Main characteristics of SAR images

Florence Tupin

Overview of the session

- **Backscattering mechanims**
- **Relief effects and geometry influence**
- **Speckle phenomenon**
  - Origine
  - Modeling
  - Multi-looking
  - Multiplicative noise model
- **Texture and log-statistics**

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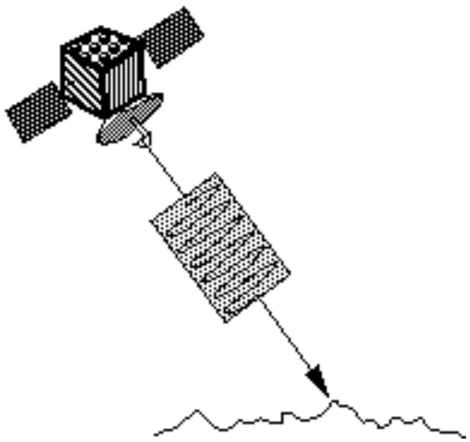
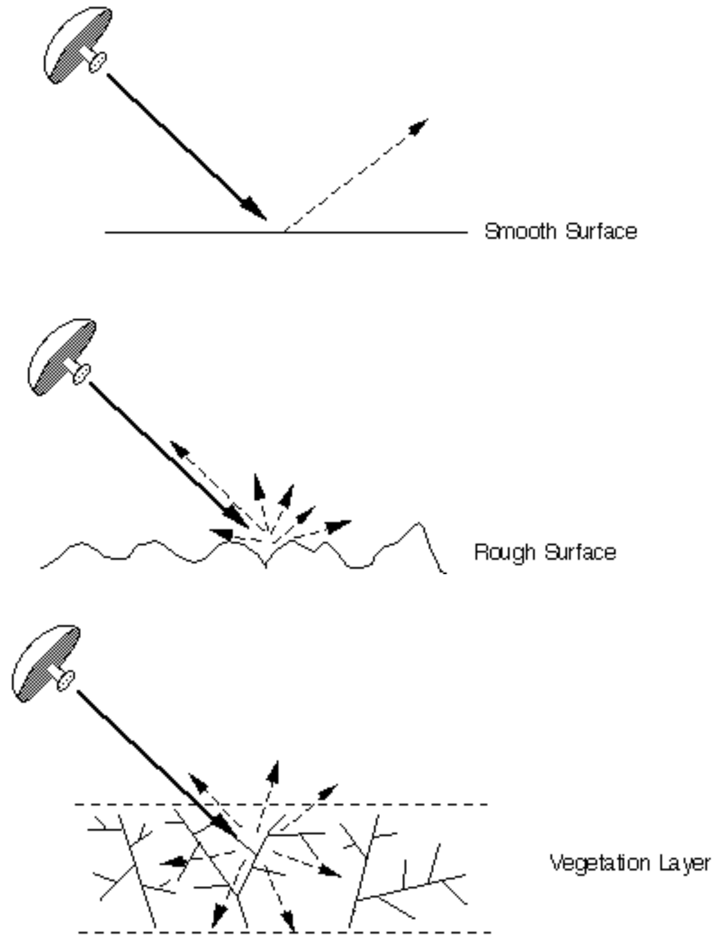
Backscattering mechanisms: surface and volume

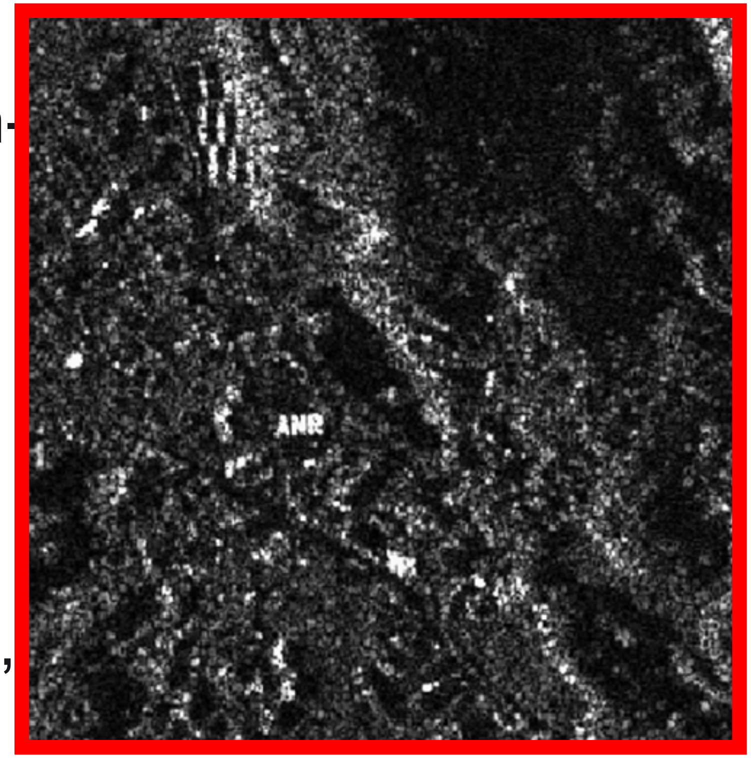




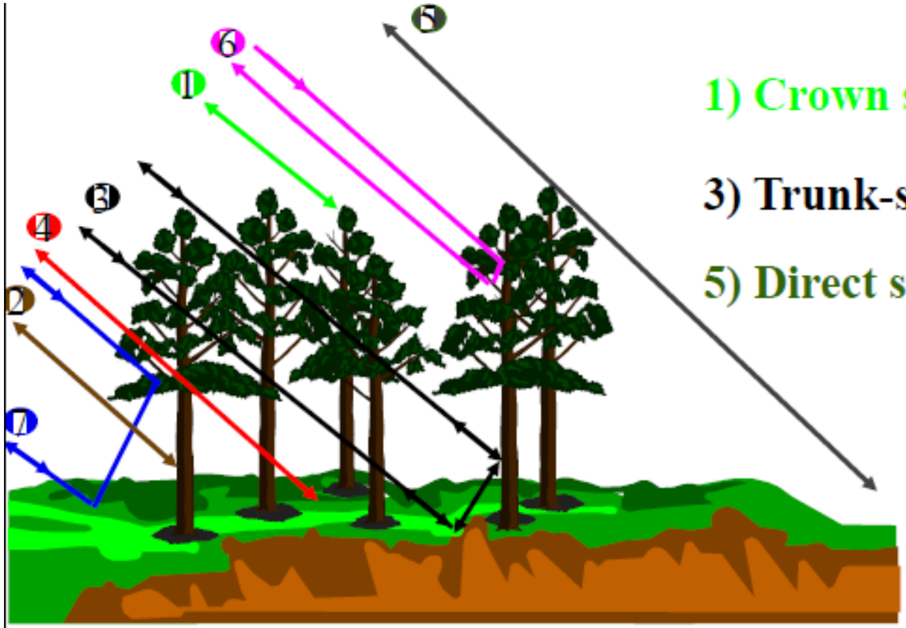
→ Strong influence on the backscattered radiometries

Targets and object appearance

- **Bright targets :**
  - Trihedral / dihedral structures (man-made objects, urban areas)
- **Surface area:**
  - Depends on the roughness
  - Depends on the geometric configuration
  - Dielectric properties (water content, humidity)
- **Many objects in the resolution cell:**
  - Speckle



Volume scattering mechanisms



1) Crown scattering

2) Trunk scattering

3) Trunk-soil interaction

4) Attenuated soil scattering

5) Direct soil scattering

6) Trunk-branch interaction

7) Soil-branch interaction

Examples of main backscattering mechanisms on the forest

◆ **Volume backscattering** mechanisms generally rely on interaction mechanisms which are highly **complex** and still not well-known. **Main trends**:

➔ Backscattering coefficient ➚ when vegetation volume (biomass) ➚

➔ Wavelength penetration ➚ when frequency ➘ , i.e. when wavelenght ➚

Backscattering of a cell

$$U_{\omega}(P,t) \approx \frac{1}{R(P)} \iint_{\Sigma} e^{j4\pi \frac{x \sin\theta}{\lambda}} A(x,y)\, ds$$

- **A(x,y) is characteristic of the imaged area**
- **A(x,y) can be complex :**
  - Amplitude : backscattering coefficient
  - Phase : delays or delocalisation inside the pixel
- **→Directivity of the backscattered signal : depends on A(x,y)**
  - The diagram of the local ground antenna is not known

Backscattering of a cell

$$U_{\omega}(P,t) \approx \frac{1}{R(P)} \iint_{\Sigma} e^{j4\pi \frac{x \sin\theta}{\lambda}} A(x,y)\, ds$$

- **An object on the ground is defined by its RCS (Radar Cross Section) or SER (Section Efficace Radar) :**
  - Depends on the material (dielectric properties, roughness)
  - Depends on the shape (geometry)
- **SER**
  - Ratio between emitted power and backscattered power
  - Depends of the antenna gain

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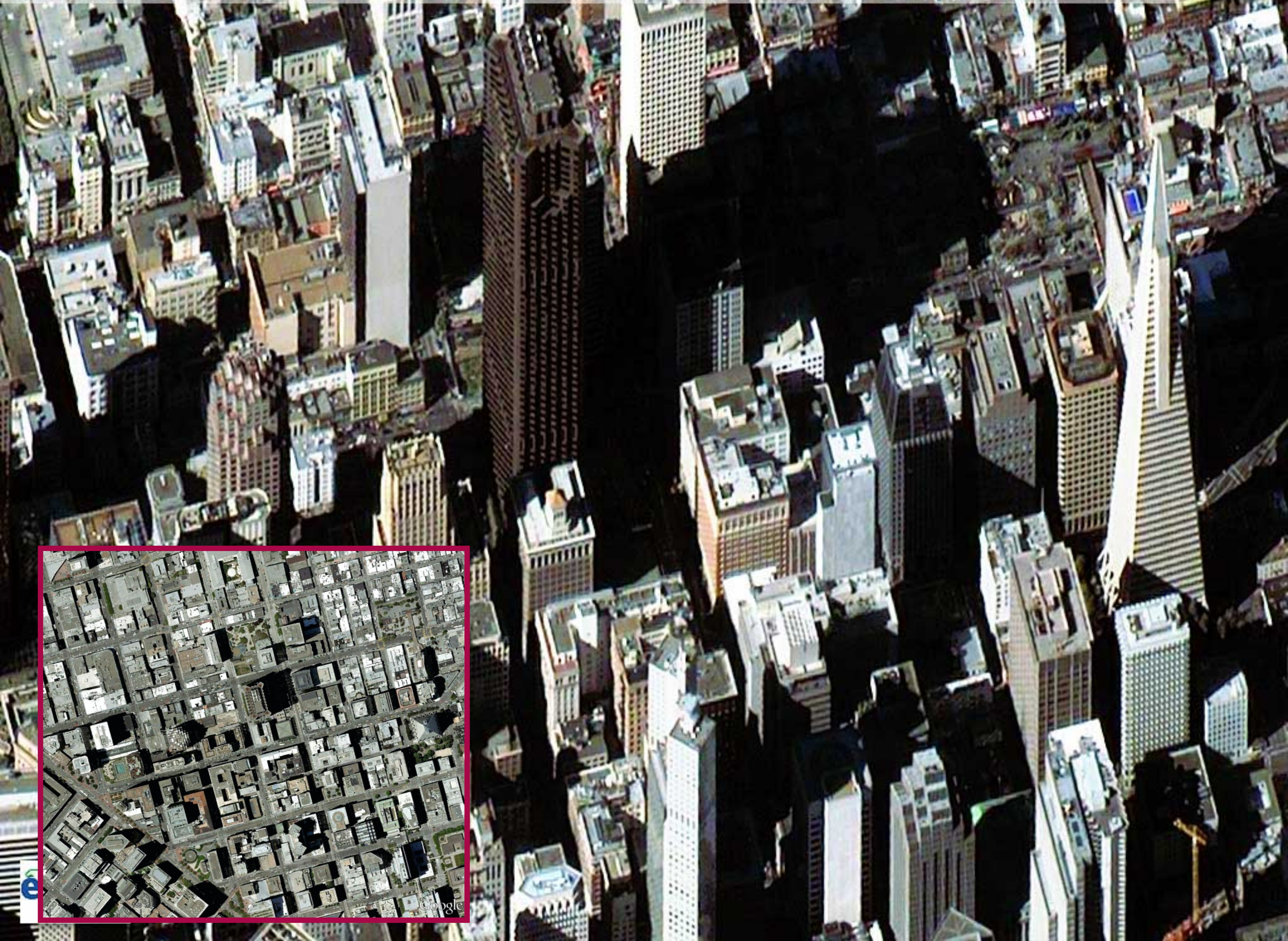
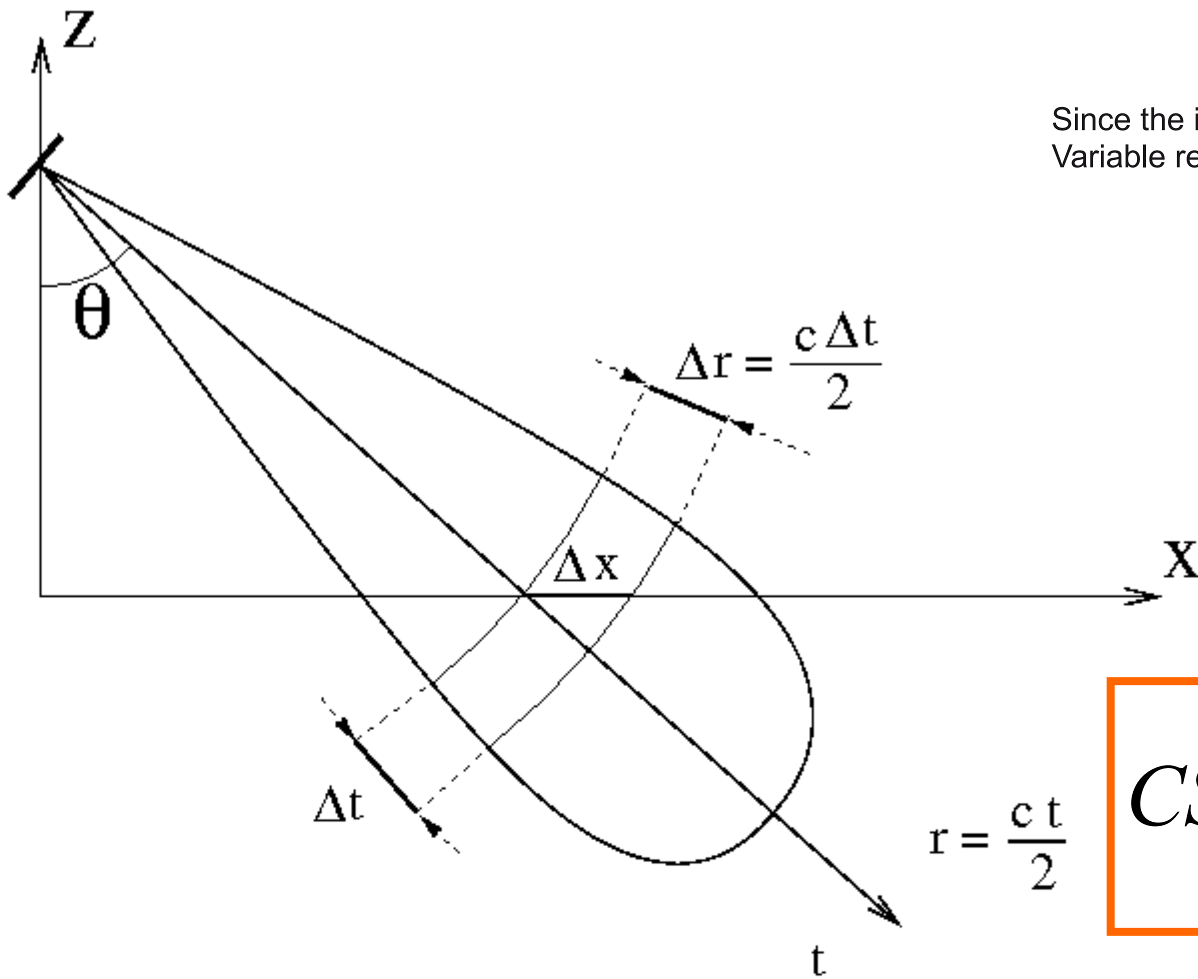
QuickBird San Francisco, December, 2001 Pan-sharpened



Influence of lateral viewing



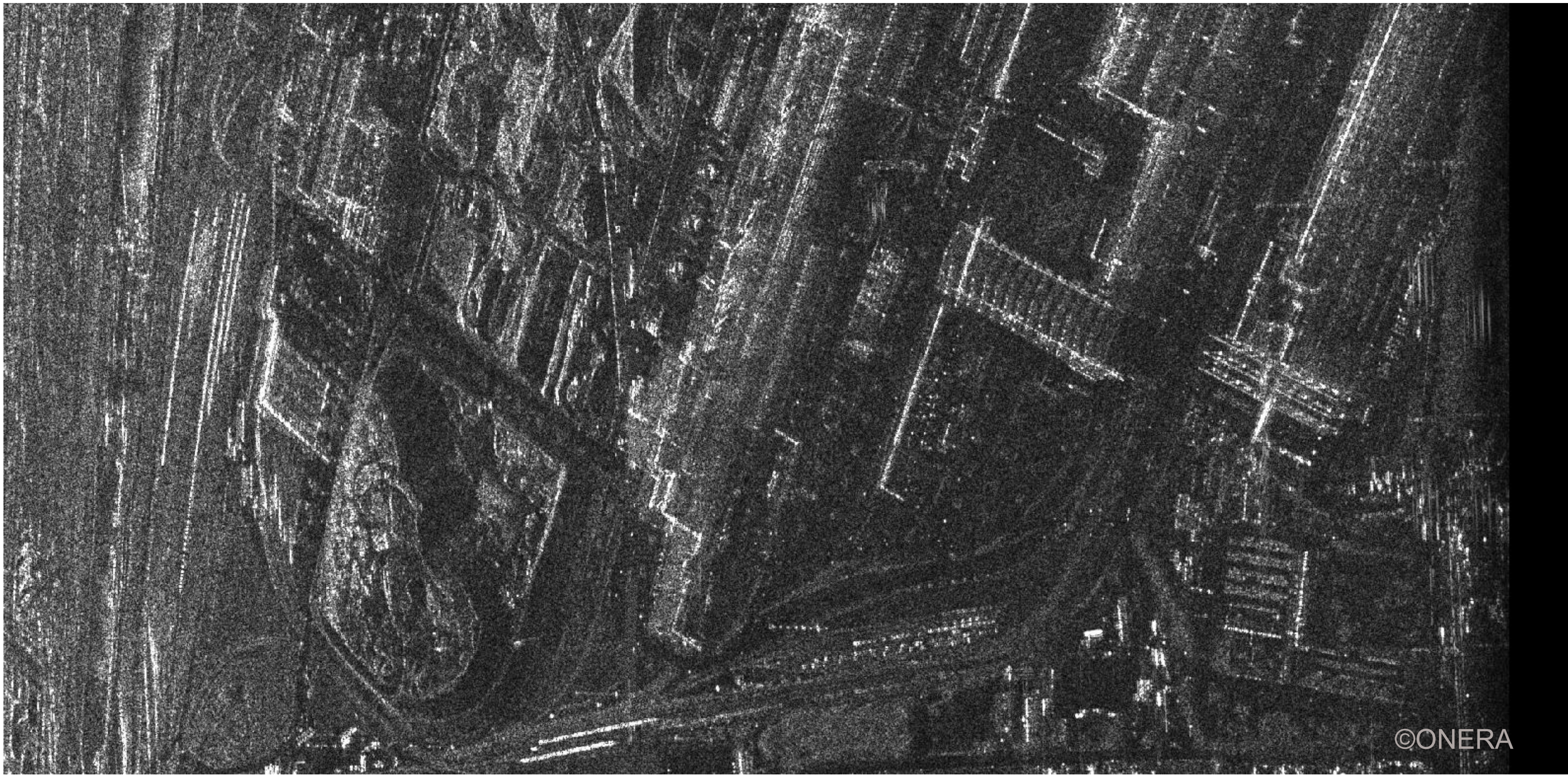
Since the incidence angle varies along the swath:
Variable resolution from near range to far range

$$CS = \Delta x = \frac{\Delta r}{\sin(\theta)}$$

Geometrical distorsions
Variable incidence angle: variable resolution

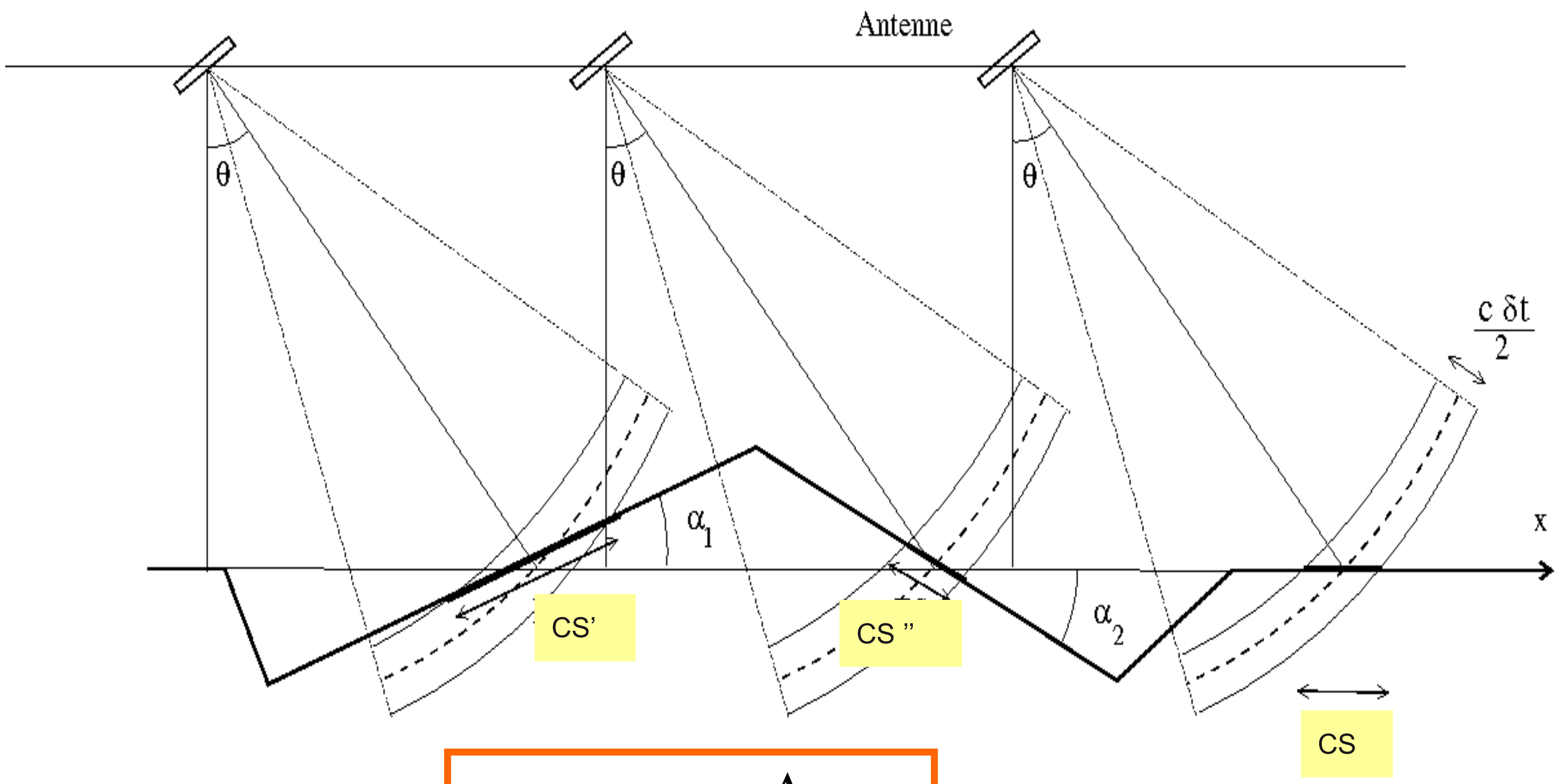
θ=6°, dx

θ=60°, dx/10



Airborn system: same δr, variable δx along the swath

Influence of relief on cell size



$$CS(\alpha) = \frac{\Delta r}{\sin(\theta - \alpha)}$$

Effets de la variation de la case sol en fonction de la pente locale : le Cap Vert

