SAR acquisition modeling

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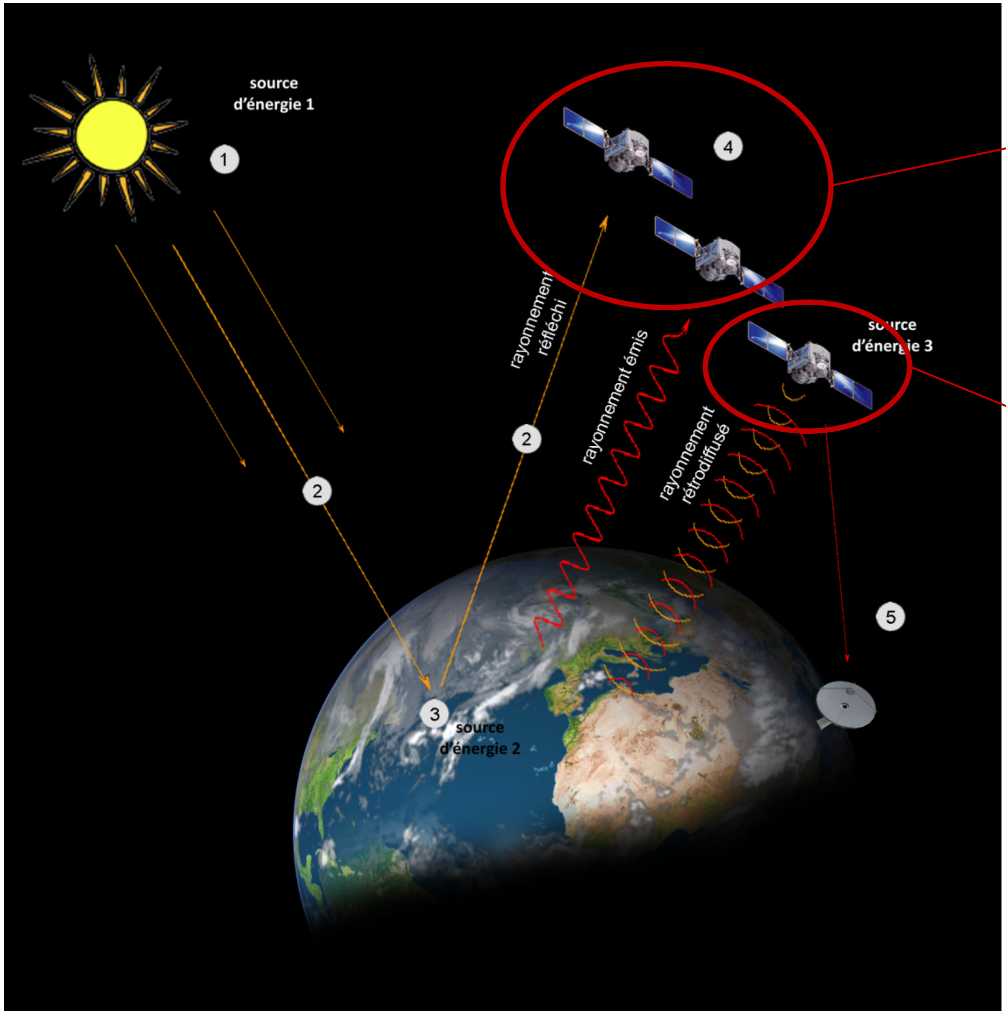
MPT - 2020

Overview of the session

- **Principles of radar sensors**
- **Examples of SAR images**
- **SAR image acquisition**
  - Chirp and range direction
  - Synthetic aperture and azimuth direction
- **Some SAR systems and applications**

