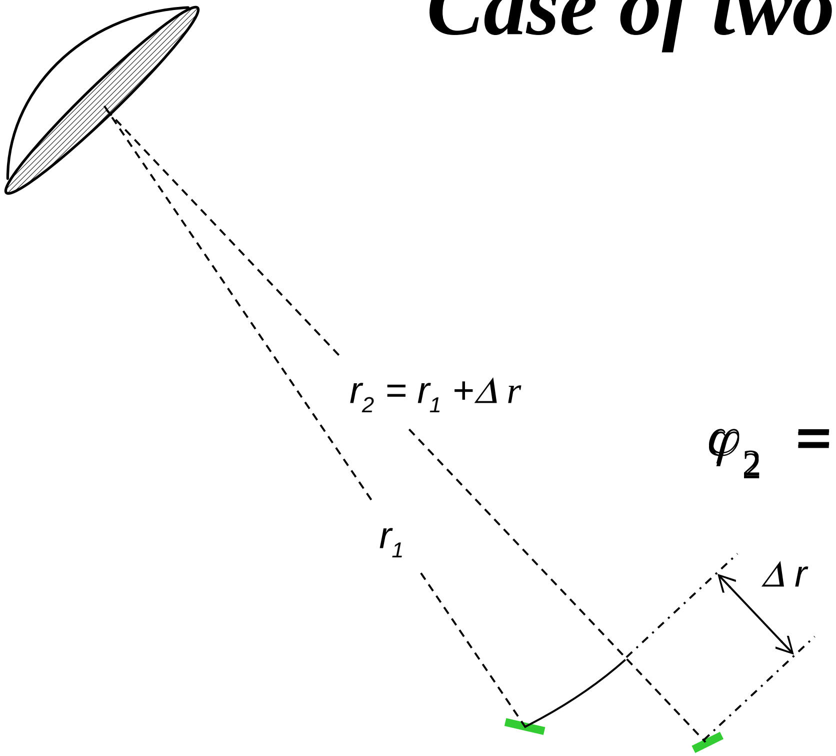
Homogeneous scene :

N elementary scatterers a_k, φ_k

randomly oriented

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

Case of two scattererers



$$A\cos(\omega_o t - \varphi_1)$$

$$A\cos(\omega_o t - \varphi_2)$$

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

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

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

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

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

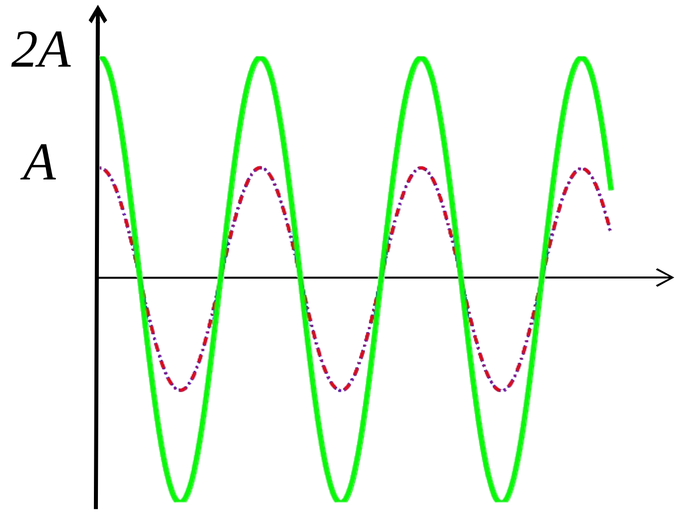
$$\Delta r = \frac{3\lambda}{8} \Rightarrow \frac{4\pi}{\lambda}\Delta r = \frac{3\pi}{2} \quad \text{et} \quad \varphi_2 = \varphi_1 + \frac{3\pi}{2}$$

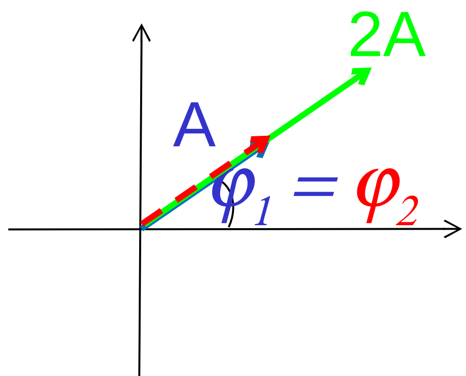
2 coherent waves sum

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

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

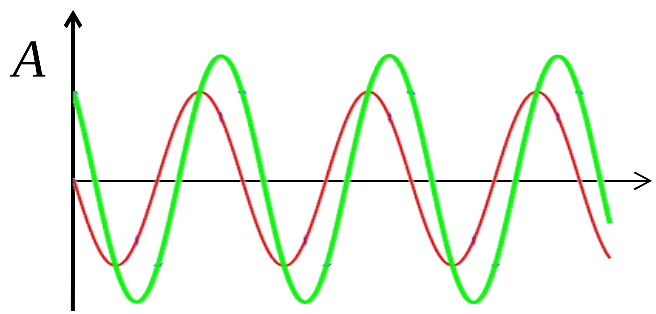
$$\varphi_2 = \varphi_1 + 2\pi$$

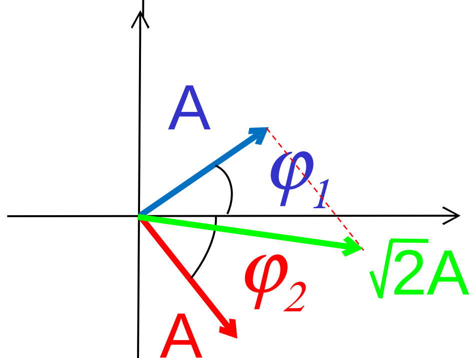




$$r_2 = r_1 + \frac{3\lambda}{8}$$

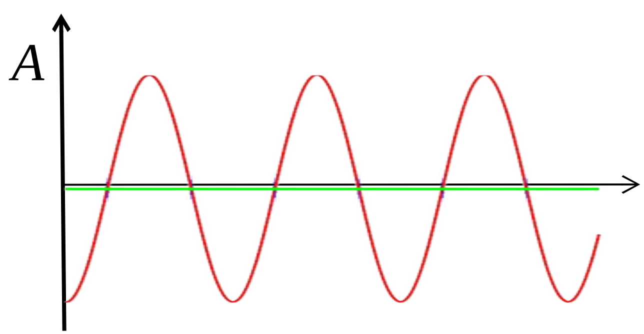
$$\varphi_2 = \varphi_1 + \frac{3\pi}{2}$$

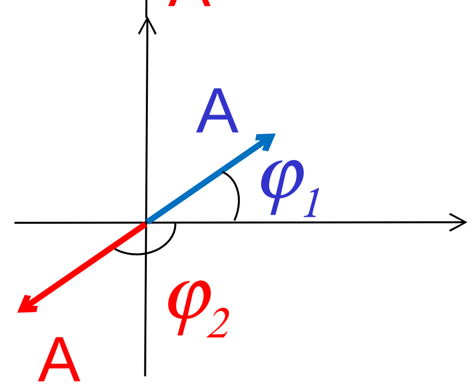




$$r_2 = r_1 + \frac{\lambda}{4}$$

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





2 coherent waves sum

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

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

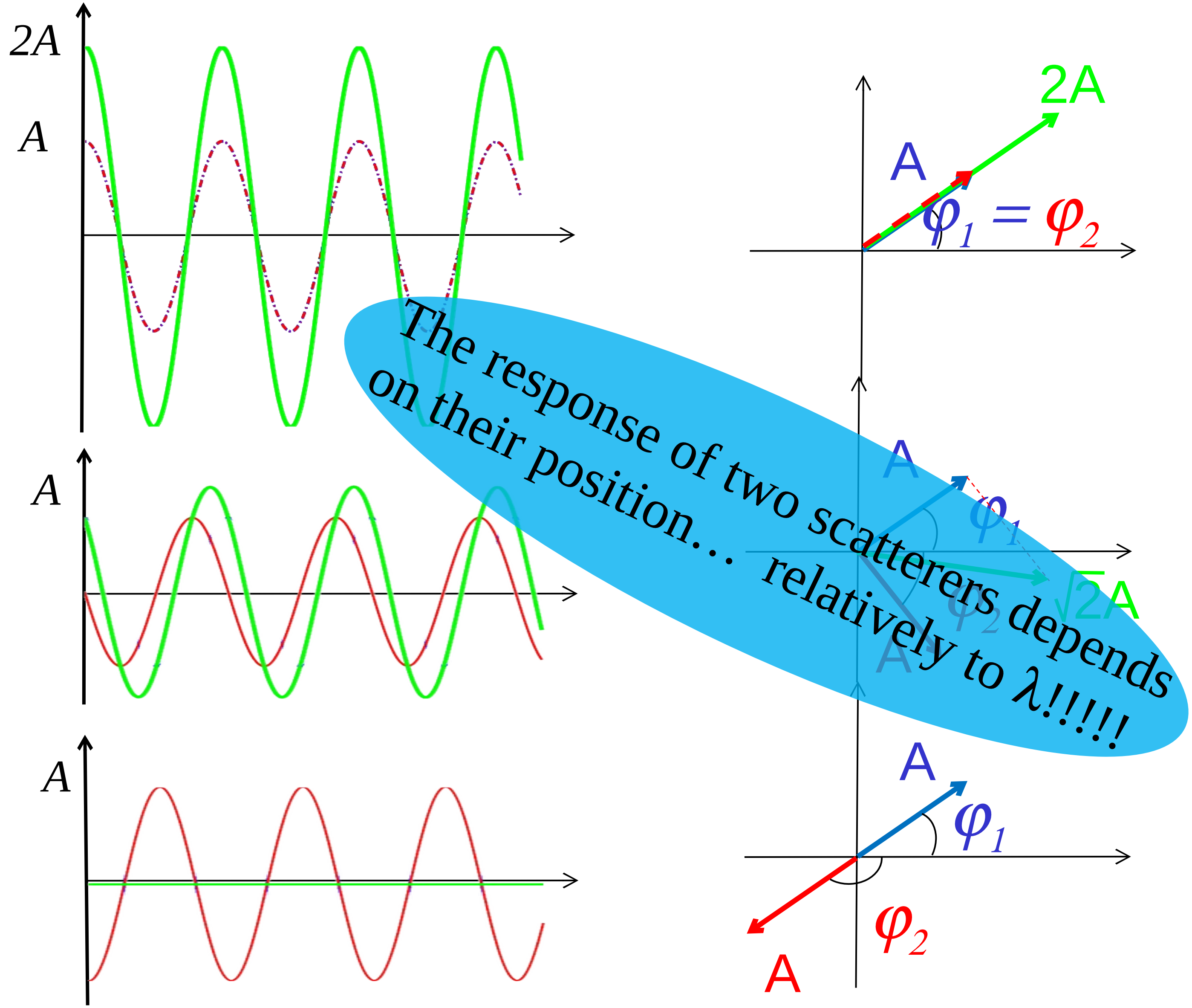
$$\varphi_2 = \varphi_1 + 2\pi$$

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

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

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

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

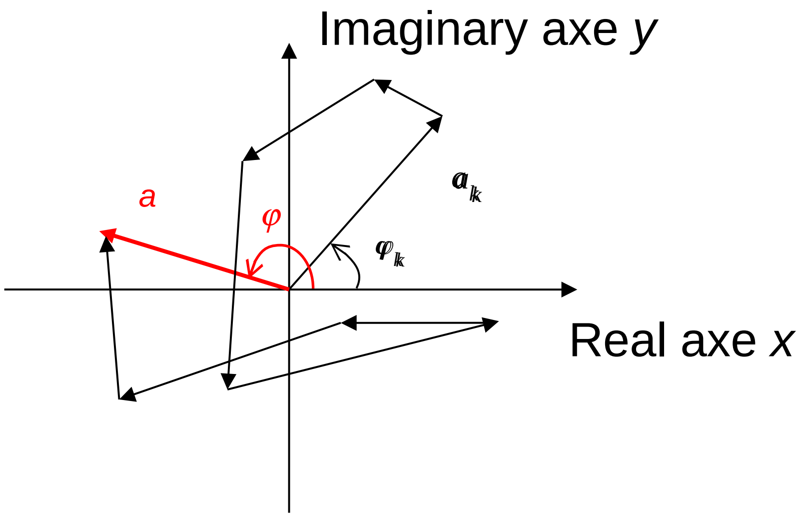


The response of two scatterers depends on their position… relatively to λ!!!!!

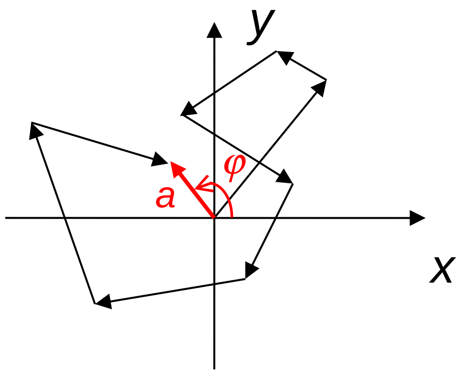
Ideal Radar reflectivity image

Radar acquisition

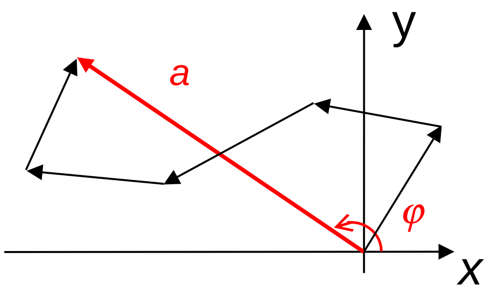
Speckle origin: coherent sum



$$z = \begin{cases} \sum_{k=1}^{N} a_k e^{j\varphi_k} = A e^{j\psi} \\ \sum_{k=1}^{N} x_k + j y_k = X + jY \end{cases}$$

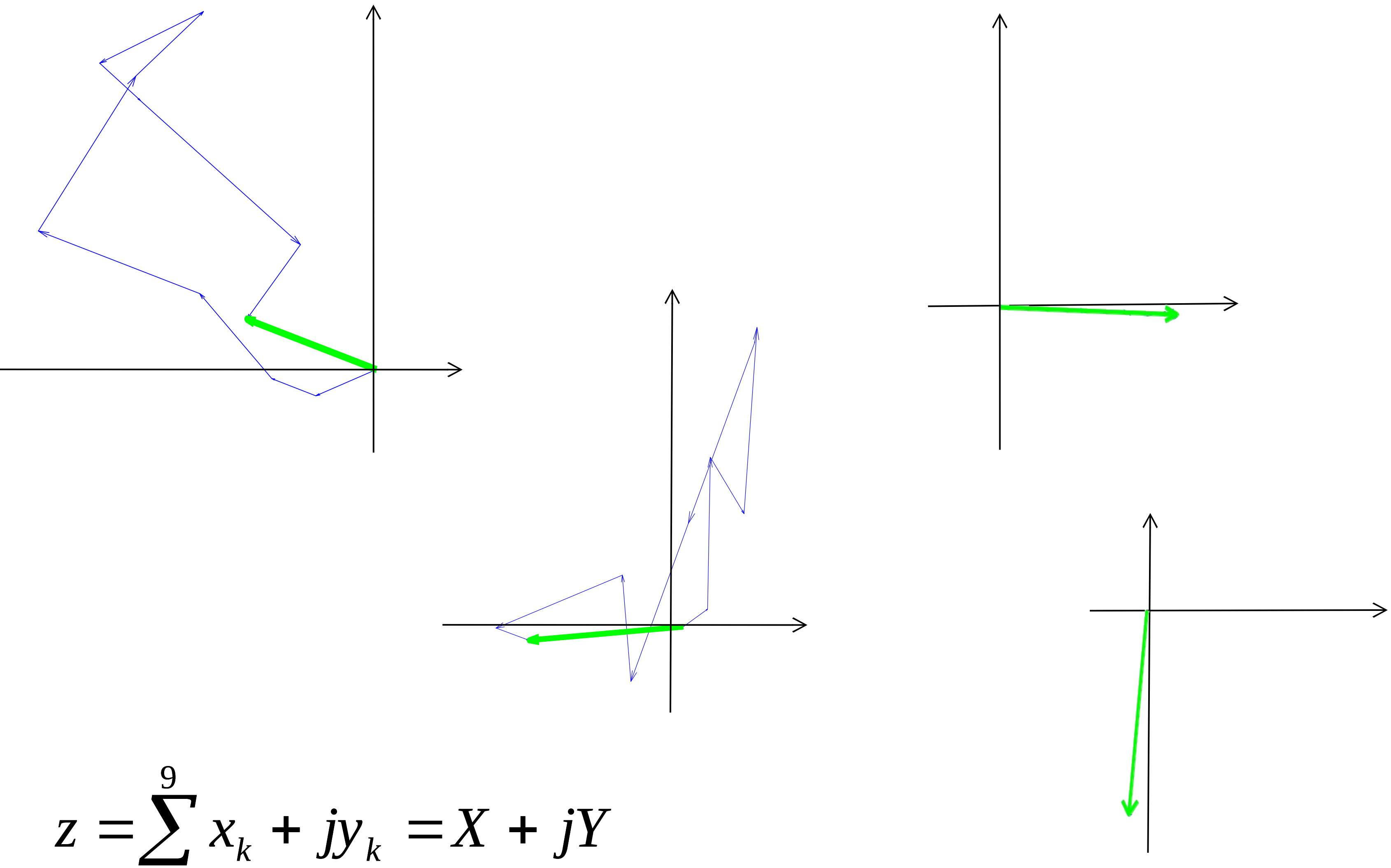


Destructive arrangement



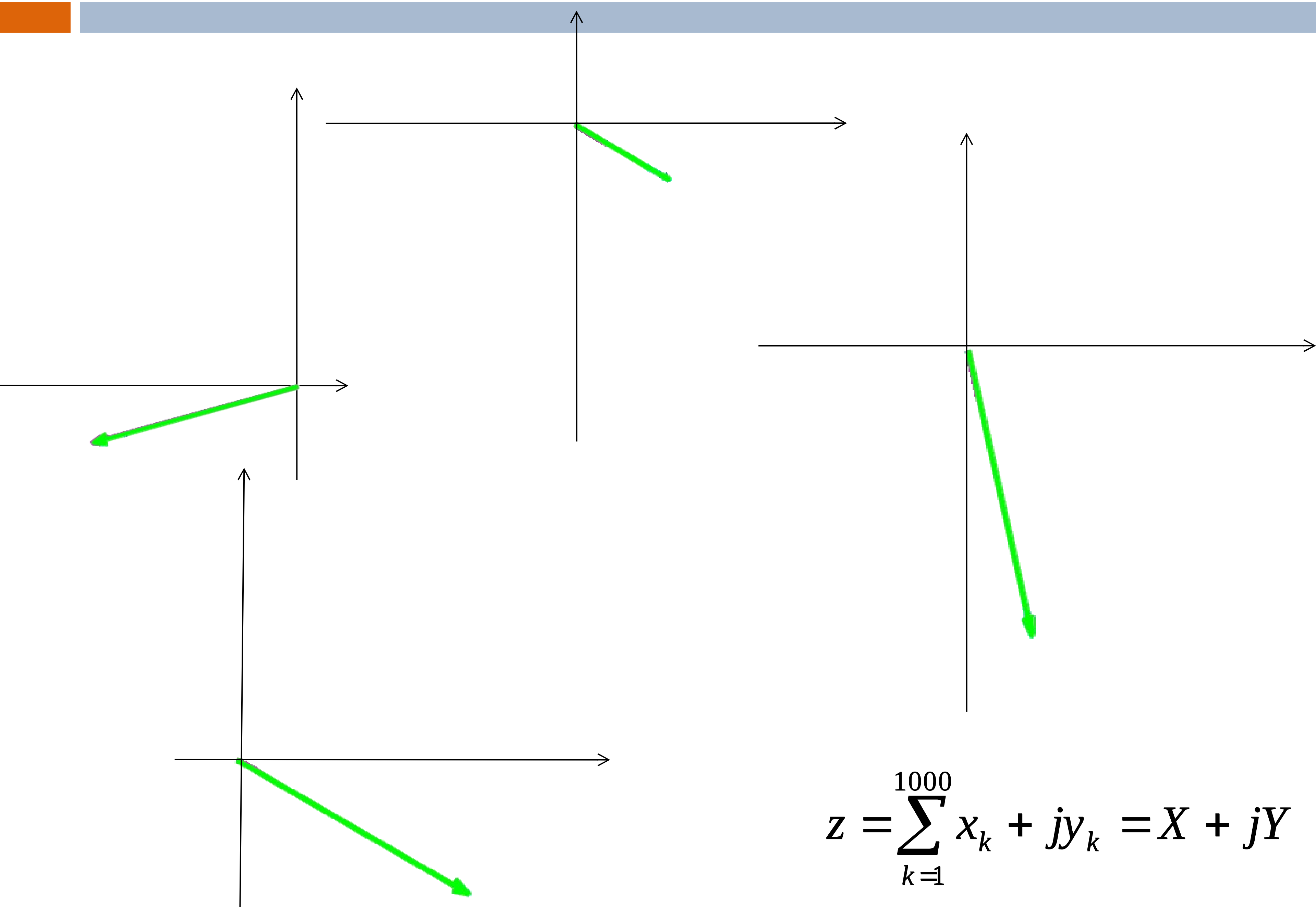
Constructive arrangement

Speckle origin: Coherent sum



$$z = \sum_{k=1}^{9} x_k + jy_k = X + jY$$

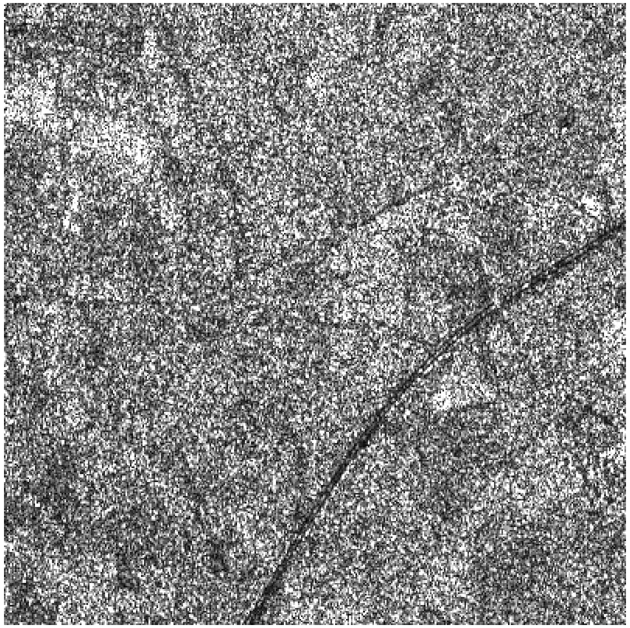
Coherent sum



$$z = \sum_{k=1}^{1000} x_k + j y_k = X + jY$$

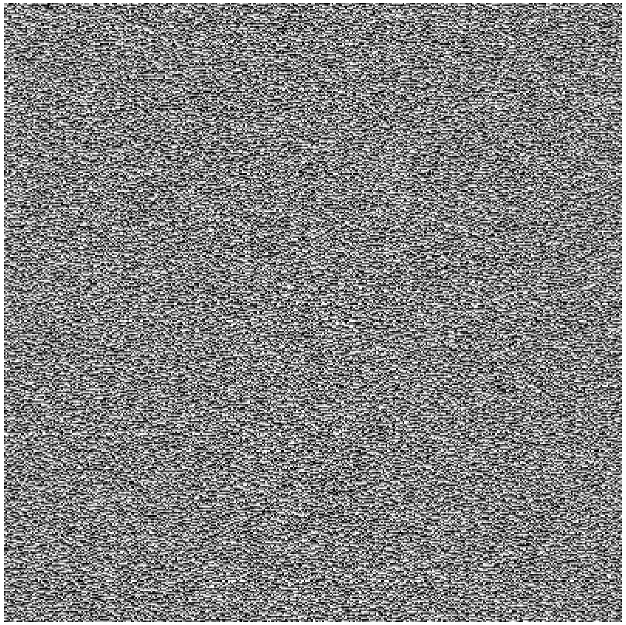
RADAR DATA = Amplitude + Phase DATA

A



Amplitude image

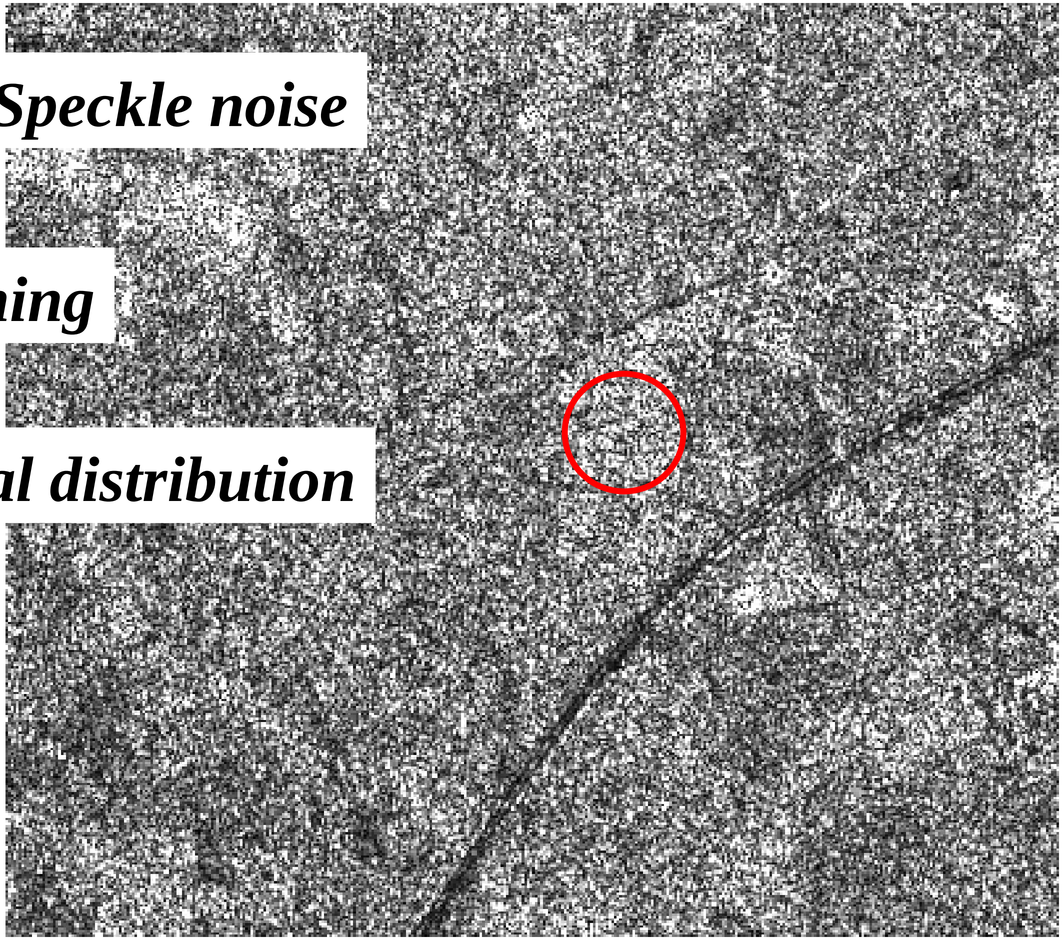
φ



Phase image

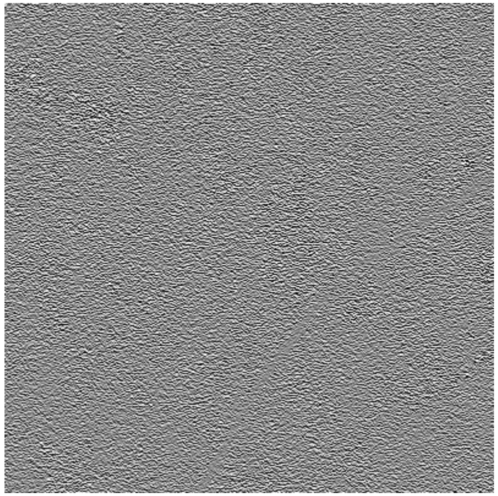
RADARSAT - Fine 1
SLC product

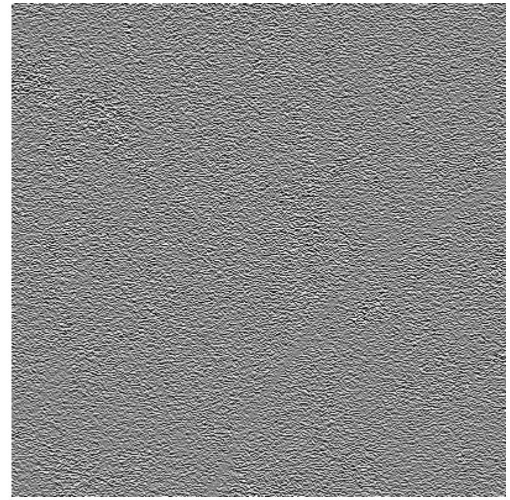
Coherent Imagery System ***Speckle noise***

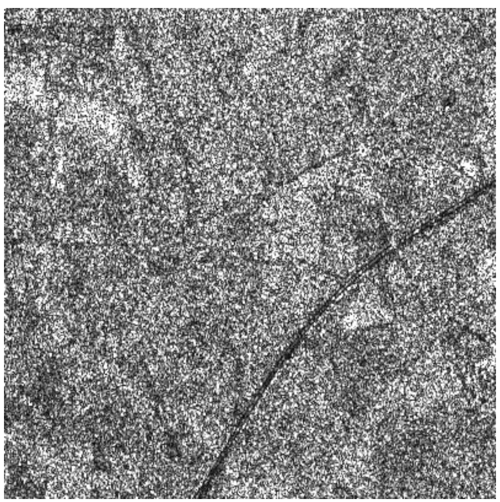


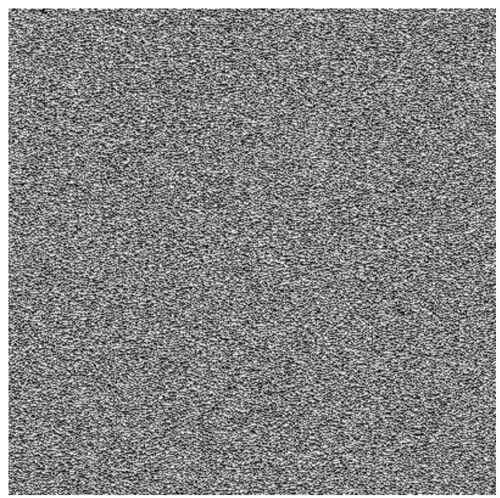
Single pixel value = no meaning

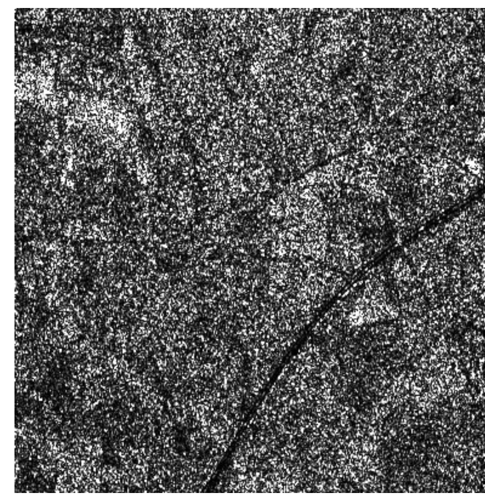
Homogeneous are = ***statistical distribution***