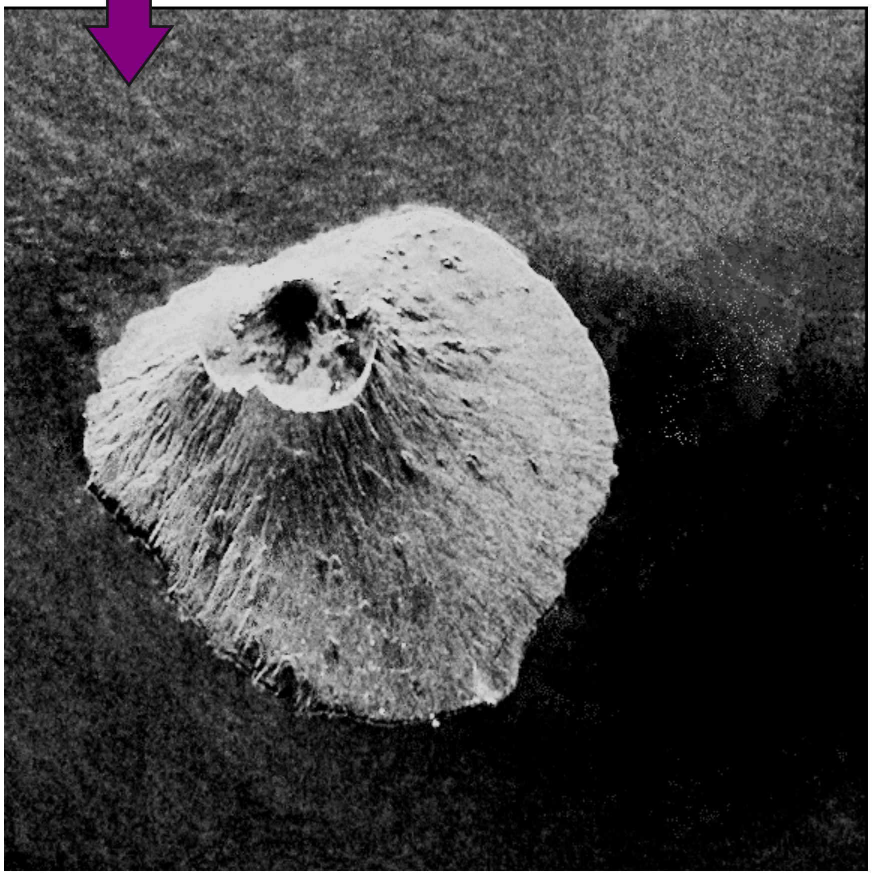
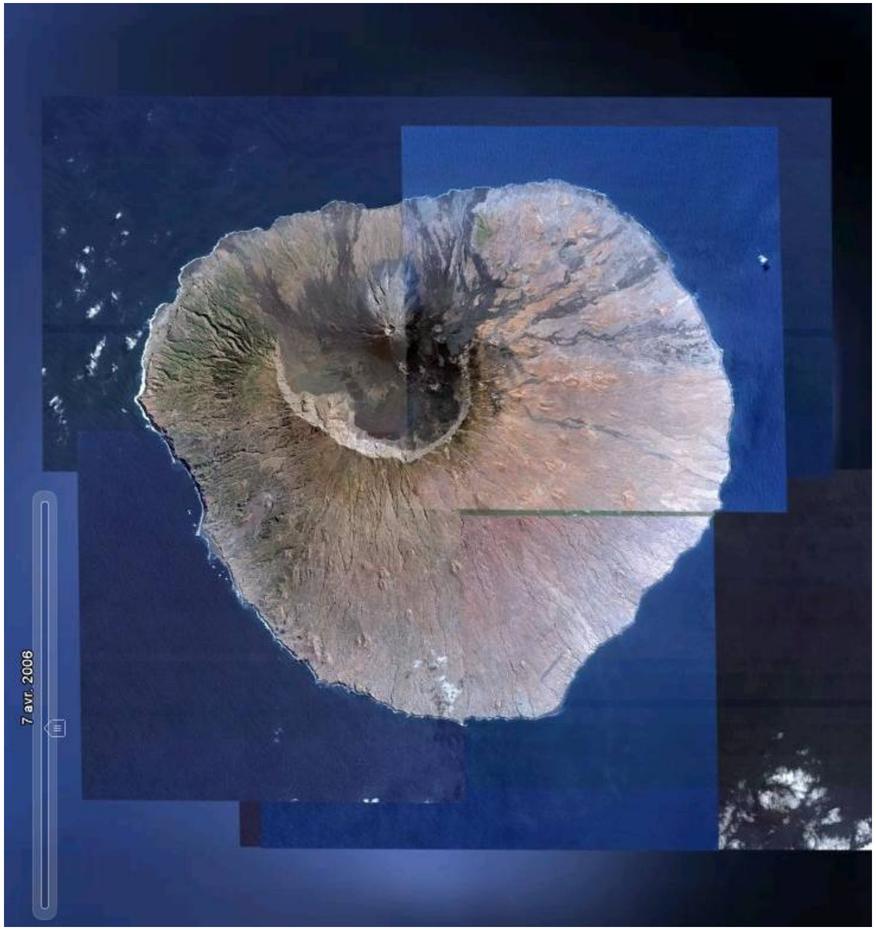
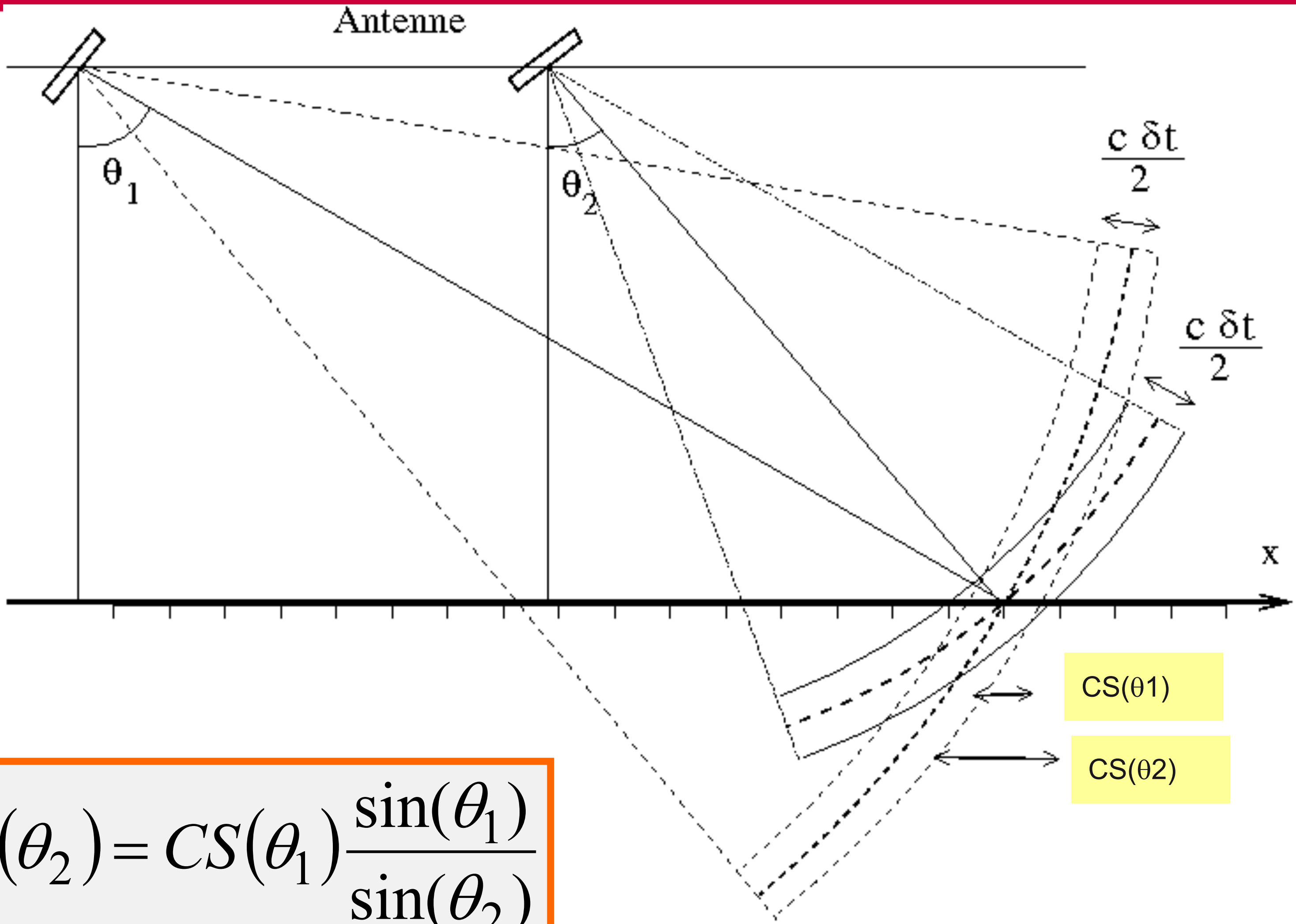


Image ERS



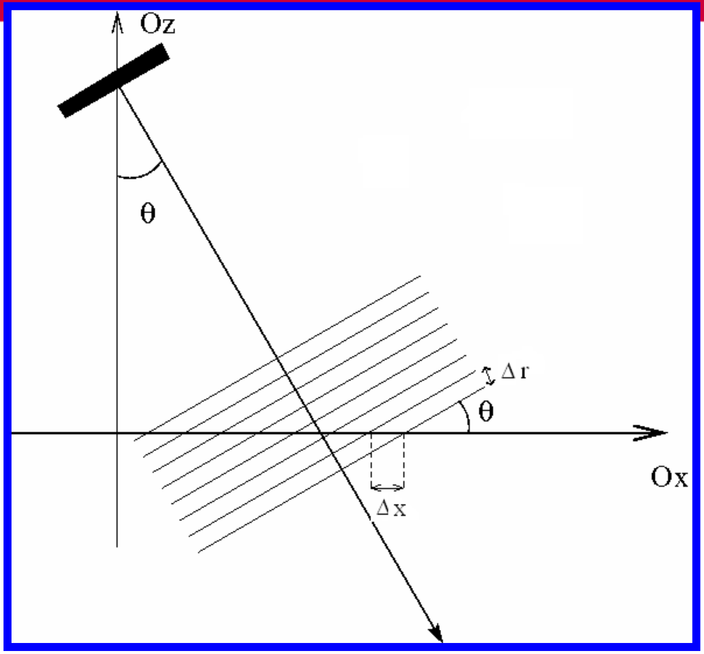
Mosaïque sur Google

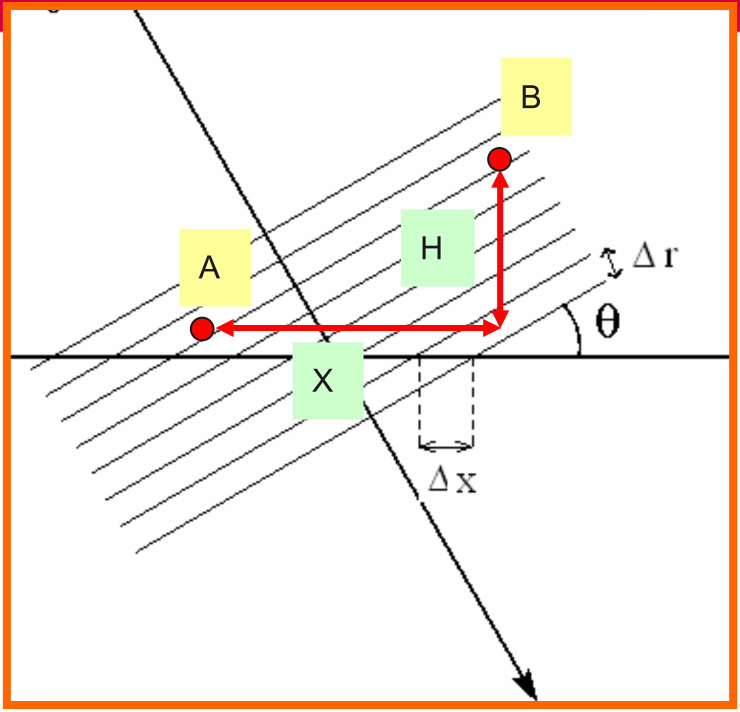
Cell size and local slope



$$CS(\theta_2) = CS(\theta_1)\frac{\sin(\theta_1)}{\sin(\theta_2)}$$

Ground range: Case $\alpha = \theta$





- Range cell : Δr
- Ground range : Δx
- Influence of local slope

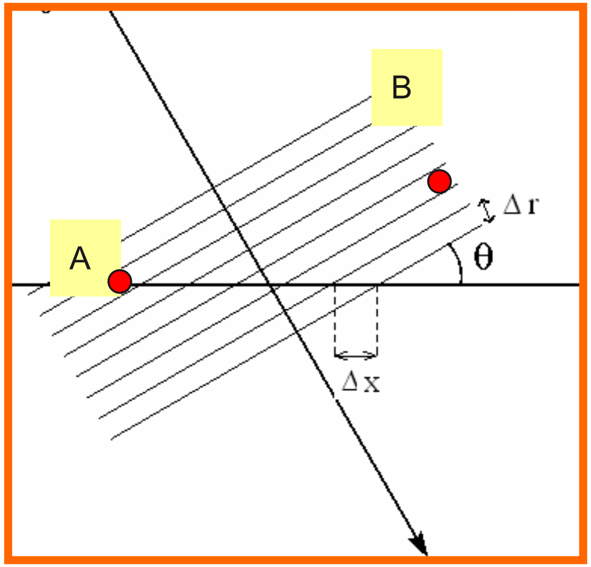
A and B in the same range cell

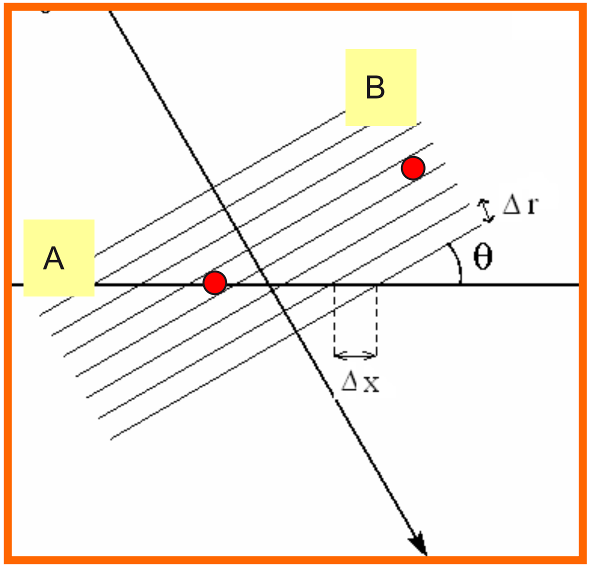
Relation between X, H et θ

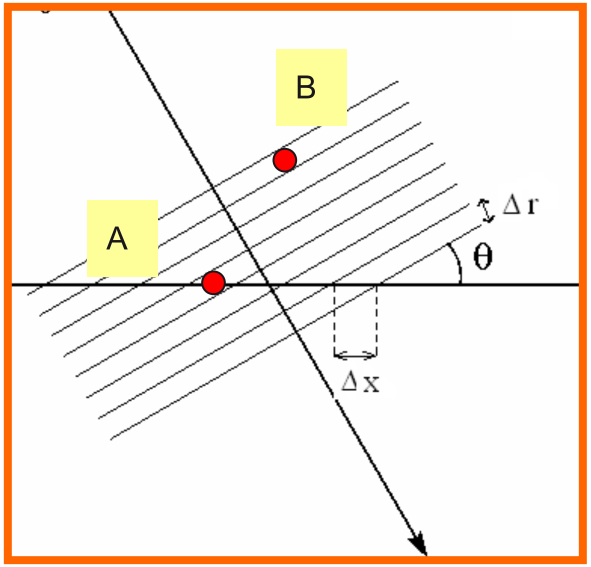
$$\tan\theta = \frac{H}{X}$$

TELECOM ParisTech

Relief – lay-over





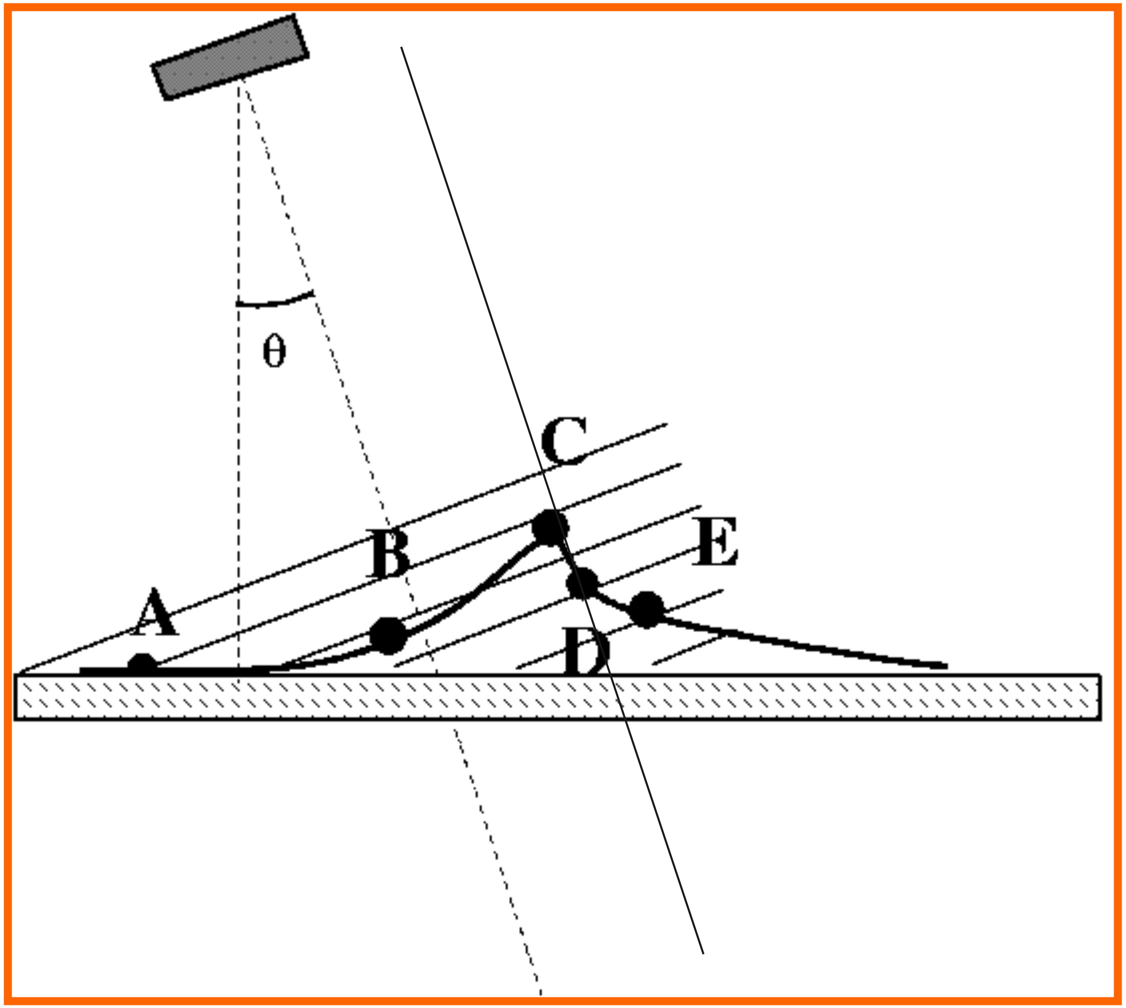


- **Weak slope : A first, then B**
- **Slope = incidence angle: A and B in the same cell**
- **Strong slope : B first, then A : « lay-over »**