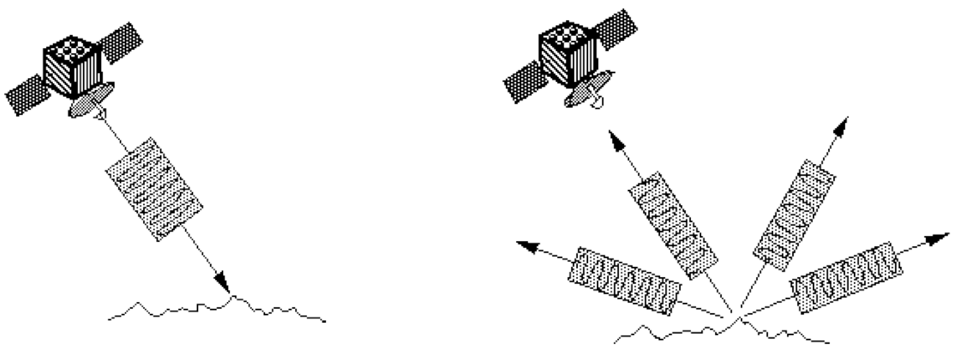
Physic measurement

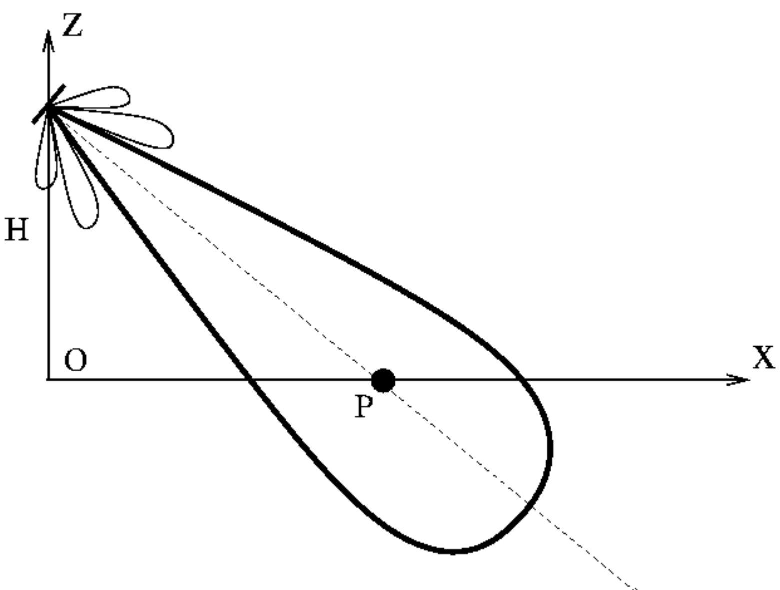


Passive sensors
- Optic domain
- Infra red

Active sensors
- radar
- lidar

Principle

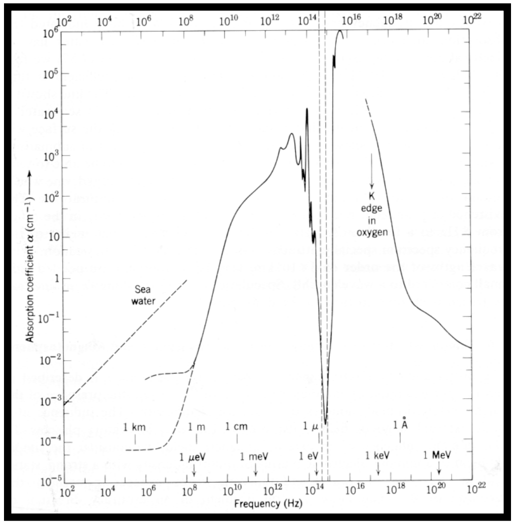




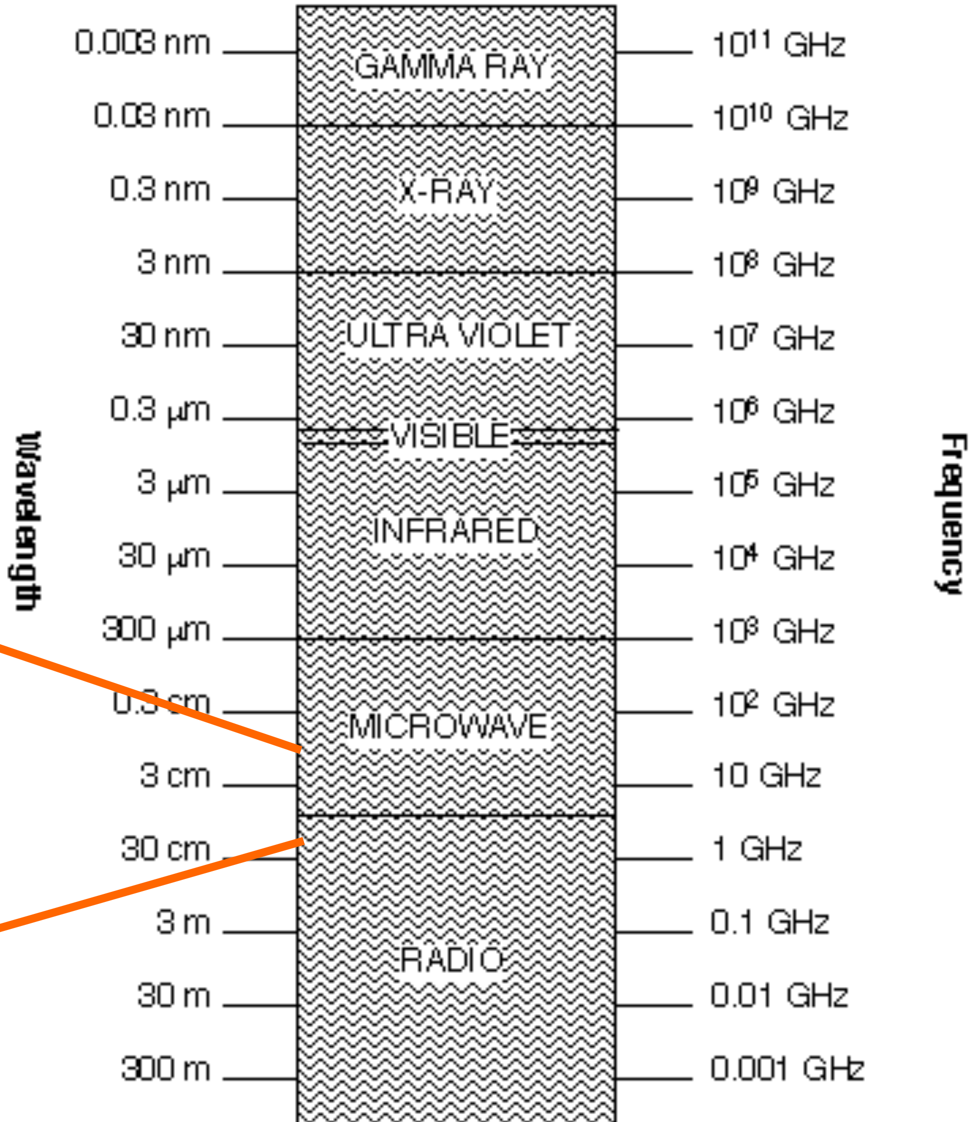
- **Radar sensor:**
  - Emission of electro-magnetiic waves
  - Recording of the back-scattered signal by the elements on the ground

- **System properties:**
  - Lateral viewing
  - Mono-static sensor

Radar sensors – Electro-magnetic waves



Radar bands:
- X ~ 2 cm (~ 9 GHz)
- C ~ 5 cm (~ 5 GHz)
- L ~ 20 cm (~ 1 GHz)



Examples of SAR images What do we see on a radar image ?

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Friedrichshafen, Allemagne
Image © 2008 GeoContent
©2007


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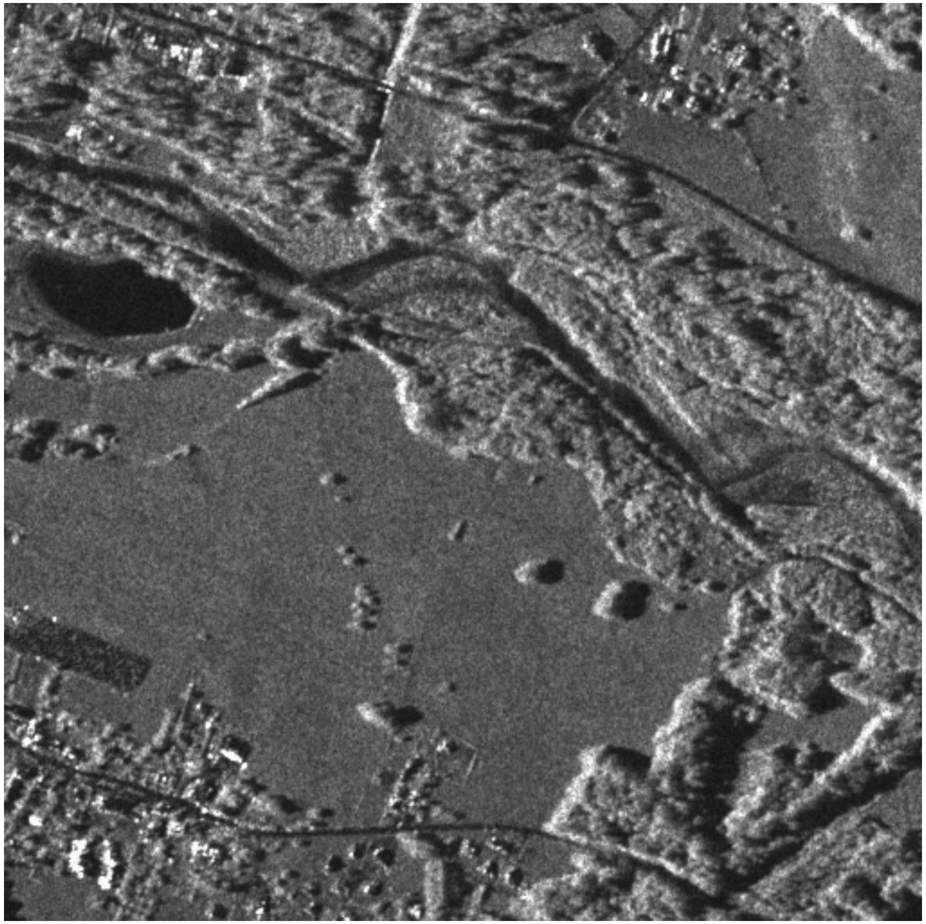
Terrasar-X : first iamge, 15th of june 2007