Real part


Imaginary part

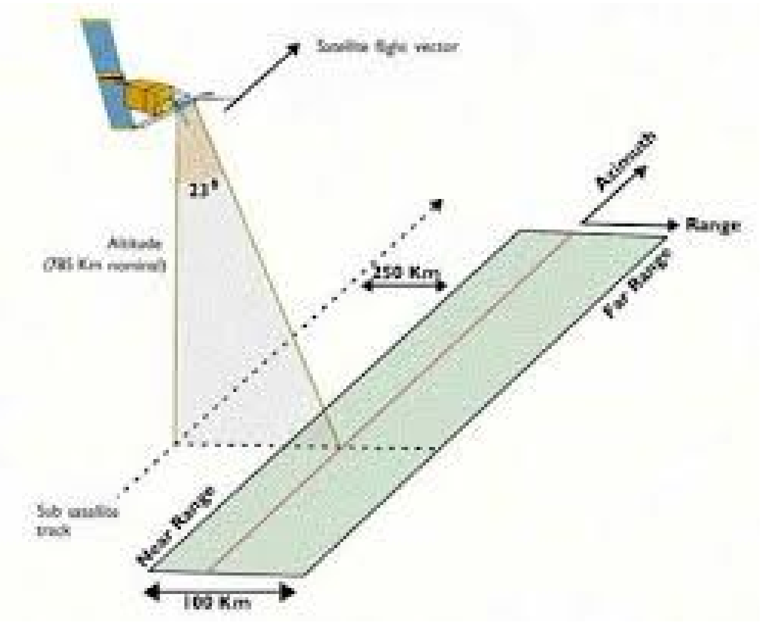

Amplitude


Phase


Intensity

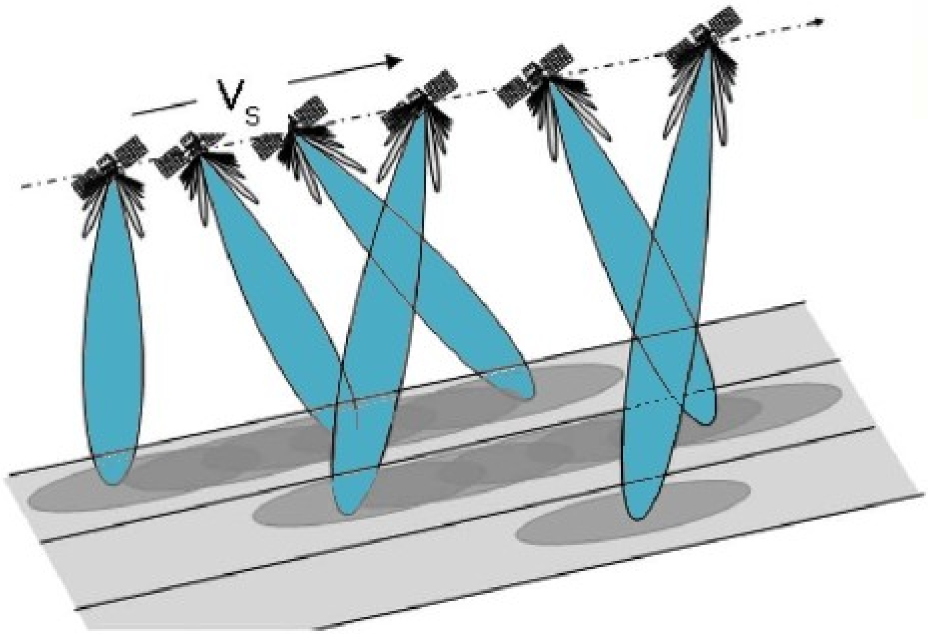
RADARSAT - Mode Fine 1 - SLC Product

SENTINEL-1 ACQUISITION MODES



STRIPMAP

INTERFEROMETRICWIDE (IW)

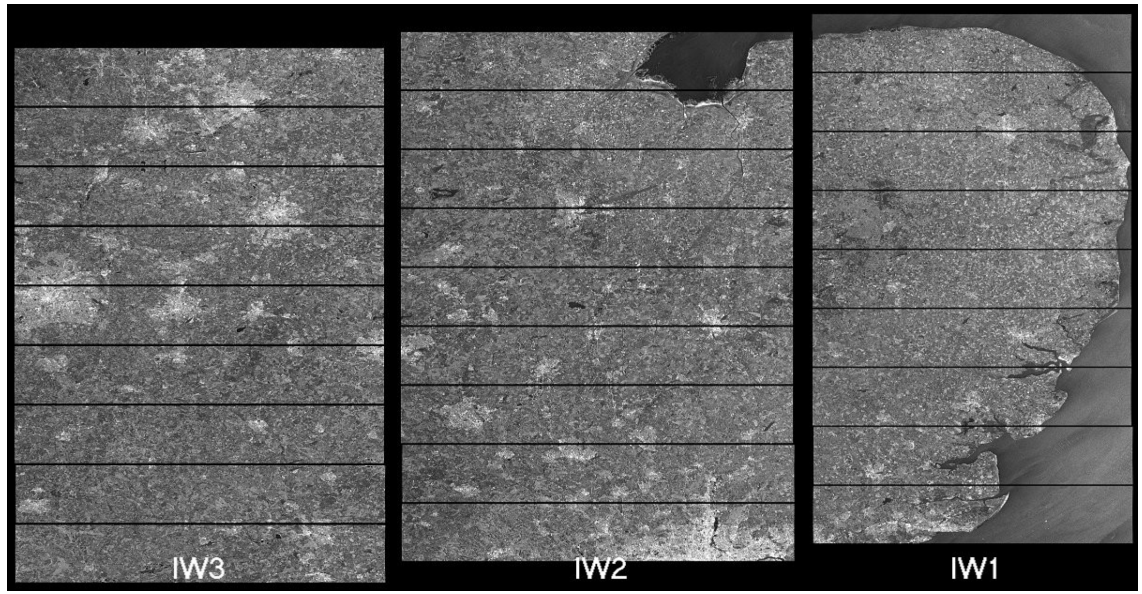


SENTINEL-1 INTERFEROMETRIC WIDE MODE

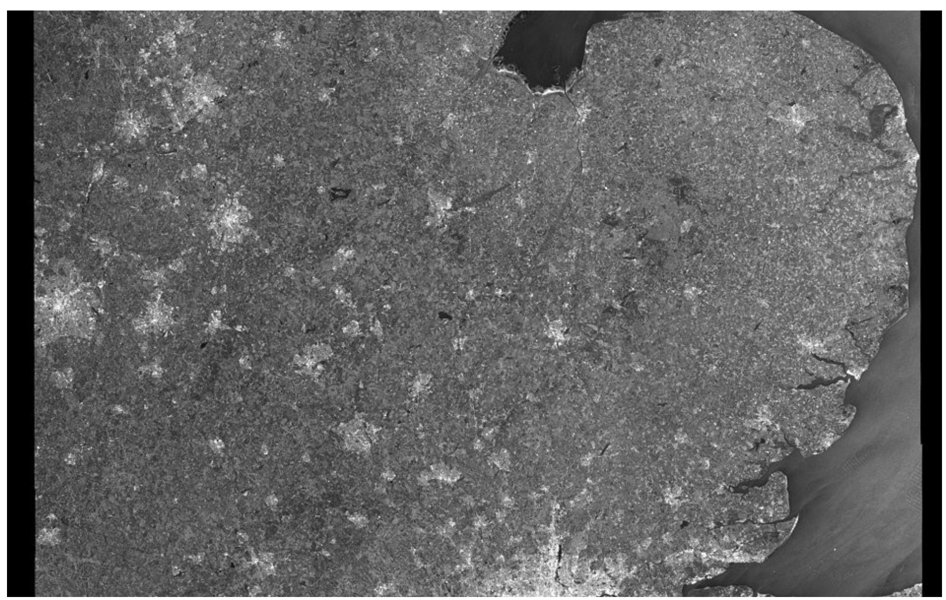
3 subswaths

SLC products

8 bursts

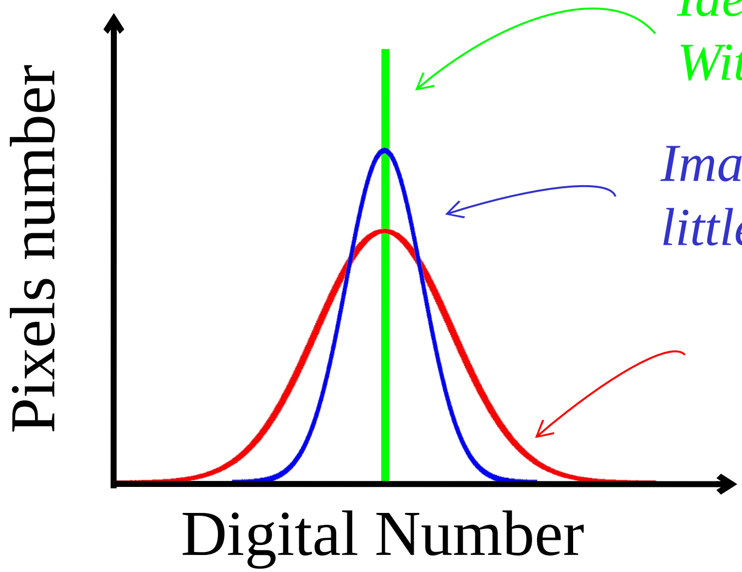


GRD products



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

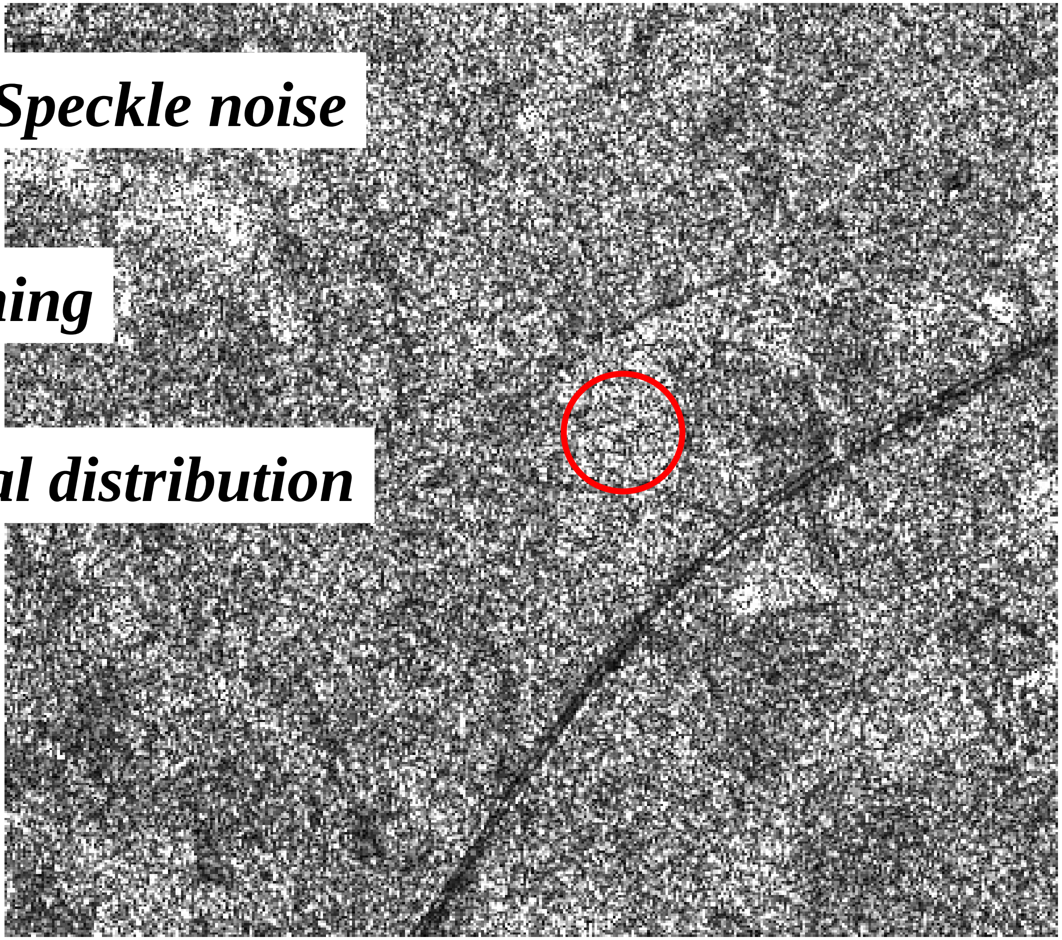
A distant vision allows to blur the pointillist effect
and to see the homogeneous areas

➔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***

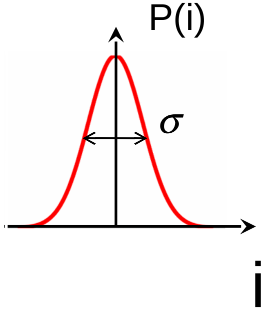


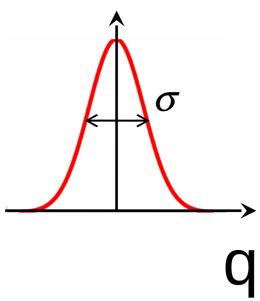
Speckle "*fully developped*" (Goodman hypothesis)

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

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

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

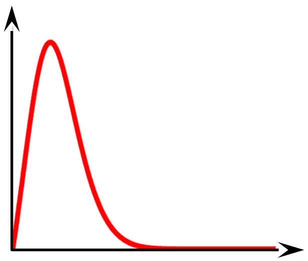
$$E(i^2)=E(q^2)=\sigma^2 = N\frac{E(a^2)}{2}$$

Homogeneous areas

Amplitude: *A*

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

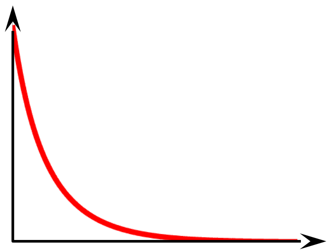
$$E(A) = \sigma\sqrt{\frac{\pi}{2}}, \quad E(A^2) = 2\sigma^2$$



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*

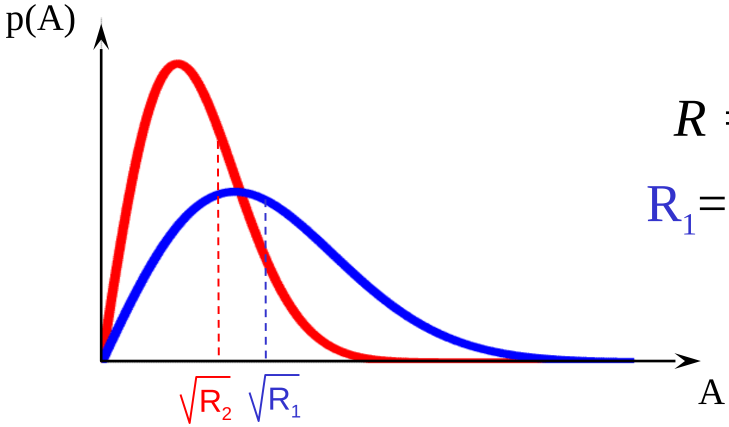
$$p_A(A/\sigma) = \frac{A}{\sigma^2}\exp\left(\frac{-A^2}{2\sigma^2}\right)$$

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

Intensity: *I*

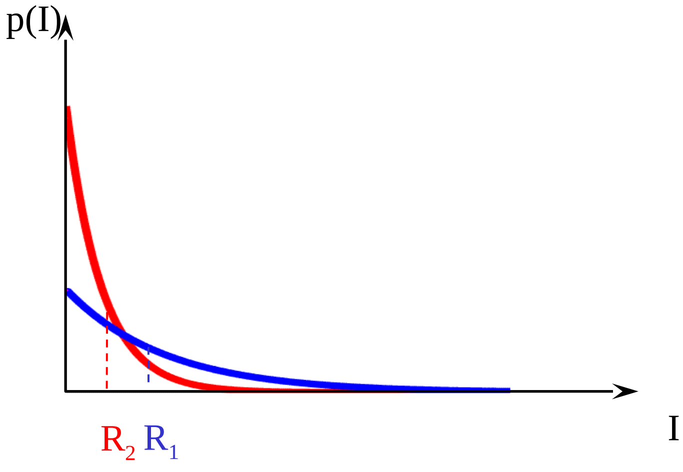
$$p_I(I/\sigma) = \frac{1}{2\sigma^2}\exp\left(\frac{-I}{2\sigma^2}\right)$$

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



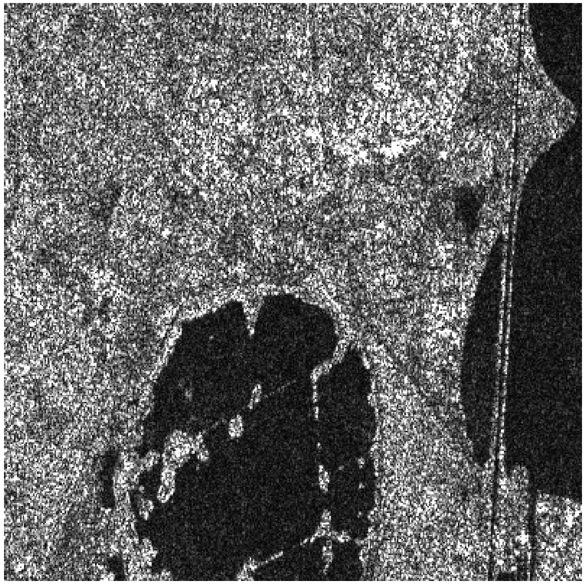
$R = 2\sigma^2$

$R_1 = 2 * R_2$



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

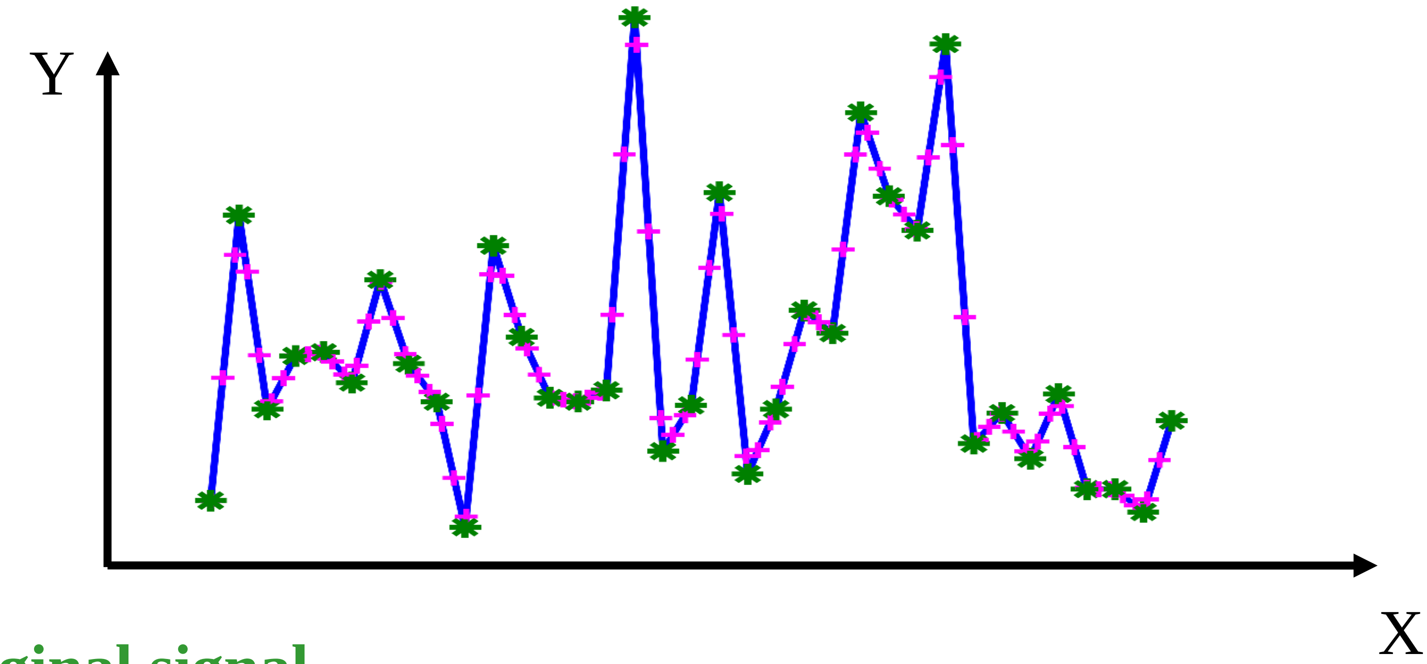
$$y = \frac{1}{N}(x_1 + x_2 + ... + x_N) \Rightarrow \begin{cases} \mathrm{var}(y) = \frac{\mathrm{var}(x)}{N} \\ E(y) = E(x) \end{cases}$$

Look number: N

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

$$\Rightarrow N = \begin{cases} \left(\frac{1}{C_{ML}}\right)^2 & \textit{Intensity data} \\ \left(\frac{0.5227}{C_{ML}}\right)^2 & \textit{Amplitude data} \end{cases}$$

Signal Processing principles



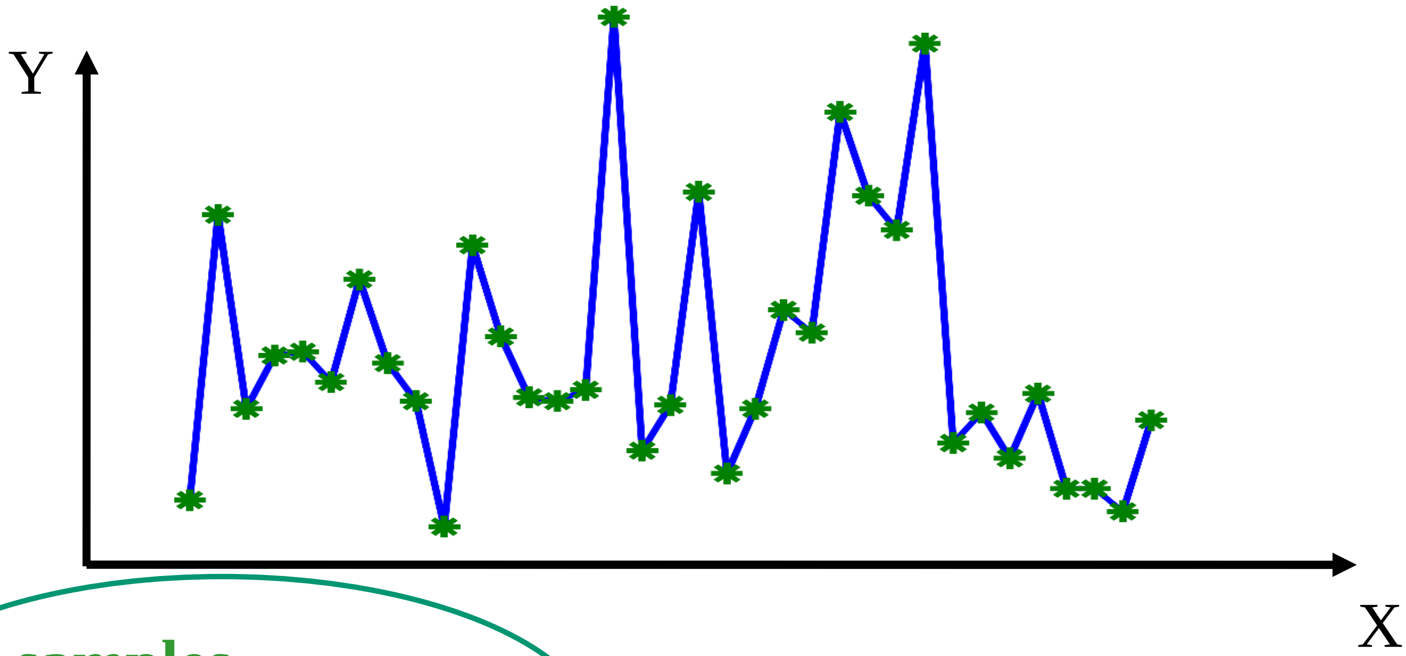
Original signal

34 samples
34 indep[t] measurements

Resampled signal

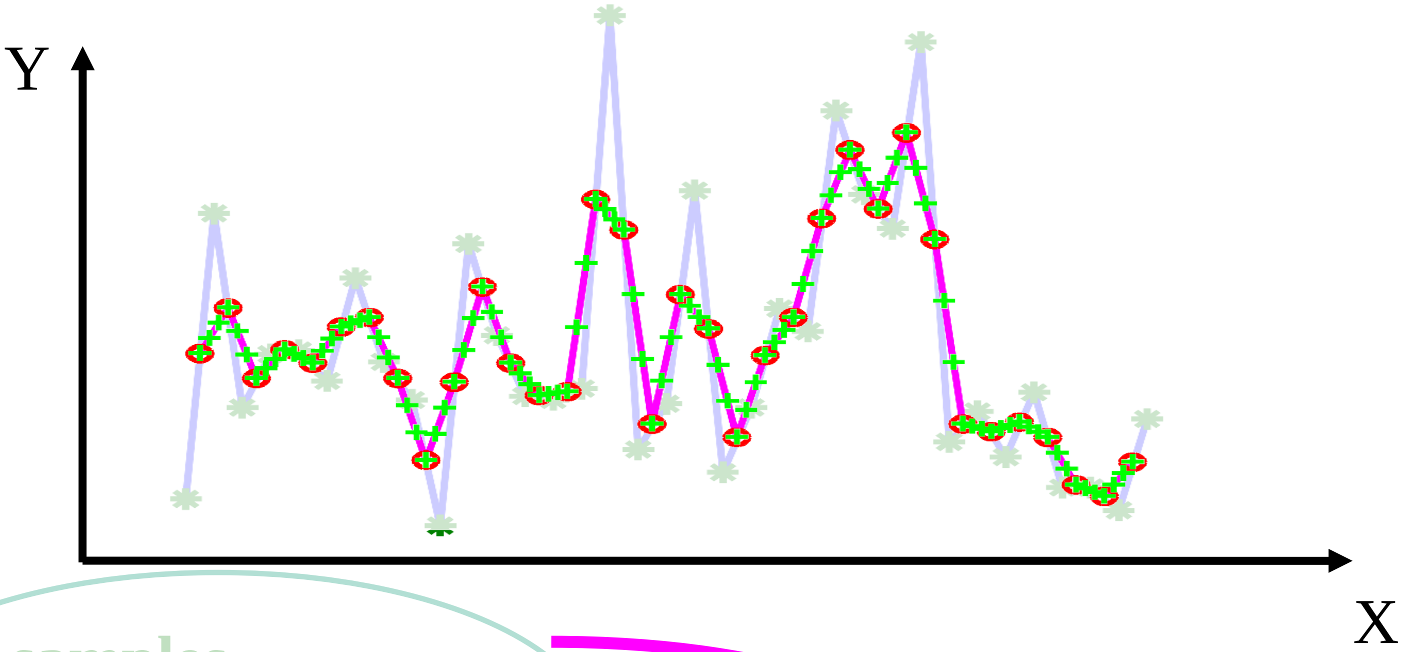
78 points (linear interpolation)
still 3**4 independant samples**
Same information

Signal Processing principles



34 samples
34 indep^t measurements
1 look **signal**

Signal Processing principles

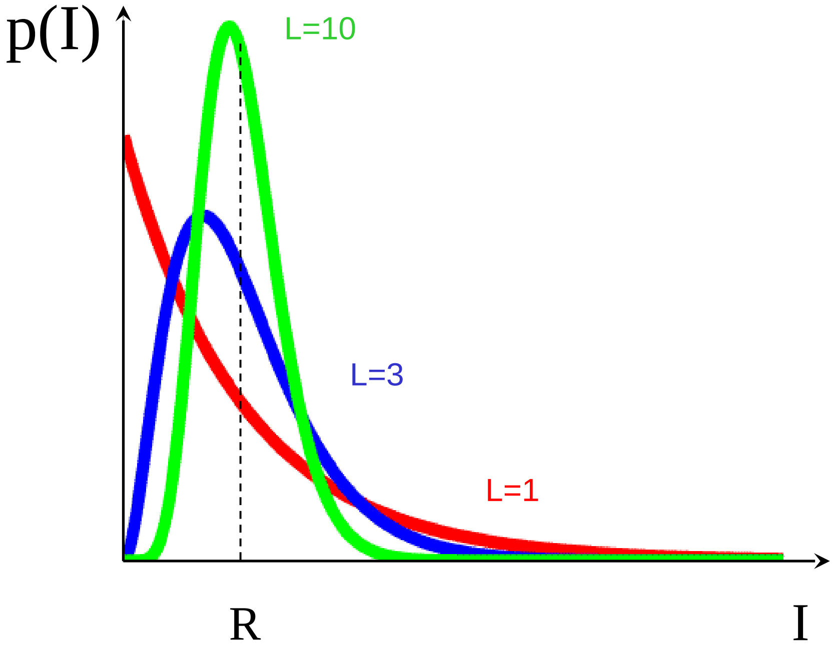


34 samples
34 indep^{t} measurements
1 look serie

33 points
2 samples 1 new sample
==> **2-looks signal**

linear resampling
2-looks signal
No additional information

multilook data



$$I_{ml} = \frac{1}{L}\sum_{k=1}^{L} I_k$$

$$p(I_{ml}/R) = \left(\frac{L}{R}\right)^{L} \frac{1}{\Gamma(L)} \exp\left(-\frac{L I_{ml}}{R}\right) I_{ml}^{L-1}$$