- Lay-over condition:

$$H > X \tan \theta$$

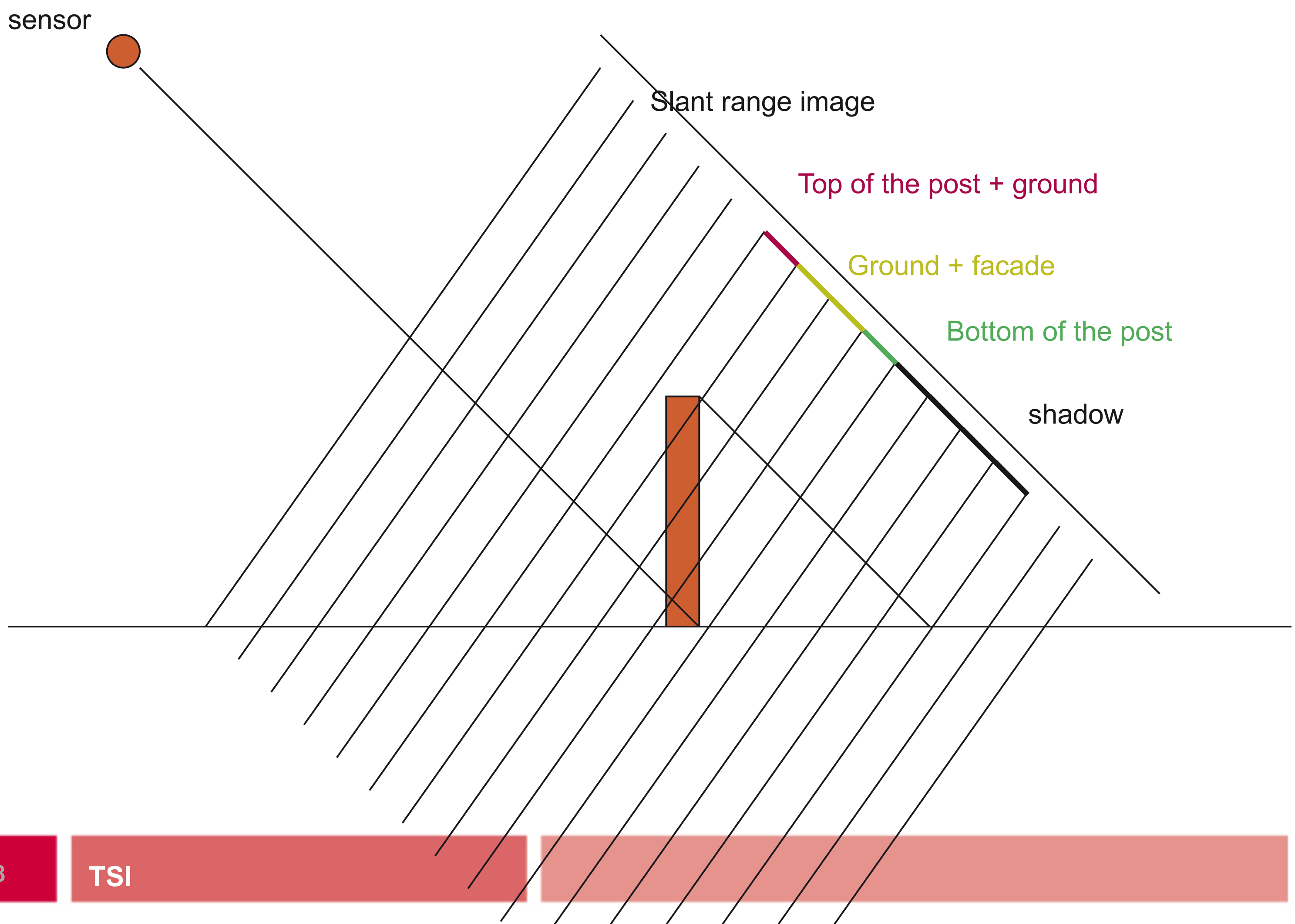
Relief – geometric distorsions



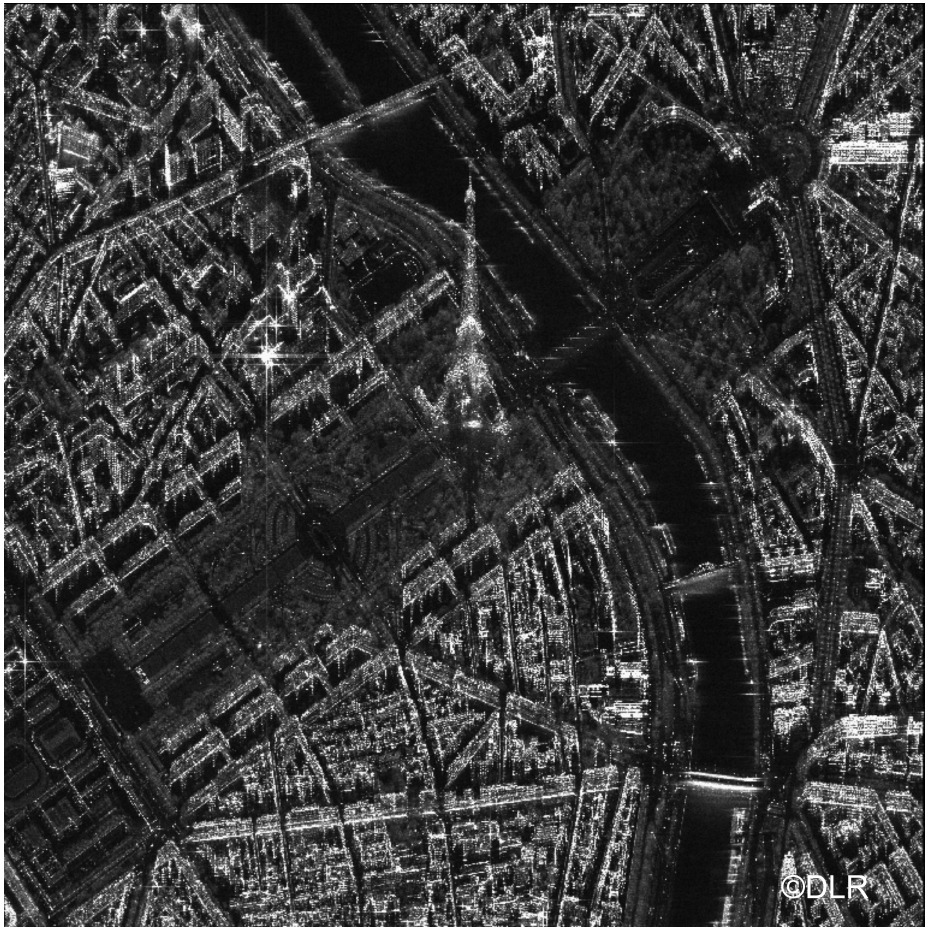
- Lay-over: C and A
- Inversion: C before B
- Shadow: D

Geometrical distorsions
Lay-over / shadow

■ **Example of a vertical post**



Eiffel tower

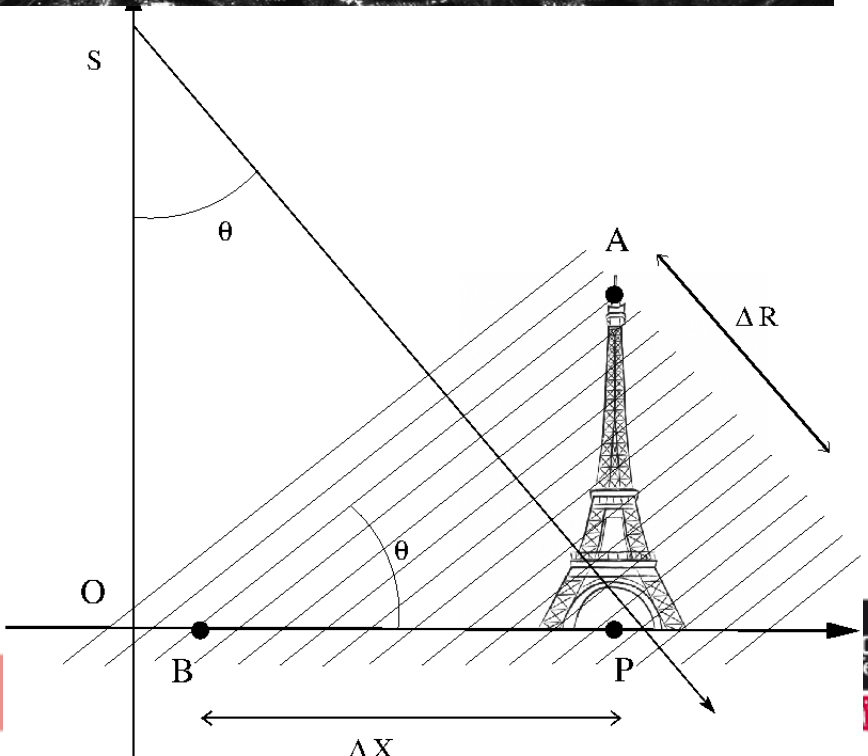


Lateral viewing

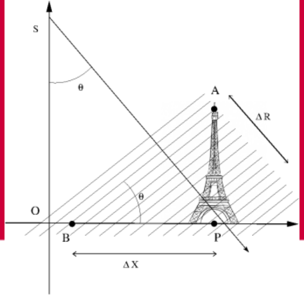
- Terrasar-X, θ~34°
- Relationship between h and BP

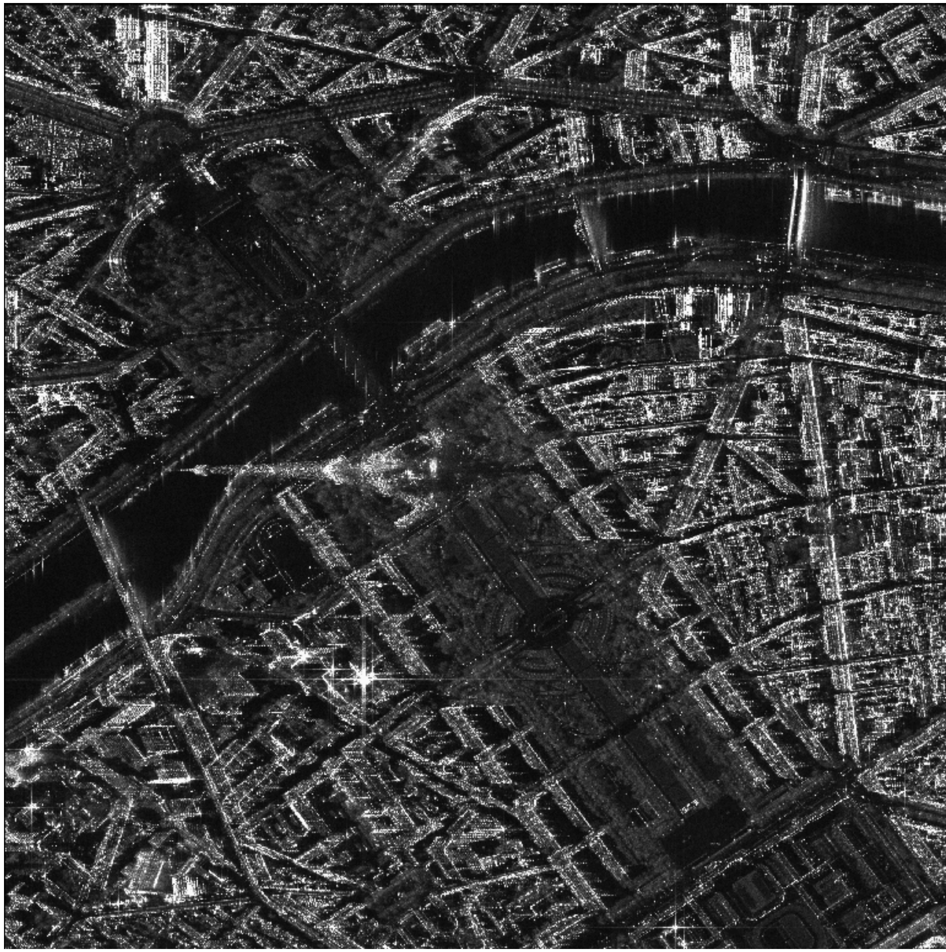
$$H = \Delta X \tan \theta$$

$$H = \frac{\Delta R}{\cos \theta}$$



Urban areas: optic / SAR





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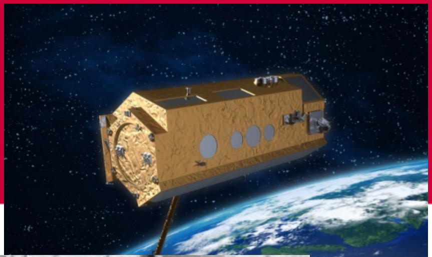
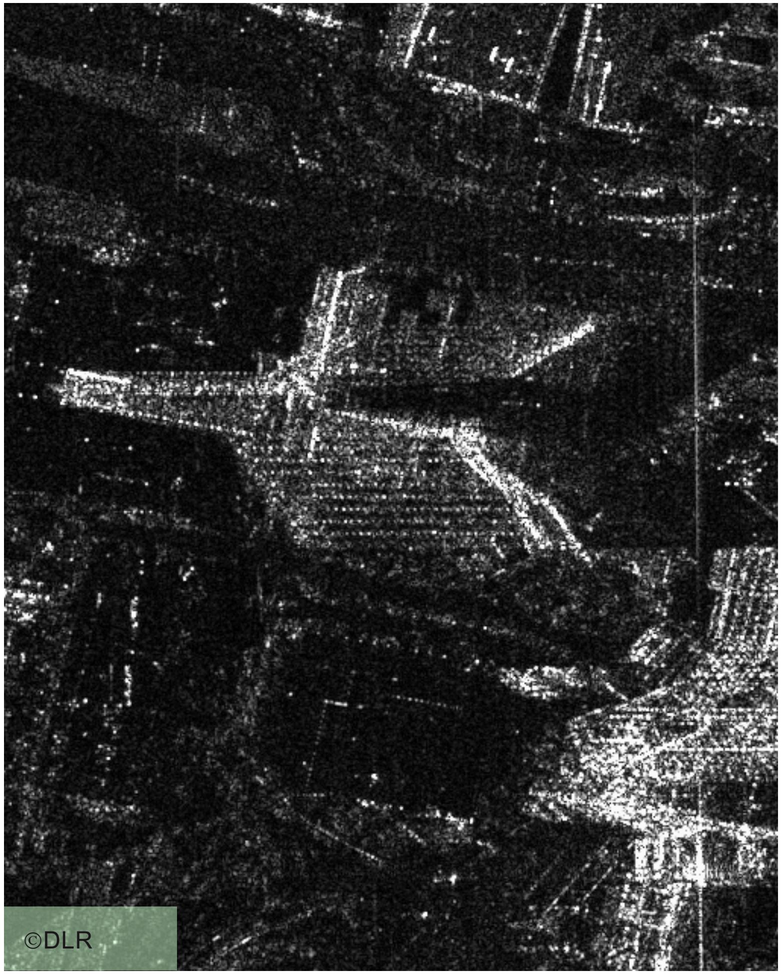
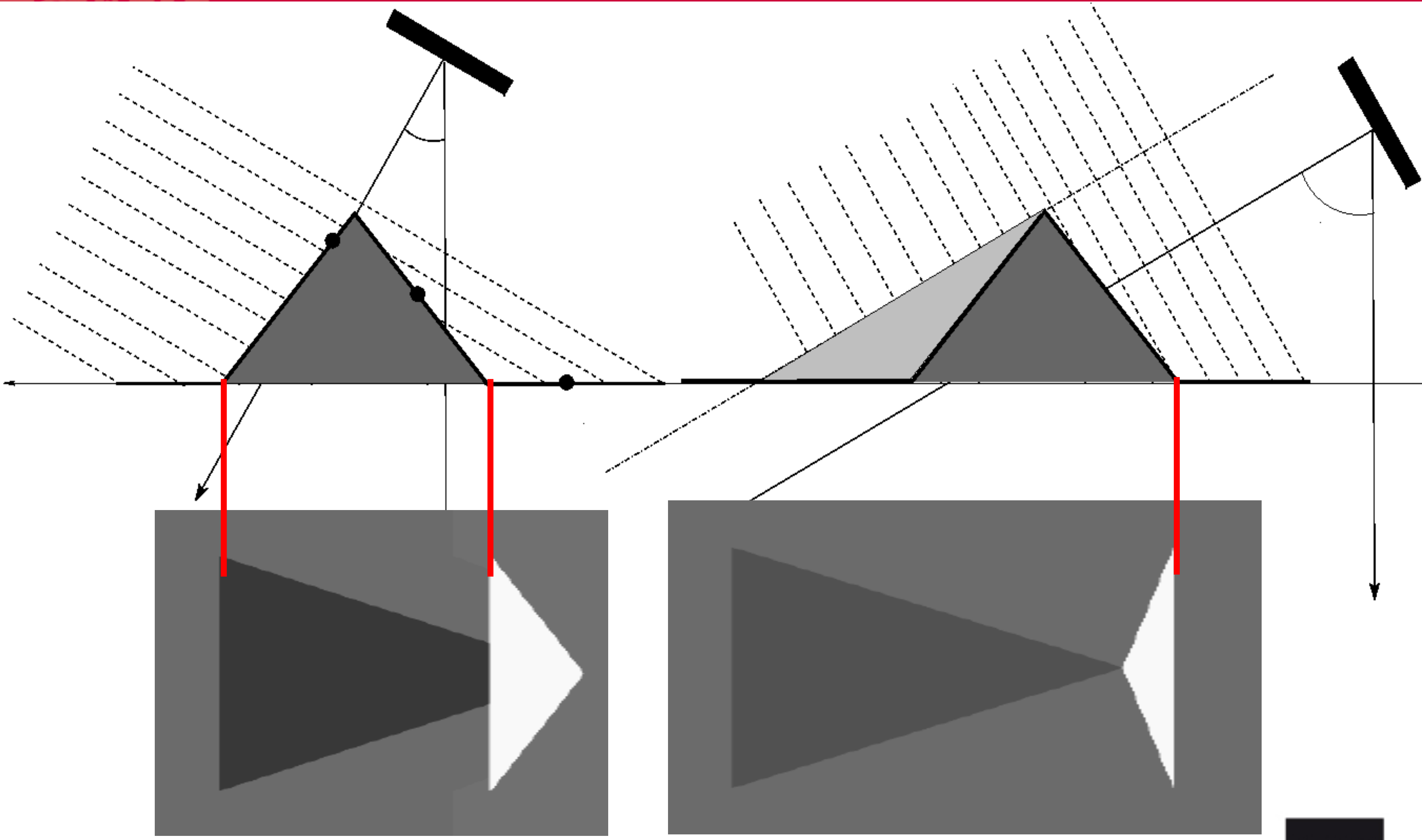
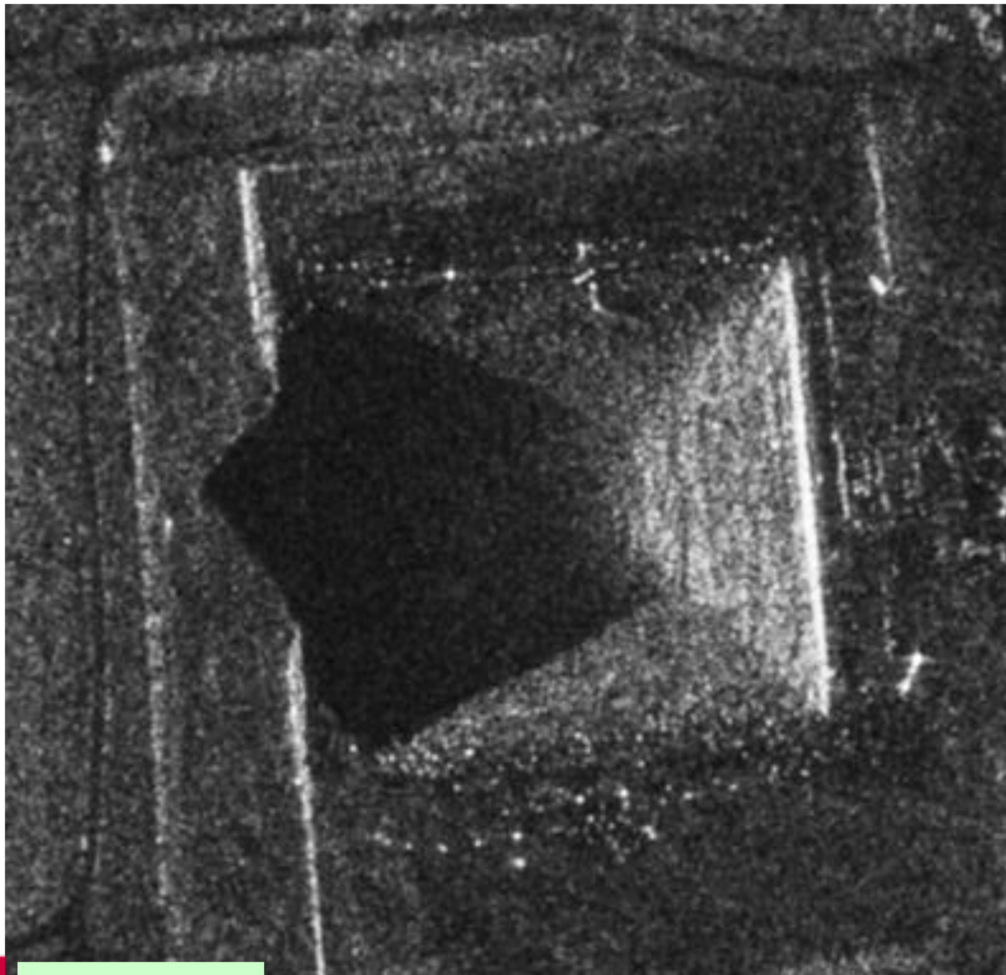