Terrasar-X image (~2m) :
ideal case (without speckle)



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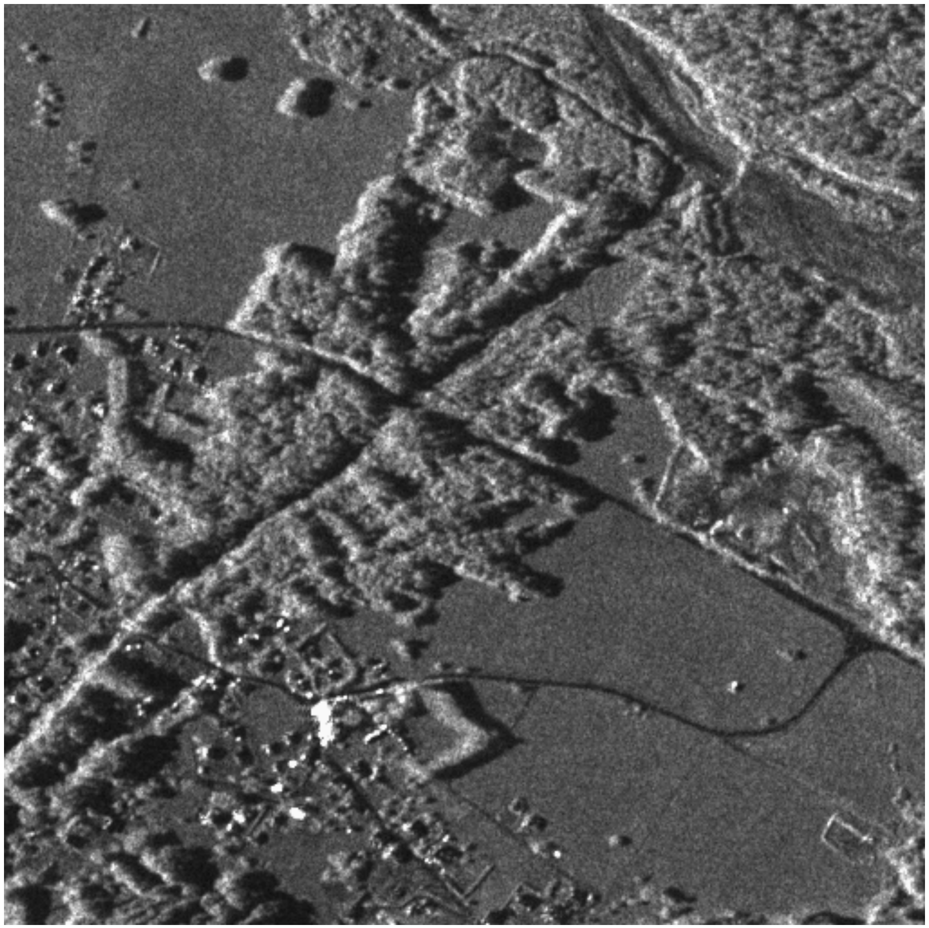
Terrasar-X image (~2m) : ideal case (without speckle)