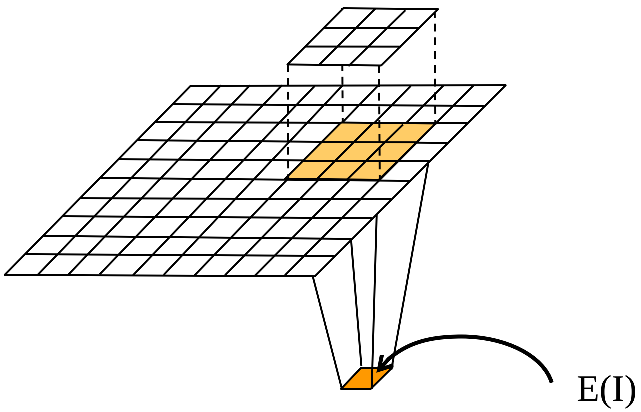
$$E(I_{ml}) = R, \quad E\left(I_{ml}^{\ 2}\right) = \frac{L+1}{L} R^2$$

$$C_{v_{I_{ml}}} = \frac{C_{v_I}}{\sqrt{L}}$$

MULTILOOK OBTENTION

in spatial domain

*Sliding window: image * window*

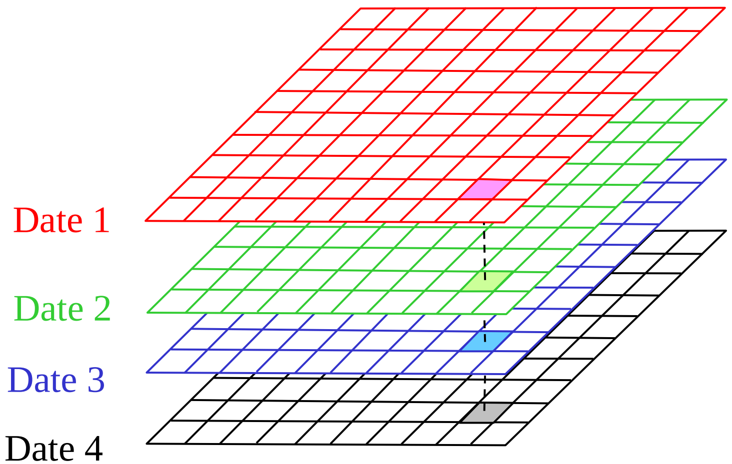


9 looks if pixel sare not correlated

Example: ERS data - PRI products : ⁂ 3 looks

Loss of spatial resolution

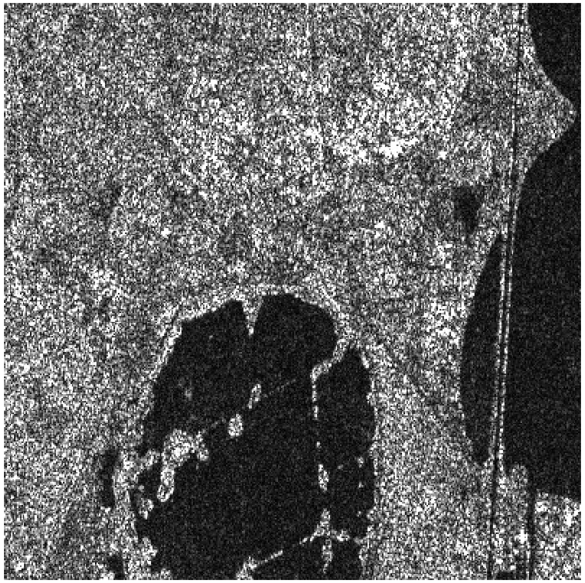
in temporal domain



4 looks if surface
has not changed

Preservation of spatial res.
Loss temporal information

Speckle: multiplicative noise



RADARSAT - Mode Fine 1

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

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

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

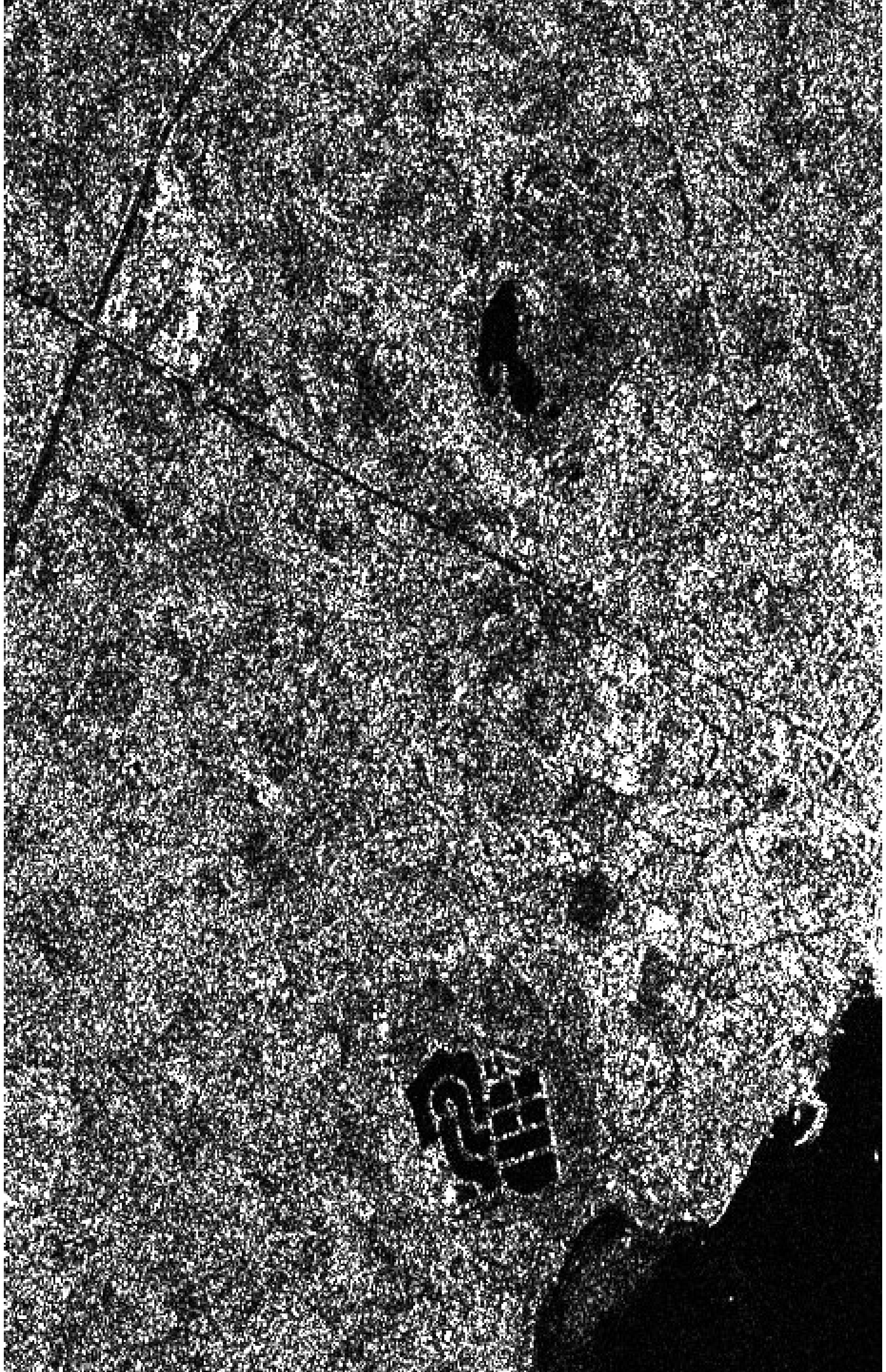
$$y = \frac{1}{N}\left(x_1 + x_2 + \dots + x_N\right) \Rightarrow \begin{cases} \mathrm{var}(y) = \dfrac{\mathrm{var}(x)}{N} \\ E(y) = E(x) \end{cases}$$

==> multilook data

Look number: ***N***

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

$$\Rightarrow N = \begin{cases} \left(\dfrac{1}{C_{ML}}\right)^2 & \textit{Intensity data} \\ \left(\dfrac{0.5227}{C_{ML}}\right)^2 & \textit{Amplitude data} \end{cases}$$

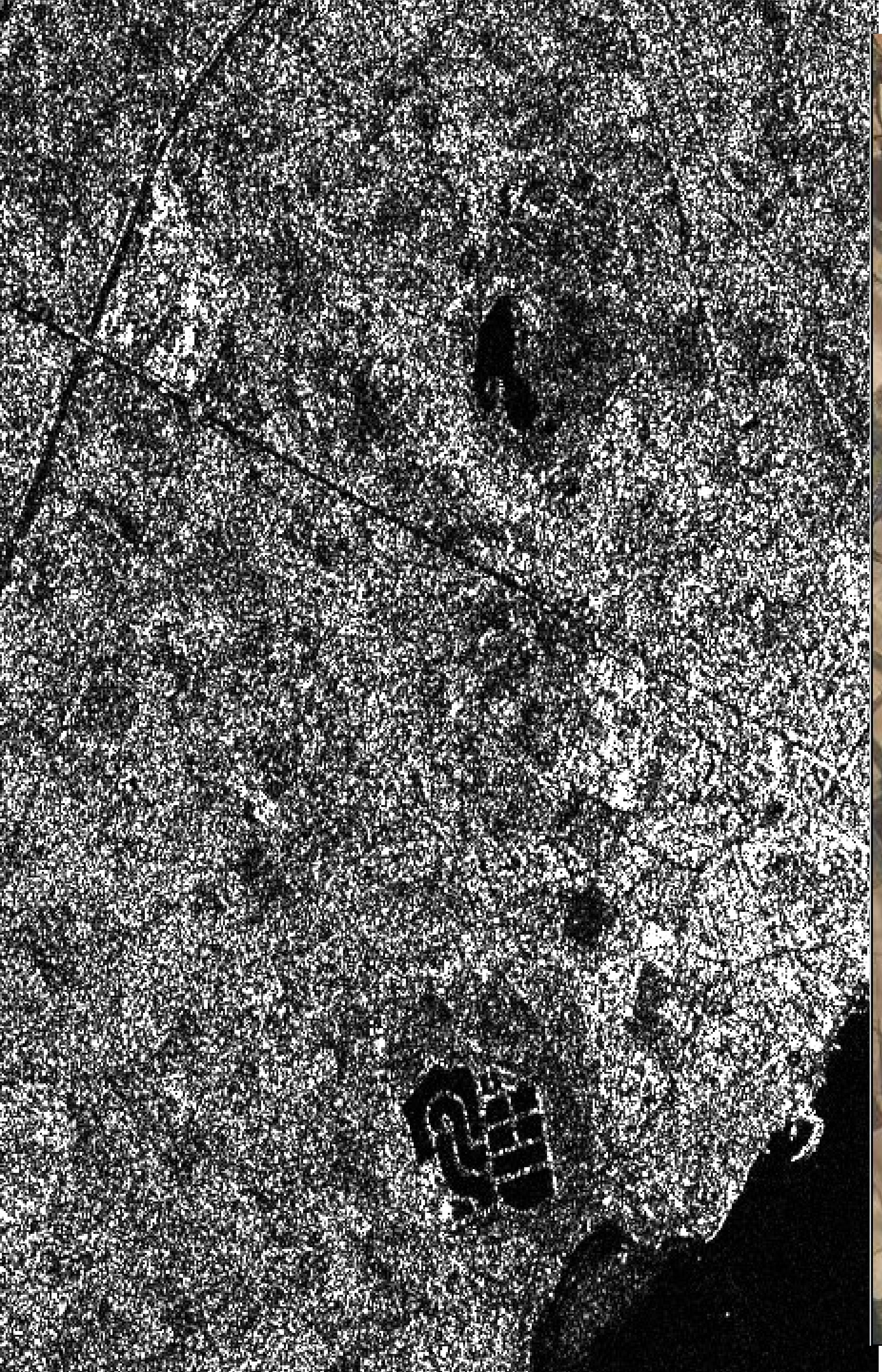


Intensity image

(from SLC product)

Sète - France: 21.06.2001

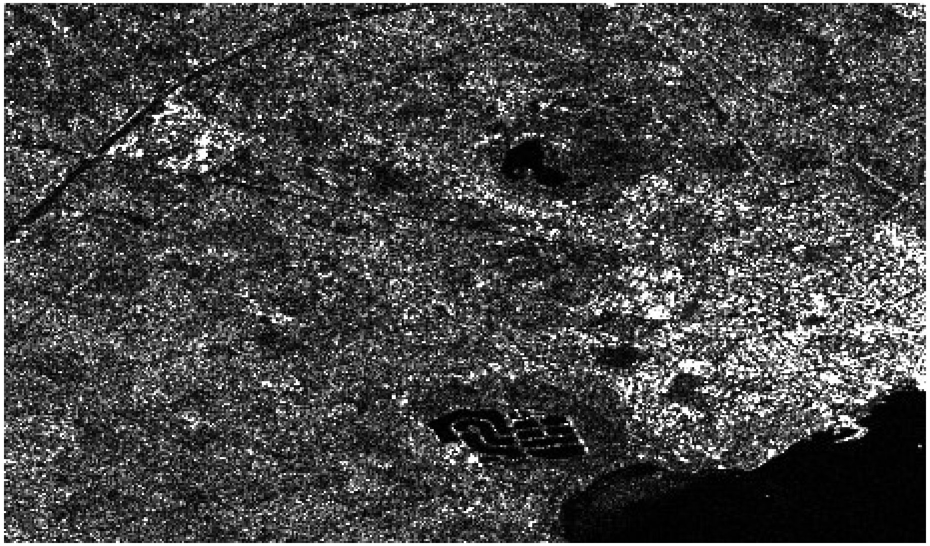
RADARSAT - FINE 1
INCIDENCE 38°, 4 x9 m

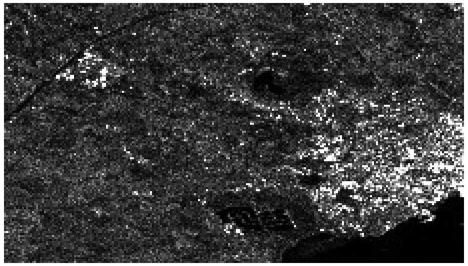



Spatial Multilook (=average) Processing

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

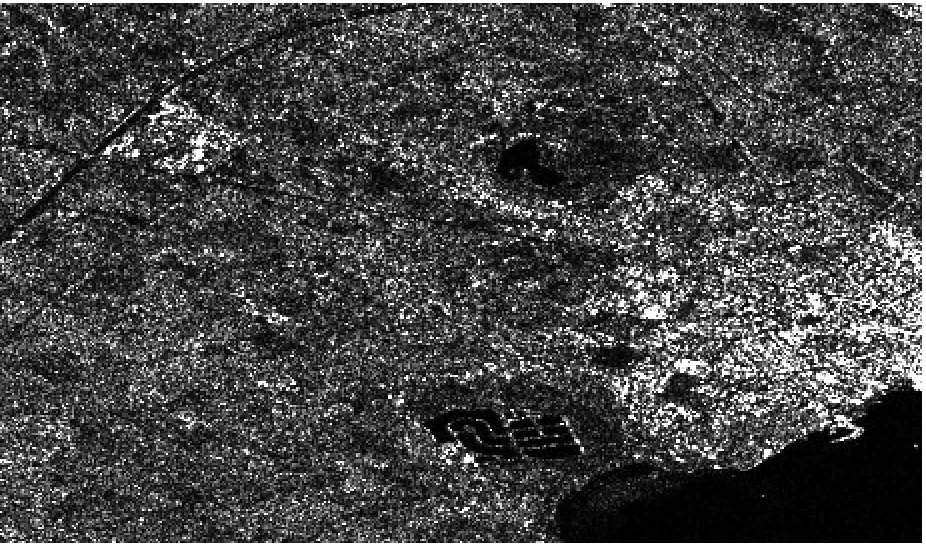
3x1 average window

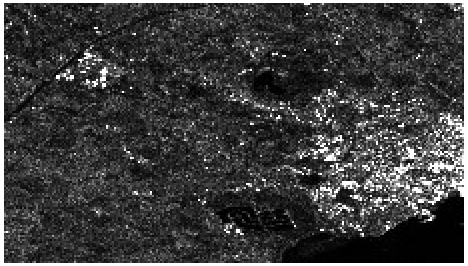
6x2 average window

< 3 Look

Due to pixels correlation!

< 12 Look





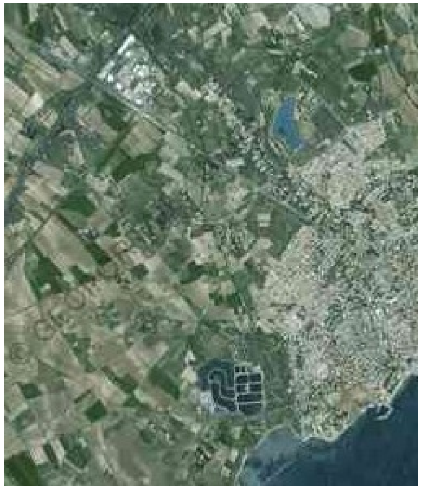
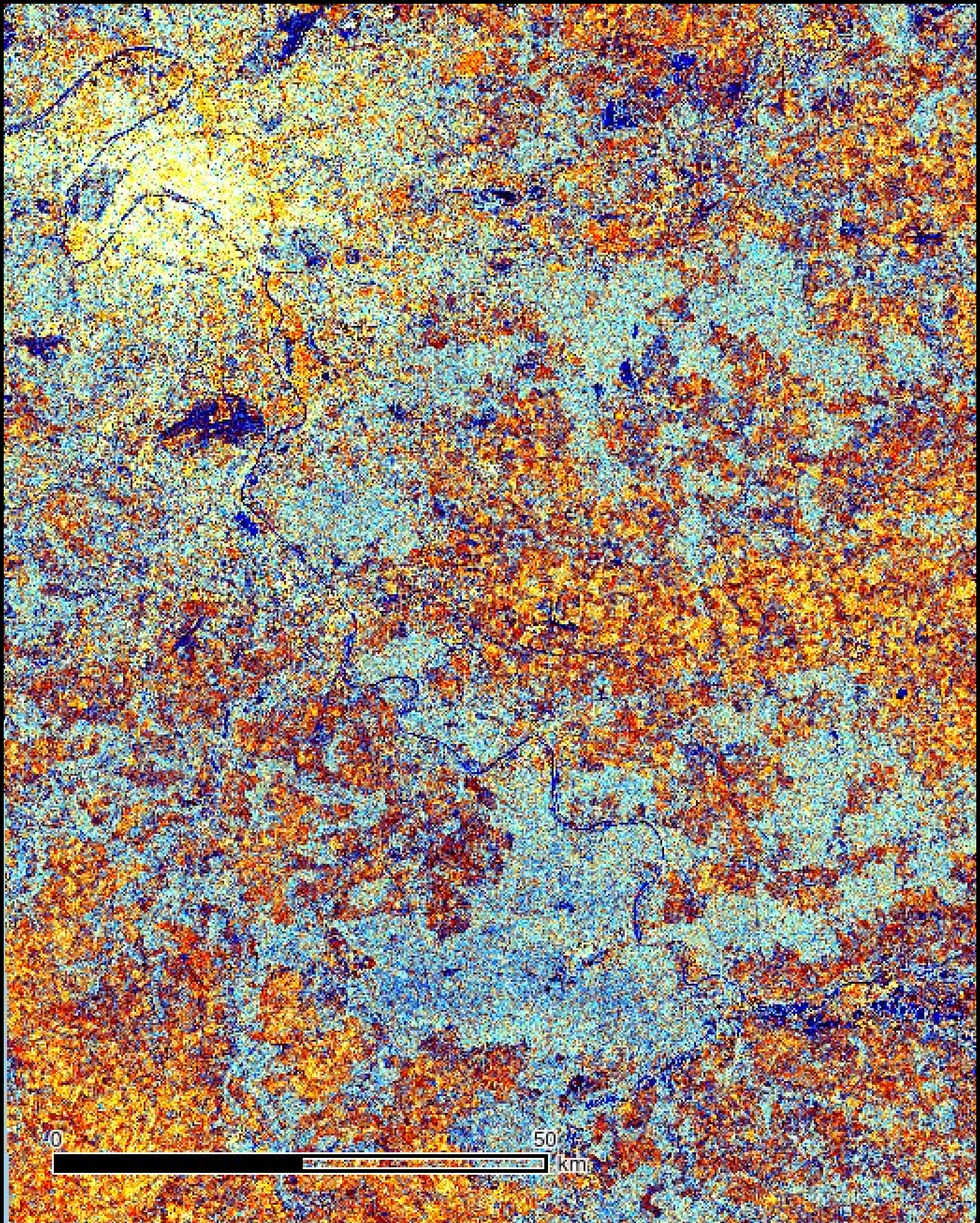


Photo aérienne (www.géoportail.fr)