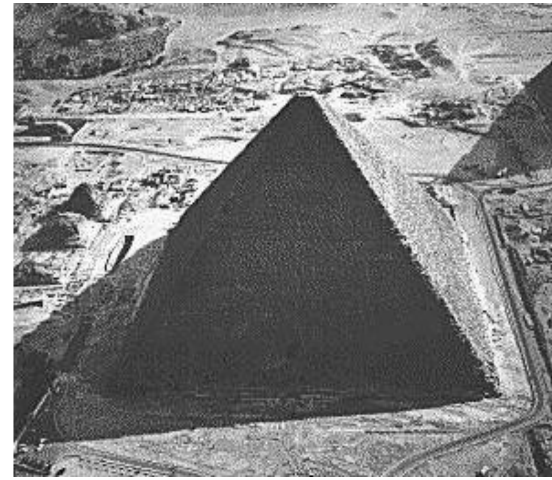


Pyramid example 30° and 60°



TERRASAR-X :Gizeh

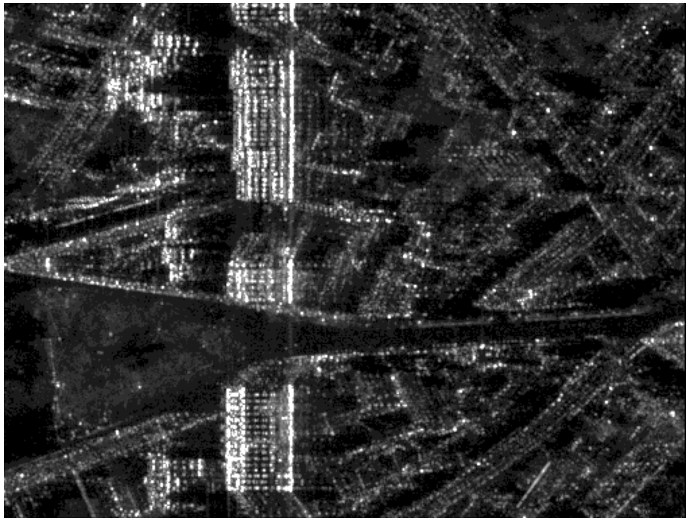


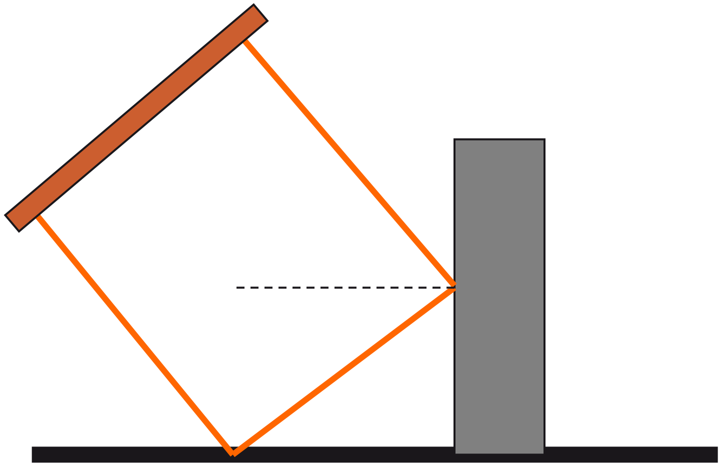


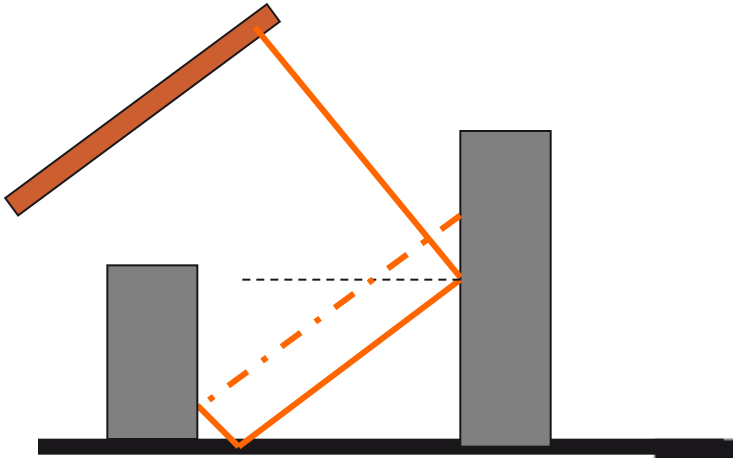
- Side : 232m
- Height : 146m
- Slope : 51°
- Incidence : 53°

Gizeh : incidence 40°

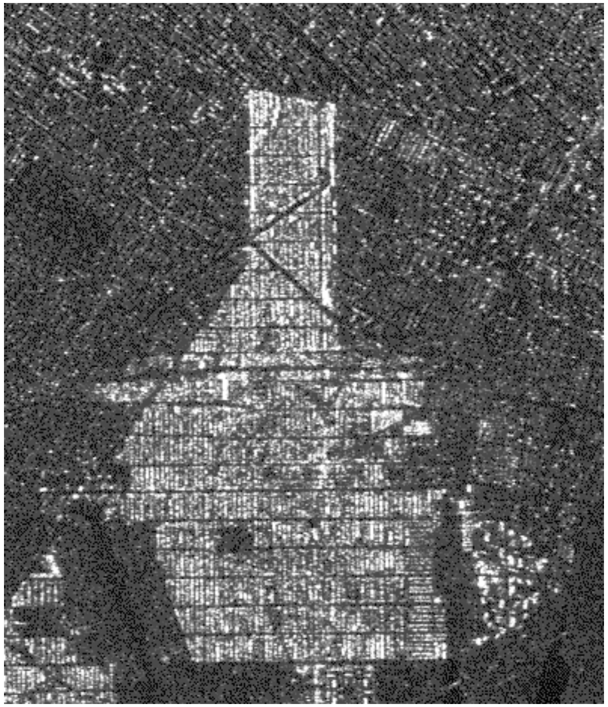
Urban areas







Influence of the viewing direction

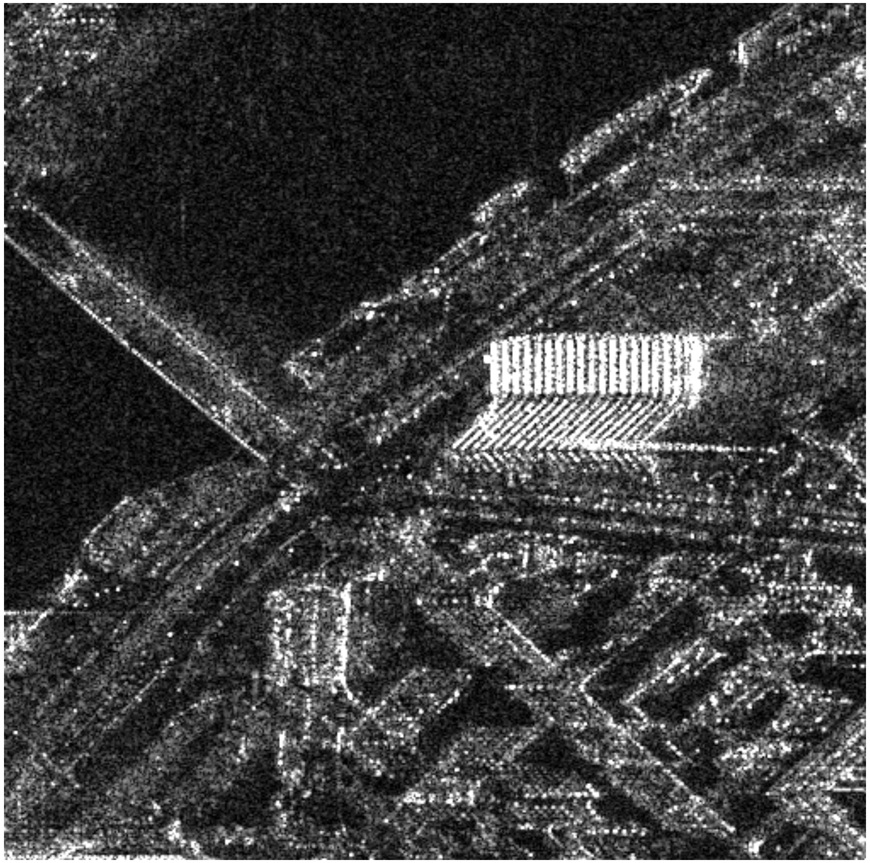


X-SAR image of Brooklyn, New-York, resolution 6.5m

Geometric effects

- **In urban areas:**
  - Shadow areas behind over-ground objects
  - Overlay phenomenon (lay-over)
  - Corner reflector wall / ground
  - Strong backscattering of facades oriented towards the sensor

Geometric effects



Geometric effects

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SAR data visualization

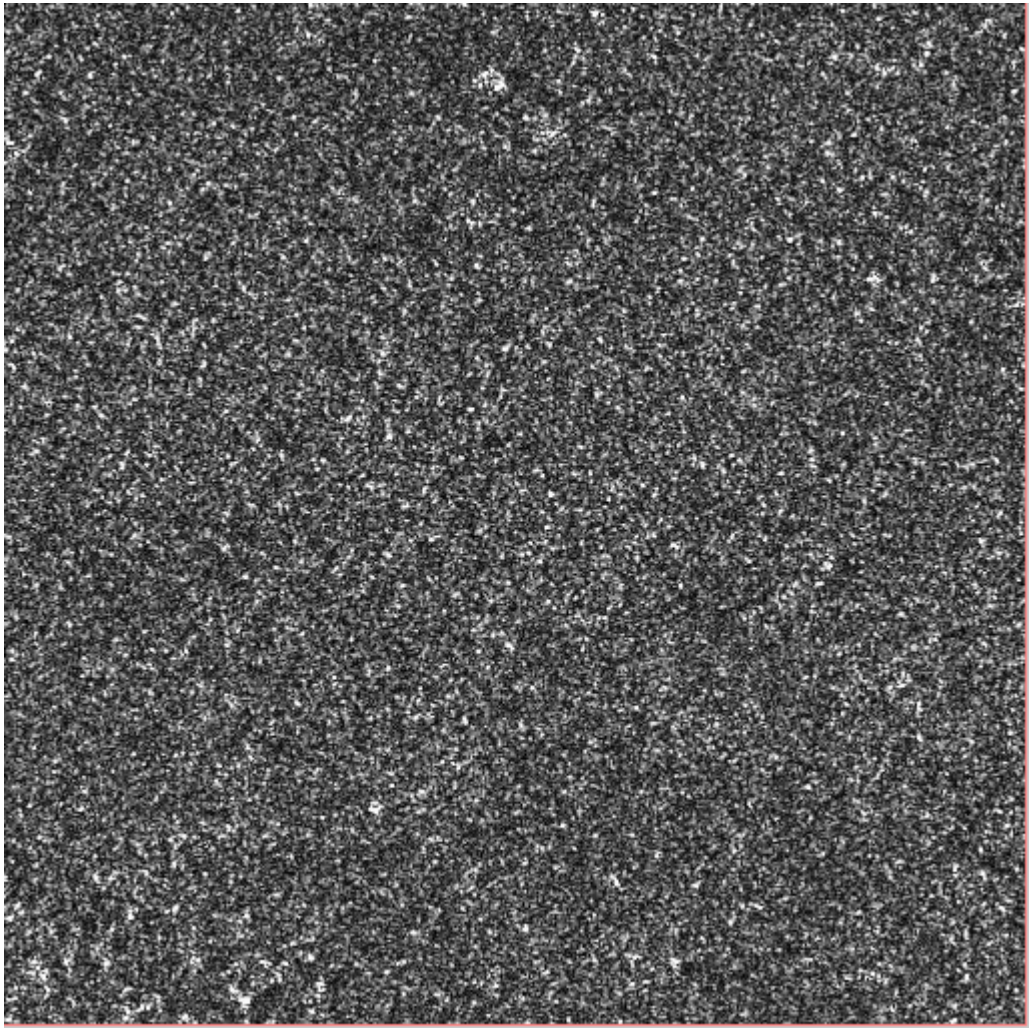
- **Data: 1 complex number per pixel**
- **Amplitude (modulus of electro-magnetic field)**
- **Dynamic:**
  - Very widespread 

  - Display of images on 8 bits gray-levels (0 to 255 values)
  - 8-bits coding should be adapted !

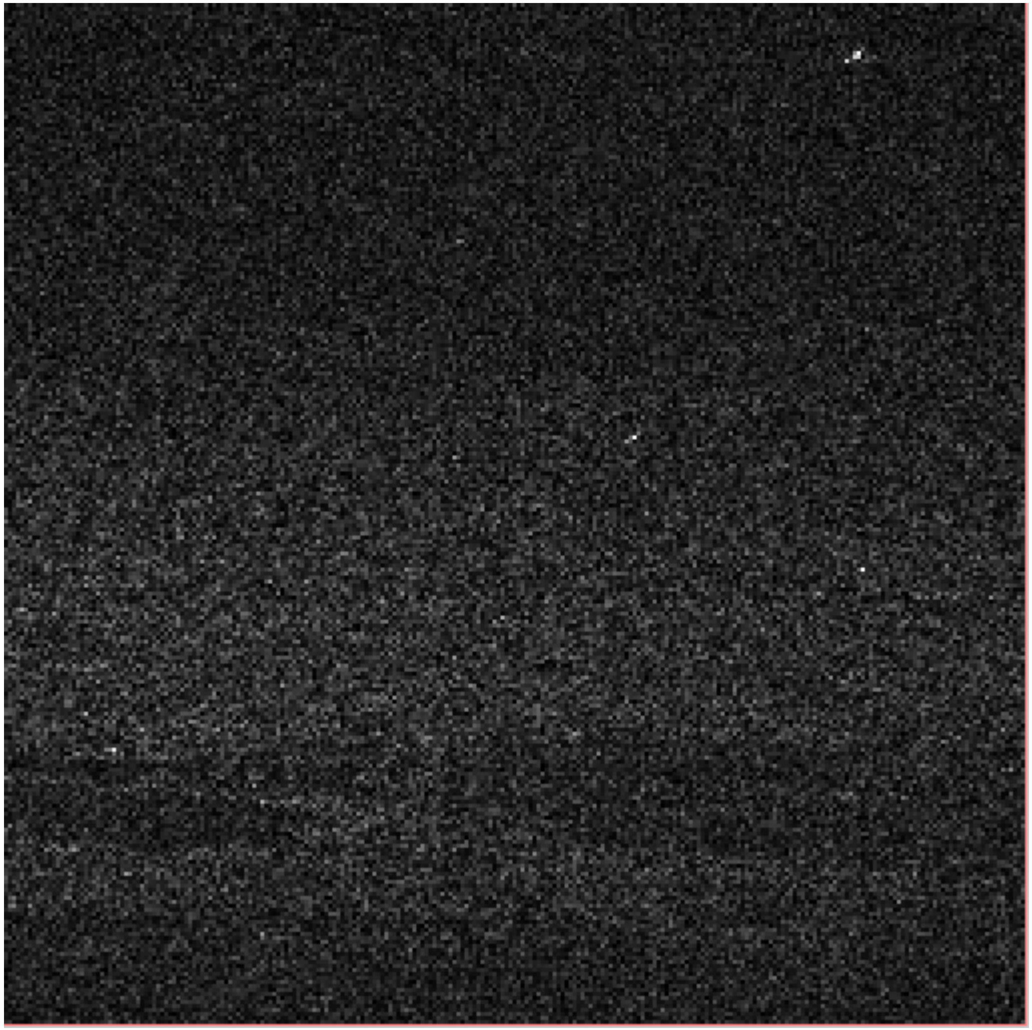
Dynamic truncation with

max = mean + 3sigma

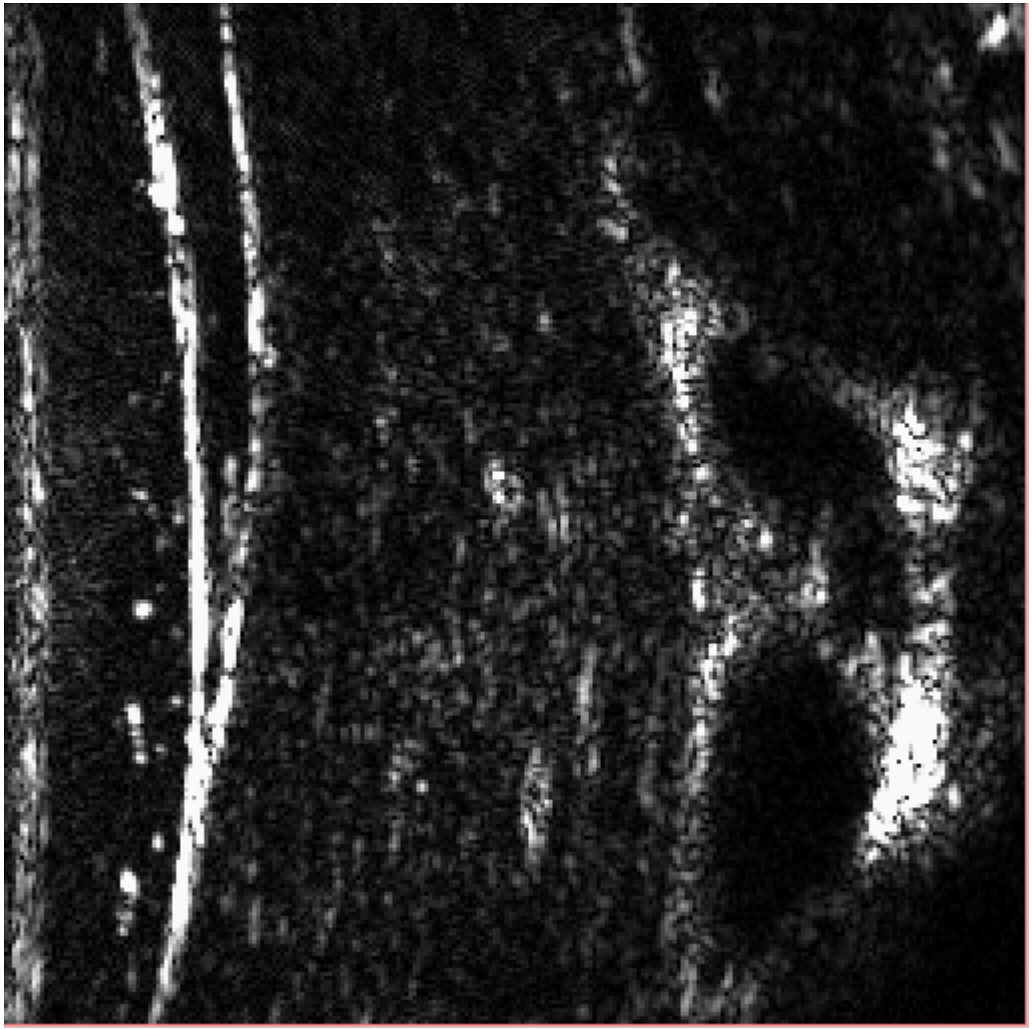
Desert in Australia (Terrasar-X)