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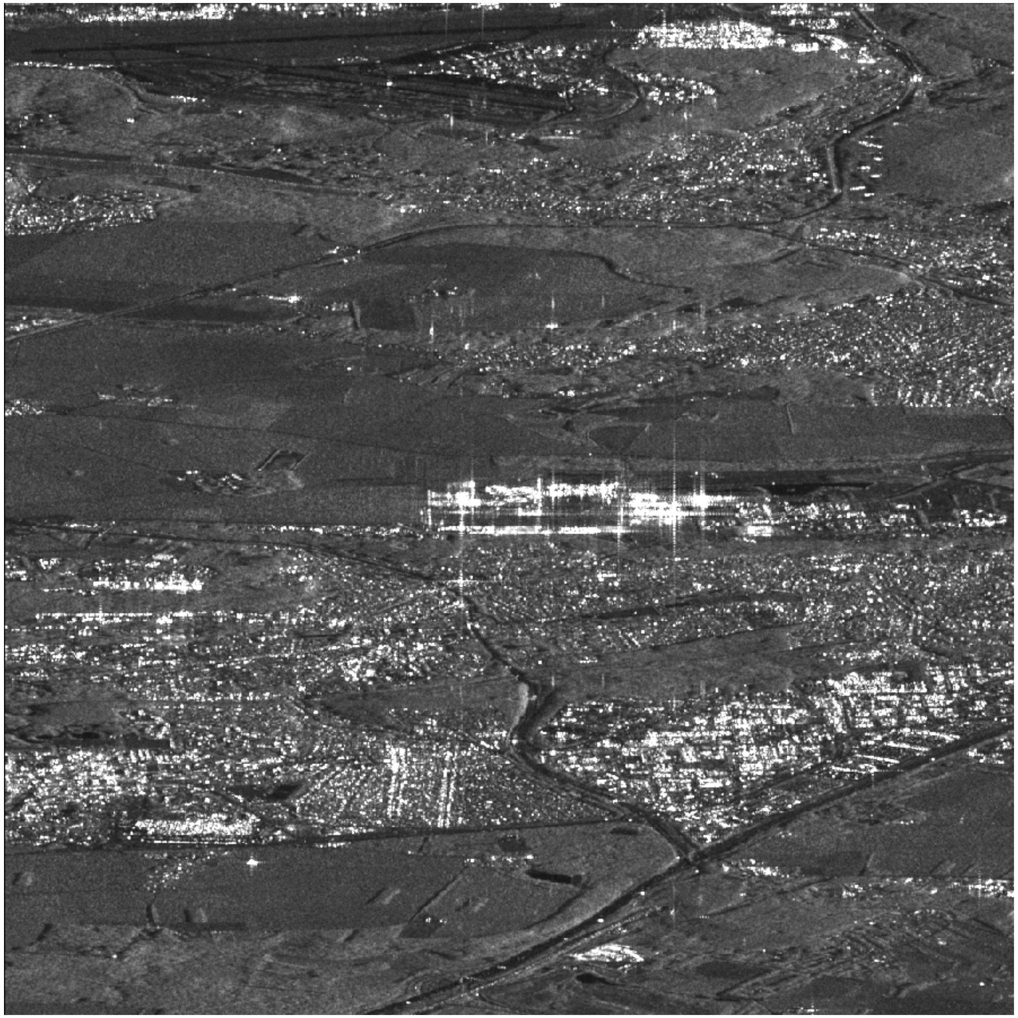
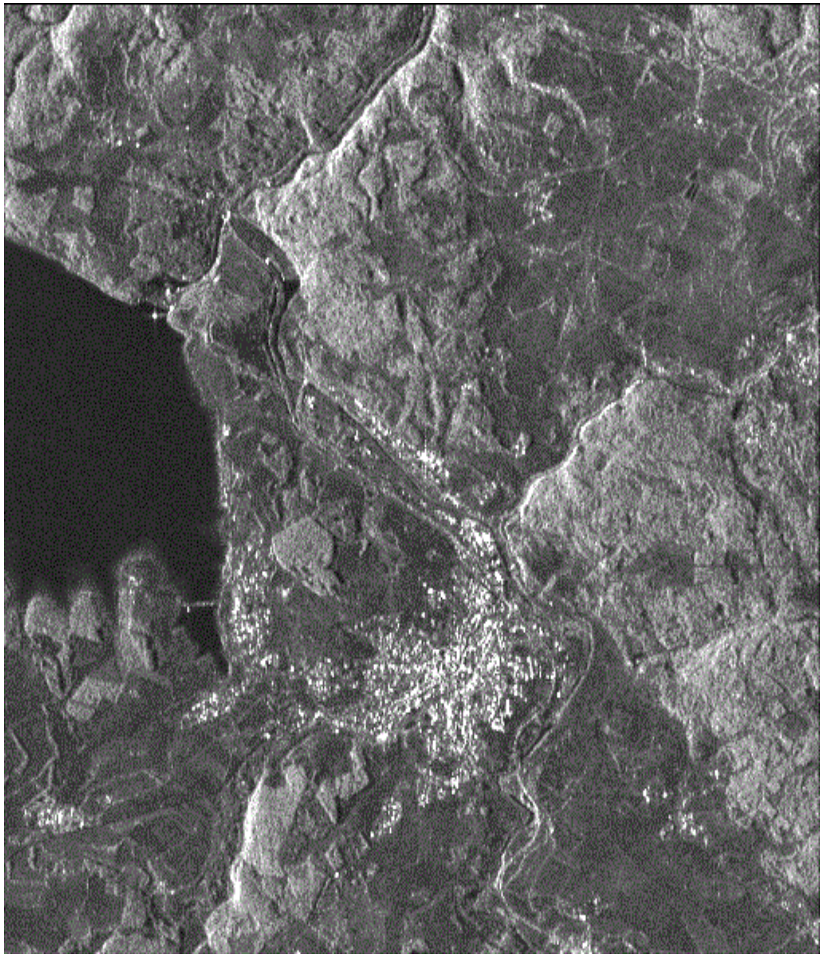
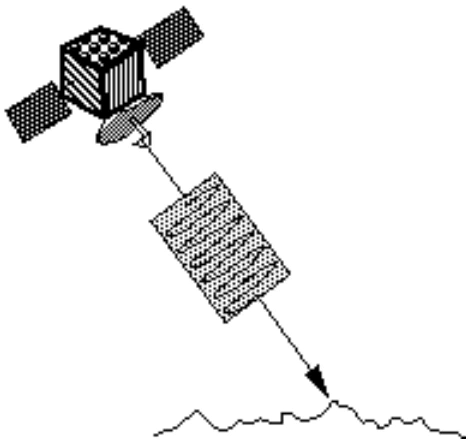
Sentinel image (~4mx10m) : ideal case (without speckle)