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

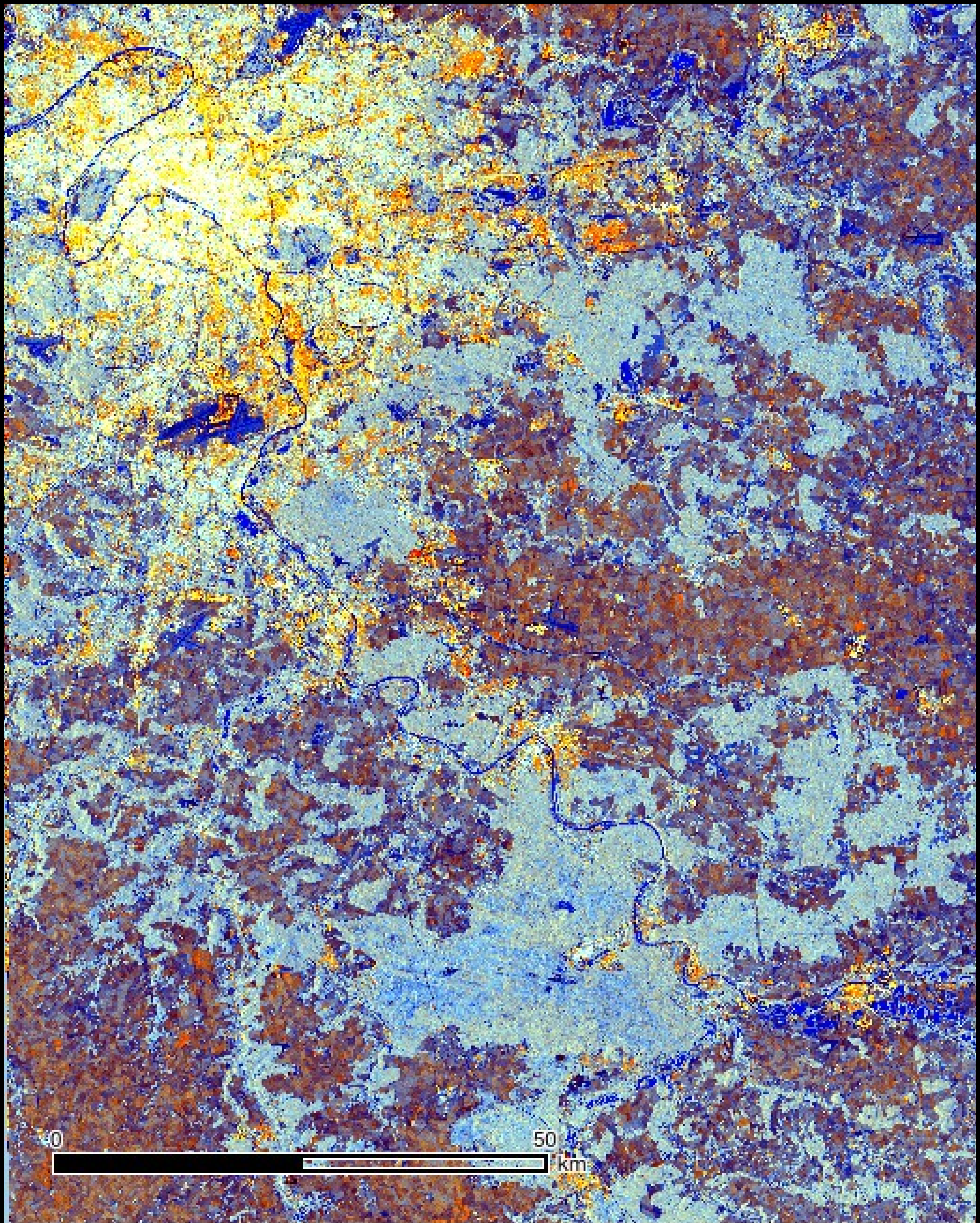
Parisian region



VV
VH
VH/VV

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

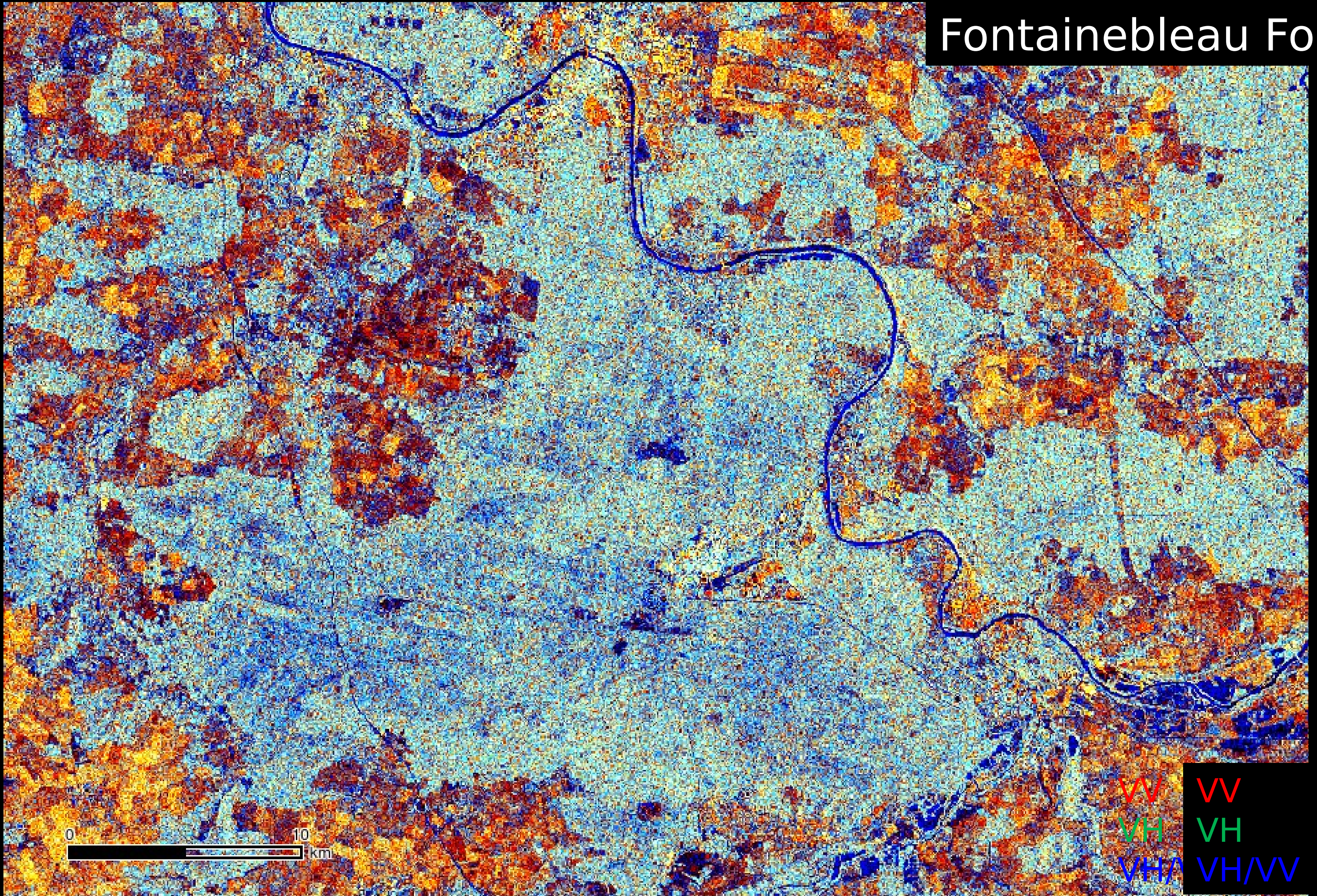
Parisian region



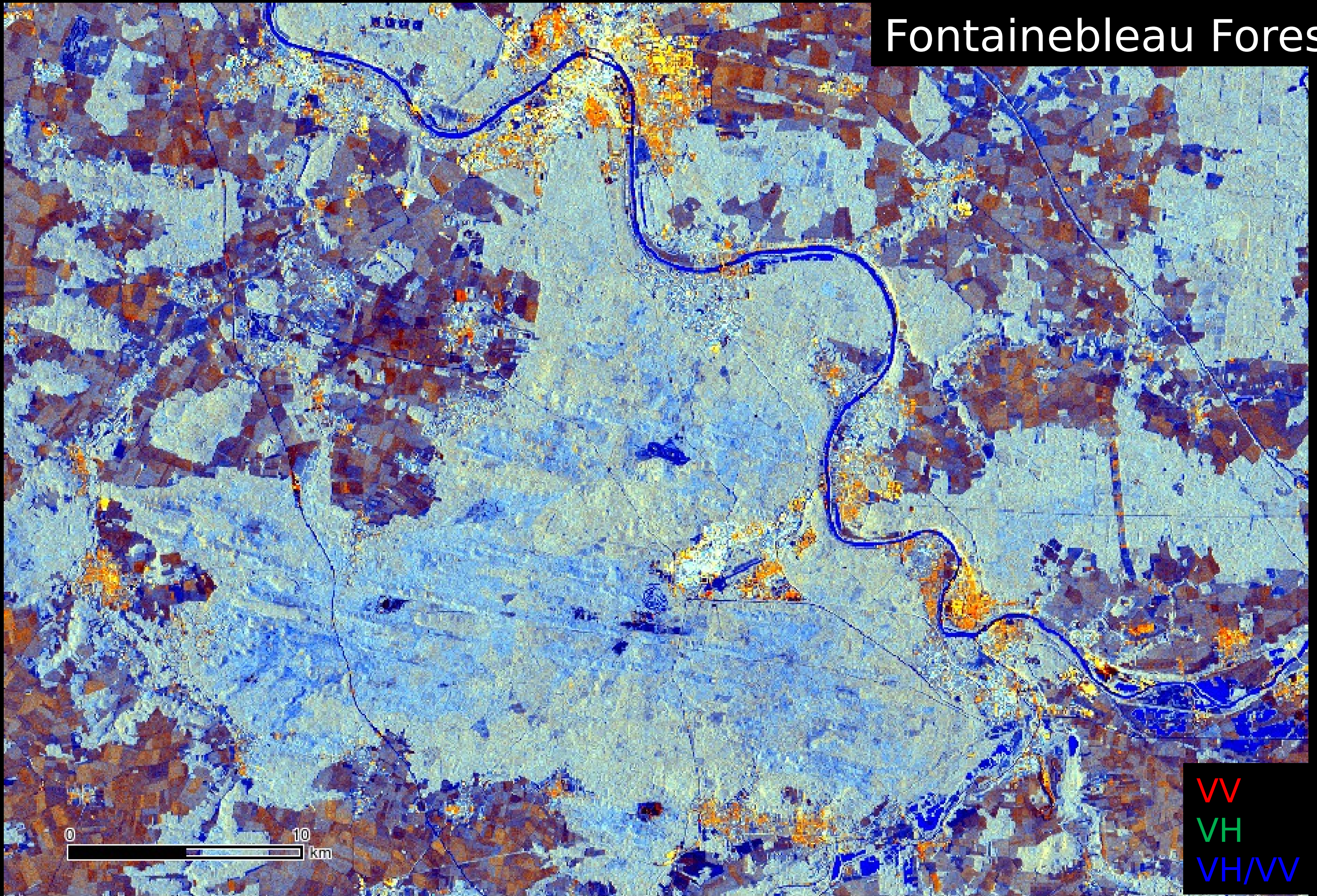
GoogleEarth Image

Parisian region

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015



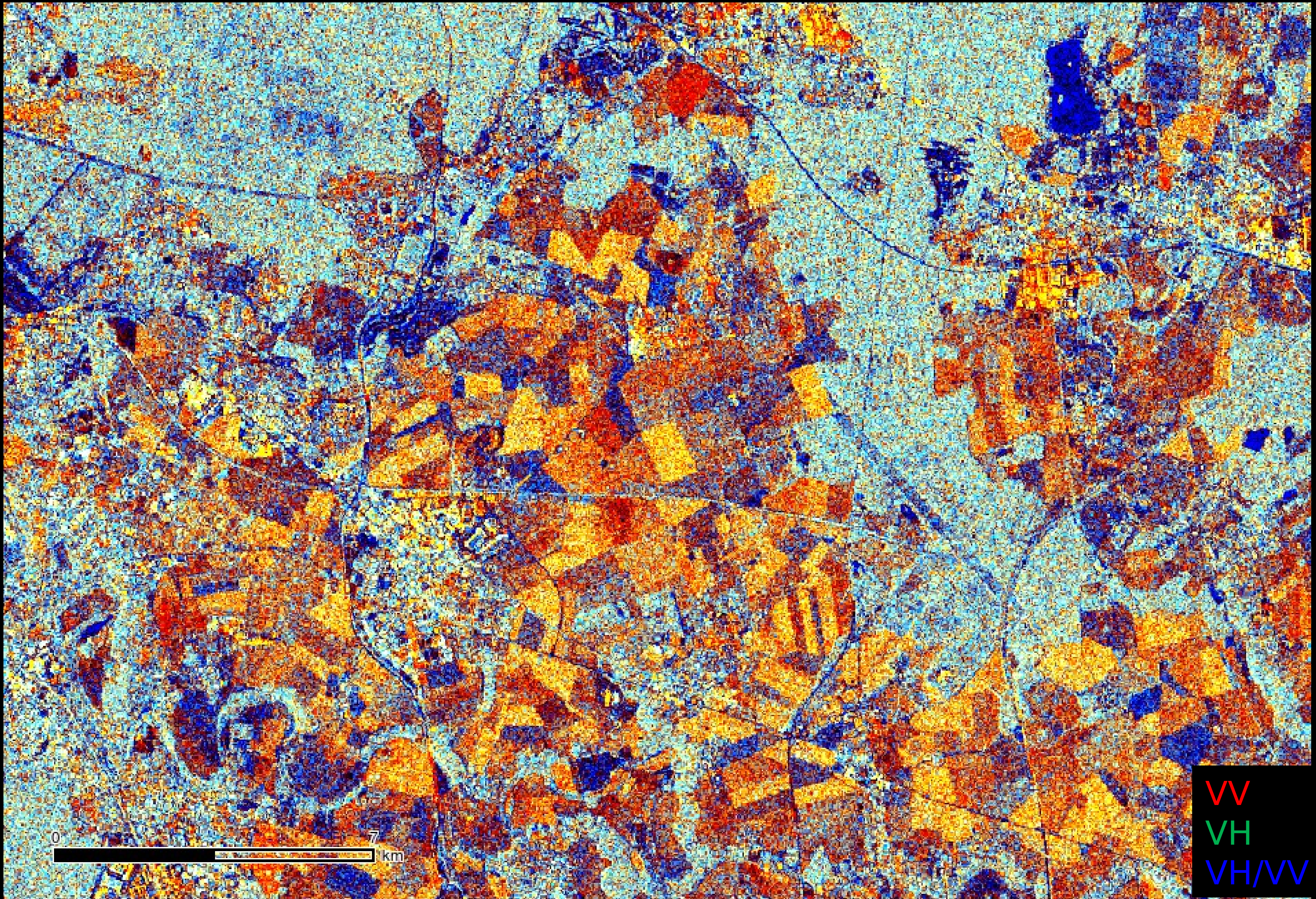
Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average
2015/03/02 - 2017/01/26



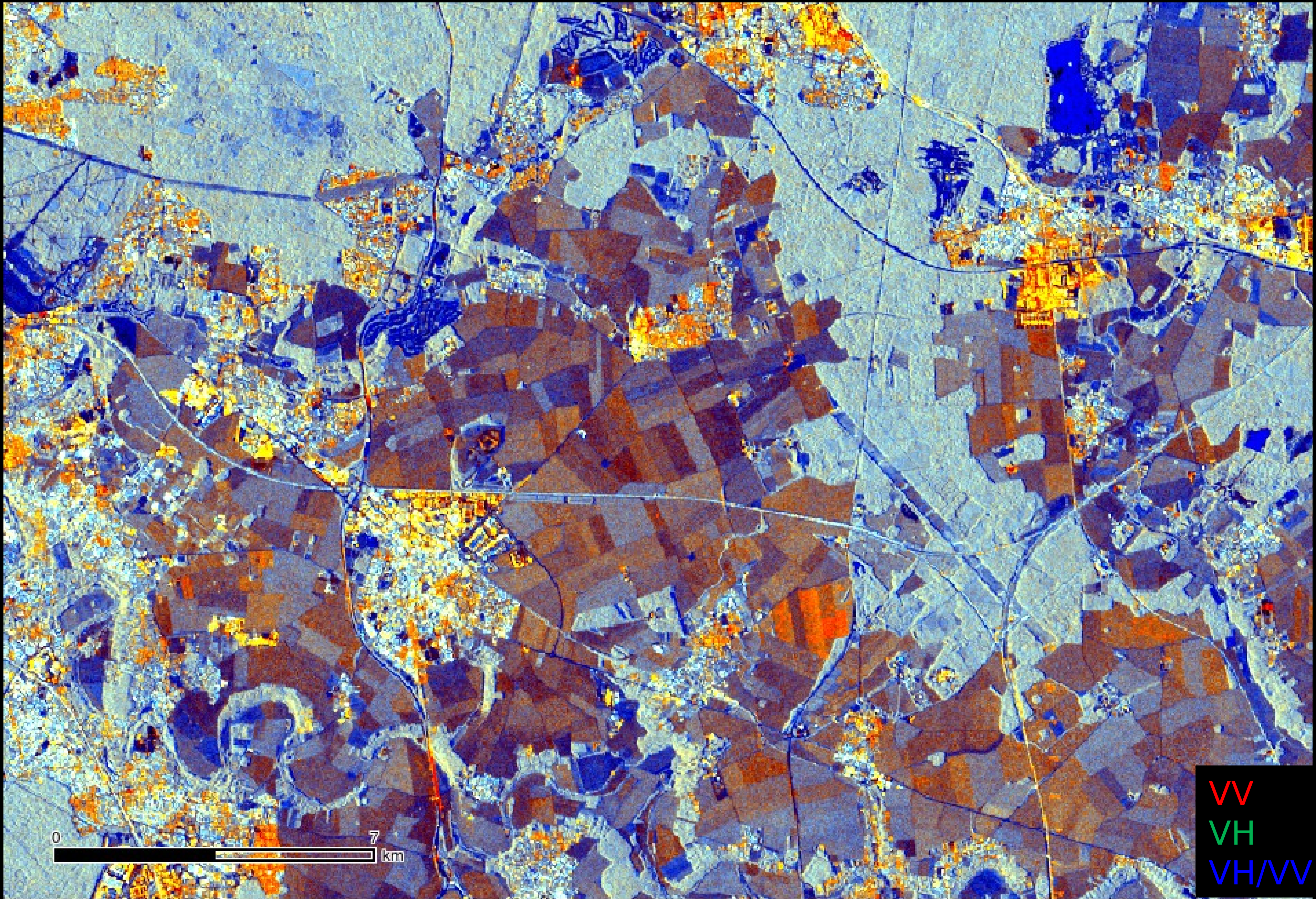
GoogleEarth Image

Fontainebleau Fores

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

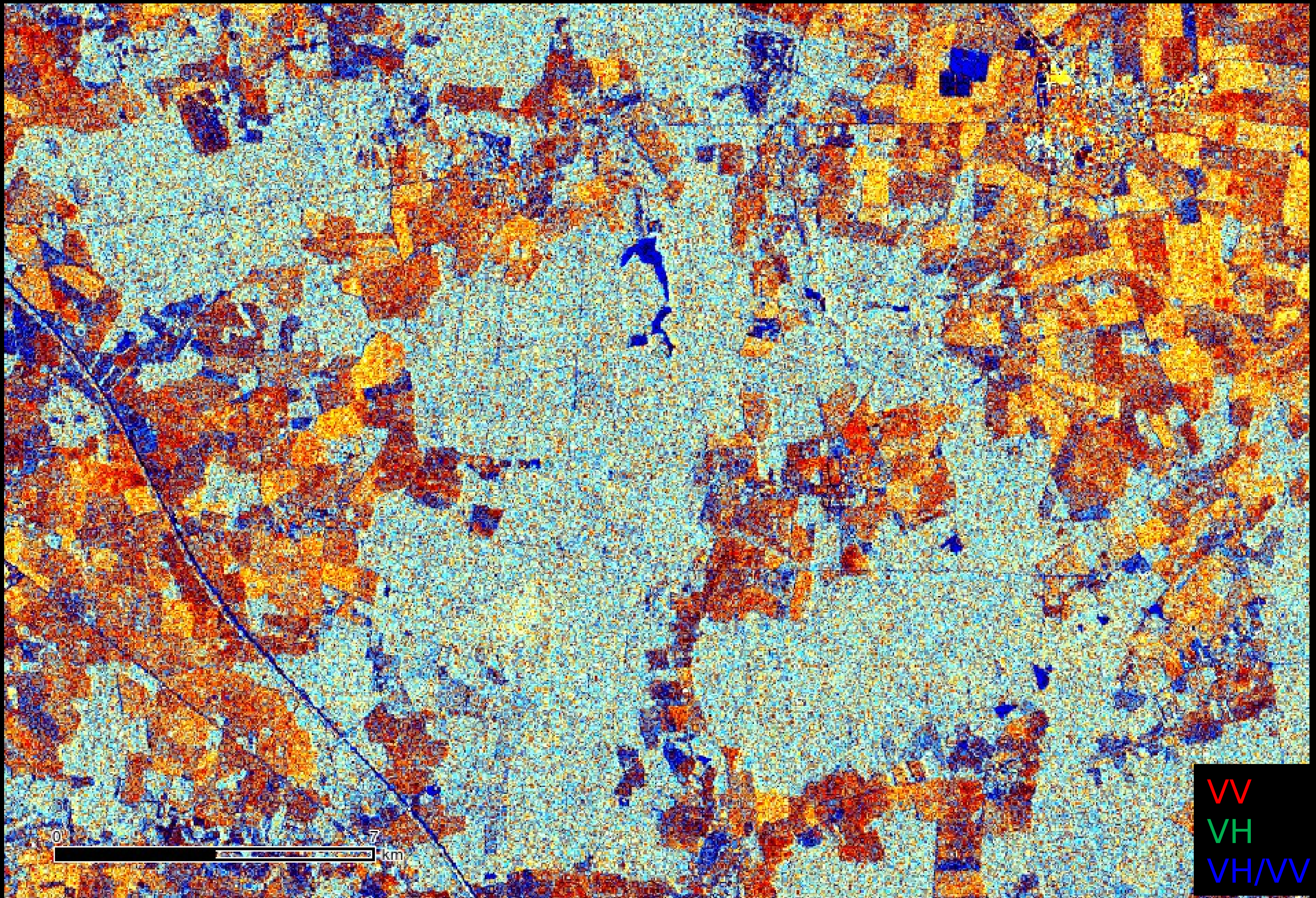


Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average
2015/03/02 - 2017/01/26

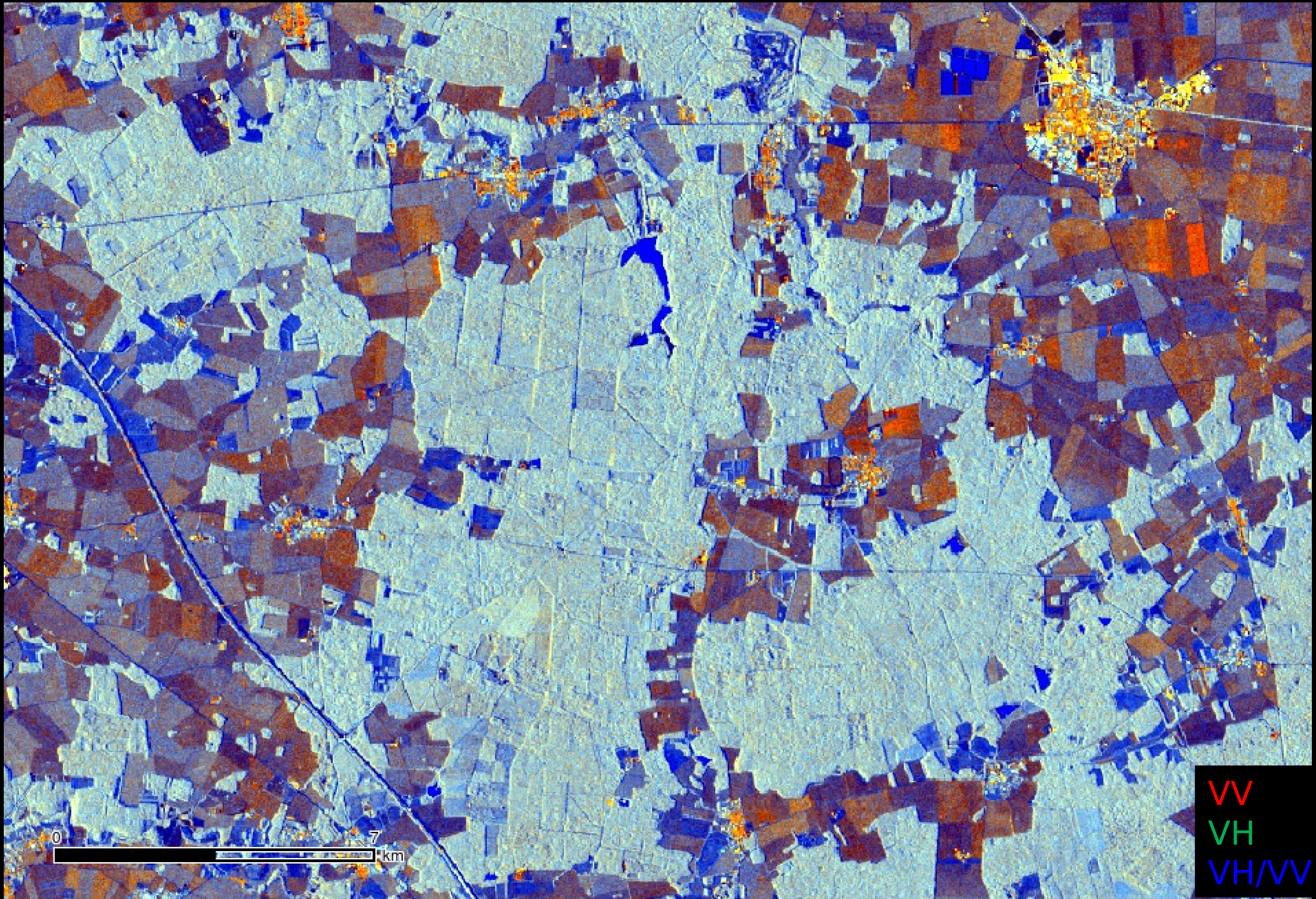


GoogleEarth Image

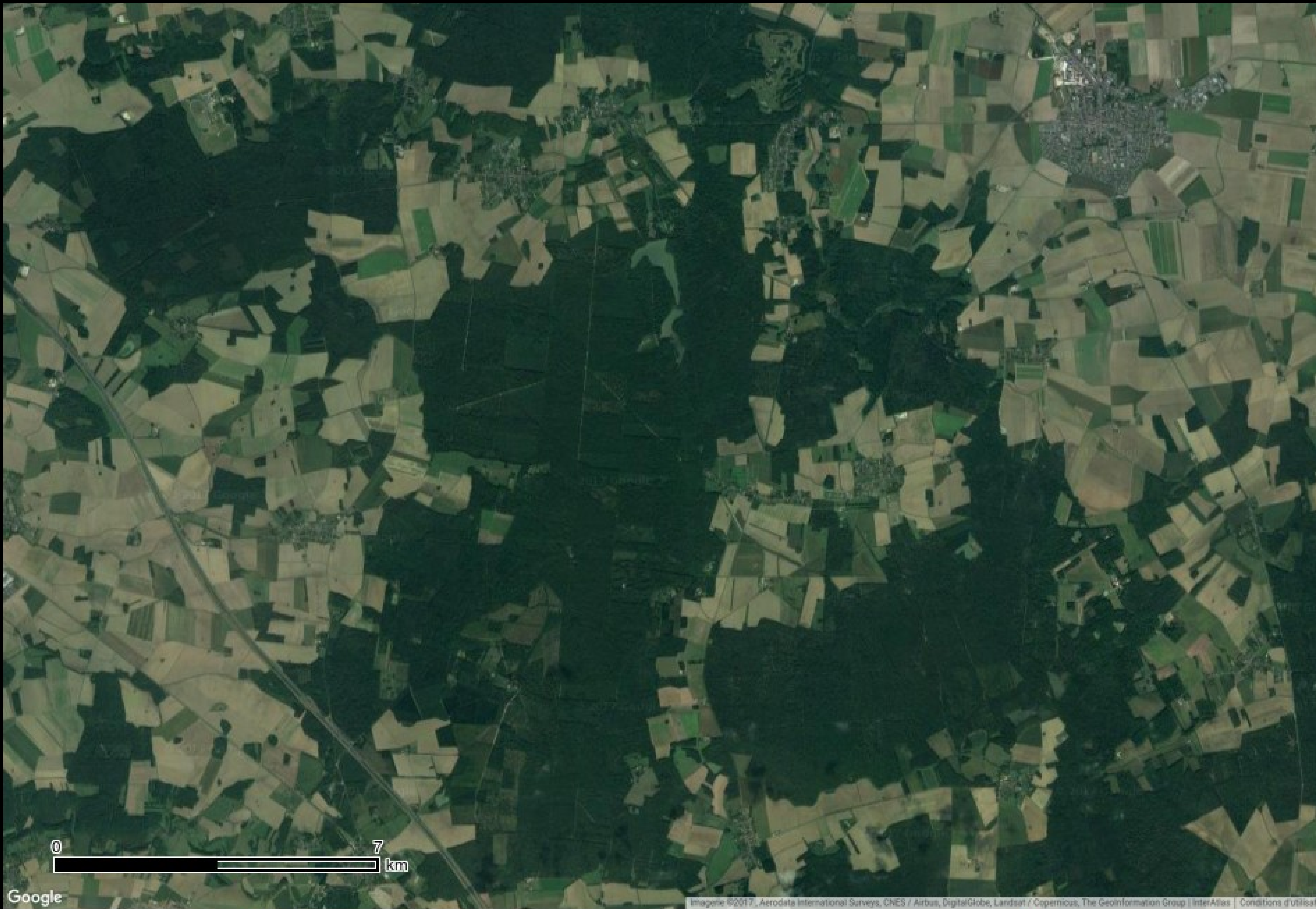
Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015



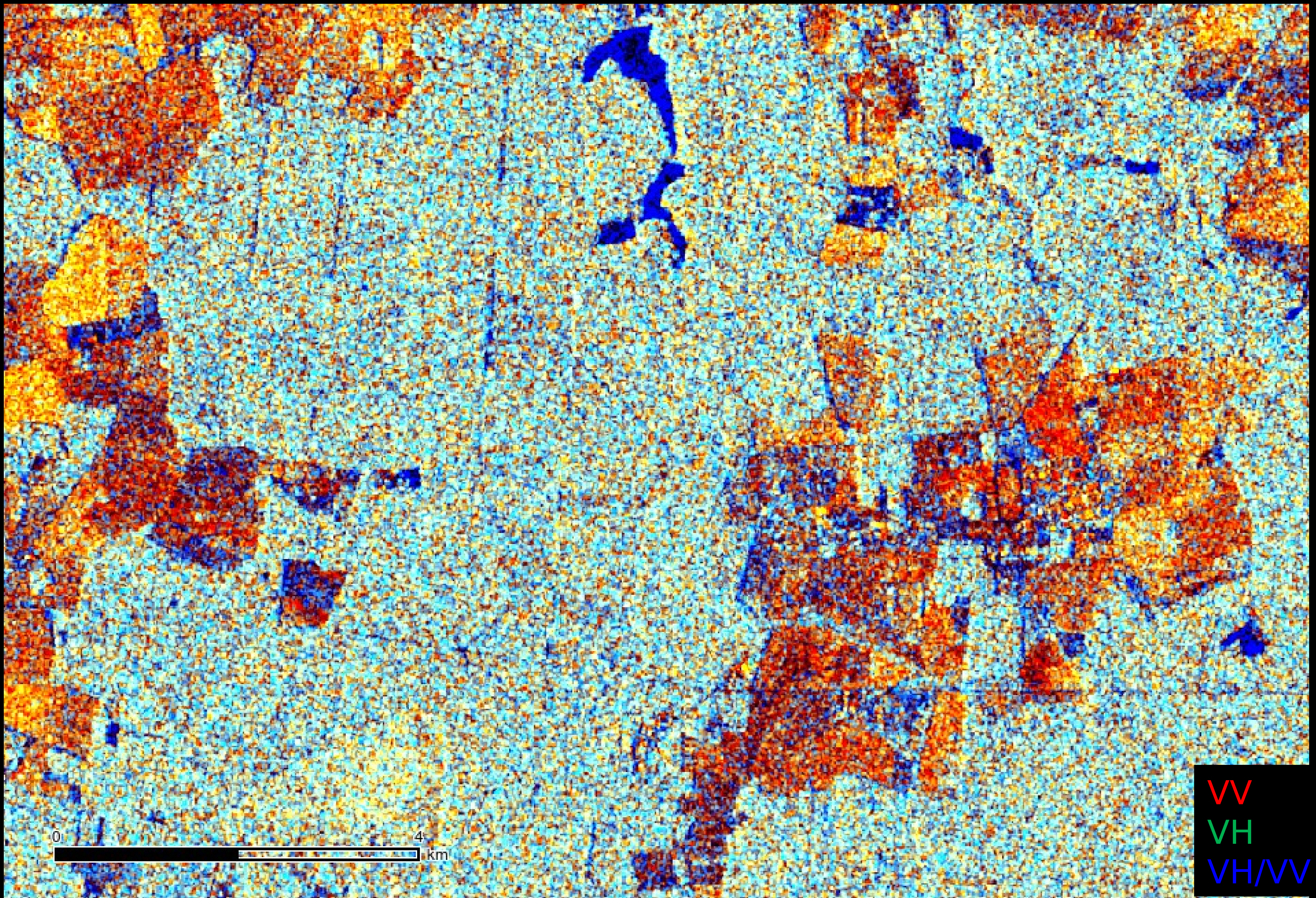
Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average
2015/03/02 - 2017/01/26



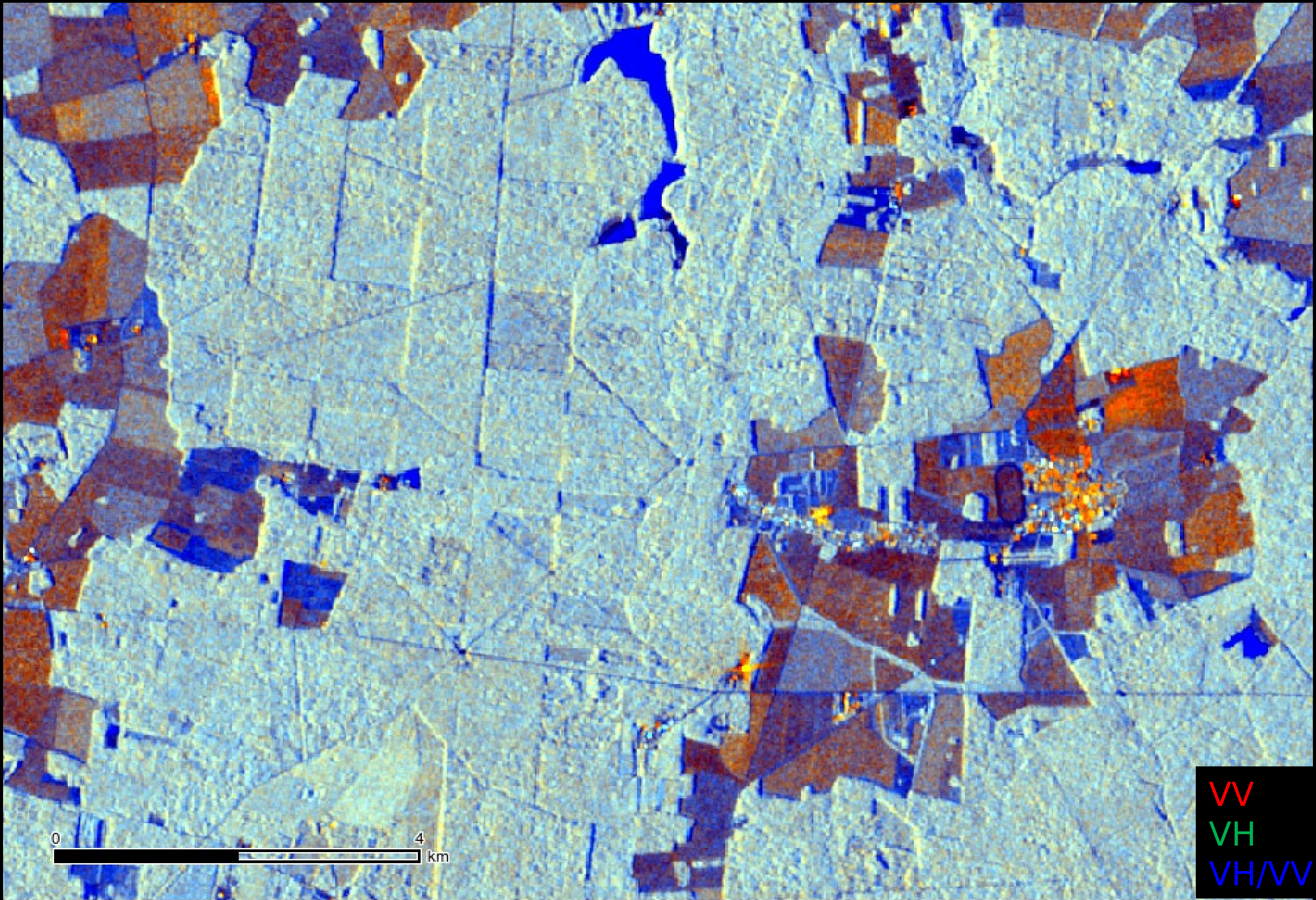
GoogleEarth Image



Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

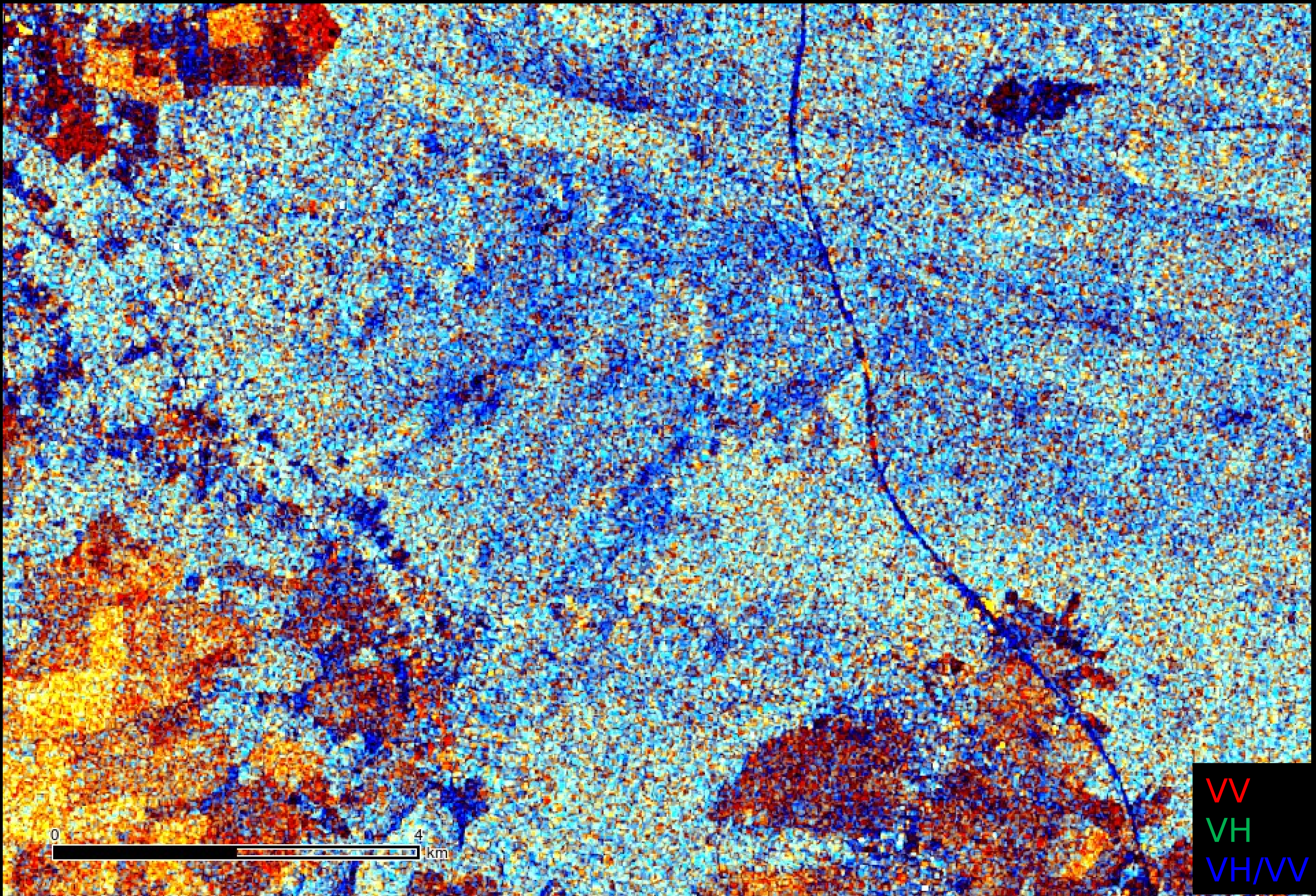


Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average
2015/03/02 - 2017/01/26