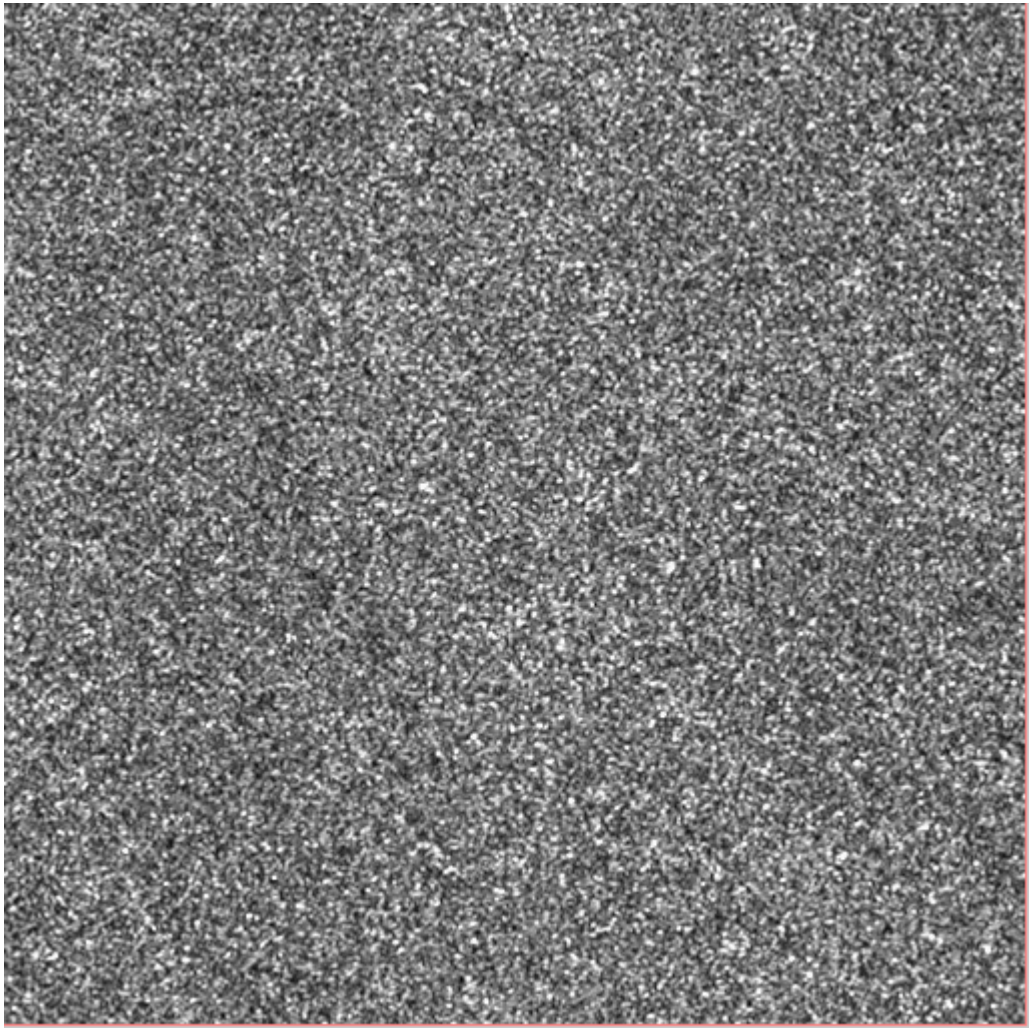
Sonar: underwater ground



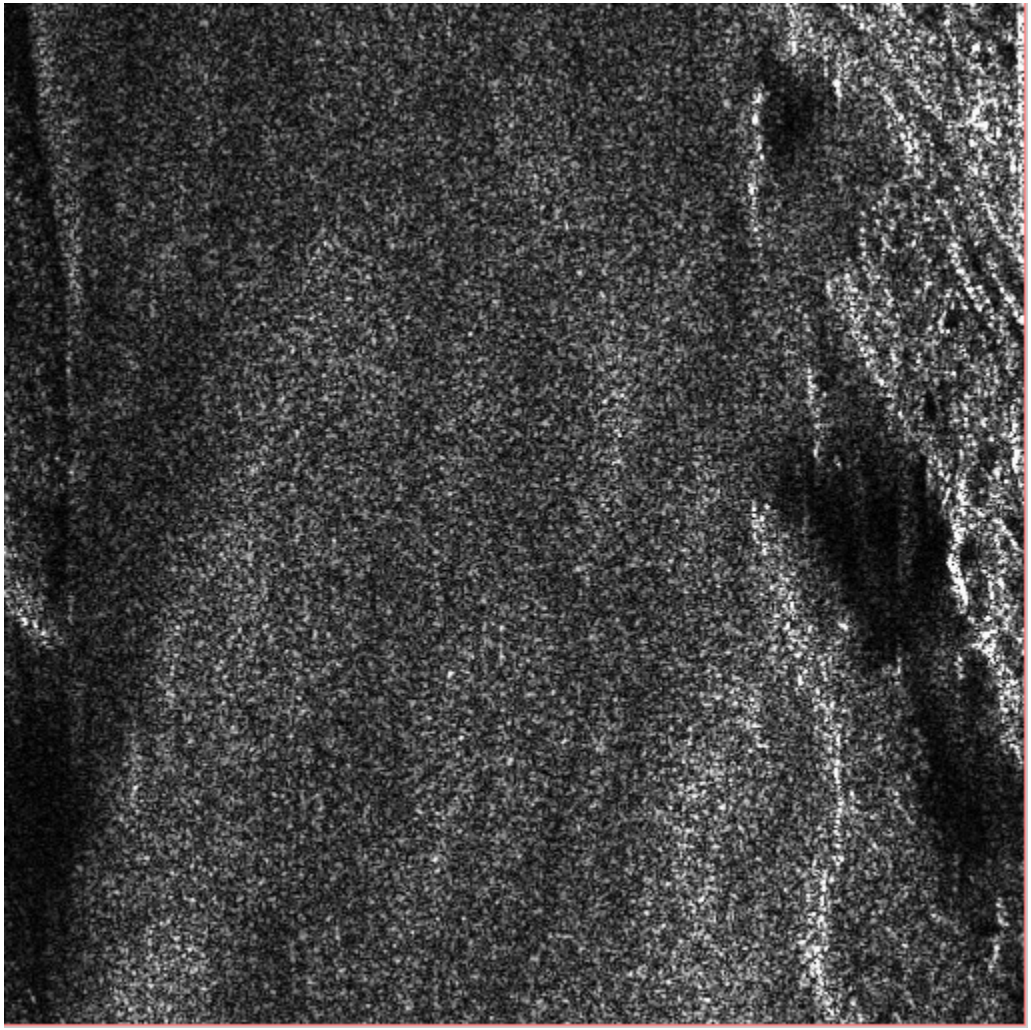
Echography



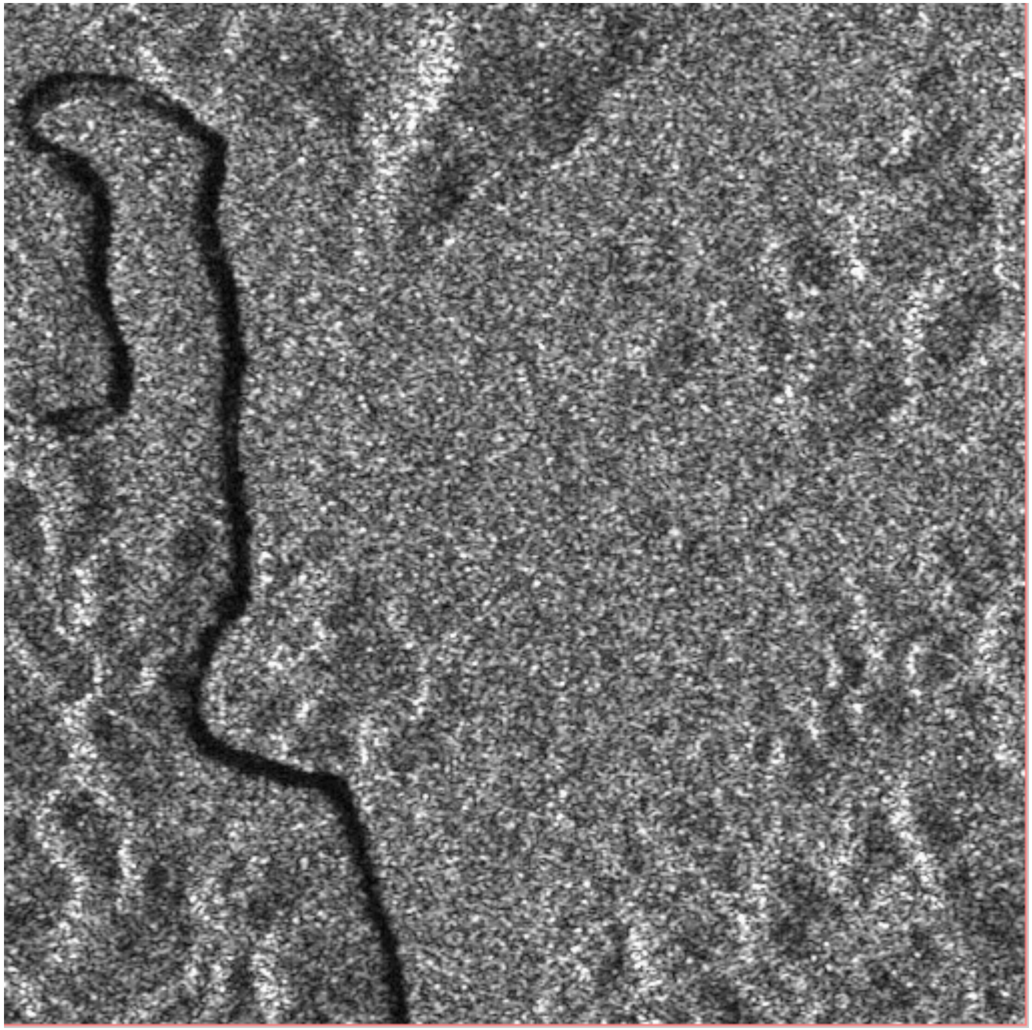
Desert of Mauritania (ERS)



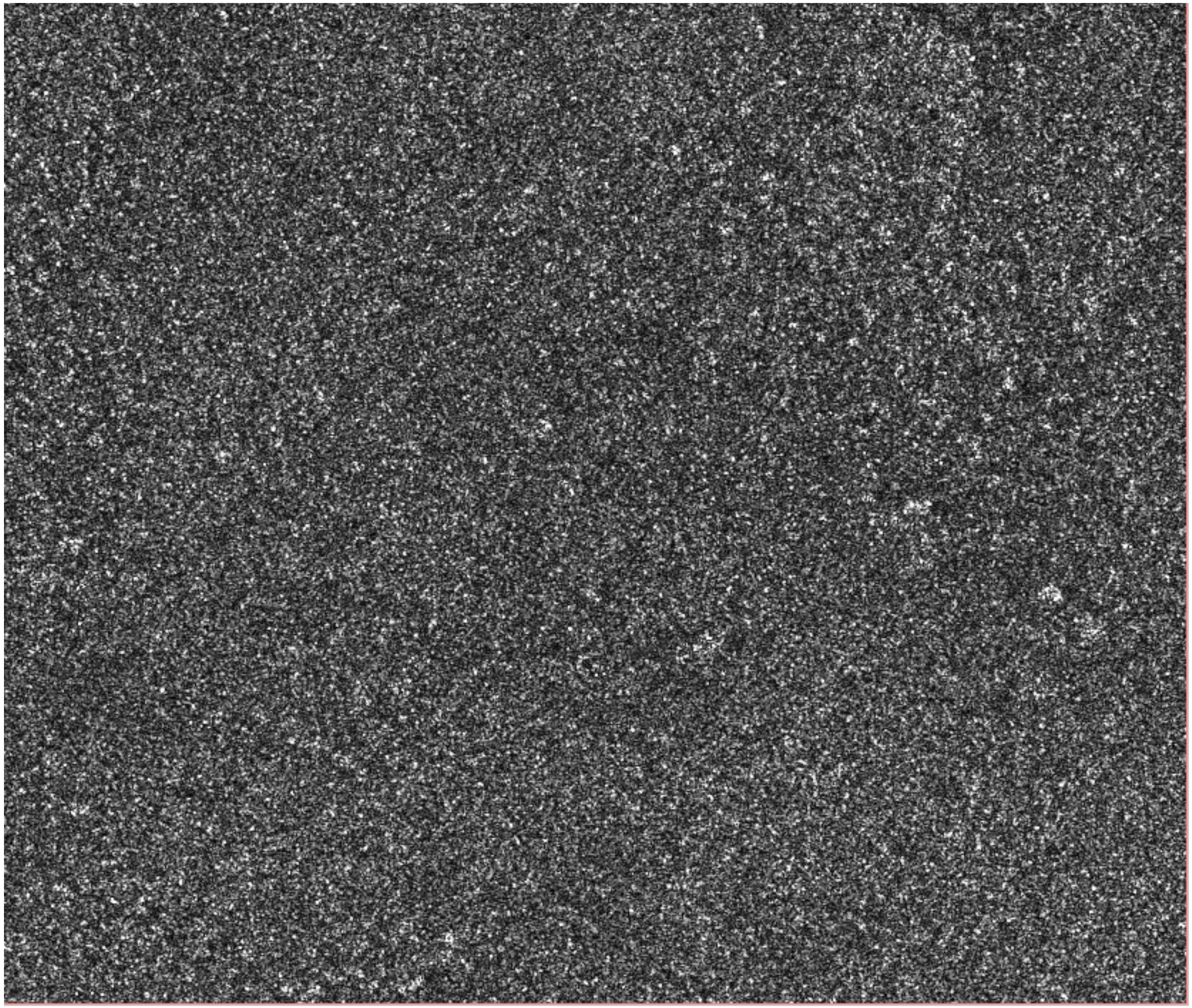
Sea – near Bergen (Terrasar-X Spotlight)



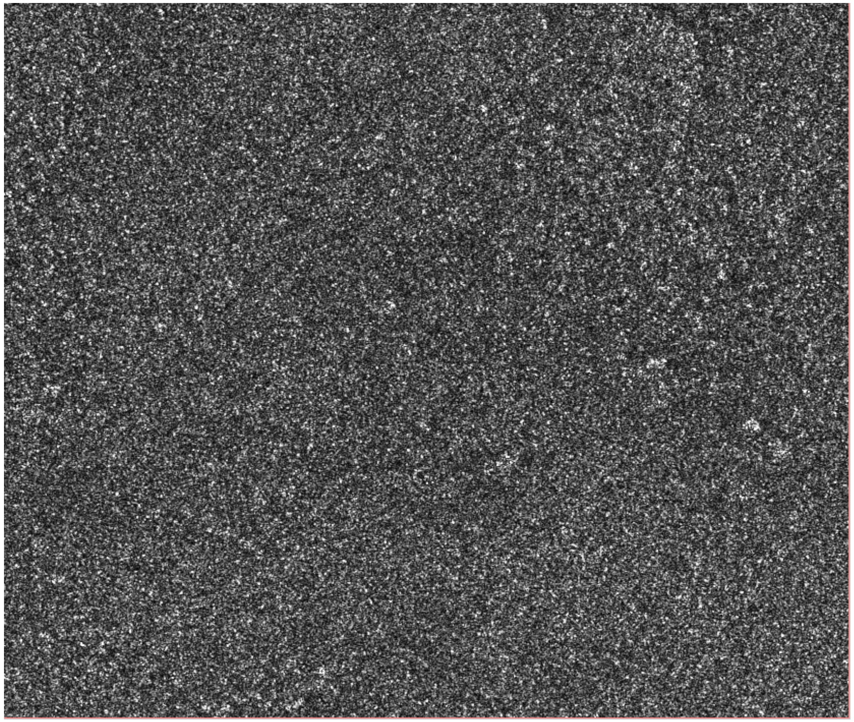
Forest in Guyana (ERS)

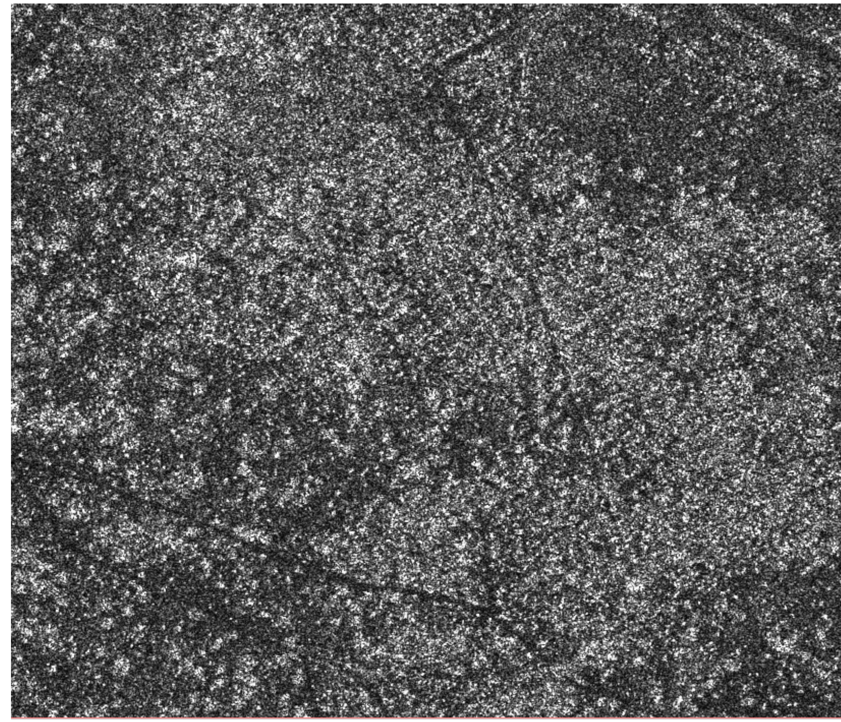


Phenomenological analysis (Terrasar-X)



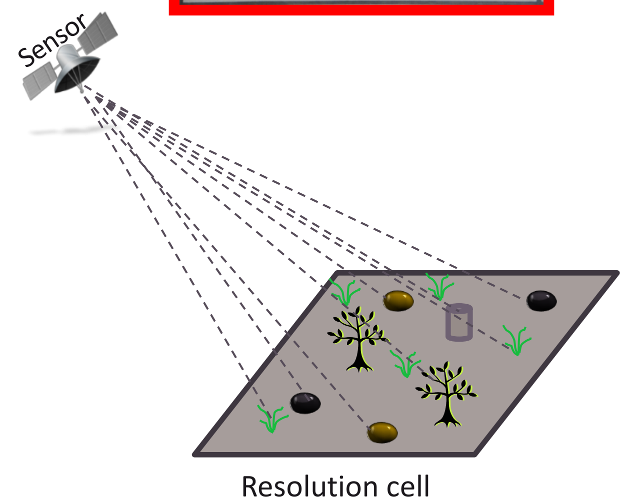
Two areas in Australia





Speckle principle

- **Size of resolution cell >> λ**
  - Elementary scatterers inside the resolution cell



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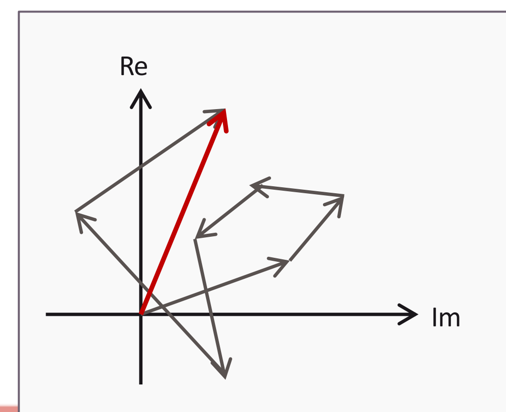
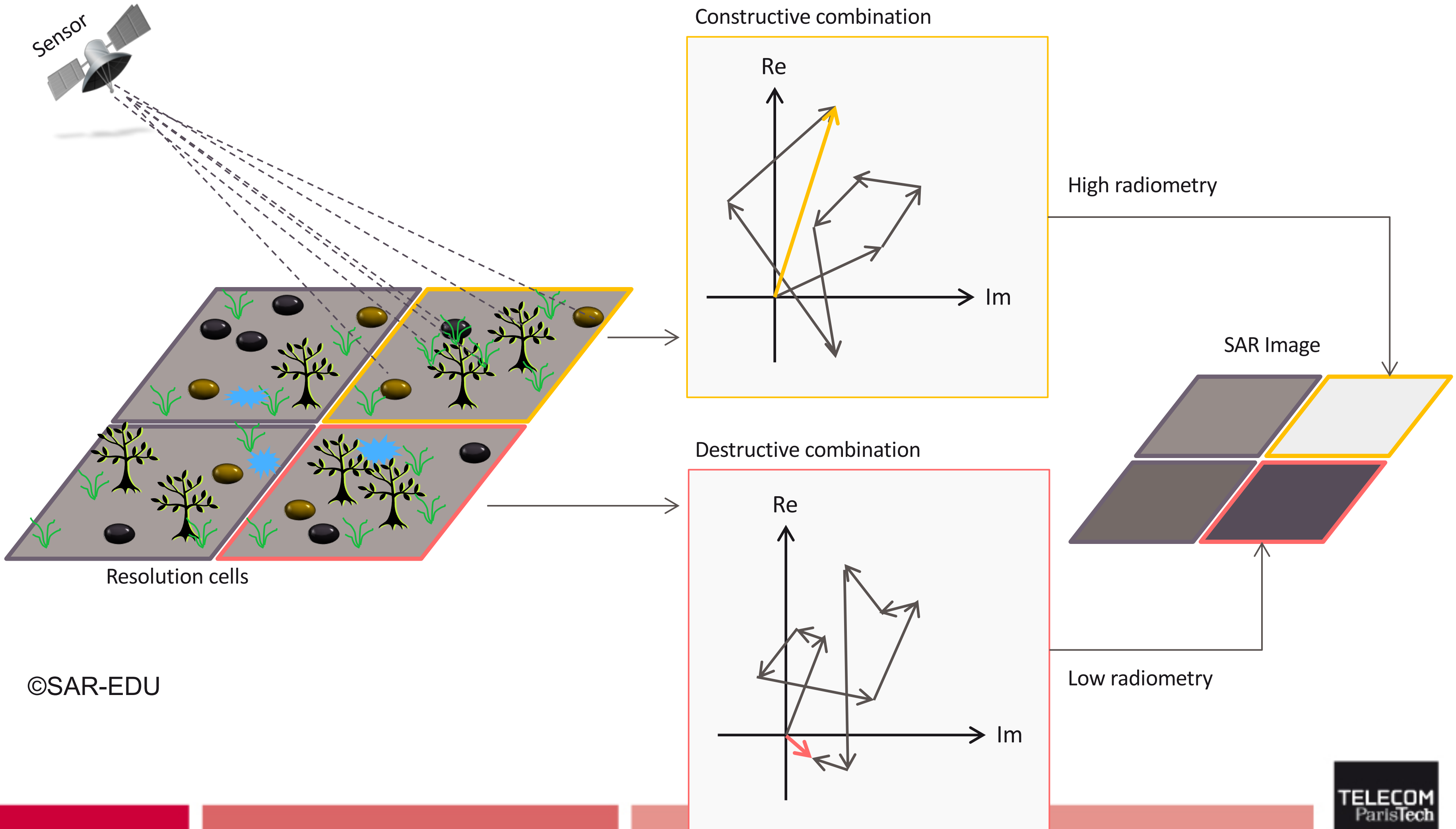
- **Coherent sum of the waves:**
  - Each scatterer backscatters the e.m wave
  - Phenomenon of interferences
  - Vectorial addition in the complex plane



What is Speckle?