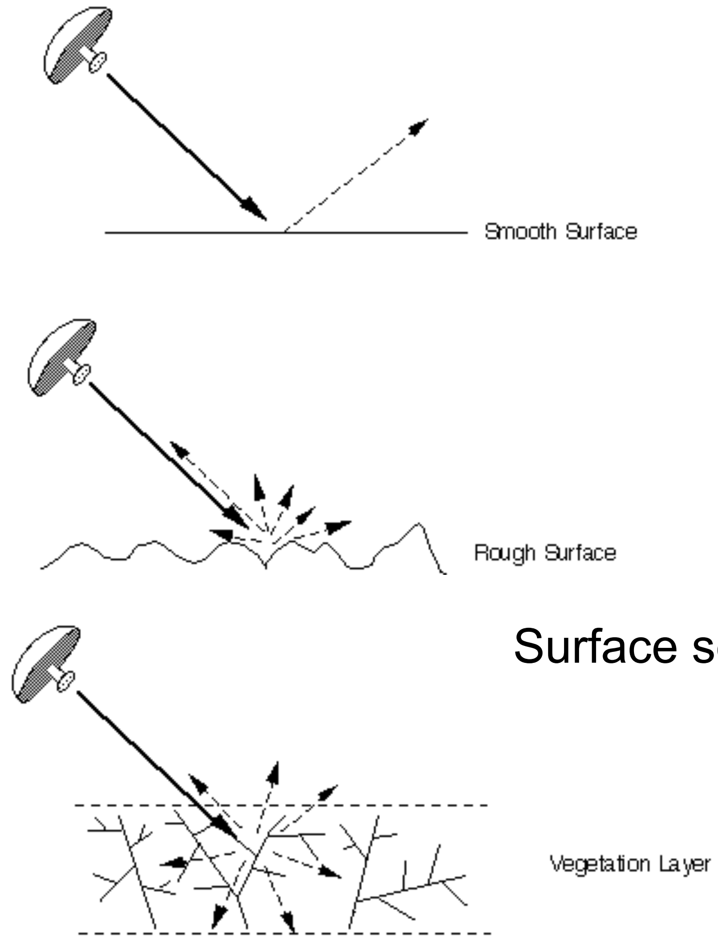


Sentinel-1 : Langogne



Backscattering mechanisms: geometry and dielectric properties

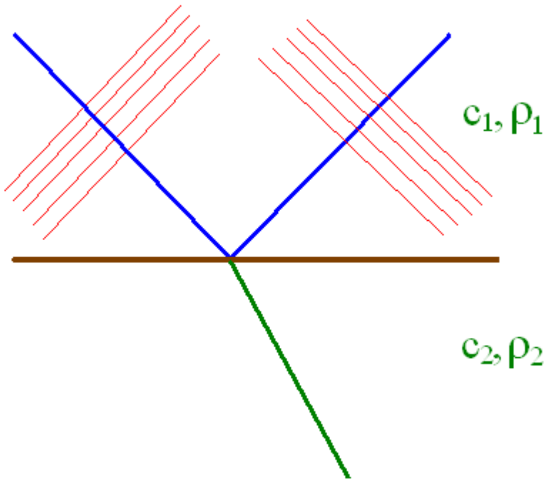


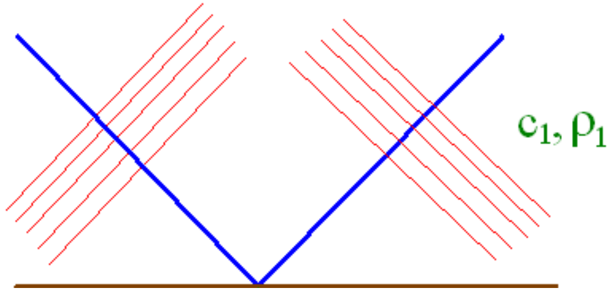


Surface scattering

Volume scattering

Backscattering mechanisms: geometry and dielectric properties





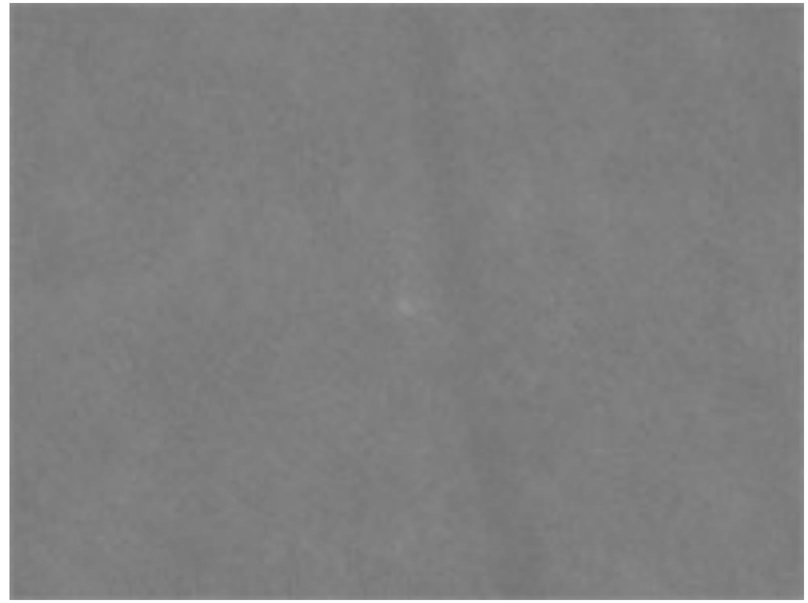
- **Reflection and refraction mechanisms**
- **Snell Descartes**

$$\theta_1' = \theta_1$$

$$\frac{1}{c_2}\sin\theta_2 = \frac{1}{c_1}\sin\theta_1$$

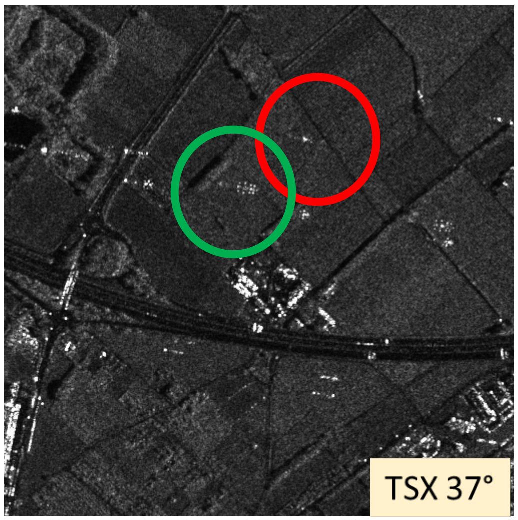
- **Case of metallic or water surfaces: full reflection**
- **Influence of soil water content and roughness**
- **Penetration depth increases with wavelength and dryness**

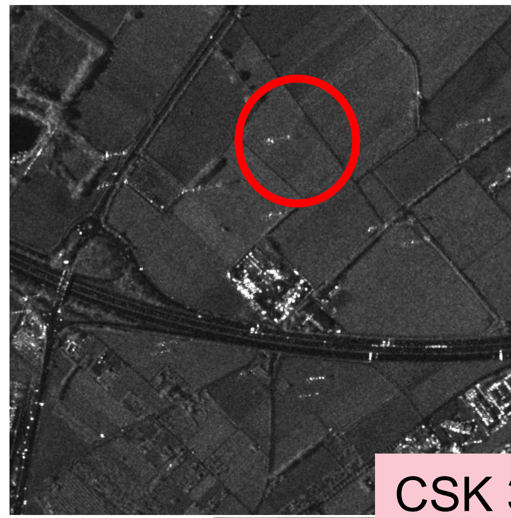
Detection of A380 engine under snow using SETHI (ONERA)

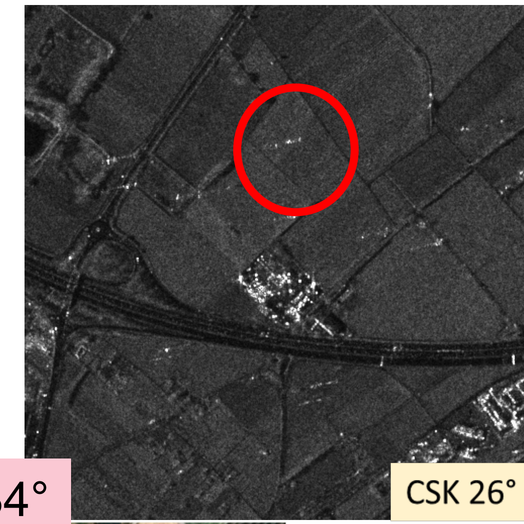


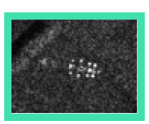
- Buried under 4m of snow
- Dry snow (-35°)
- SAR penetration in the snow

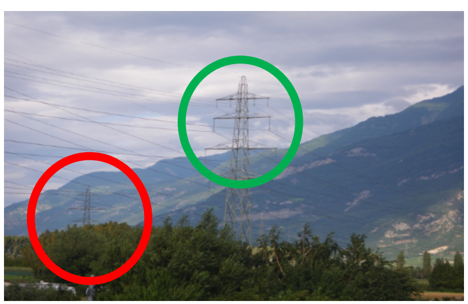
TSX and CSK on Martigny (no speckle)
Pylon characteristics