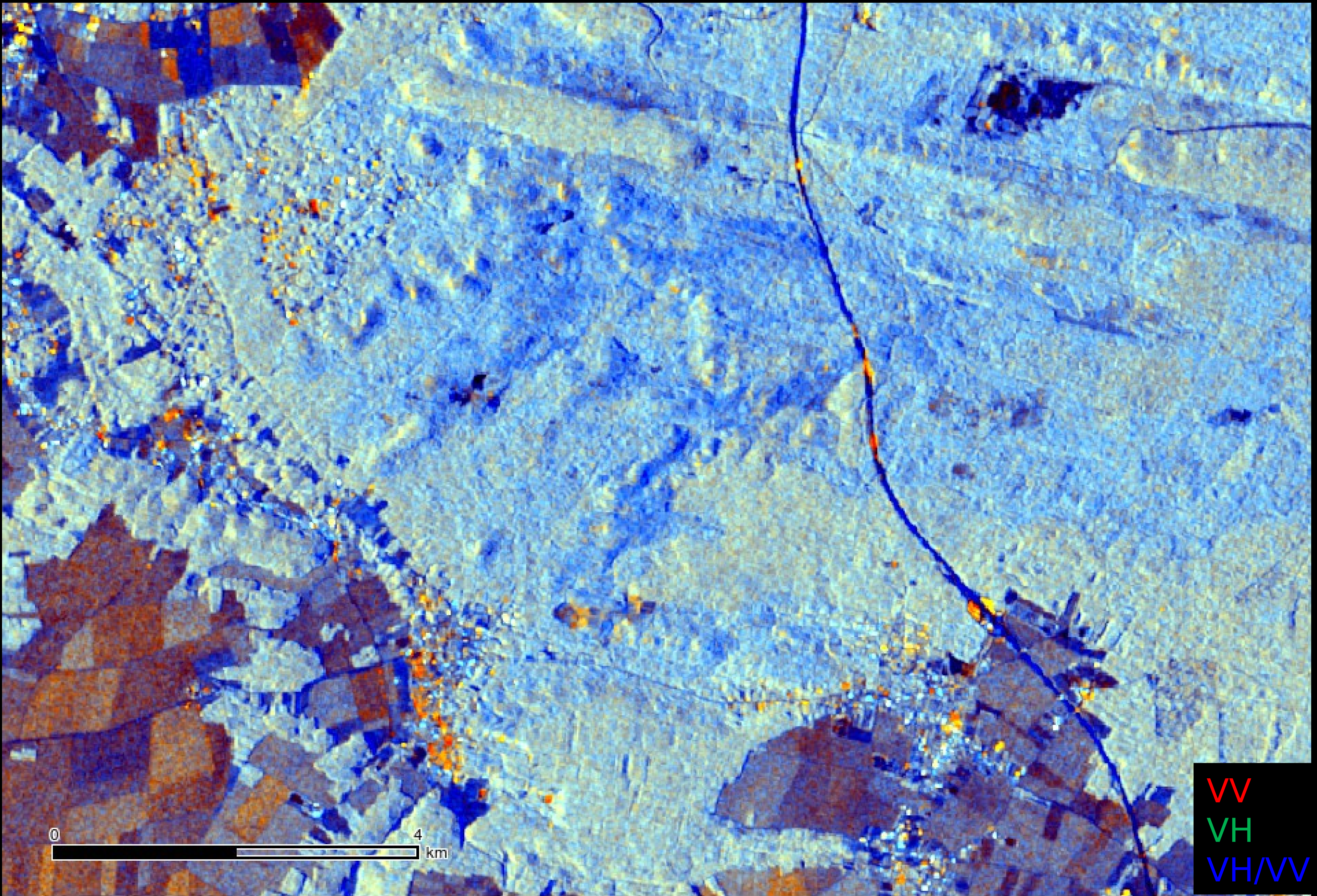
GoogleEarth Image

Sentinel-1 RADAR BACKSCATTERING IMAGE : Acquisition 2015

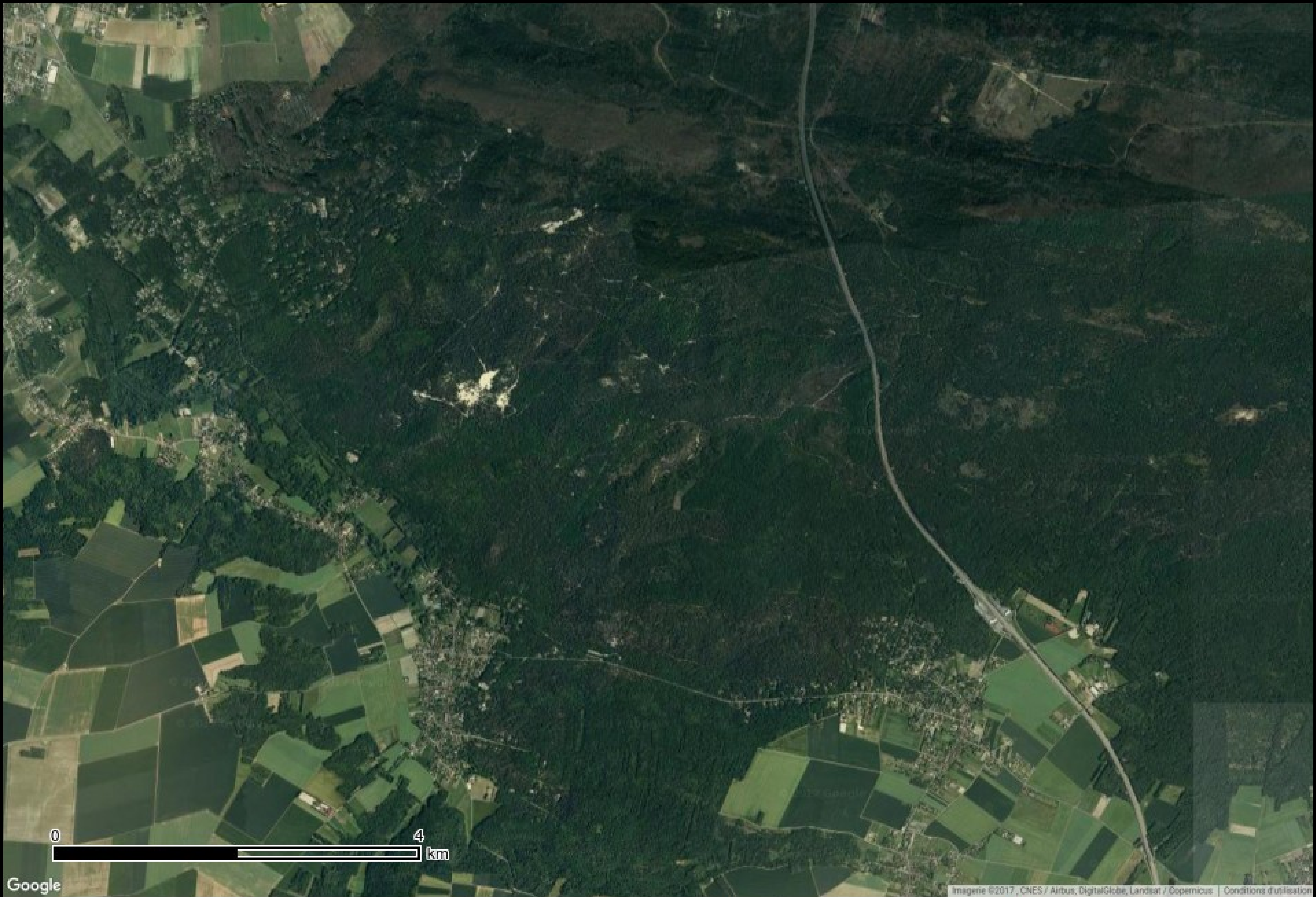


Sentinel-1 RADAR BACKSCATTERING IMAGE : Temporal average

2015/03/02 - 2017/01/26

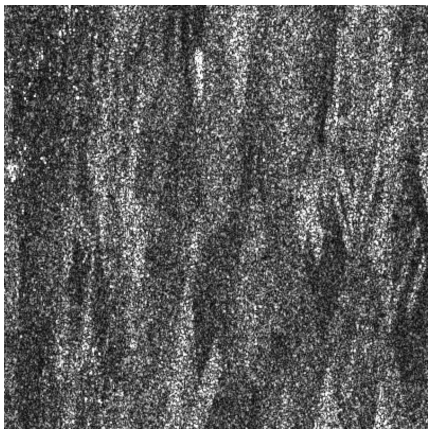


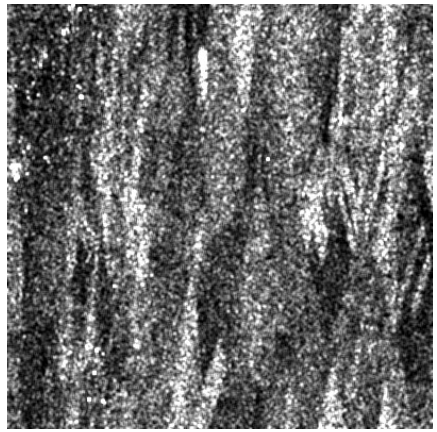
GoogleEarth Image

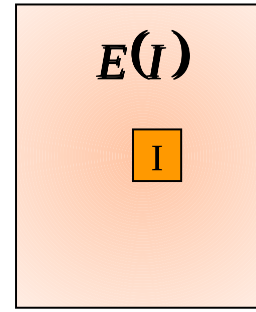


Goal: estimate $R \approx \sigma^{\circ}$

Most simple: Box Filtering: I ⟷ E(I)







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

Inconvenients: Details lost, fuzzy introduction

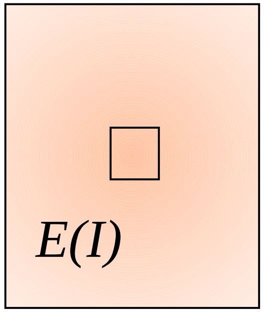
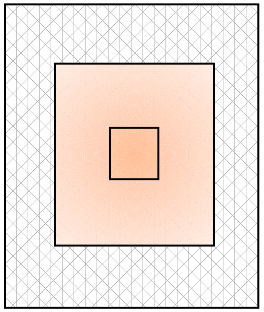
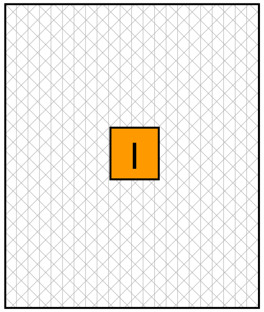
Other classical filters: (median, Sigma, math. morph…..): WORST!

==> 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	Heterogeneous area	Very Heterogeneous area
		
Average over the whole neighbourhood	Reduce the neighbourhood size	Keep the central pixel value (no averaging)

- necessary to discriminate homogeneity of local neighborhood

Coefficient of variation:

$$c_v = \frac{std\,dev}{mean}$$

$$c_v = \frac{1}{\xi \overline{N}}$$ *over* ***homogeneous*** *area*

$$C_v \geq \frac{1}{\xi \overline{N}}$$ *over* ***heterogeneous*** *area*

Kuan and Lee Filters

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

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

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

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

$N < 3$ ==> Lee < Kuan

N 3 ==> Lee Kuan

Frost Filter

Weghting of the neighbour pixels relative to its distance

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

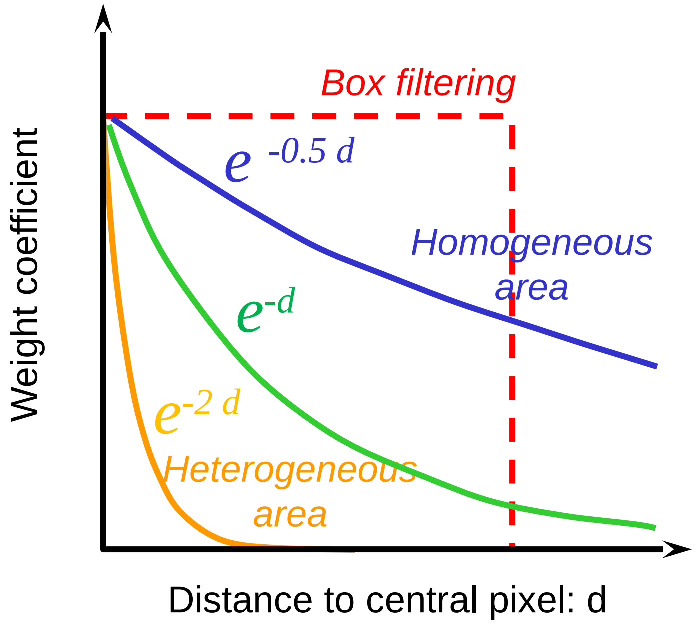
(MMSE criteria)

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: $p(R/I)=\dfrac{p(I/R).p(R)}{p(I)}$

Hypothesis on *p(R): Γ* law

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

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

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)

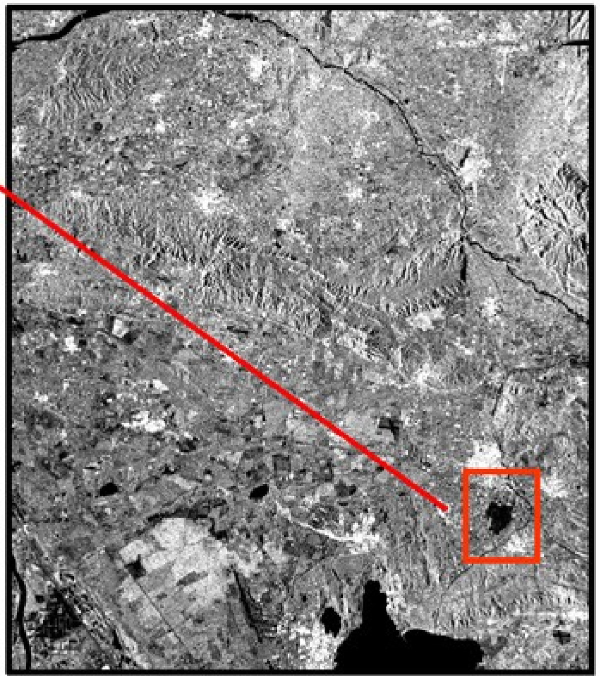

Boxcar 9x9


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

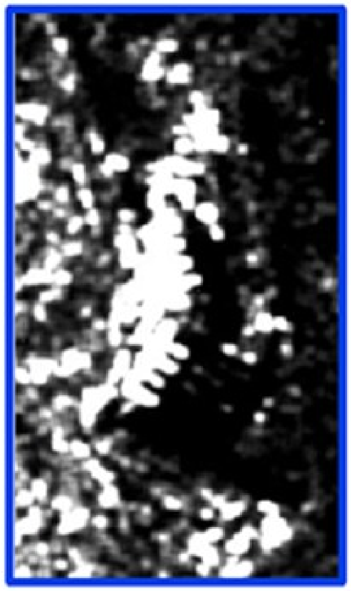
Filtered image

• 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

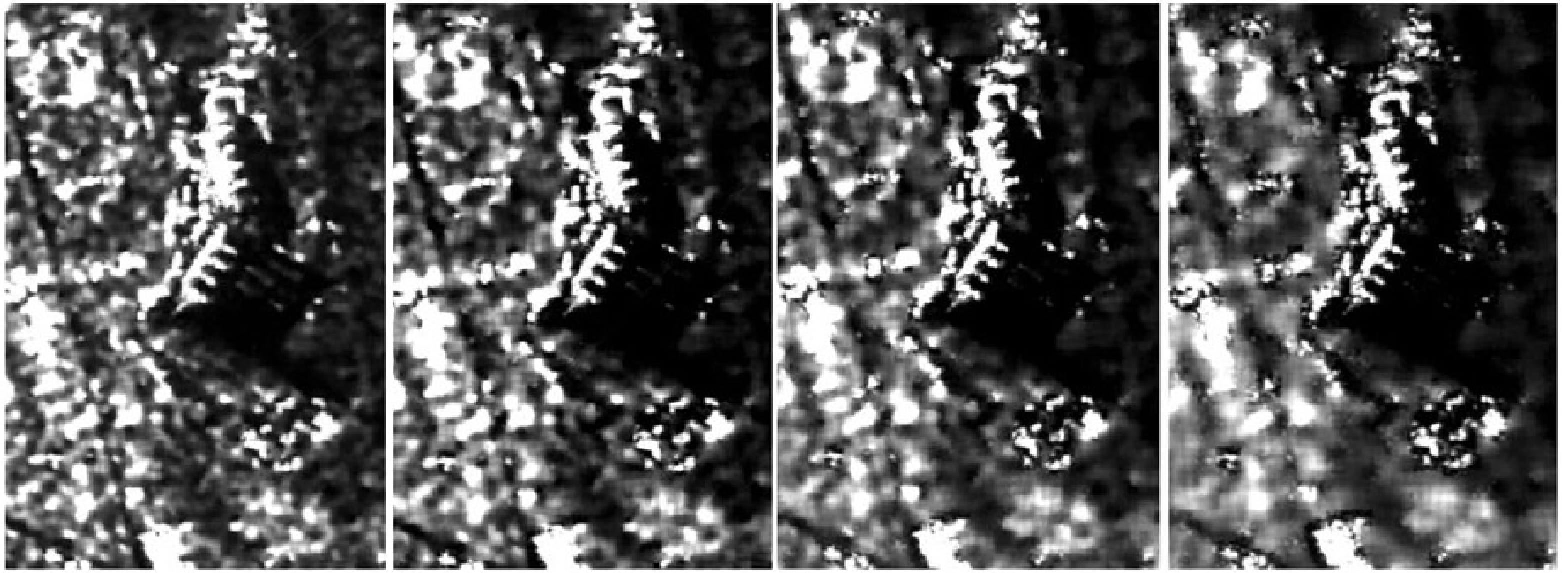
Gamma-Gamma MAP 7x7

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

CONCLUSION

- Radar images (coherent waves): ==> ***SPECKLE***

==> single pixel value not significant (random)

==> *main drawback for classification algorithms*

- Best processing for speckle reduction: ***AVERAGE*** *i.e.* E(I)

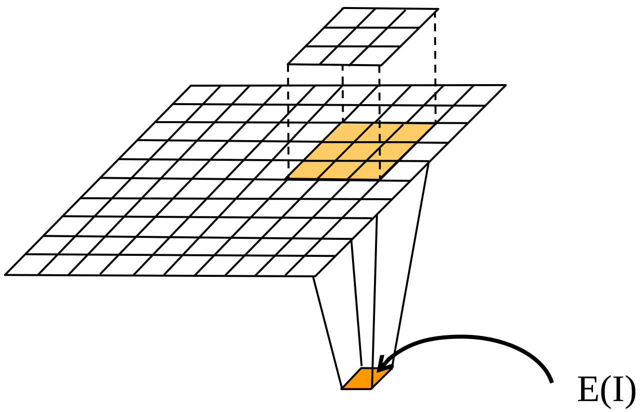
- Over ***homegeneous*** area: All the filters: $\hat{R} = E(I)$
- ***Adaptative*** filters (Lee, Frost, Kuan,….)

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

MULTILOOK OBTENTION

in spatial domain

*Sliding window: image * window*

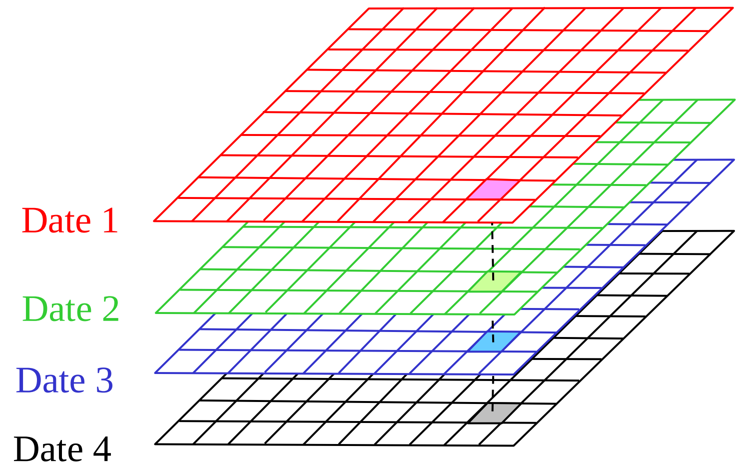


9 looks if pixel sare not correlated

Example: ERS data - PRI products : 3 looks

Loss of spatial resolution

in temporal domain

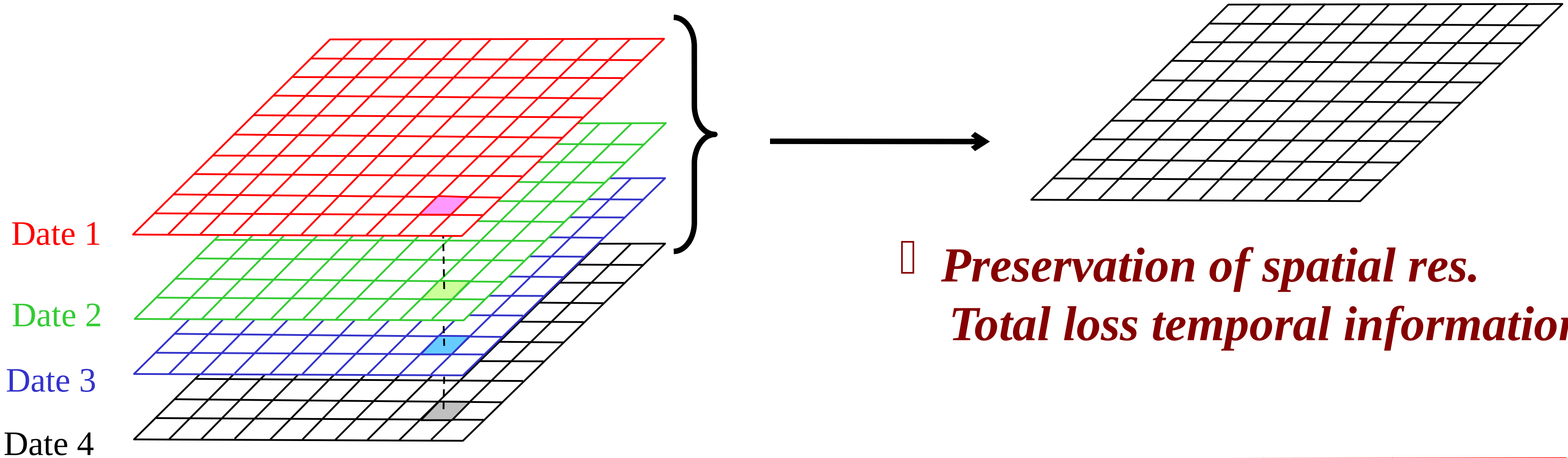


4 looks if surface
has not changed

Preservation of spatial res.
Loss temporal information

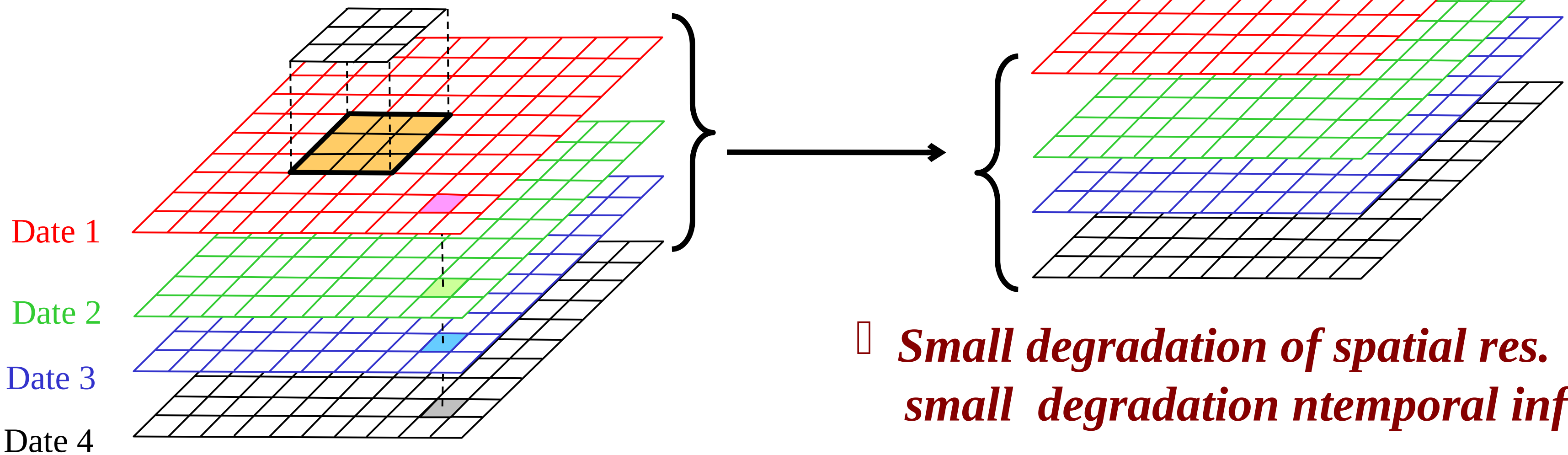
Spatio-temporal Filter (Sentinel-1)

temporal domain



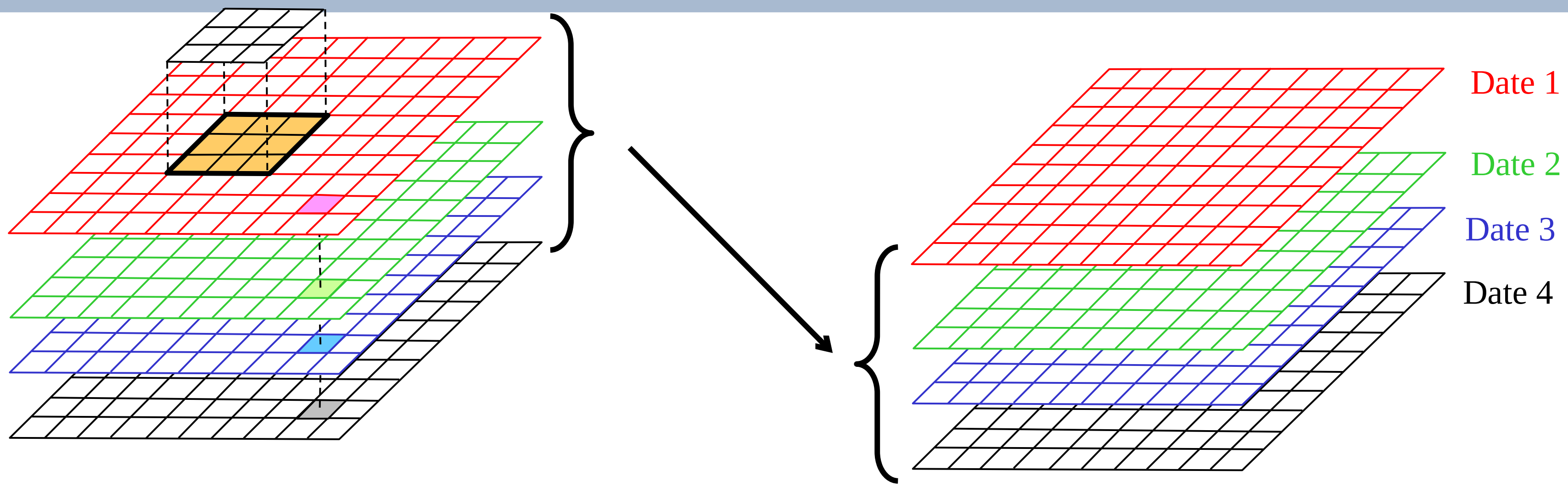
- ***Preservation of spatial res.***
  Total loss temporal information

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:

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

temporal average:
i.e. same for a pixel at any date

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)

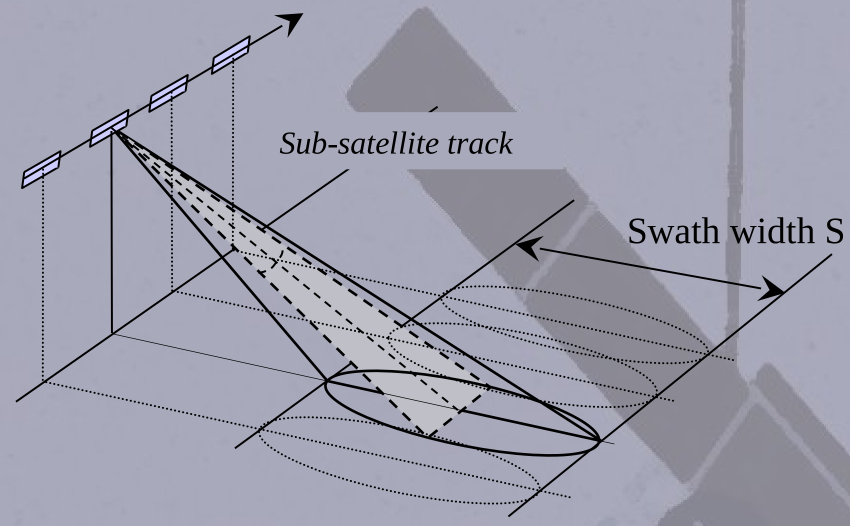
  spatio temporal filter (better preservation of spatio-temp. info)