Speckle principle

- **No acces to the scatterers inside the resolution cells (even if it is deterministic!)**
- **Random variable modeling:**

  ⇒ **backscattering modeled by a r.v !**

- **Why developing models for the backscattered field ?**
  - Prediction of the performances of image processings
  - Choice of the thresholds
  - Developement of model based methods

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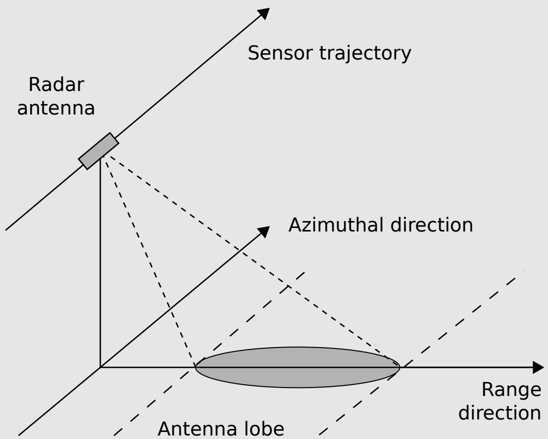
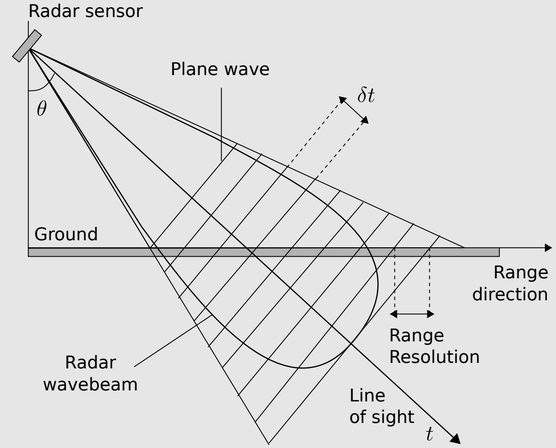
Speckle modeling

SAR data acquisition



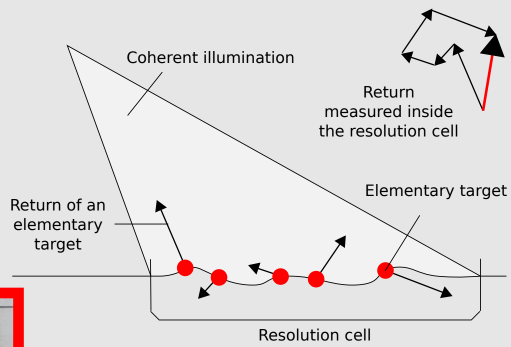


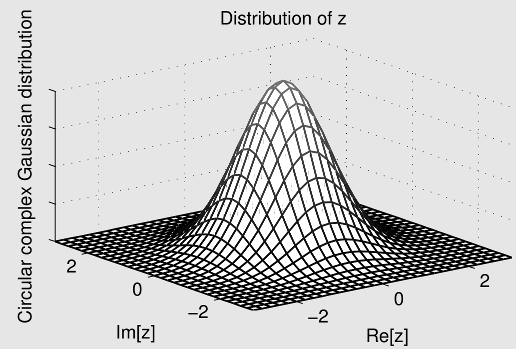
Synthetic aperture radar (SAR) imagery

- Active sensor: emits a wave and measures its echoes
- SAR: At each pixel: complex amplitude of the echo $z = Ae^{j\varphi}$
- Amplitude: $A = |z|$
- Intensity: $I = A^2 = |z|^2$
- Phase: $\varphi = \arg z$

Speckle modeling

Origins of speckle in SAR / coherent imaging systems / interferences





see [Goodman, 1976]

Coherent summation of N punctual echos

$$z = \sum_{i}^{N} z_i, \quad z_i \in \mathbb{C} \ .$$

Goodman model (rough surfaces):

1. $z_1, ..., z_N$ iid,
2. $\Re(z_i)$ and $\Im(z_i)$ iid,
3. $|z_i|$ and $\arg z_i$ independent.

- By the law of large numbers wrt N

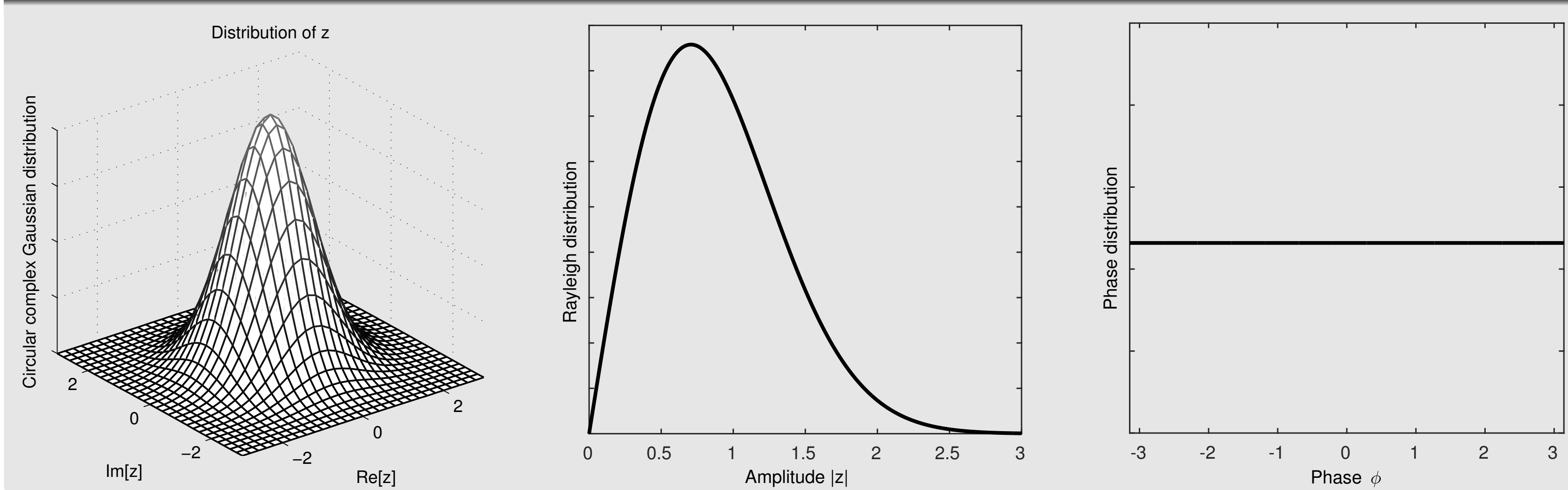
$$p(z|R) \triangleq p(\Re(z), \Im(z)|R) = \frac{1}{\pi R} \exp\left(-\frac{|z|^2}{R}\right)$$

where $R > 0$ is the quantity of interest.

- R is linked to the radar cross-section ($R =$ reflectivity).

Speckle modeling

Statistics of the circular complex Gaussian distribution



$z = Ae^{j\varphi}$ is distributed according to a complex circular Gaussian, thus

- $\varphi = \arg(z)$ uniformly distributed in $[-\pi, \pi]$, $\Rightarrow$ phase is non-informative.
- $I = |z|^2$ exponentially distributed: $p(I \mid R) = \frac{1}{R} \exp\left(-\frac{I}{R}\right)$.
- $A = |z|$ Rayleigh distributed: $p(A \mid R) = \frac{2A}{R} \exp\left(-\frac{A^2}{R}\right)$.

  $\Rightarrow$ heavy right tail.
- I or A are sufficient statistics for R: $\mathbb{E}[I] = \mathbb{E}[A^2] = R$.

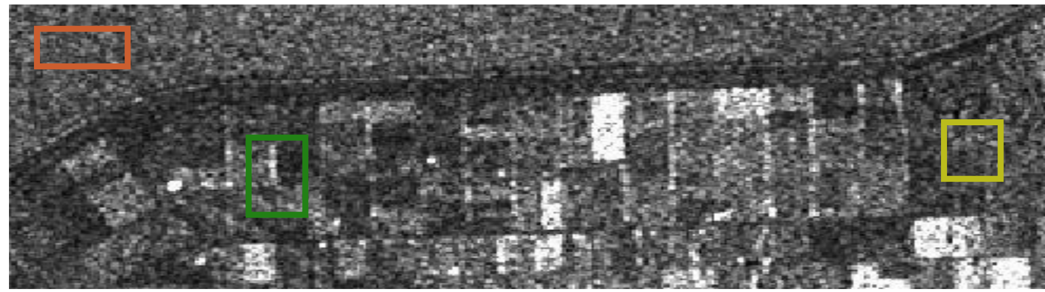
  $\Rightarrow$ many SAR applications focus only on $|z|$.

Coefficient of variation

$$p(I) = \frac{1}{R} e^{\left(-\frac{I}{R}\right)}$$

$$\mu_I = \sigma_I = R$$

$$\gamma_I = \frac{\sigma_I}{\mu_I} = 1$$

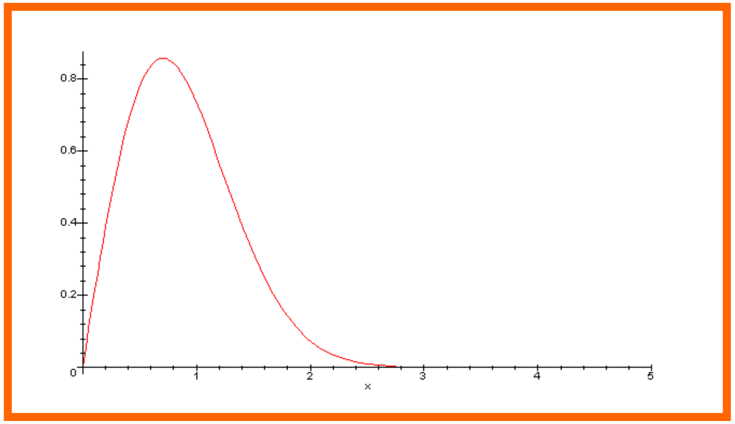


hererogeneity measure = coefficient of variation

Goodman model - amplitude

Amplitude distribution:

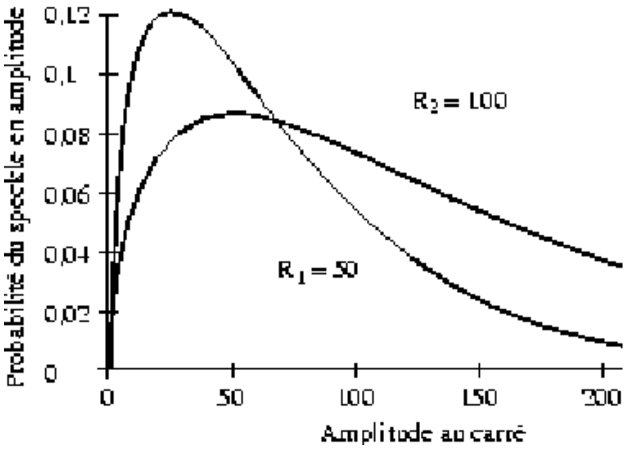
$$p(A) = \frac{2A}{R} e^{\left(-\frac{A^2}{R}\right)}$$



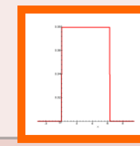
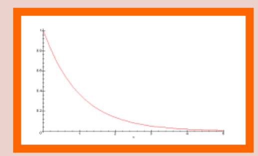
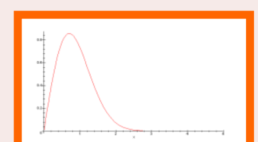
Rayleigh pdf

$$R = 2\sigma^2 \propto \sigma^0$$

- $\mu_A = \sqrt{\frac{\pi R}{4}}$
- $\gamma_A = \frac{\sigma_A}{\mu_A} = \sqrt{\frac{4}{\pi} - 1} \approx 0.523$



Goodman model (homogenous area)

Data	Pdf
Real part Imaginary part	Gaussian pdf 0 mean $R = 2\sigma^2 \propto \sigma^0$ 
Phase	Uniform pdf 
Intensity	Negative exponential pdf $\mu_I = \sigma_I = R$ 
Amplitude	Rayleigh pdf $\mu_A = \sqrt{\frac{\pi R}{4}}$ 

Overview of the session

- **Backscattering mechanims**
- **Relief effects and geometry influence**
- **Speckle phenomenon**
  - Origine
  - Modeling
  - Multi-looking
  - Multiplicative noise model
- **Texture and log-statistics**

Multi-look processing

- **Averaging N i.i.d samples reduces the variance by N**

$X_1, X_2, ..., X_N$ samples

$$X^{ML} = \frac{1}{N}\sum_i X_i$$

$$\begin{cases} E(X^{ML}) = E(X_i) \\ \mathrm{Var} X^{ML} = \dfrac{\mathrm{Var} X_i}{N} \end{cases}$$

- **Which data ?**
  - Complex data ? $z_1, z_2, ..., z_N$
  - Intensity data ? $I_1, I_2, ..., I_N$
  - Amplitude data ? $A_1, A_2, ..., A_N$

Multi-looking

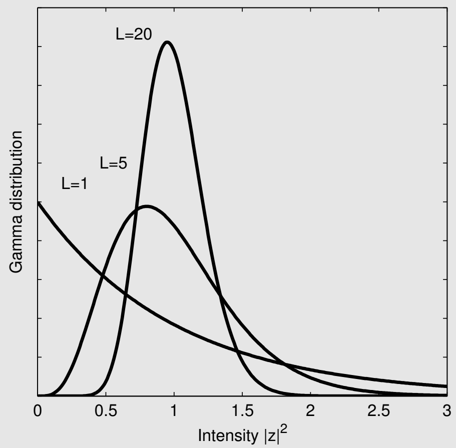
- Increase signal to noise ratio using spatial/temporal average

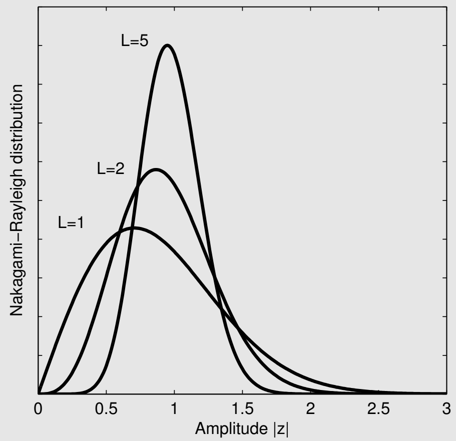
$$I = I_{\text{ML}} = \frac{1}{L}\sum_{t=1}^{L}|z_t|^2 = \frac{1}{L}\sum_{t=1}^{L} I_t$$

- As I_t are iid, I is gamma distributed

$$p(I \mid R, L) = \mathop{\bigstar}_{t=1}^{L} p(I_t \mid R) = \frac{L^L I^{L-1}}{\Gamma(L) R^L} \exp\left(-\frac{LI}{R}\right),$$

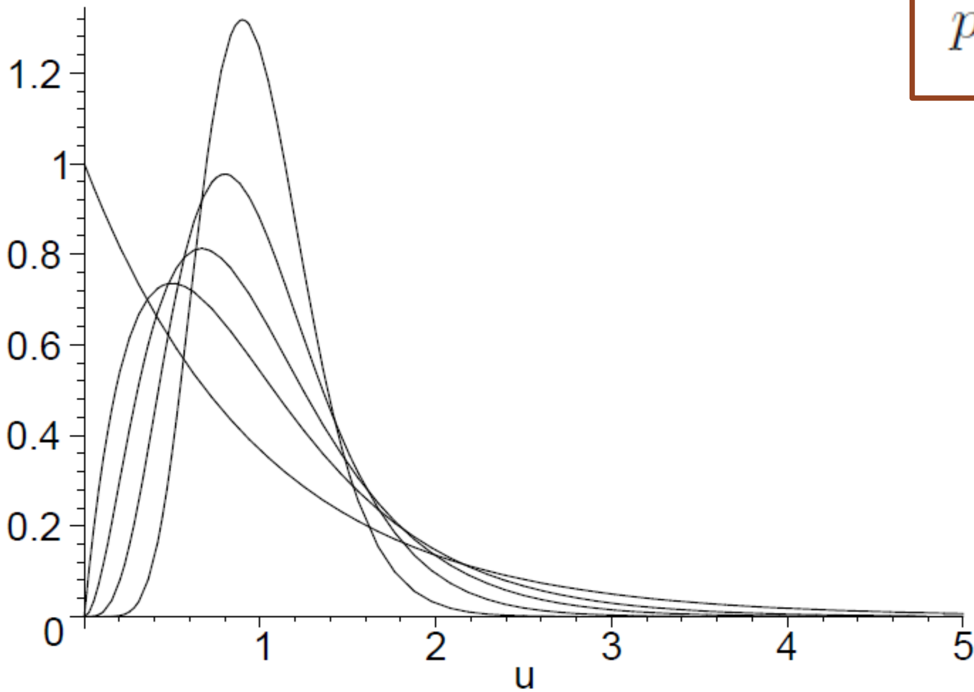
- $A = A_{\text{ML}} = \sqrt{I_{\text{ML}}}$ is Nakagami-Rayleigh distributed.





Intensity multi-looking

- **Averaging of L intensity samples:**
  - Convolution of neg. exp. pdf : Gamma pdf
  - L: number of looks



$$p(I|R) = \frac{L^{L-1}}{\Gamma(L)} \frac{I^{L-1}}{R^L} \exp(-L\frac{I}{R})$$

$$\mu_I = R \qquad \sigma_I = \frac{R}{\sqrt{L}}$$

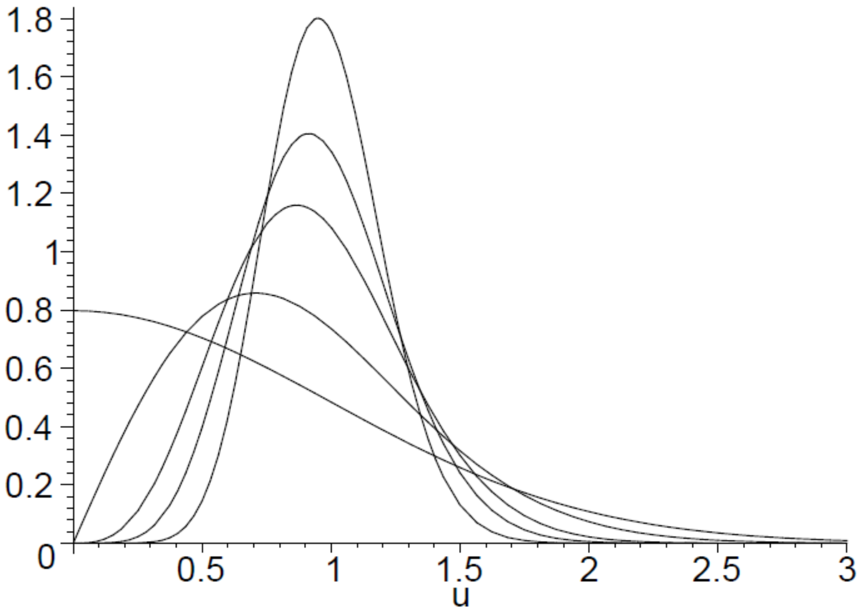
$$\gamma_I = \frac{1}{\sqrt{L}}$$

Amplitude multi-looking

- **Square root of the average of L intensity samples**
  - Nakagami pdf
  - L: number of looks

$$p(A|R) = \frac{2L^L}{\Gamma(L)} \frac{A^{2L-1}}{R^L} \exp(-L\frac{A^2}{R})$$

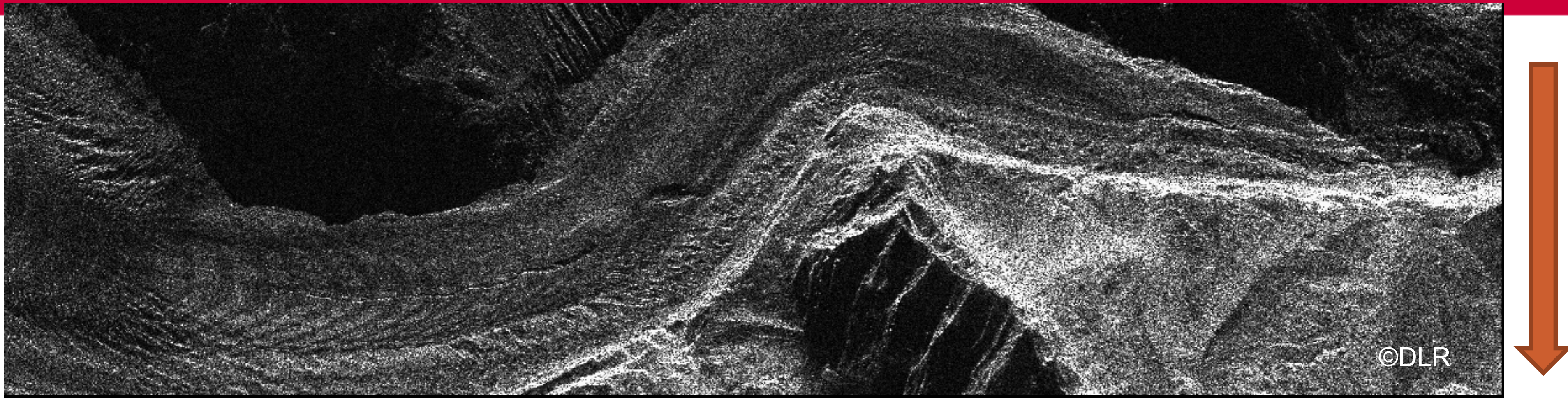
$$\gamma_A = \frac{0.523}{\sqrt{L}}$$

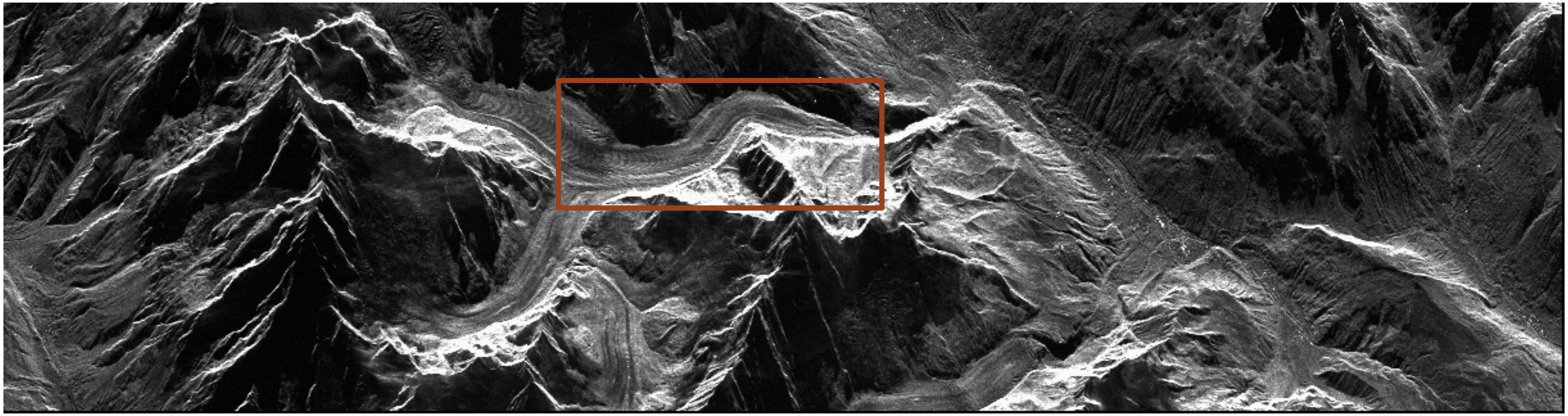


Multi-looking

- **Which samples ?**
  - Historically :
    - Azimuth sub-band decomposition of the complex spectrum
    - Decrease of spatial resolution to improve radiometric resolution
  - Spatial samples
    - Mean filter
    - Loss of spatial resolution
  - Temporal samples
    - Not iid ?