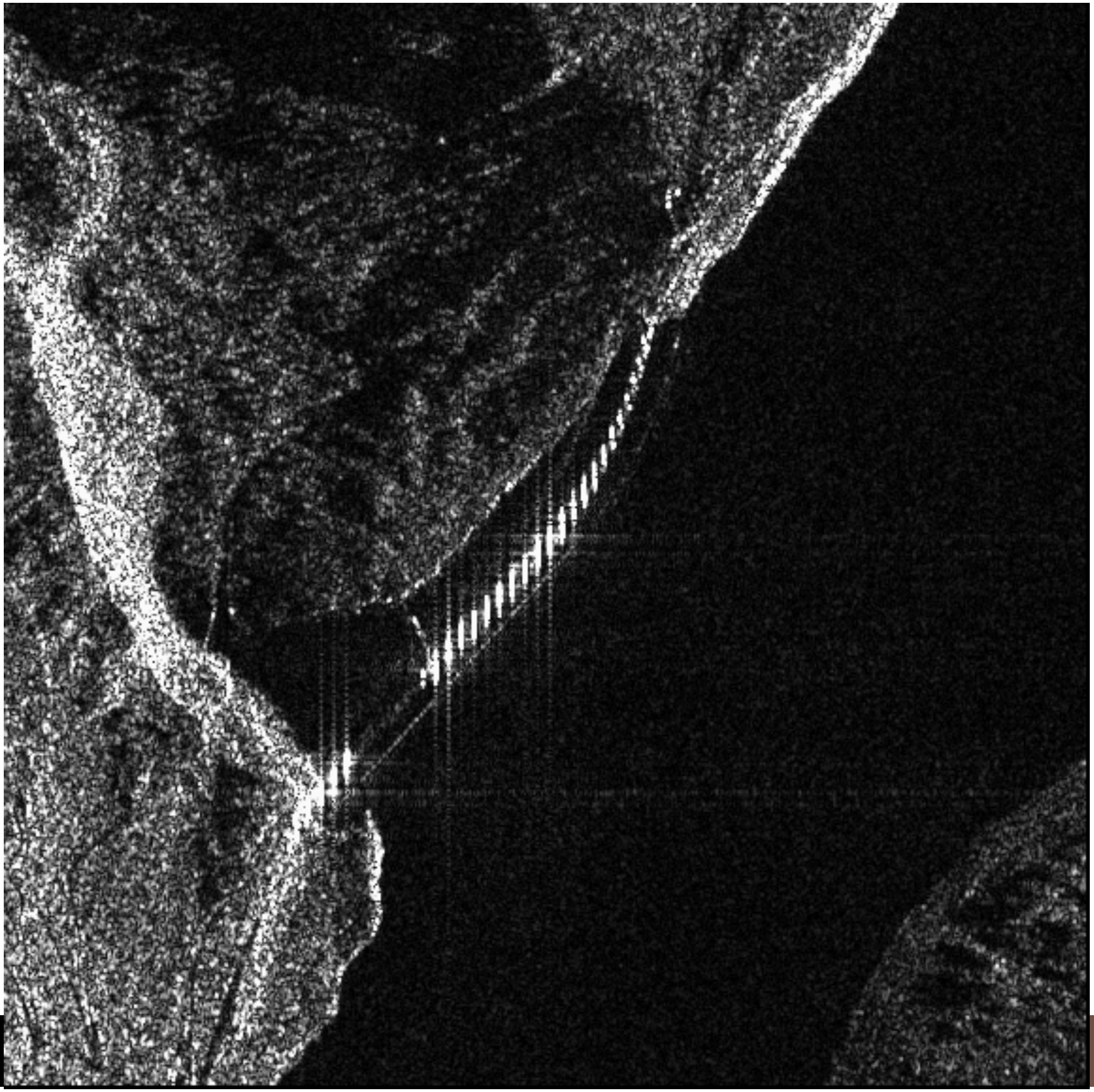




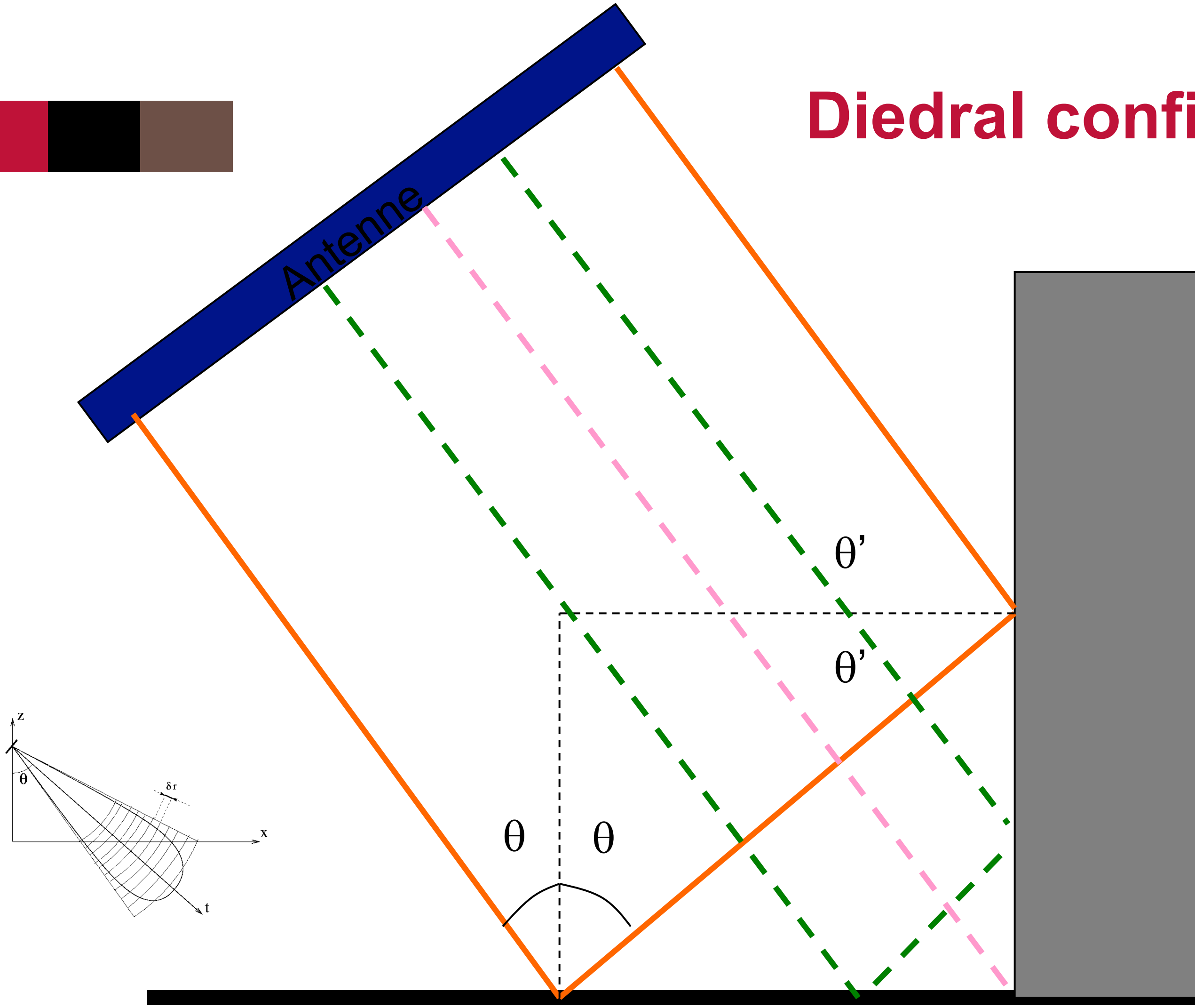


CSK 34°

Roseland lake (Terrasar-X):
Black water and strong back-scatterers….