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

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

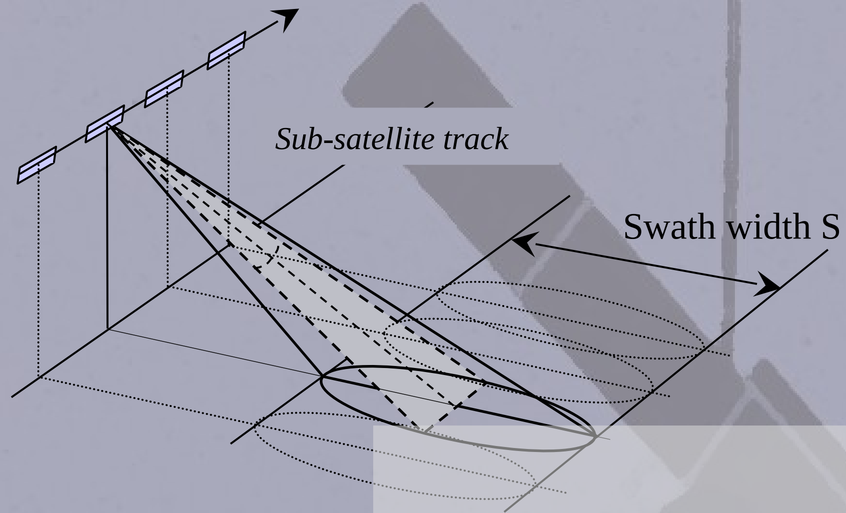
  heteregeneous areas: average over ***smallest neighbourhood***

Side looking radar sensors (λ > cm)



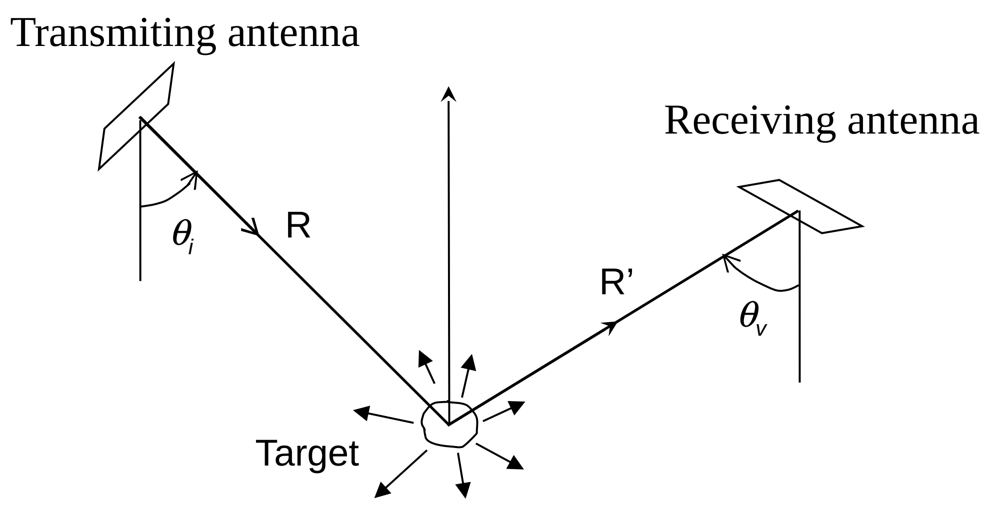
Scatterometers		***SAR: Synthetic Aperture Radar***
	Raw echoes recording	
Incoherent sum ***(I)***		***Coherent*** *sum* ***(A, ϕ)***
	Spatial resolution	
Low (25 – 50 km)		***fine*** (1 - 30 m)
	Radiometric resolution	
High (400 Looks)		***Low*** (speckle)
	Original application	
sea (winds)		***Land - sea***

Side looking radar sensors (λ > cm)



Scatterometers		SAR: Synthetic Aperture Radar
	Raw echoes recording	
Incoherent sum ***(I)***		***Coherent*** sum ***(A, ϕ)***
	Spatial resolution	
Low (25 – 50 km)		***fine*** (1 - 30 m)
	Radiometric resolution	
High (400 Looks)		***Low*** (speckle)
	Original application	
sea (winds)		***Land - sea***

The radar equation



Transmited power:

$$P_i = \frac{P_e G_e}{4\pi} d\Omega \qquad (W)$$

Receiving irradiance at distance R:

$$E_i = \frac{P_e G_e}{4\pi R^2} \qquad (W / m^2)$$

Radar Cross Section (m²)

Intercepted power from the target *(W)*:

$$P_s = \frac{P_e G_e}{4\pi R^2} RCS$$

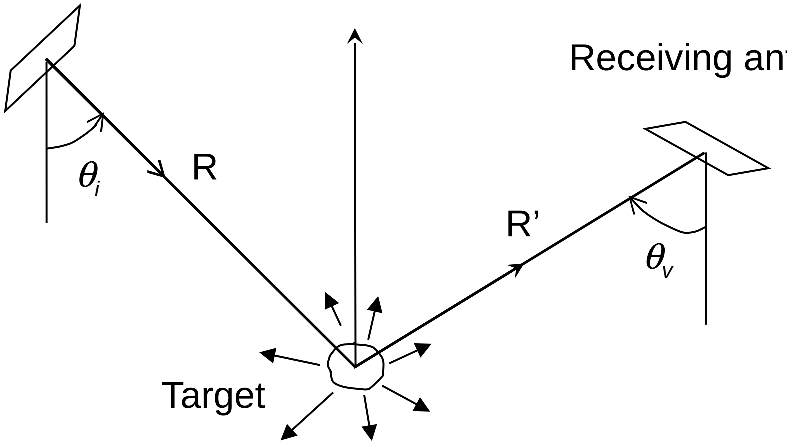
Intensity emited from the target (isotrope):

$$I = \frac{P_S}{4\pi} = \frac{P_e G_e}{4\pi R^2} \frac{RCS}{4\pi} \qquad (W / sr)$$

Power received by surface dS at distance R':

$$P_r = I\, d\Omega = I \frac{dS}{R'^2} = \frac{P_e G_e}{4\pi R^2} \frac{RCS}{4\pi R'^2} dS \qquad (W)$$

The radar equation



Power received by dS at distance R'

$$P_r = \frac{P_e G_e}{4\pi R^2} \frac{RCS}{4\pi R'^2} dS \qquad (W)$$

Recived irradiance at distance R'

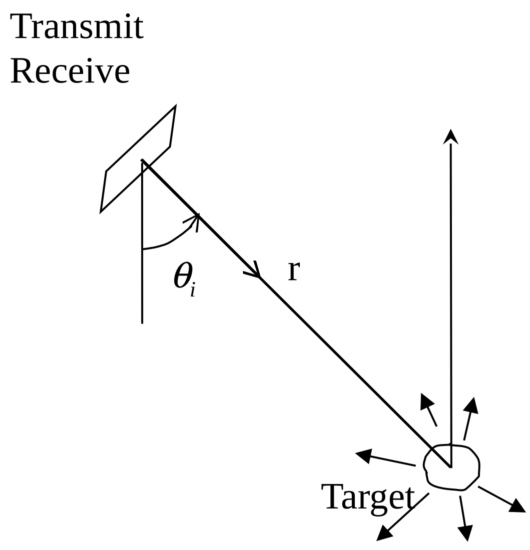
$$E_r = \frac{P_e G_e}{4\pi R^2} \frac{RCS}{4\pi R'^2} \qquad (W/m^2)$$

Power received by the antenna: $P_r = E_r \, dA = E_r \frac{G_r \lambda^2}{4\pi} = \frac{P_e G_e}{4\pi R^2} \frac{RCS}{4\pi R'^2} \frac{G_r \lambda^2}{4\pi} \quad (W)$

The RADAR equation

Received power by the antenna *(monostatic case)*:

$$P_r = \frac{P_e G_e(r)}{4\pi r^2}\frac{RCS}{4\pi r^2}\frac{G_r(r)\lambda^2}{4\pi}$$ *(point target)*



Over extended surfaces *(N elementary sactterers)*:

$$\langle P_r \rangle = \frac{\lambda^2}{(4\pi)^3}\sum_{k=1}^{N} P_{ek} G_{ek}(r_k) G_{rk}(r_k)\frac{1}{r_k^4} RCS$$

Radar Backscattering Coeficient: σ⁰

$$\sigma^0 = \left\langle \frac{RCS}{dS_k} \right\rangle$$ *(m²/m²)*

 Analogous to the reflectance in Optical domain

$$\langle P_r \rangle = \frac{\lambda^2}{(4\pi)^3} P_e \int_{Surf\,obs.} G_e(r) G_r(r) \frac{1}{r^4}\sigma^0 dS$$

$$\boxed{\langle P_r \rangle = \frac{\lambda^2}{(4\pi)^3} P_e \frac{1}{r_0^4}\sigma^0 G_e(r_0) G_r(r_0) S_{eff}}$$

with
$$\begin{cases} r = r_0 \quad et \quad \sigma^0 = cste \text{ over obs. surf.} \\ \int_{Obs.Surf.} G_e(r) G_r(r) dS = G_e(r_0) G_r(r_0) S_{eff} \end{cases}$$

The RADAR equation

over extended surfaces:

$$\langle P_r \rangle = \frac{\lambda^2}{(4\pi)^3} P_e \frac{1}{r_0^4} \sigma^0 G_e(r_0) G_r(r_0) S_{eff}$$

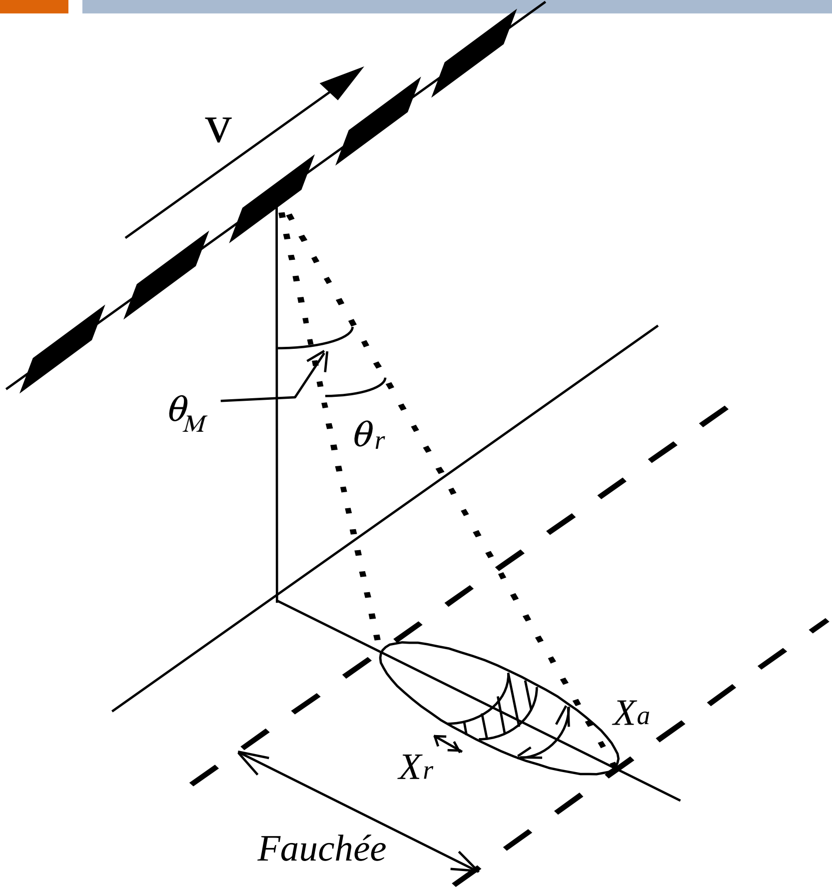
==> $$\sigma^0 = \frac{(4\pi)^3 r_0^4}{\lambda^2} \frac{1}{G_e(r_0) G_r(r_0)} \frac{\langle P_r \rangle}{P_e} \frac{1}{S_{eff}}$$ *(m^2/m^2)*

σ^0 high dynamic

==> dB units *(log. scale)*

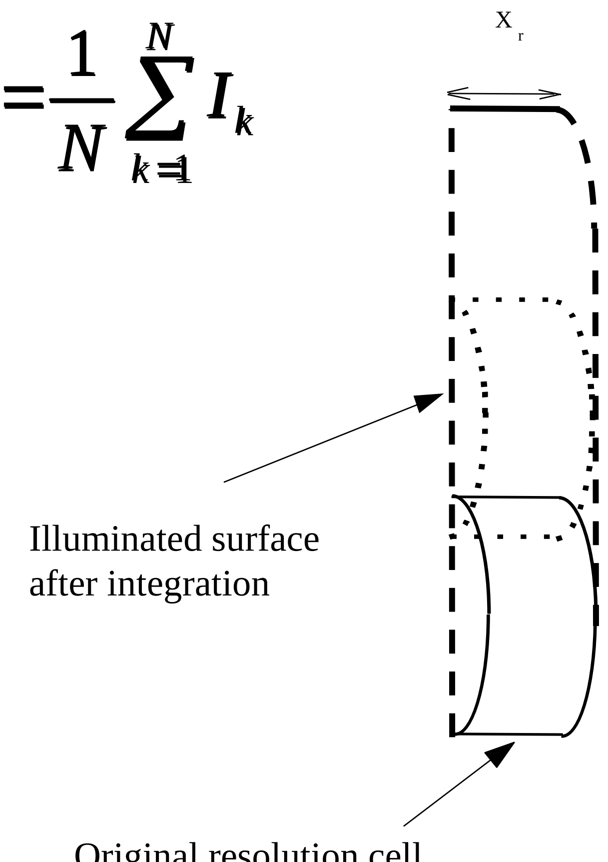
$$\sigma^0_{dB} = 10.\log_{10}\left(\sigma^0_{Nat}\right)$$

Scatterometer principle



- ***Incoherent average (I) of received echoes during a given integration time t_c***

$$I = \frac{1}{N}\sum_{k=1}^{N} I_k$$



Radiometric resolution

Given by the parameter $k_p = \frac{\sqrt{\mathrm{var}(P_r)}}{\langle P_r \rangle} = \frac{\sqrt{\mathrm{var}(\sigma^0)}}{\sigma^0} = \frac{1}{\sqrt{M}}$ M: Looks number

PRF < $B_D = \frac{2V}{L}$ ⇒ Shannon not respected

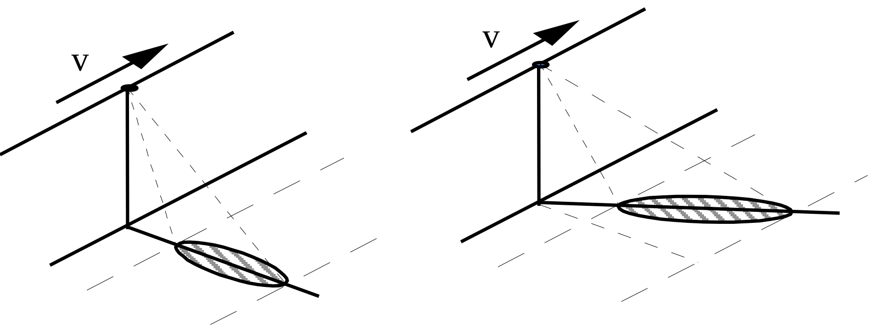
Number of ***independant*** echoes received: $\boldsymbol{M = PRF \cdot t_c}$

ERS: *V=7.7 km.s*$^{-1}$*; L=2.5 m; PRF= 115 Hz;*

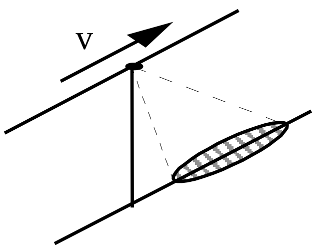
⇒ B_D = *6 kHz*

M = 384 ⇒ $\boldsymbol{K_p = 5\%}$

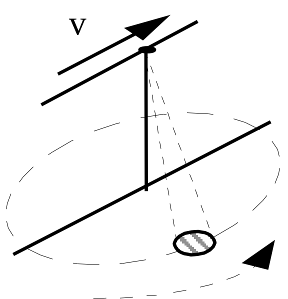
Scatterometers: acquisitions configurations



large swath
combined use □ several azimuths



Large incidence range
Small swath width

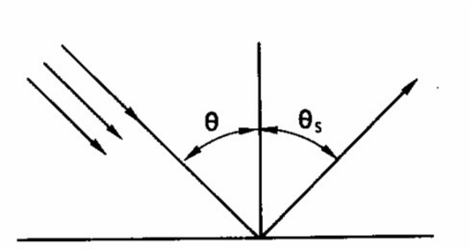


Large swath
Constant incidence angle
Each point looked uder 2 azimuths

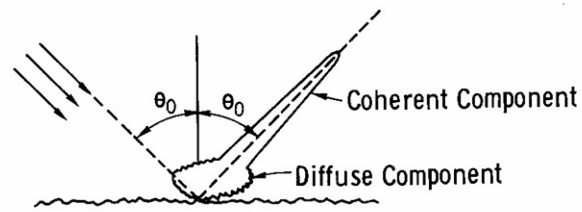
Diffusion de surface

sol: milieu homogène ==> diffusion à l'interface air/sol

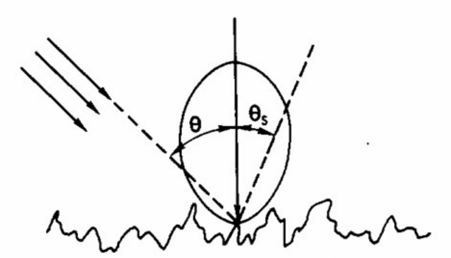
Influence de la rugosité



surface lisse

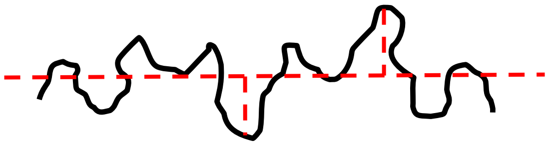


surface peu rugueuse



surface rugueuse

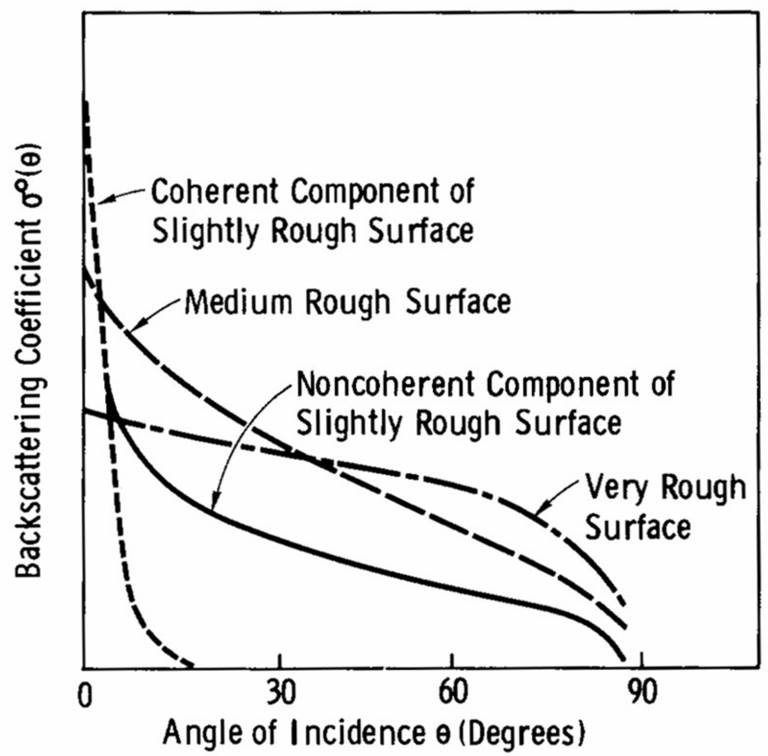
critère de Rayleigh: surface lisse $\sigma < \dfrac{\lambda}{32\cos\theta}$



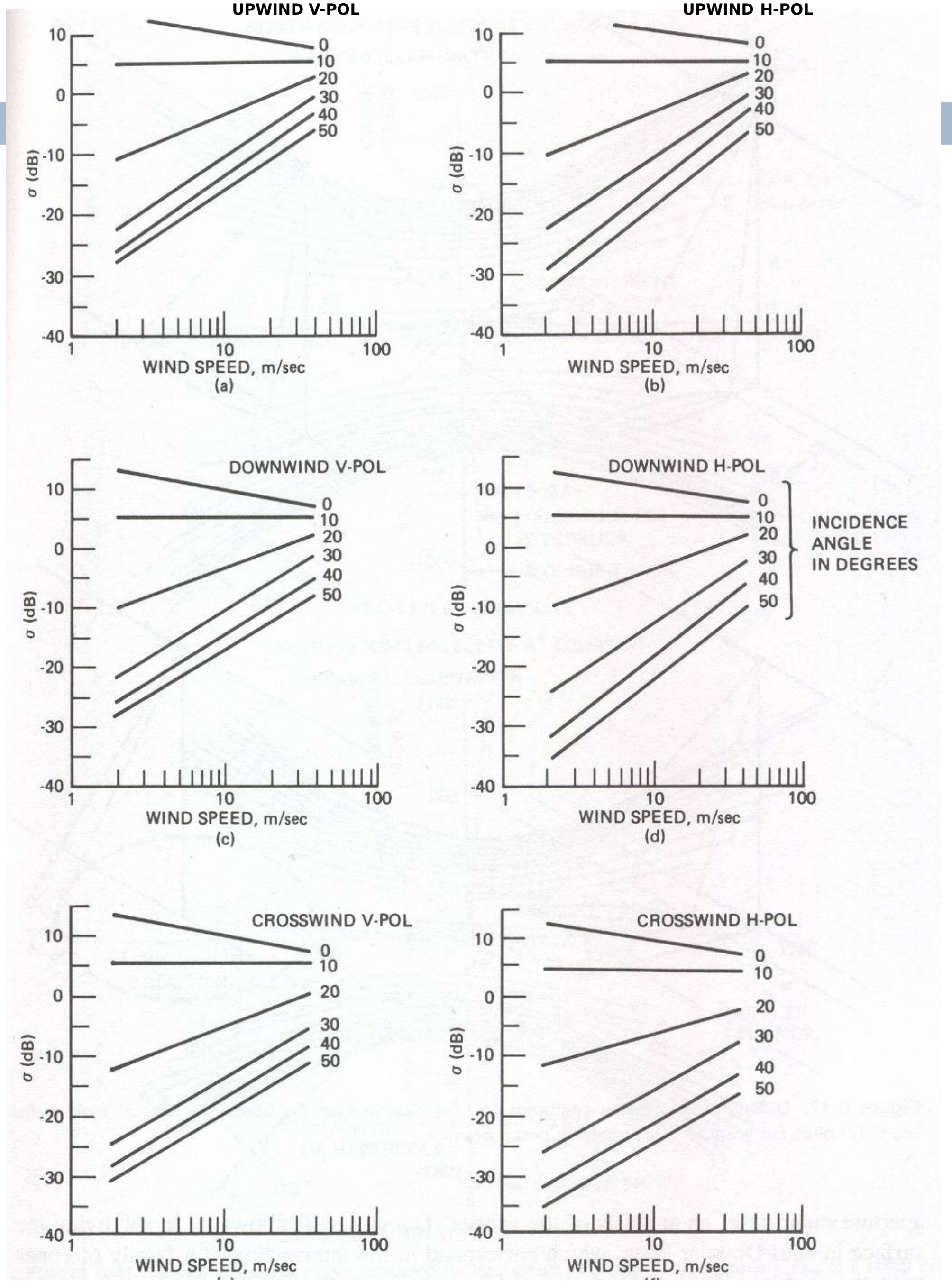
σ: rms height

ERS (λ = 5 cm, θ = 23°): $\sigma > 2.10^{-2}$: beaucoup de sols rugueux!