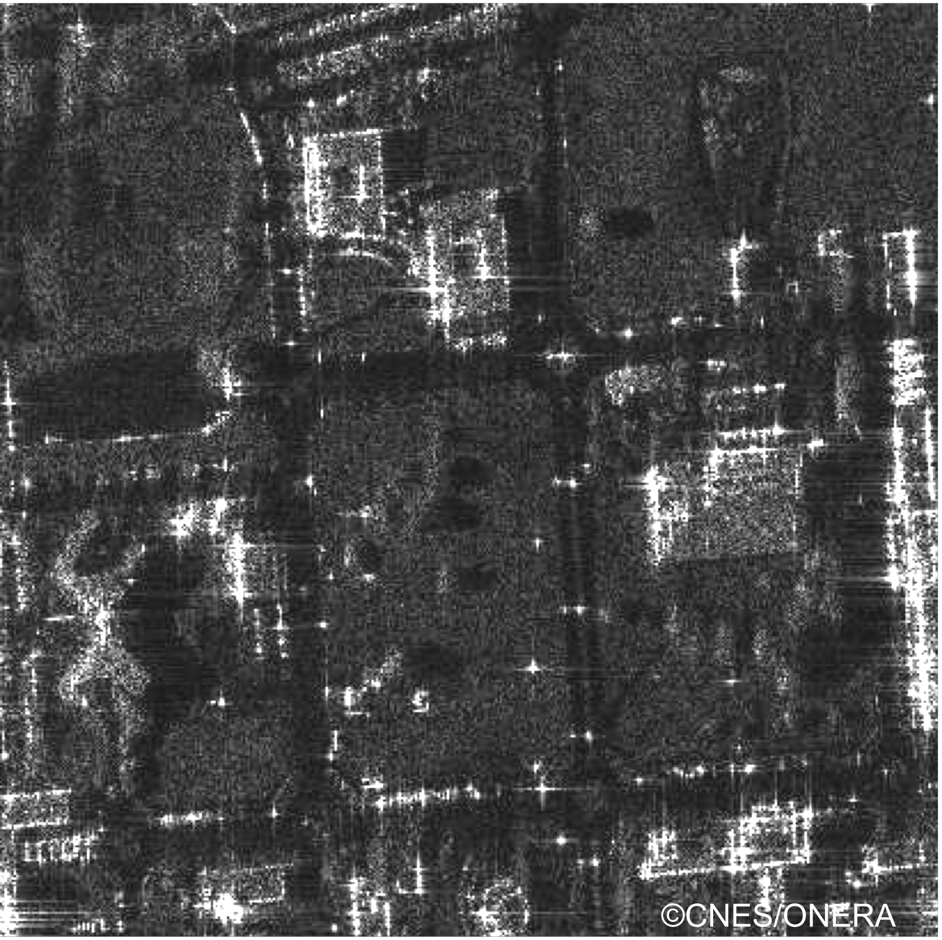
Multi-looking : less speckle, less resolution

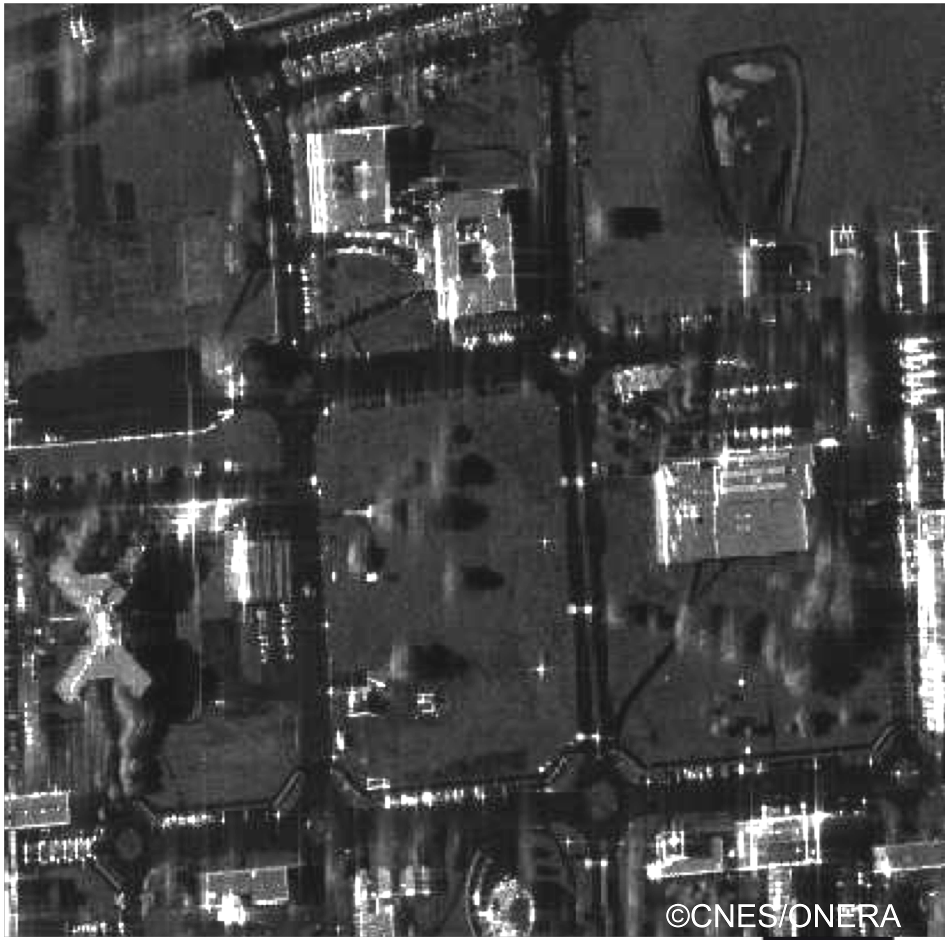




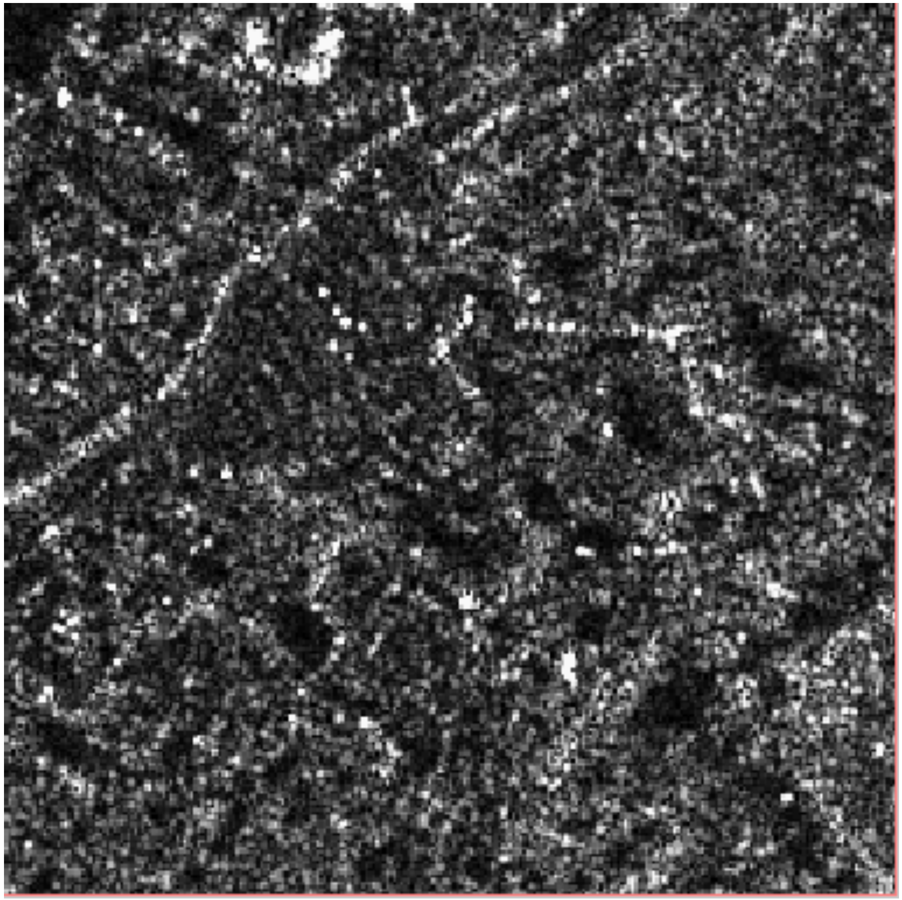
- 10x10 multi-looking : easier image interpretation

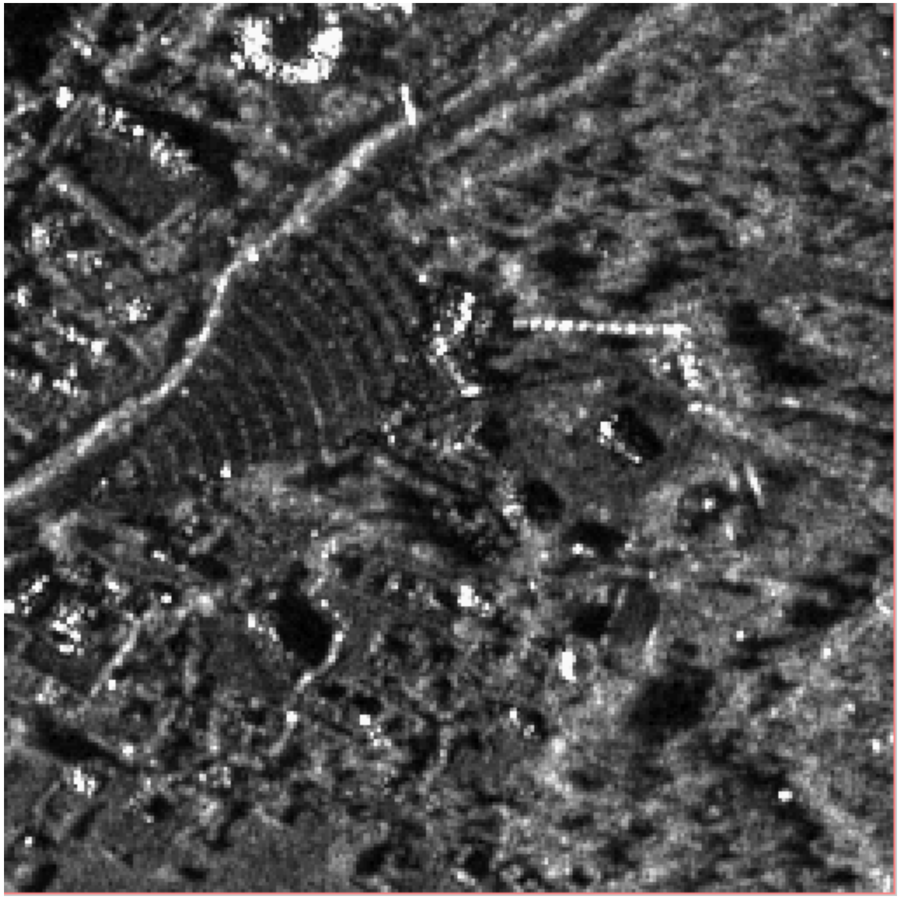
Spatial multi-looking





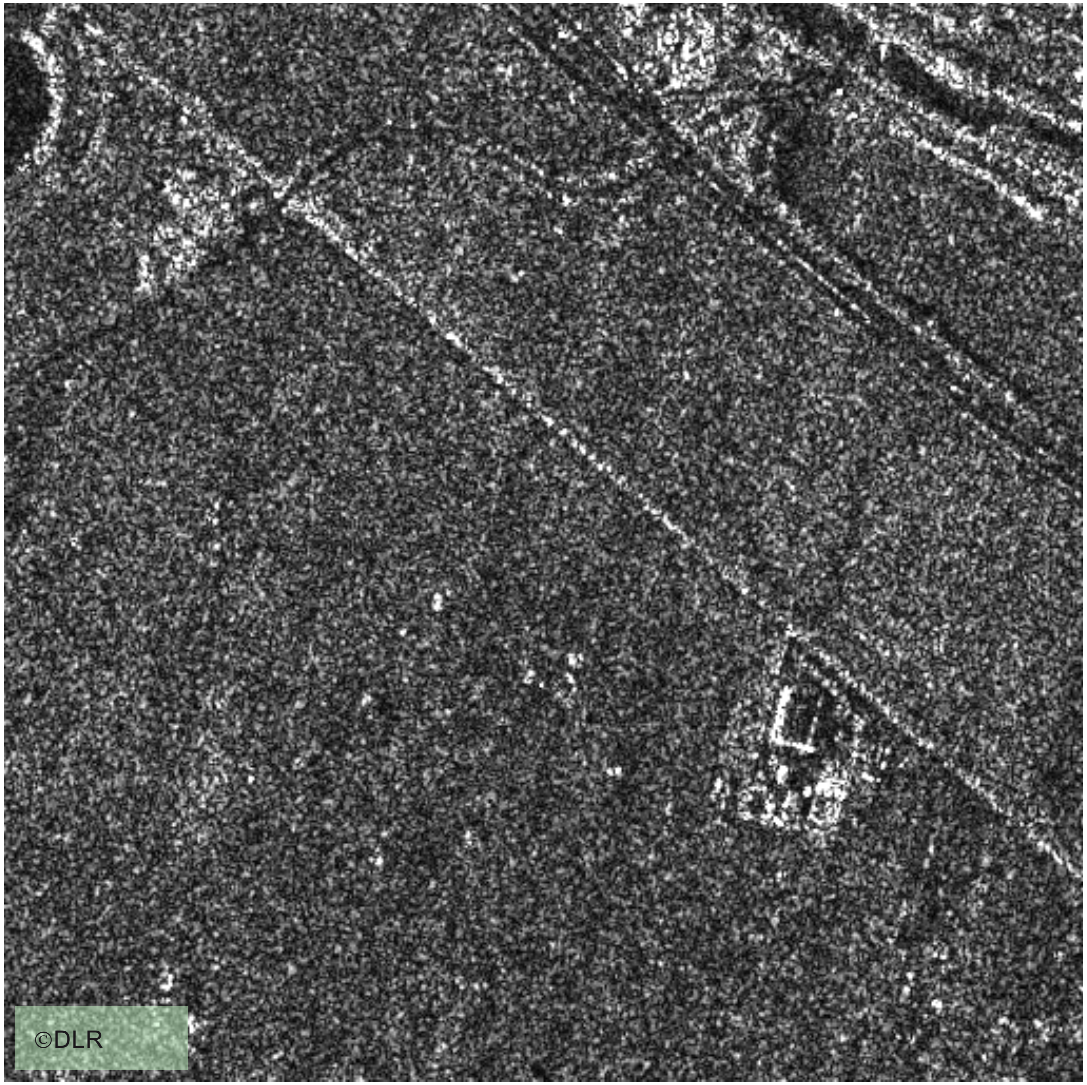
Temporal multi-looking (13 images)

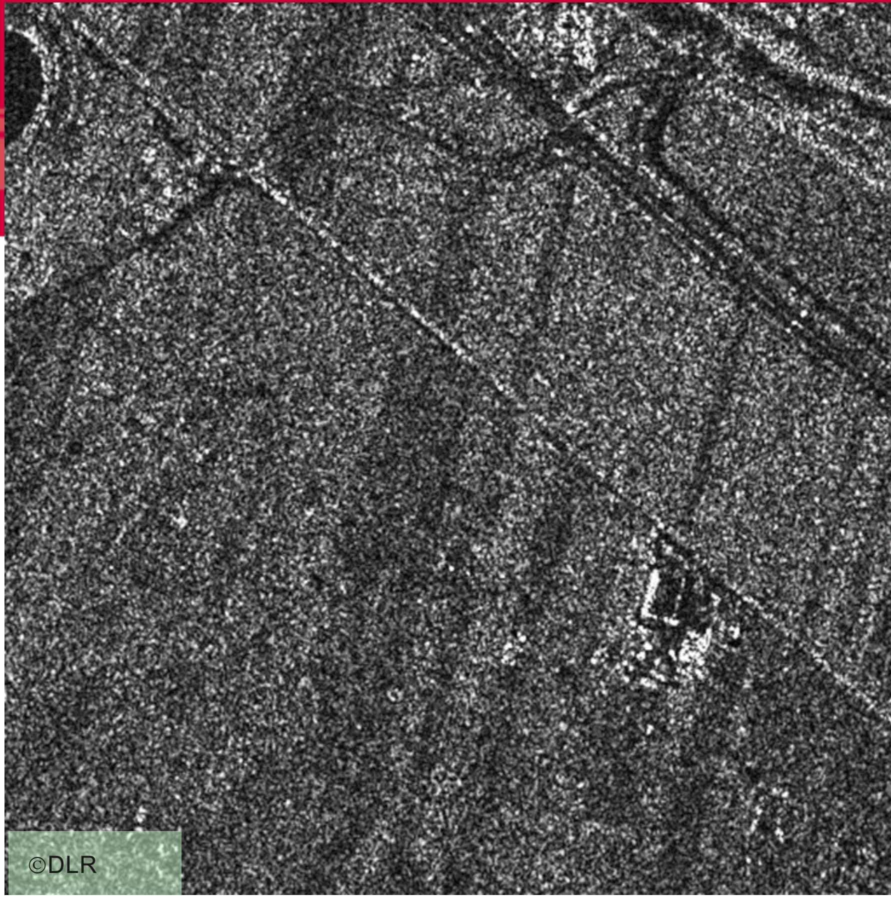




Original TerraSAR-X image

Video of the temporal multi-looking





Temporal average of 26 images TSX

Very efficient
Very simple
Only valid for stable areas


CARROSSERIE
Jacky et Frère
Tél. 04.50.93.68.60
PASSY PNEUS

Equivalent number of looks (ENL)

- **For a multi-look image:**
  - The number of looks is usually less than the theoretical number of views because of the correlation between samples
  - ENL computation
    - Choice of a physically homogeneous area
    - Computation of the coefficient of variational
    - Inversion of the relationship (amplitude or intensity)
- **Use:**
  - To adjust statistical models
  - To evaluate the efficiency of a filtering method

Overview of the session

- **Backscattering mechanims**
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- **Texture and log-statistics**

Multiplicative model

- **Modeling of the speckle noise as multiplicative:**

$$\boxed{I = R.S}$$

$$E(S) = 1$$

$$\mathrm{Var}(S) = \frac{1}{L}$$

$$p(S) = \frac{L^{L-1}}{\Gamma(L)} S^{L-1} \exp(-LS)$$

- **Texture modeling with scene pdf:**

$$p(I = RS) = \int p(R) p(S = \frac{I}{R}) \frac{1}{R} dR$$

$$p(I) = \int p(R) p(I|R)) dR$$

Homomorphic approaches

Goodman model of fully developed speckle

SAR intensity is distributed according to a Gamma distribution:

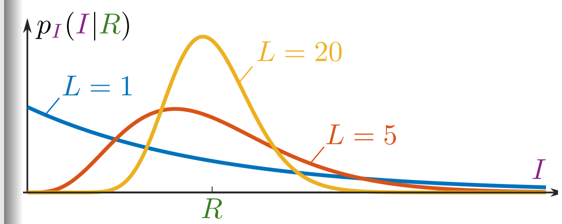
$$p_I(I|R) = \frac{L^L I^{L-1}}{\Gamma(L) R^L} \exp\left(-L\frac{I}{R}\right) \text{ with } R \text{ the radar reflectivity.}$$

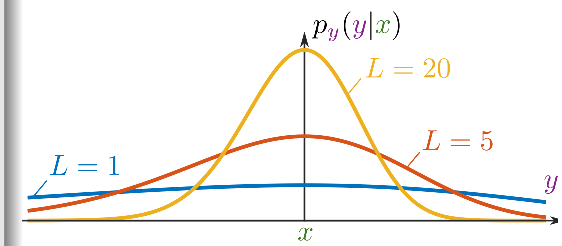
$$\rightarrow \ \mathbb{E}[I] = R$$
$$\rightarrow \ \mathrm{Var}[I] = R^2/L$$