Diedral configuration: wall



- Same paths for e.m waves
- All backscattered signals in the same radar cell

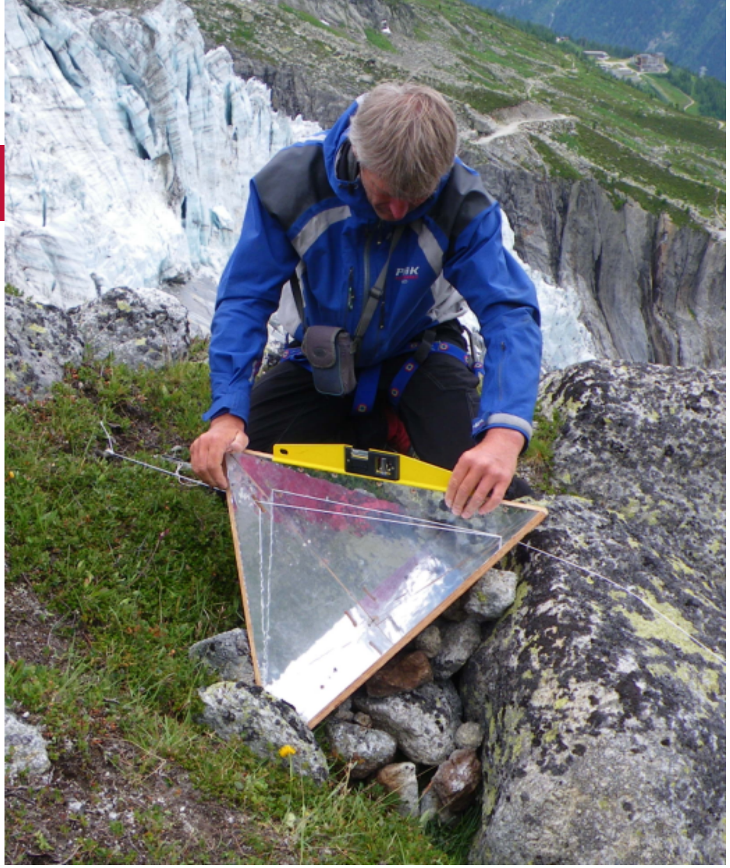
- $2\theta + 2\theta' = \pi$ >> backscattered signal in the incidence direction

Canonic targets: triedral configuration
Calibration purposes (« corner reflector »)

- **A trihedral: 3 plates (size a) with 90°**
- **Backscattered signal in the same resolution cell**

$$\sigma_{trièdre} = \frac{4\pi\, a^4}{3\, \lambda^2}$$

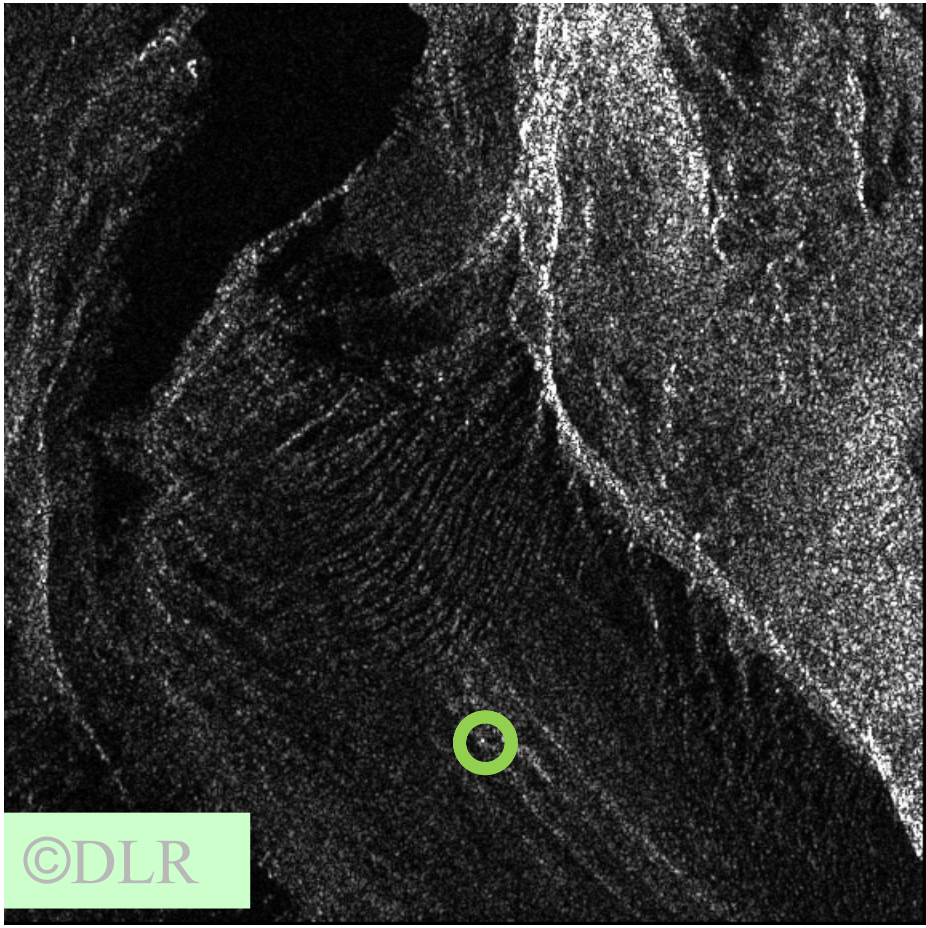
$$\theta_a = \pm 20°$$
$$\theta_b = \pm 20°$$



Isolated targets

- **« corner reflector »**
  - Allmost omni-directional
  - Overrides the backscattered signal in the resolution cell