Diffusion de surface

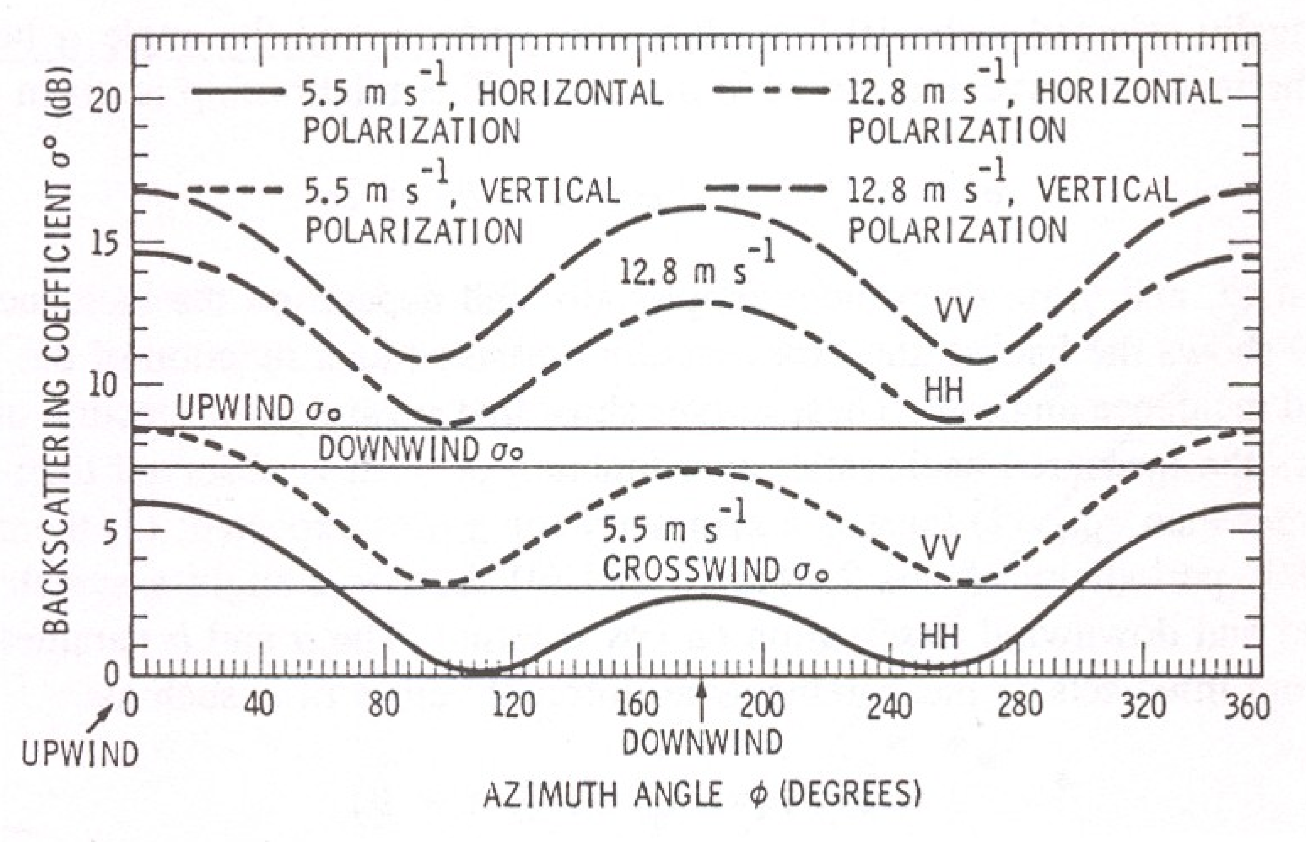


réponse radar en fonction de la vitesse du vent



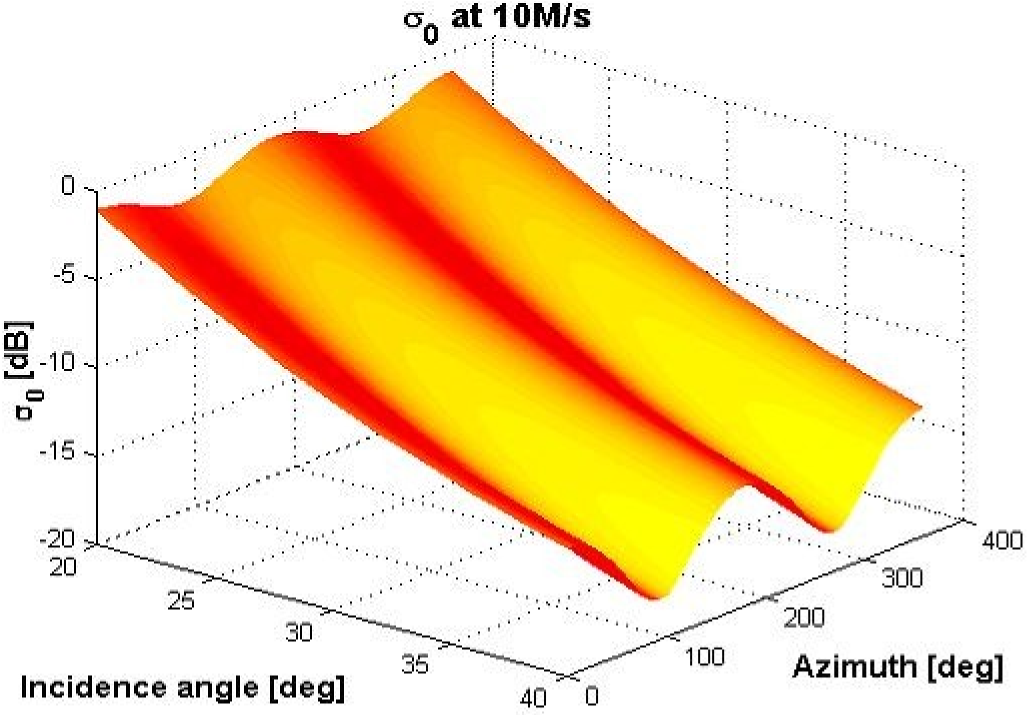
Elachi & Van Zyl

Signature azimutale de la réponse radar sur l'océan



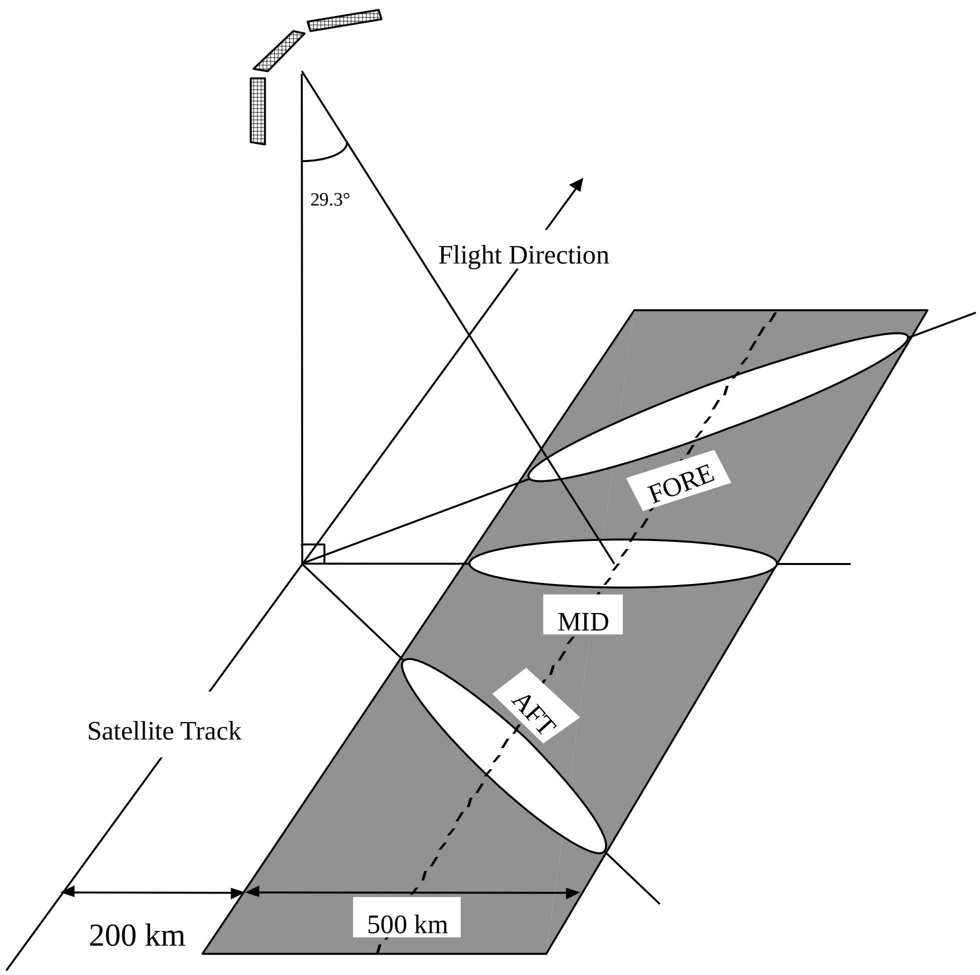
Elachi & Van Zyl

Signature angulaire de la mer



Arnesen et al., 2004

Diffusiomètre vent ERS



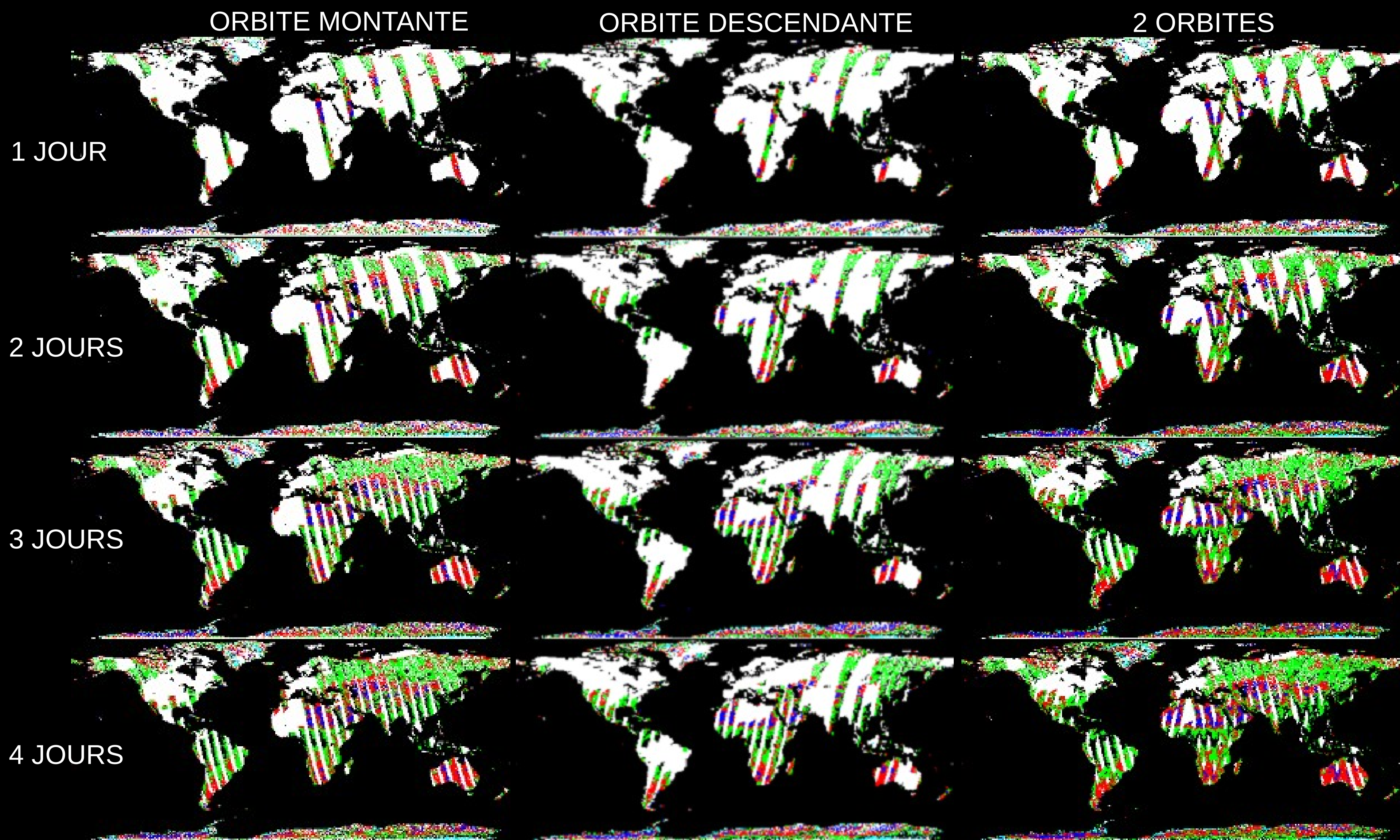
- **Bande C** (5.3 GHz)
- Polarisation **VV**
- pluri-incidence

  18° - 59°
- résolution spatiale

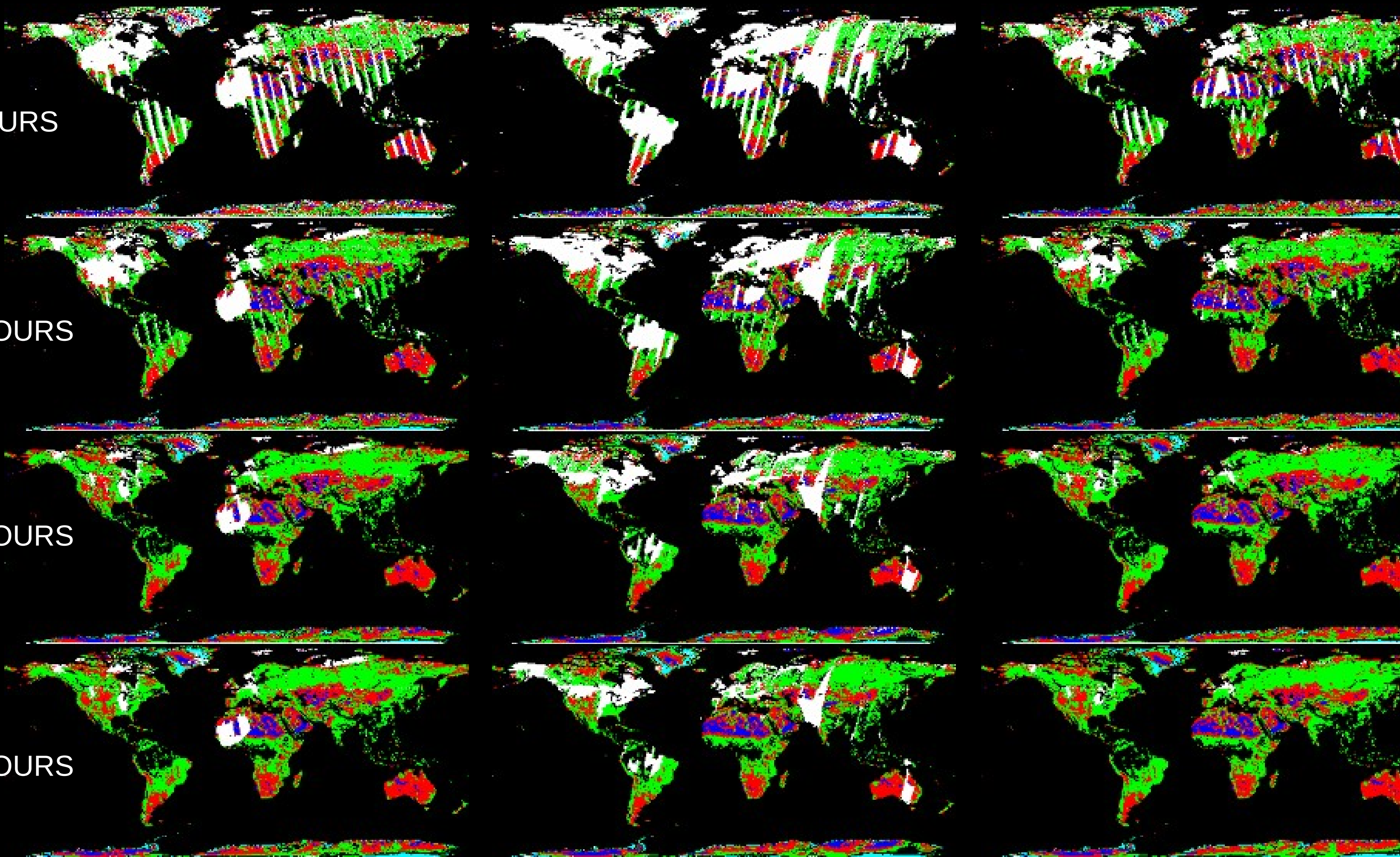
  ~ 50 km
- Répétitivité temporelle **~ 5 jours suivant la latitude**

 Destiné à l'estimation de la vitesse et la direction des vents sur les océans

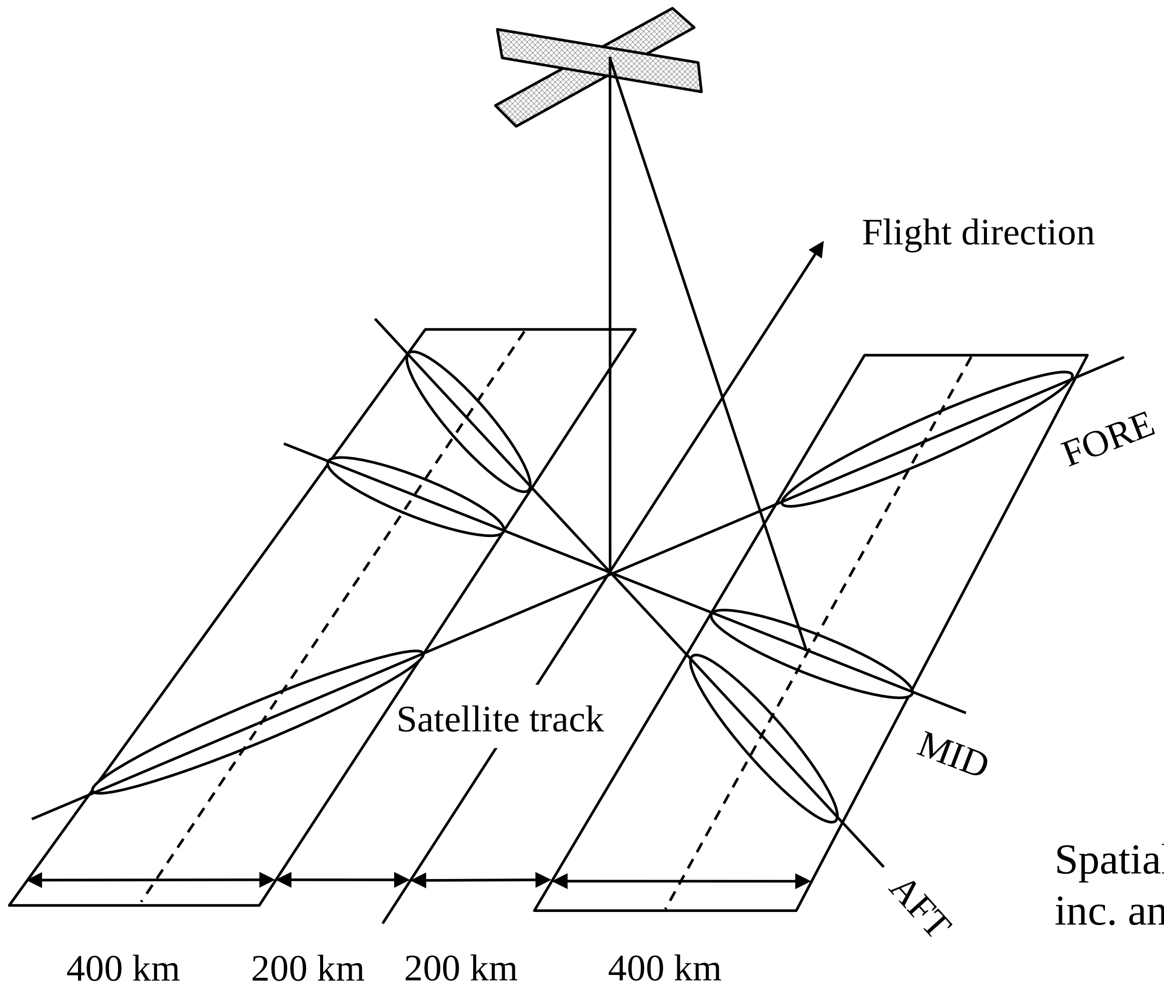
COUVERTURE SPATIALE DU DIFFUSIOMETRE ERS
SUR LES TERRES EMERGEES



COUVERTURE SPATIALE DU DIFFUSIOMETRE ERS SUR LES TERRES EMERGEES



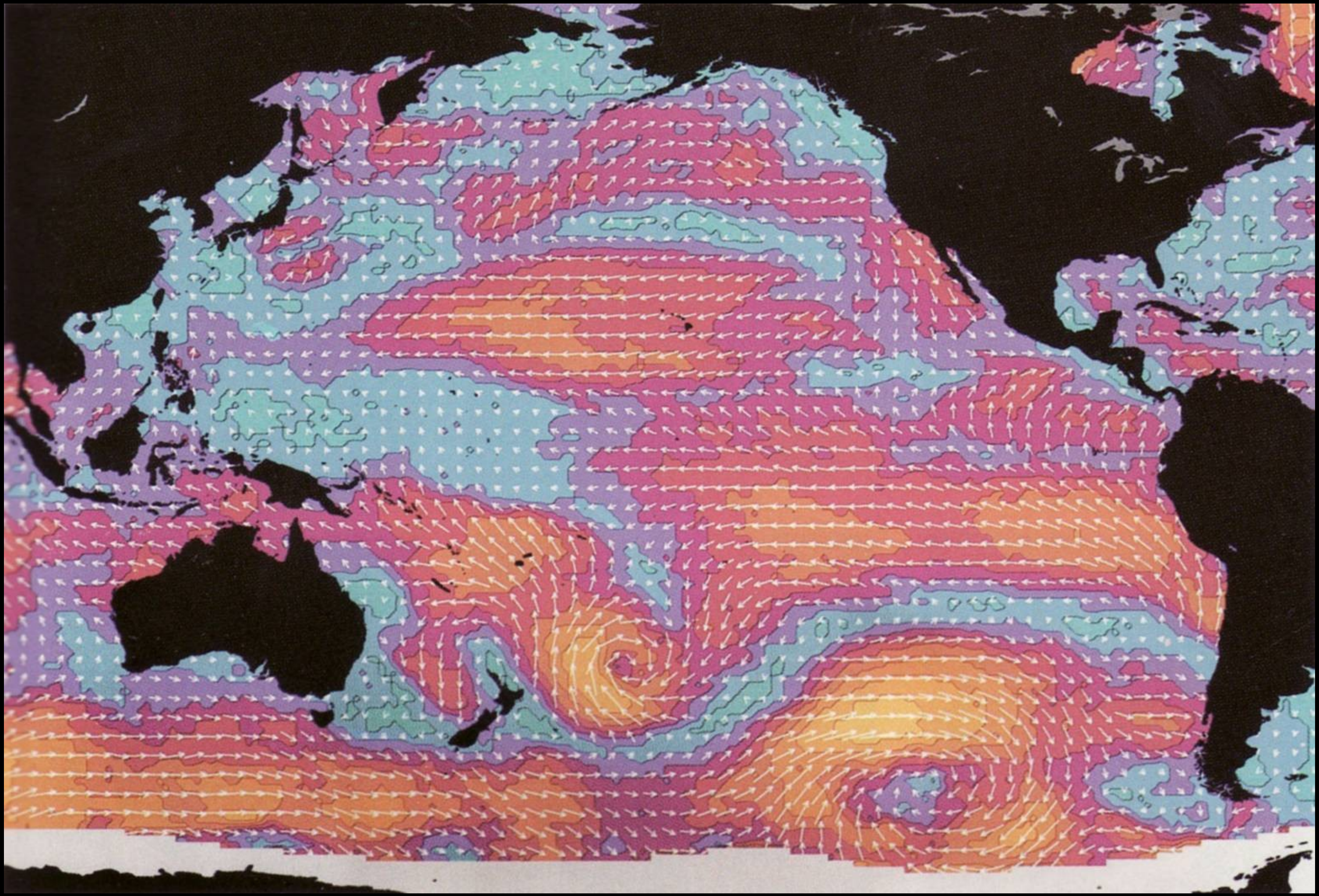
NSCAT CONFIGURATION



Spatial resolution: 25 km
inc. angle: 20 - 60 °

Wind speed and direction estimated by the SEASAT scatterometer

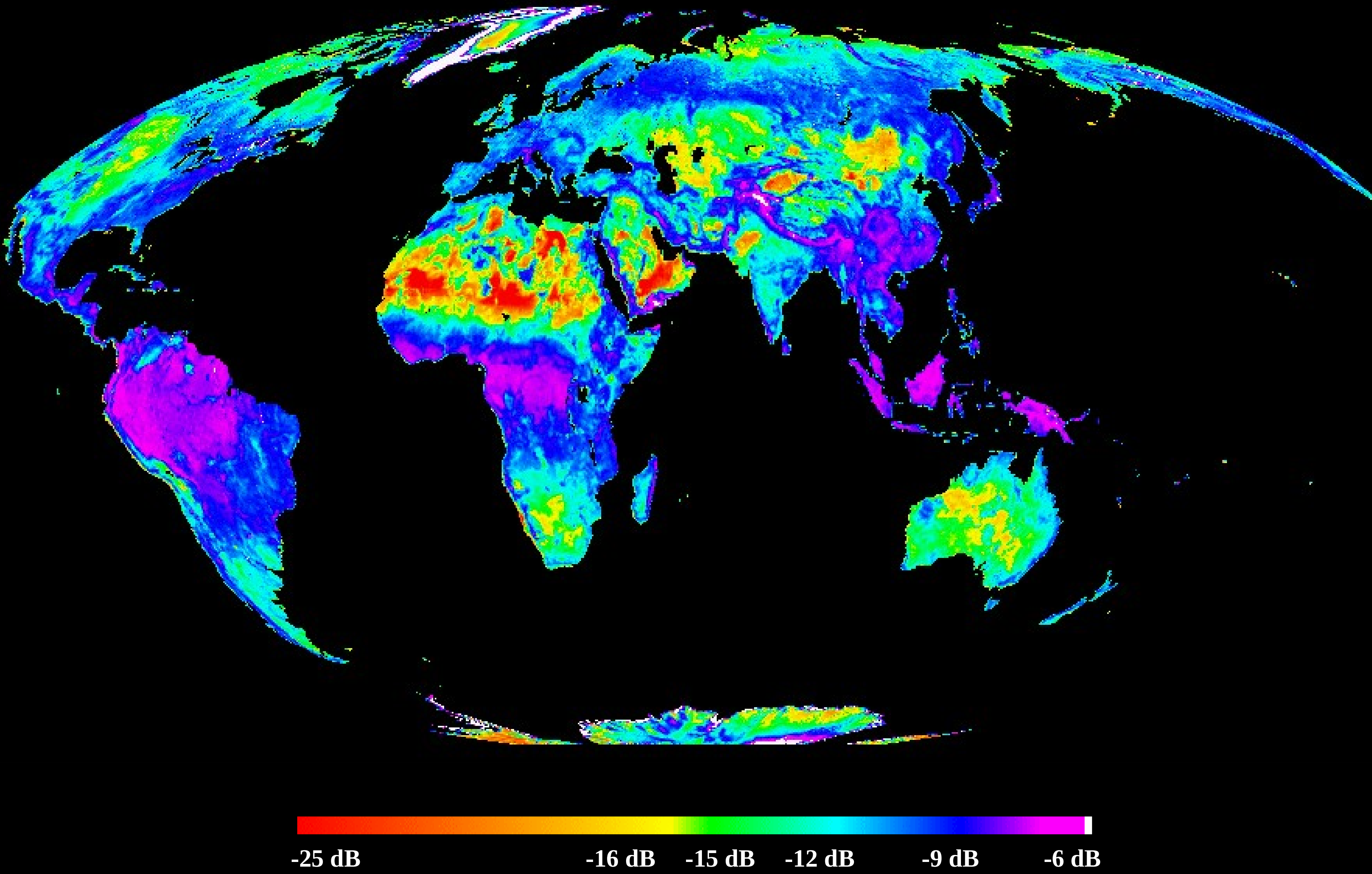
september 6 – 8 1978



Source: Elachi & Van Zyl

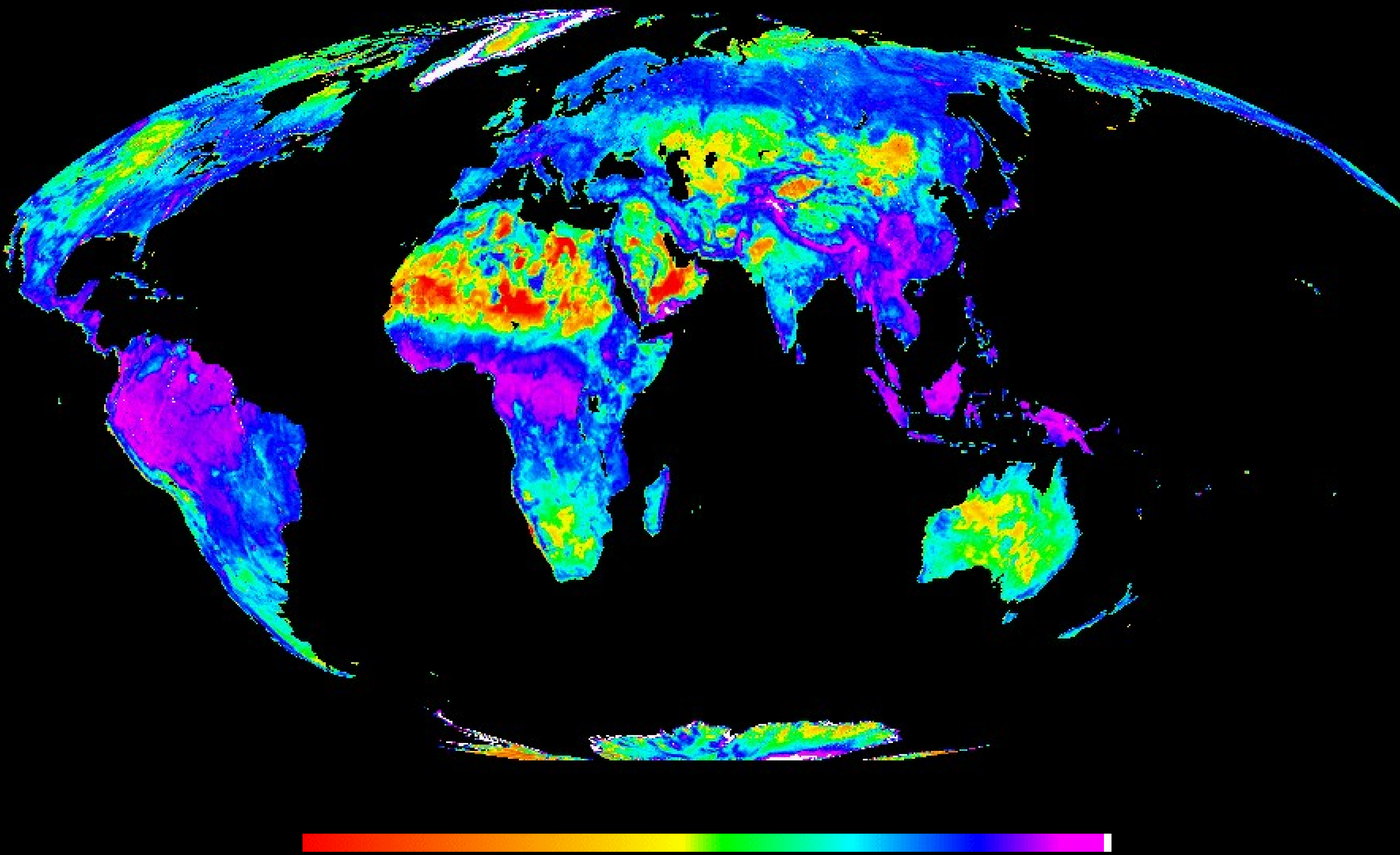
ERS Scatterometer ^{0}(40°)

May 1992



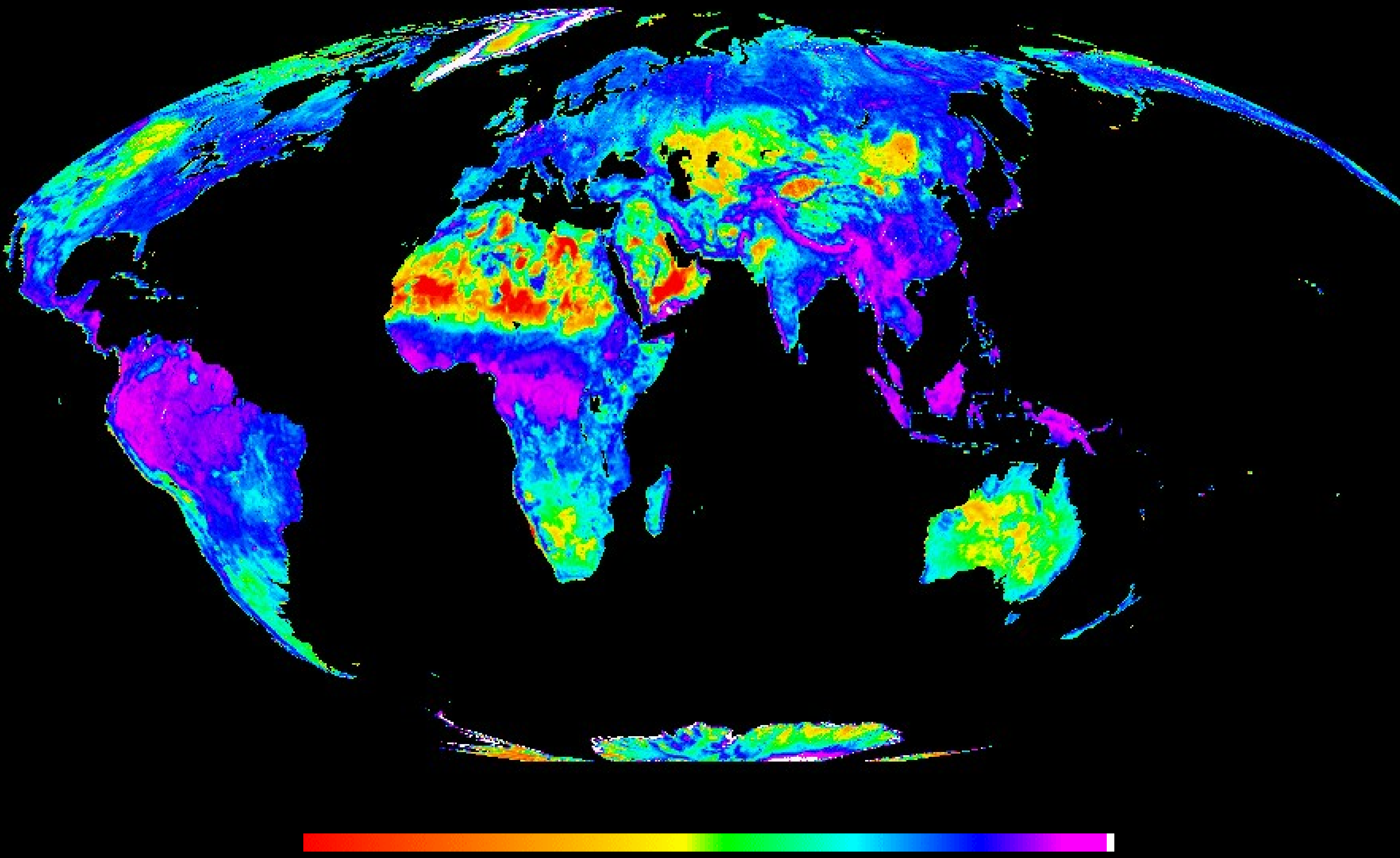
ERS Scatterometer ^{0}(40°)