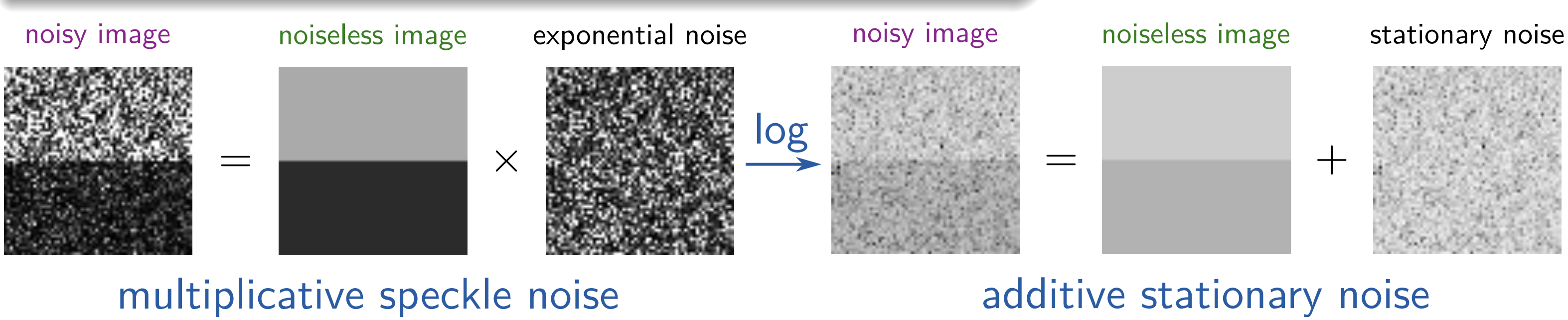
The log of the intensity follows a Fisher-Tippett distribution:

$$p_y(y|x) = \frac{L^L}{\Gamma(L)} e^{L(y-x)} \exp\left(-L e^{y-x}\right)$$

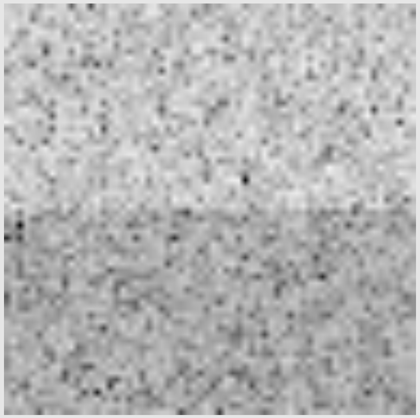
$$\rightarrow \ \mathbb{E}[y] = x - \log L + \Psi(L)$$
$$\rightarrow \ \mathrm{Var}[y] = \Psi(1, L) \qquad (\Psi \text{ : polygamma})$$

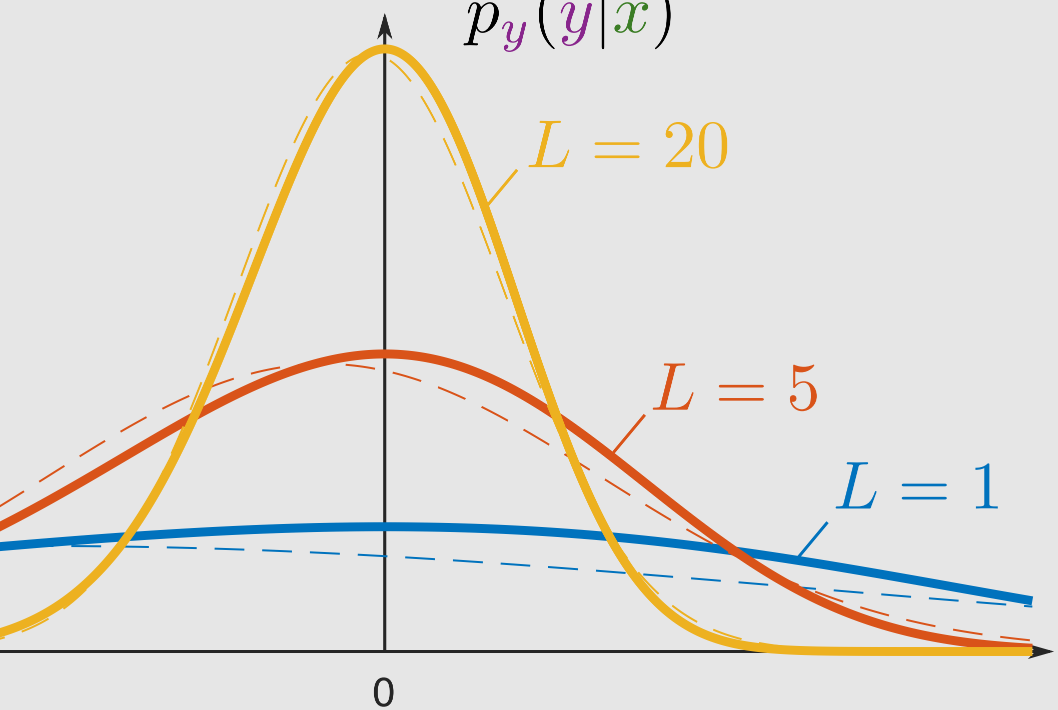






Gaussian approximation of log-transformed speckle





approximate log-transformed speckle as additive white Gaussian noise
→ not very good for small L: asymmetry towards lower values
→ not centered (a debiaising step is needed)

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Texture

Texture modeling

- Use of a multiplicative model:

Image (I) = texture (R) x speckle (S)

Distribution modeling:

  - Speckle: fully developed speckle (Goodman model)
  - Texture: proposal of different distributions

- Probabilistic tools:
  - Mellin transform
  - Log-statistics

Mellin convolution and associated tools

- Mellin convolution for positive r.v:

$$r(I) = \int_0^\infty p(R)\,\gamma\left(\frac{I}{R}\right)\frac{dR}{R} = p \hat{*} \gamma$$

- Modeling of many textures on SAR:

S distribution	R distribution	I distribution
Gamma	dirac	Gamma
Gamma	Gamma	K
Gamma	Gamma inverse	Fisher

Mellin convolution

- **Convolution and Fourier transform:**

$$r = p * q = \int_{-\infty}^{\infty} p(u)q(x-u)du \Leftrightarrow TF(r) = TF(p).TF(q)$$

  - Adapted to additive noise

- **Mellin convolution and Mellin transform:**

$$r = p \hat{*} q = \int_{0}^{\infty} p(u)q\left(\frac{x}{u}\right)\frac{du}{u} \Leftrightarrow TM(r) = TM(p).TM(q)$$

  - Adapted to multiplicative noise

Statistics et log-statistics

- **Statistics : pdf defined on $\Re$**
  - Use of the Fourier transform
  - Convolution: additive noise
  - Characteristic functions
  - Gaussian pdf: defined on $\Re$
- **Log-statistics : pdf defined on $\Re^+$**
  - Use of Mellin transform
  - Mellin convolution: multiplicative noise
  - Characteristic function of «second kind»
  - Gamma pdf : defined on $\Re^+$

Characteristic functions, moments and cumulants

$$\Phi(f) = TF(p) = \int_{-\infty}^{+\infty} e^{2j\pi x f} p(x)dx$$

$$m_k = (-j)^k \left. \frac{d^k \Phi(f)}{df^k} \right|_{f=0}$$

$$\kappa_k = (-j)^k \left. \frac{d^k \log(\Phi(f))}{df^k} \right|_{f=0}$$

$$\tilde{\Phi}(s) = TM(p) = \int_0^{\infty} x^{s-1} p(x)dx$$

$$\tilde{m}_k = \left. \frac{d^k \tilde{\Phi}(s)}{ds^k} \right|_{s=1}$$

$$\tilde{\kappa}_k = \left. \frac{d^k \log(\tilde{\Phi}(s))}{ds^k} \right|_{s=1}$$

Convolution and Mellin convolution

$$r = p * q = \int_0^{\infty} p(u) q(x-u)\, du$$

$$TF(r) = TF(p).TF(q)$$

$$\Phi[r] = \Phi[p]\Phi[q]$$

$$r = p \,\hat{*}\, q = \int_0^{\infty} p(u) q\left(\frac{x}{u}\right)\frac{du}{u}$$

$$TM(r) = TM(p).TM(q)$$

$$\tilde{\Phi}[r] = \tilde{\Phi}[p]\tilde{\Phi}[q]$$

Estimation of moments and log-moments

$$\Phi(f) = TF(p) = \int_{-\infty}^{+\infty} e^{2j\pi x f} p(x)dx$$

$$m_k = (-j)^k \left. \frac{d^k \Phi(f)}{df^k} \right|_{f=0}$$

$$= \int_{-\infty}^{+\infty} x^k p(x)dx$$

$$\hat{m}_k = \frac{1}{N} \sum_{i=1}^{N} (x_i)^k$$

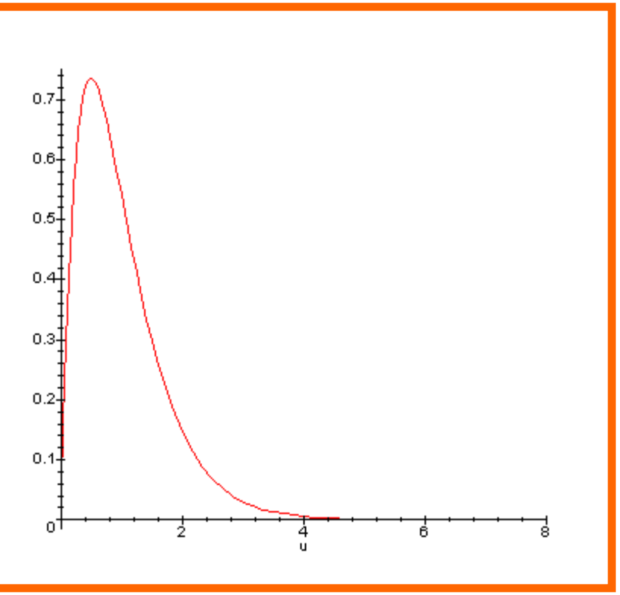
$$\tilde{\Phi}(s) = \mathrm{TM}(p) = \int_0^{\infty} x^{s-1} p(x)dx$$

$$\tilde{m}_k = \left. \frac{d^k \tilde{\Phi}(s)}{ds^k} \right|_{s=1}$$

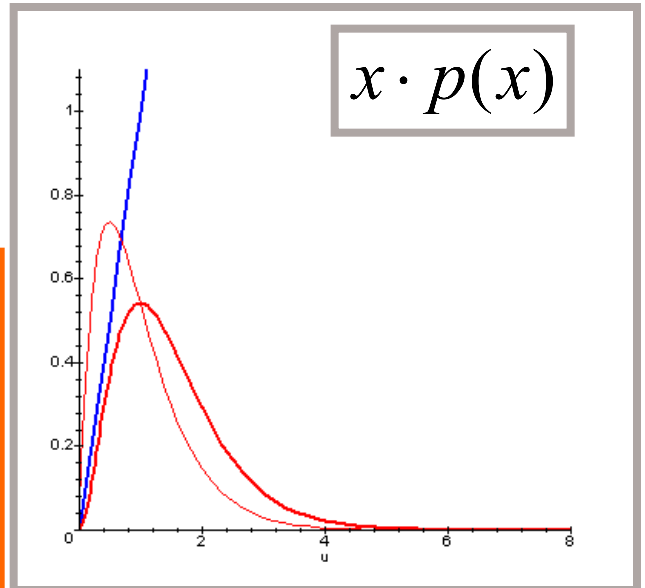
$$= \int_0^{+\infty} (\log(x))^k p(x)dx$$

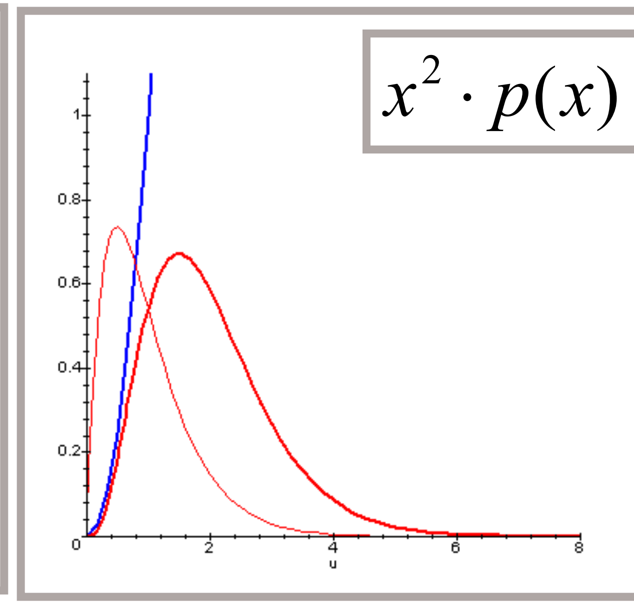
$$\hat{\tilde{m}}_k = \frac{1}{N} \sum_{i=1}^{N} \log(x_i)^k$$

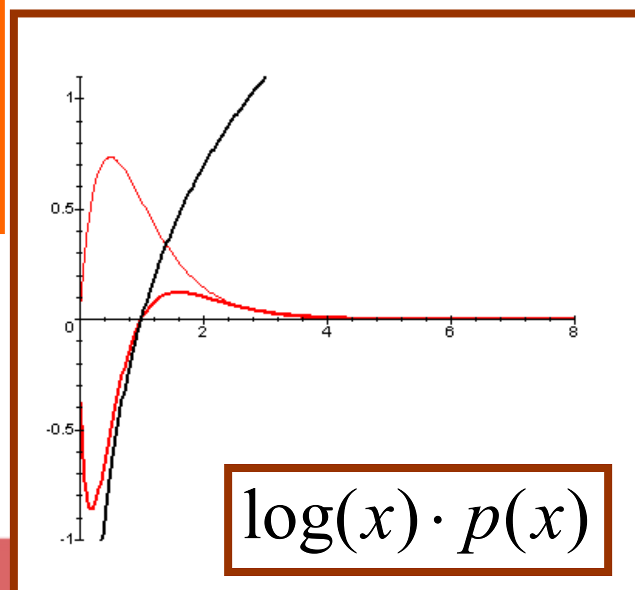
Moments et log-moments

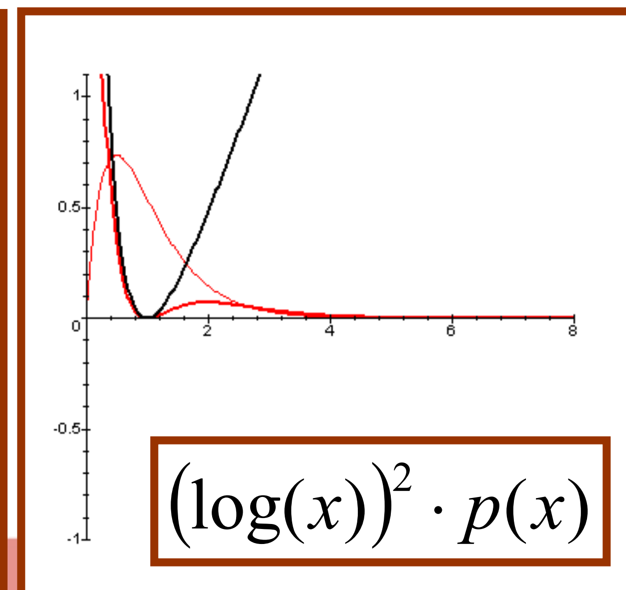


L=2









Example of Rayleigh-Nakagami pdf

$$G[L,\mu](x)=\frac{1}{\Gamma(L)}\frac{1}{\mu}\left(\frac{Lx}{\mu}\right)^{L-1}e^{-\frac{Lx}{\mu}}$$

$$RN[L,\mu](x)=\frac{2}{\Gamma(L)}\frac{\sqrt{L}}{\mu}\left(\frac{\sqrt{Lx}}{\mu}\right)^{2L-1}e^{-\left(\frac{\sqrt{Lx}}{\mu}\right)^2}$$

$$\widetilde{\Phi}_{\mathrm{G}}(s)=\mu^{s-1}\frac{\Gamma(L+s-1)}{L^{s-1}\Gamma(L)}$$

$$\widetilde{\Phi}_{\mathrm{RN}}(s)=\mu^{s-1}\frac{\Gamma\left(L+\frac{s-1}{2}\right)}{L^{\frac{s-1}{2}}\Gamma(L)}$$

$$\widetilde{\kappa}_{1,\mathrm{G}}=\log(\mu)+\Psi(L)-\log(L)$$
$$\widetilde{\kappa}_{2,\mathrm{G}}=\Psi(1,L)$$

$$\widetilde{\kappa}_{1,\mathrm{RN}}=\log(\mu)+\frac{1}{2}(\Psi(L)-\log(L))$$
$$\widetilde{\kappa}_{2,\mathrm{RN}}=\frac{1}{4}\Psi(1,L)$$

$$\widetilde{\kappa}_{k}=\Psi(k-1,L)$$

$$\widetilde{\kappa}_{k,\mathrm{RN}}=\left(\frac{1}{2}\right)^{k}\Psi(k-1,L)$$

Practical use of log-cumulants to analyze textures

- **Computation of log-cumulants:**

$$\widehat{\kappa_1} = \frac{1}{N}\sum_{i=1}^{N} \ln(x_i)$$

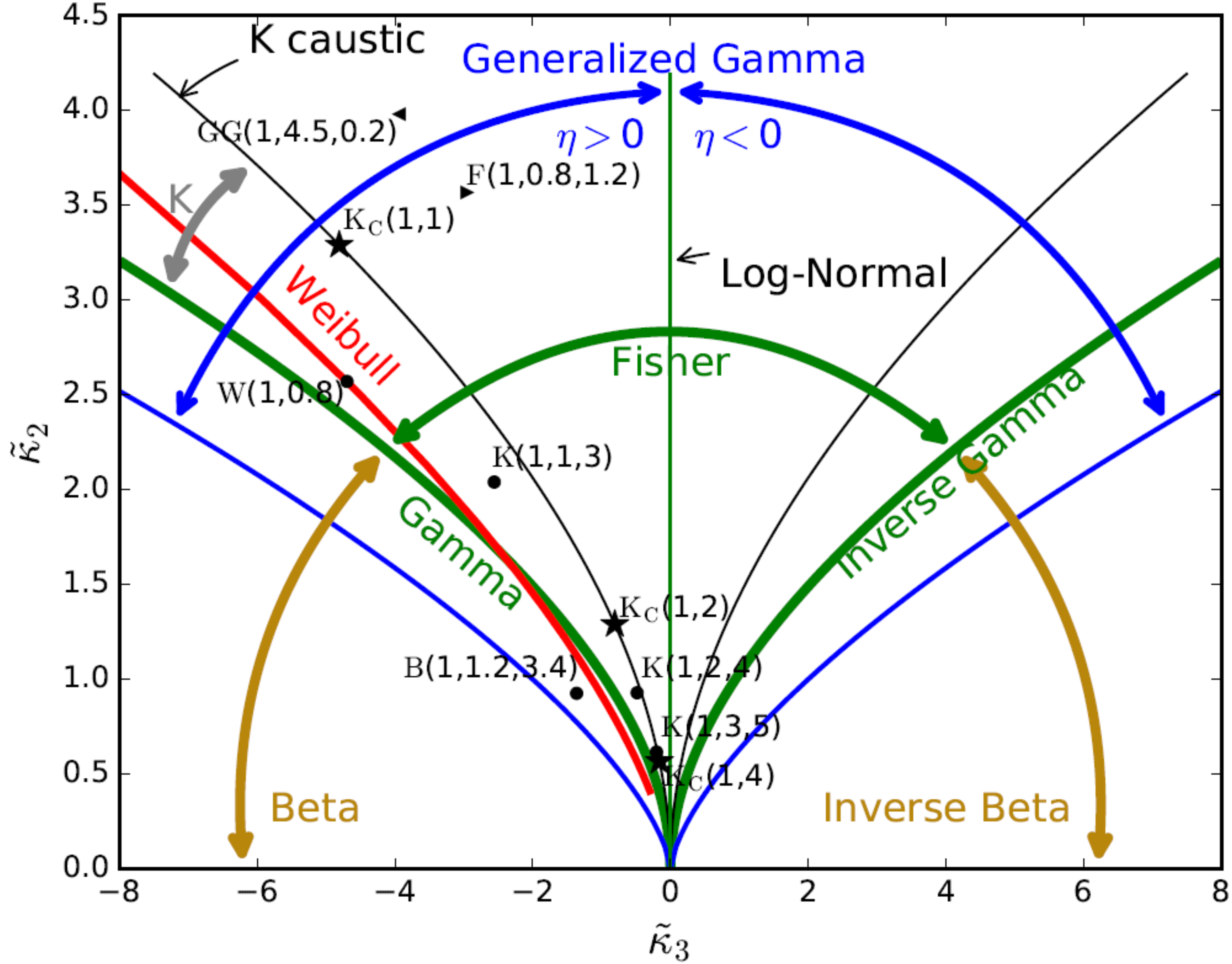
$$\widehat{\kappa_2} = \frac{1}{N}\sum_{i=1}^{N} (\ln(x_i))^2 - \frac{1}{N^2}\left(\sum_{i=1}^{N} \ln(x_i)\right)^2$$

$$\widehat{\kappa_3} = \frac{1}{N}\sum_{i=1}^{N} (\ln(x_i))^3 - \frac{3}{N^2}\left(\sum_{i=1}^{N} \ln(x_i)\right)\left(\sum_{i=1}^{N} (\ln(x_i))^2\right) + \frac{2}{N^3}\left(\sum_{i=1}^{N} \ln(x_i)\right)^3$$

- **For known pdf : inversion to recover pdf parameters**

- **For unknown pdf: positioning in the log-cum3 / log-cum2 diagram**

Log-cum3 / log-cum2 diagram



Summary of the session (1)

- **Backscattering of the objects**
  - Parameters: roughness, geometric configuration, di-electric properties
- **Geometric effects in SAR imagery**
  - Especially for HR SAR and urban areas (shadows, lay-overs, corner reflectors)
- **Speckle phenomenon:**
  - Well modeled by Goodman model for rough surfaces
  - Amplitude: Rayleigh - Nakagami
  - Intensity: Gamma
  - Homogeneity measure: coefficient of variation

Summary of the session (2)

- **Multi-looking: averaging of L samples**
  - Incoherent (intensity)
  - ENL deduced from coefficient of variation
- **Log-statistics**
  - Give more reliable estimates to compute the distribution parameters
  - The log-cum1 / log-cum2 diagram allows an easy visualization of the distribution positioning