June 1992



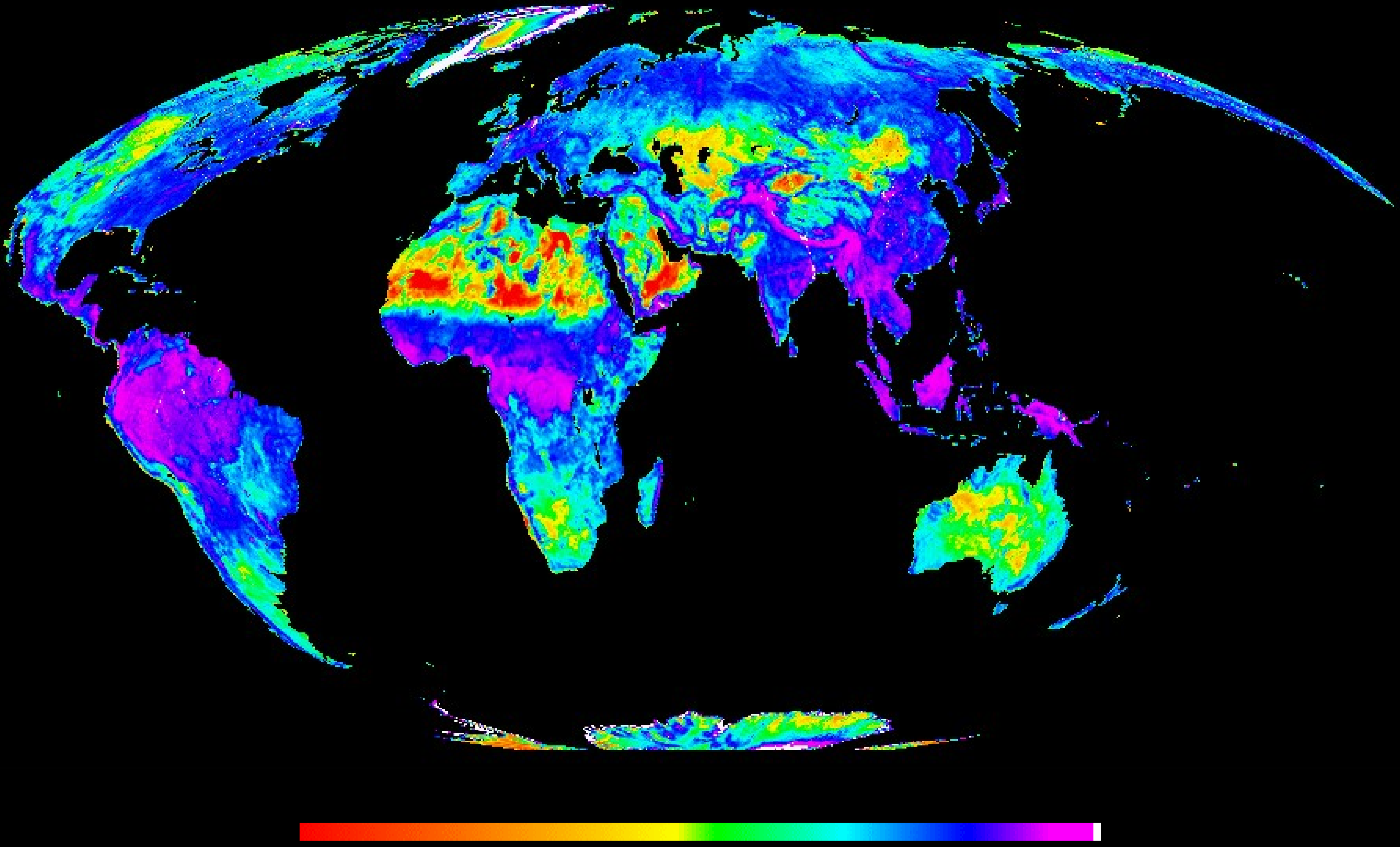
ERS Scatterometer ^{0}(40°)

July 1992



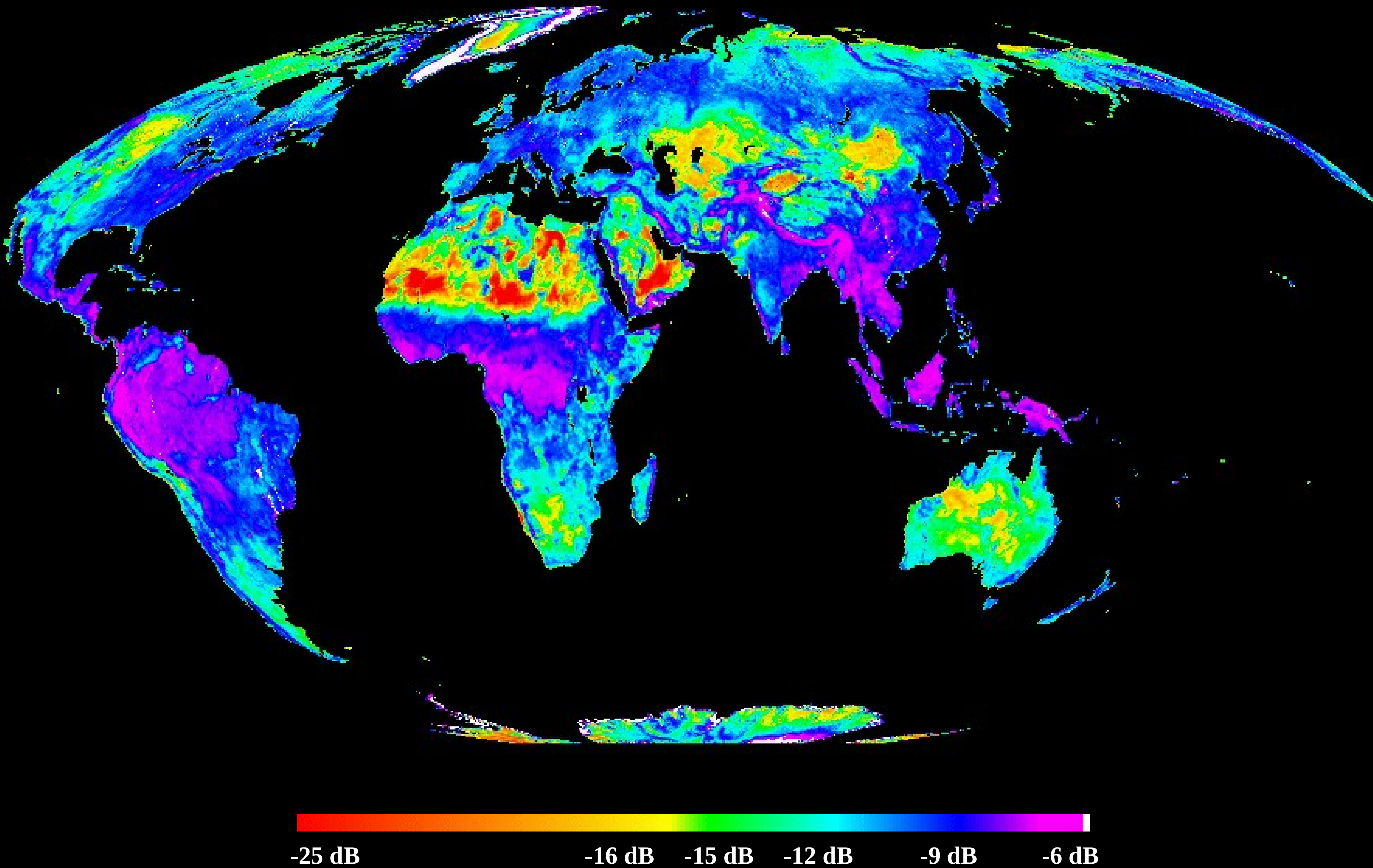
ERS Scatterometer $^{0}(40°)$

August 1992



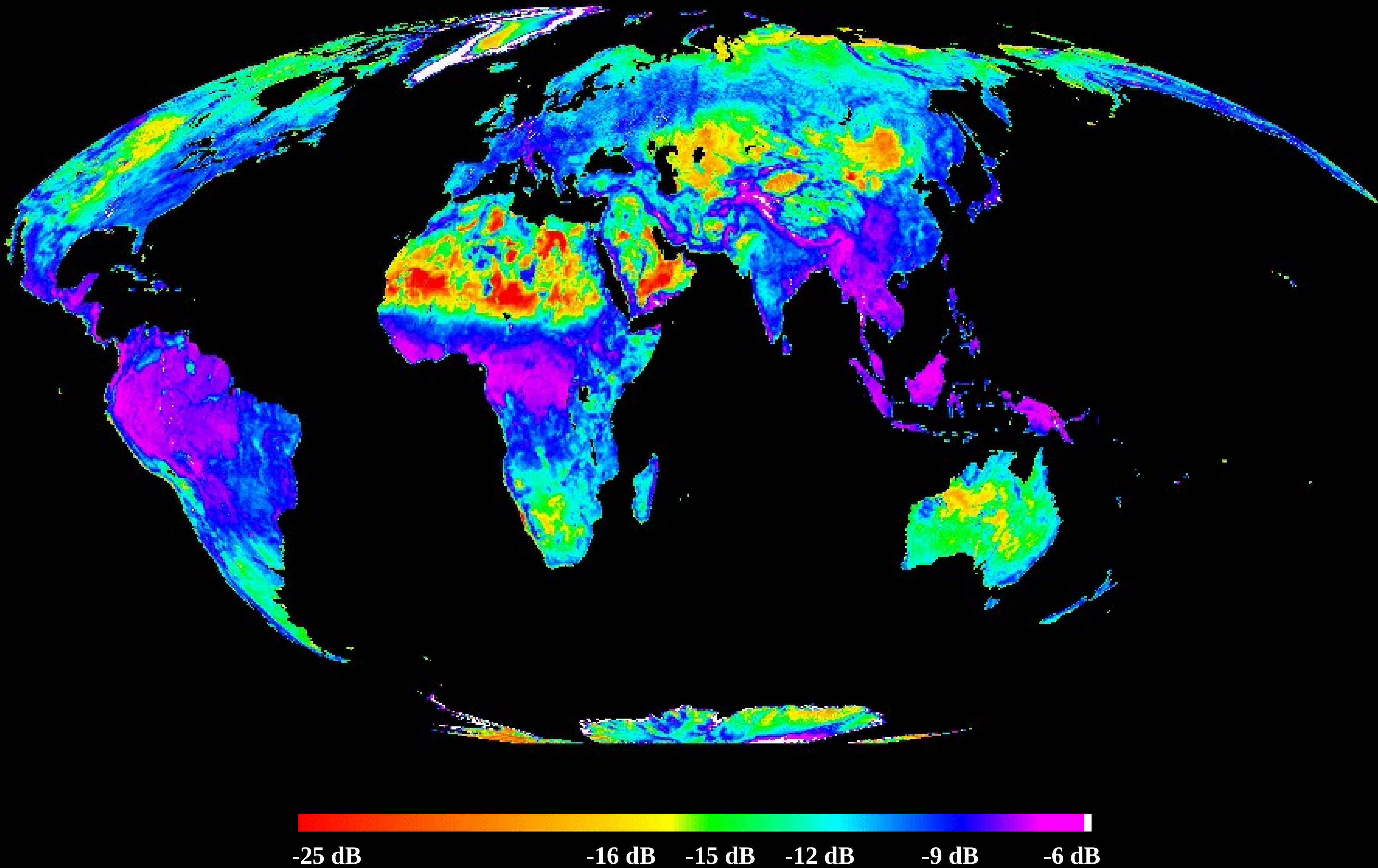
ERS Scatterometer ^{0}(40°)

September 1992



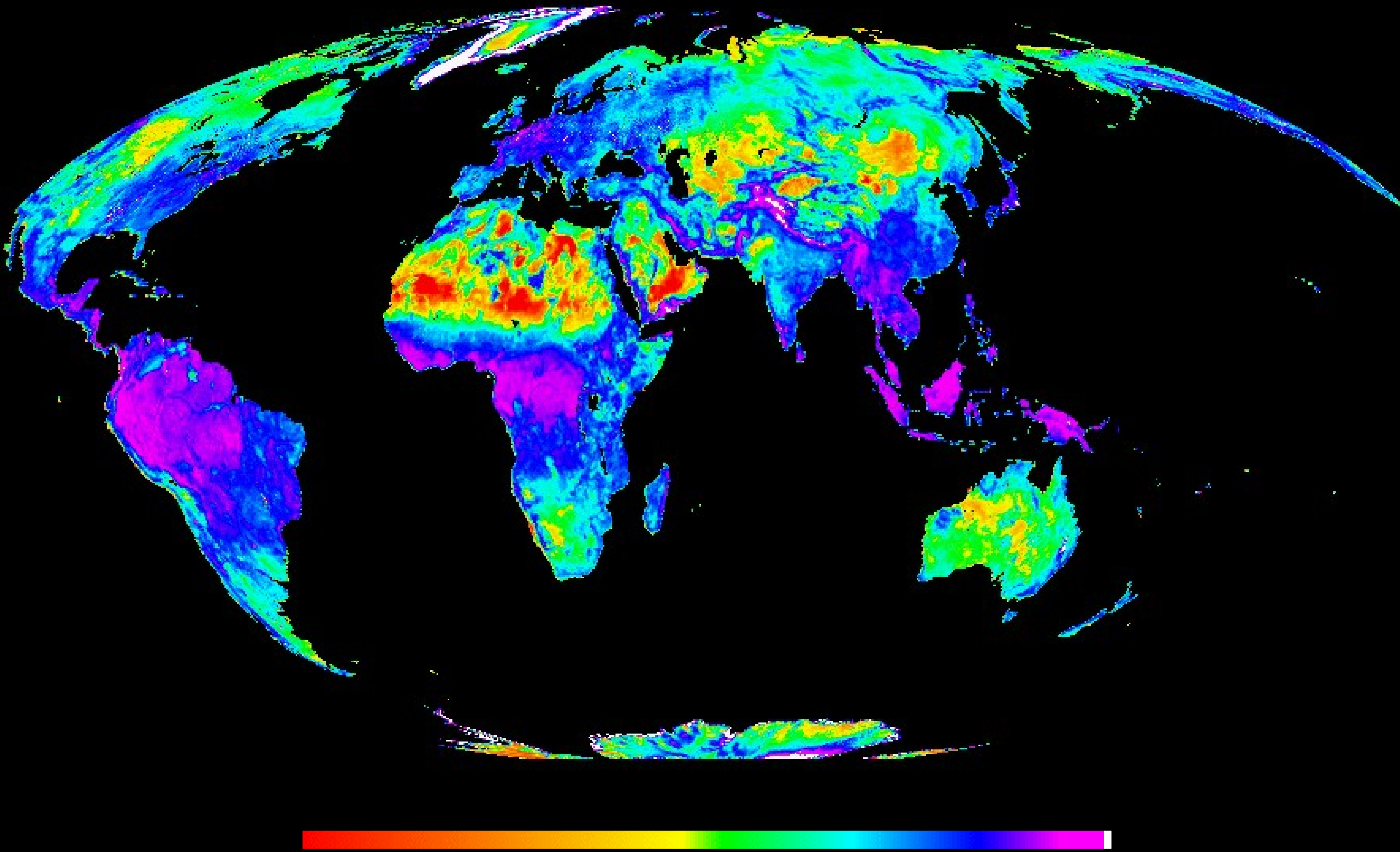
ERS Scatterometer ^{0}(40°)

October 1992



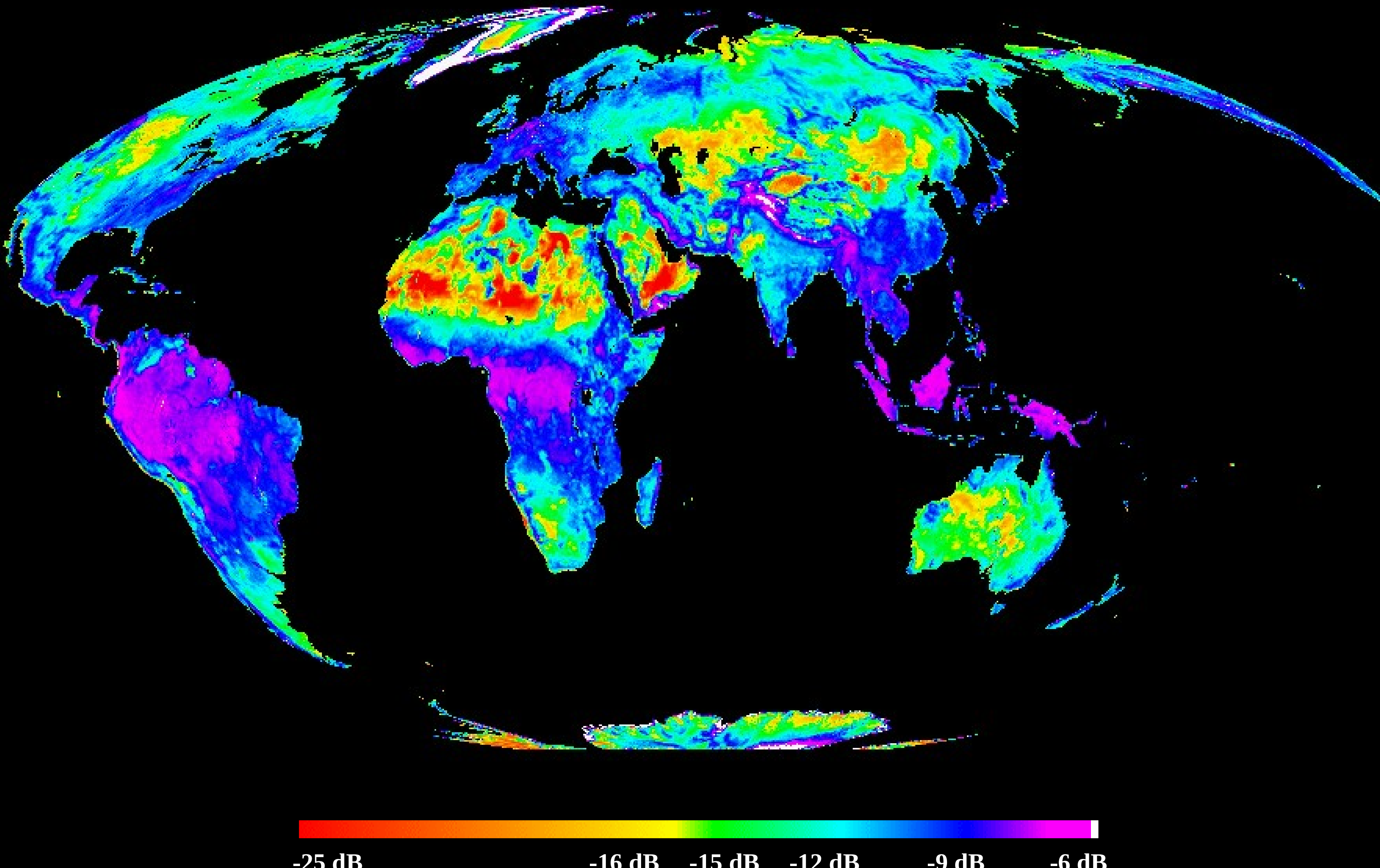
ERS Scatterometer $^{0}(40°)$

November 1992



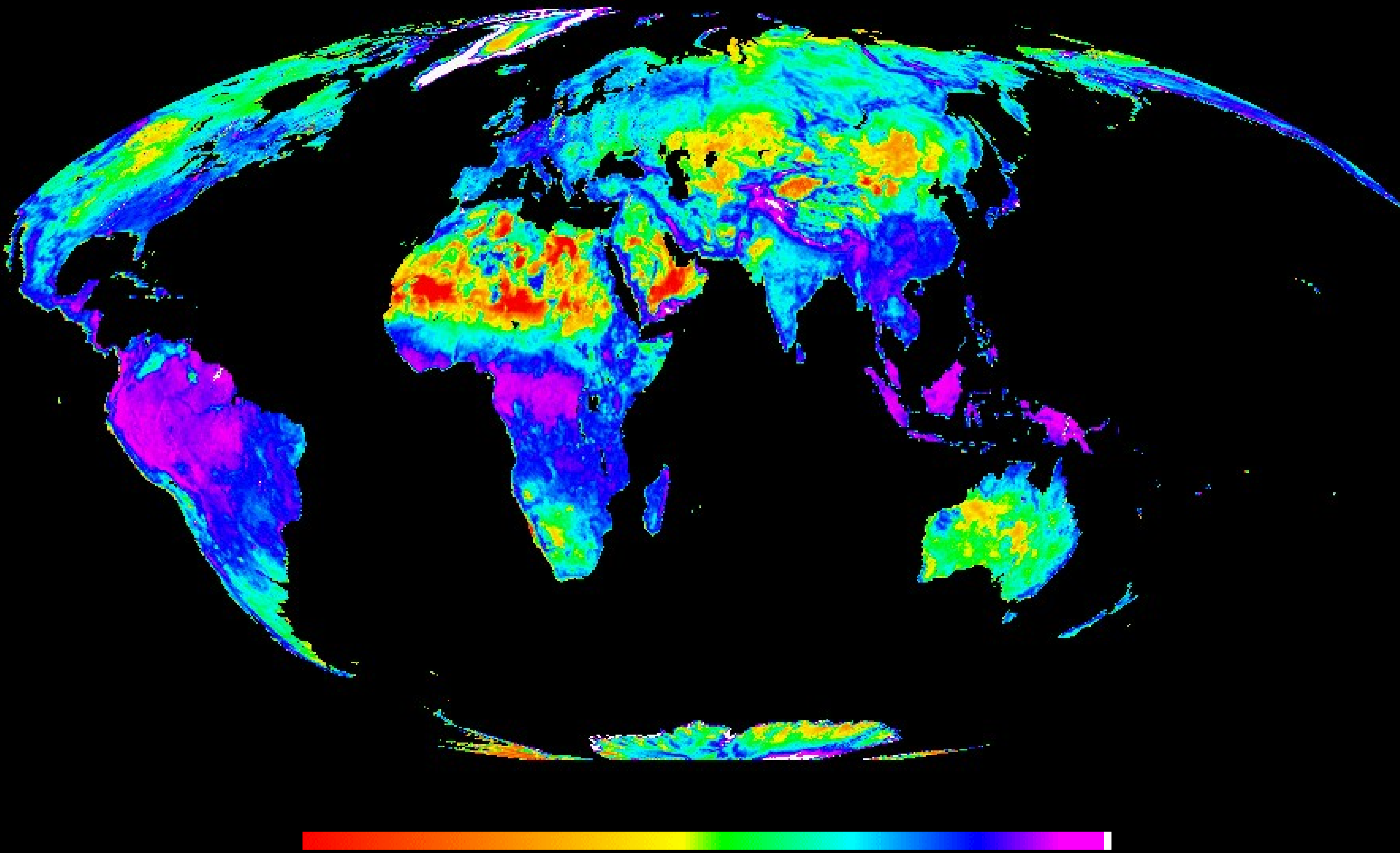
ERS Scatterometer $^{0}(40°)$

December 1992



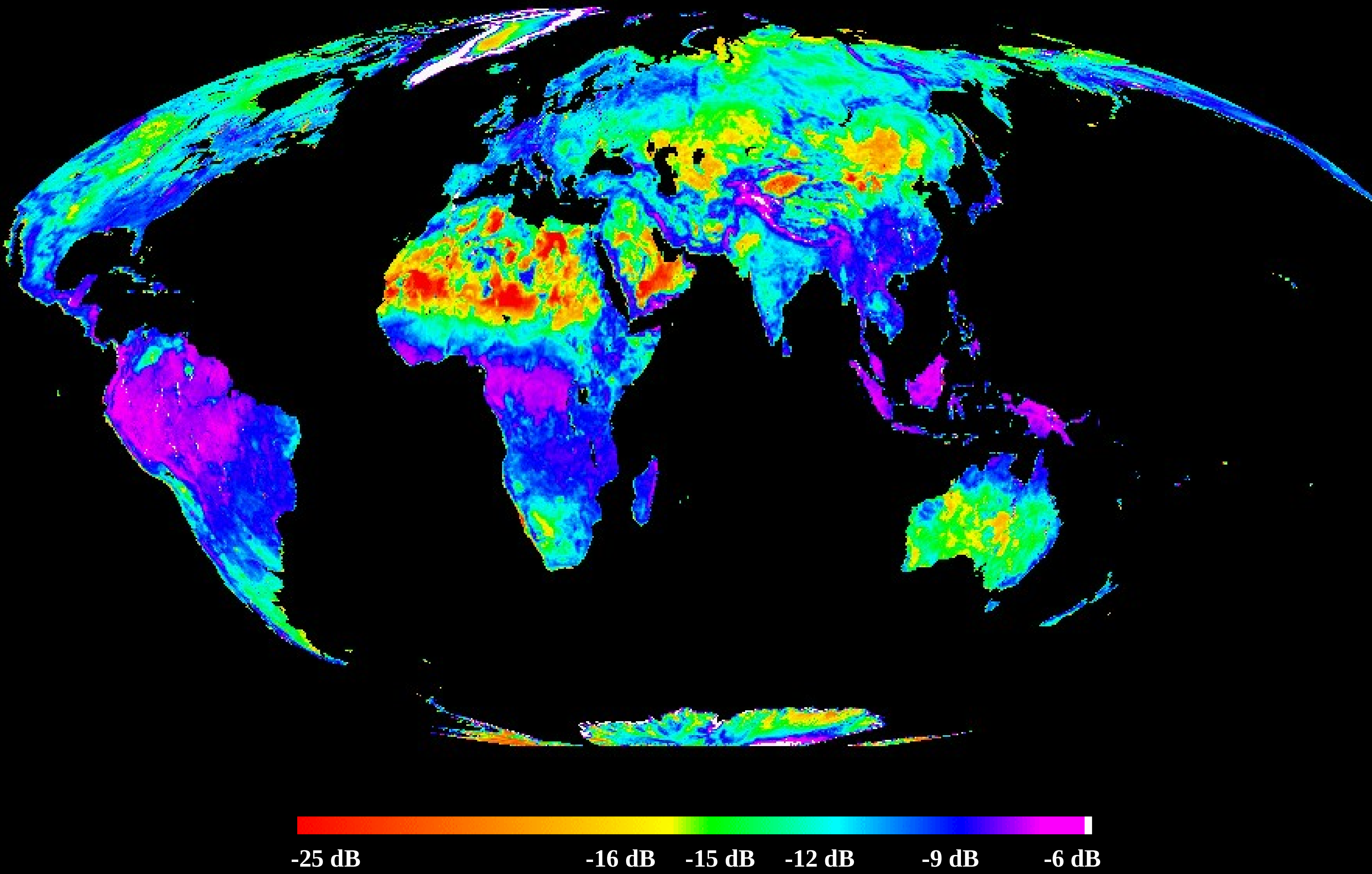
ERS Scatterometer ^{0}(40°)

January 1993



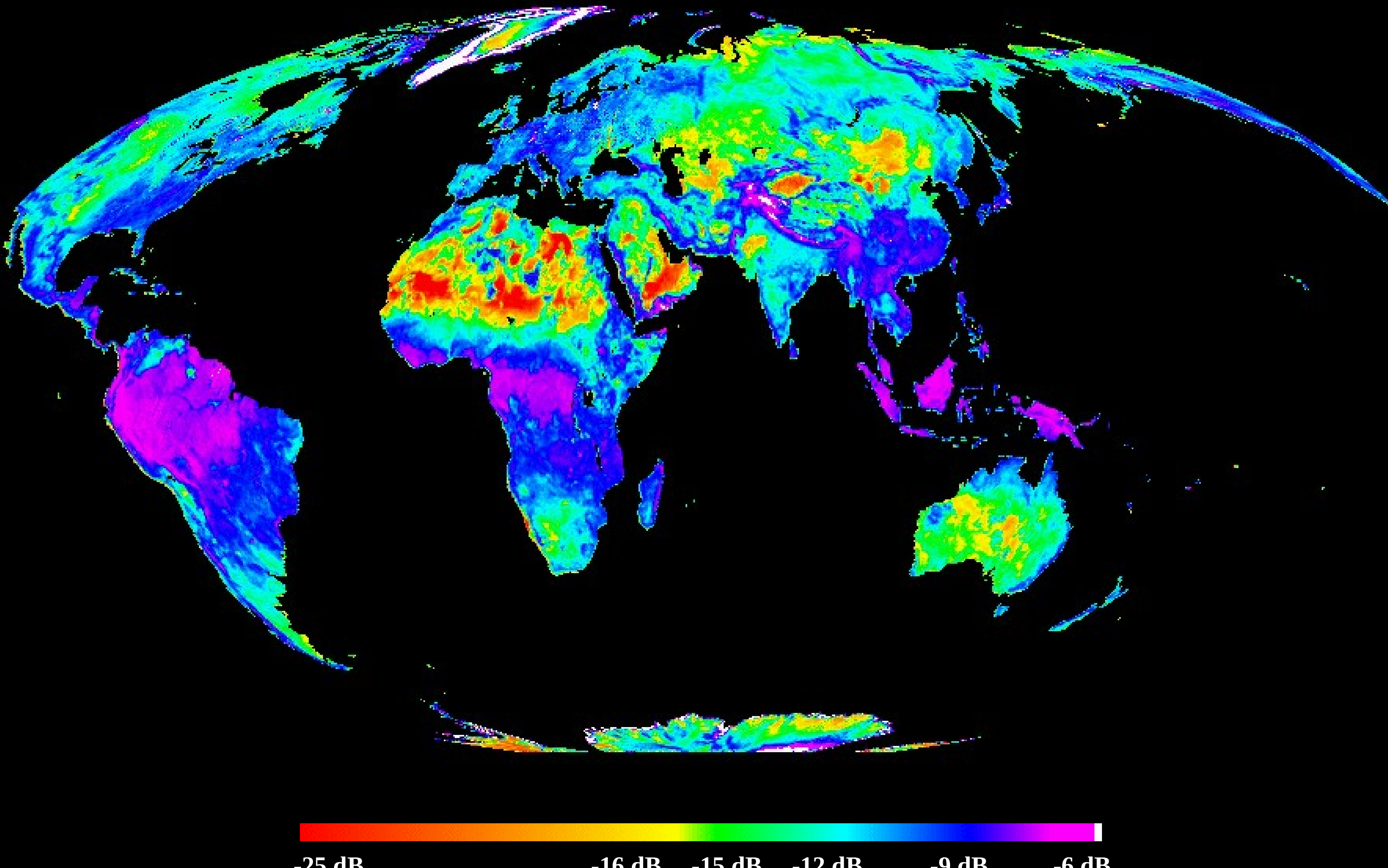
ERS Scatterometer $^{0}(40°)$

February 1993



ERS Scatterometer ^{0}(40°)

March 1993



ERS Scatterometer ^{0}(40°)

April 1993