Ice tracking: artificial corner reflectors on the Glacier



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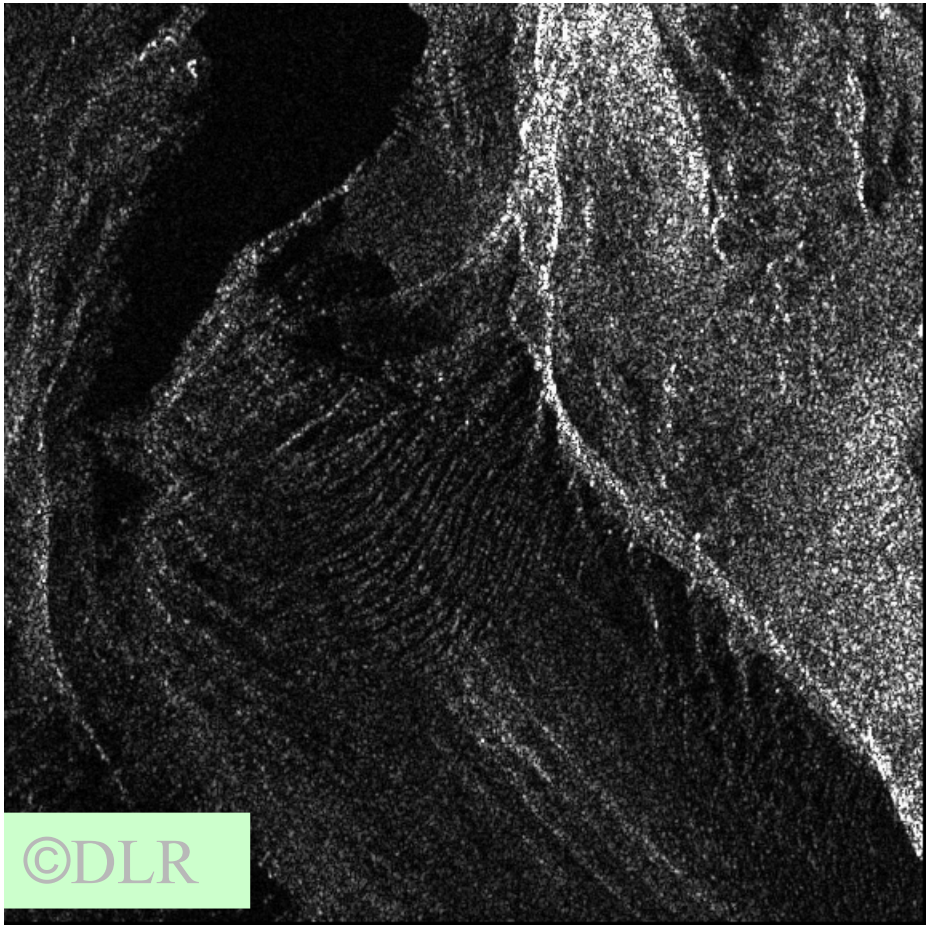
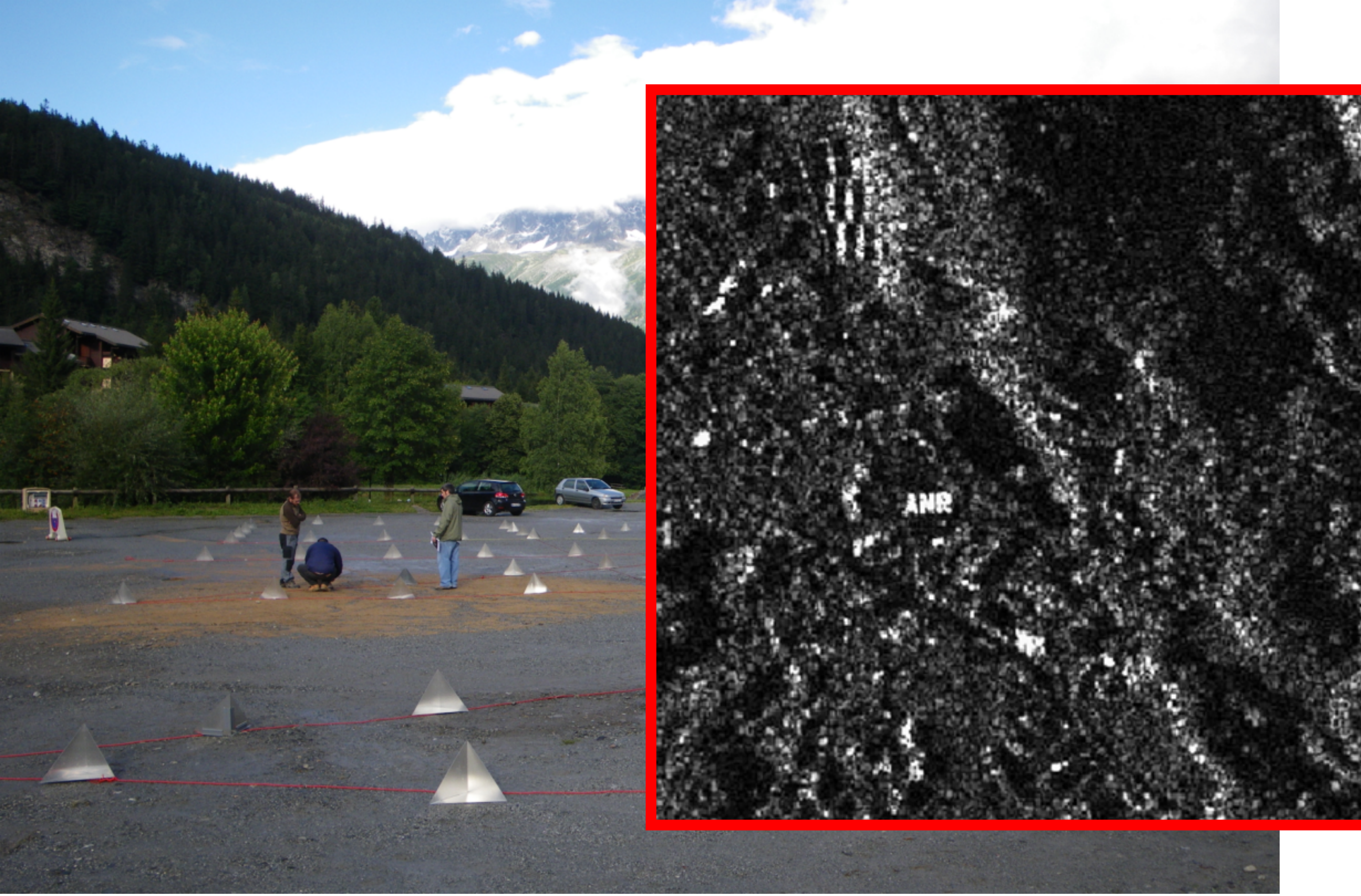
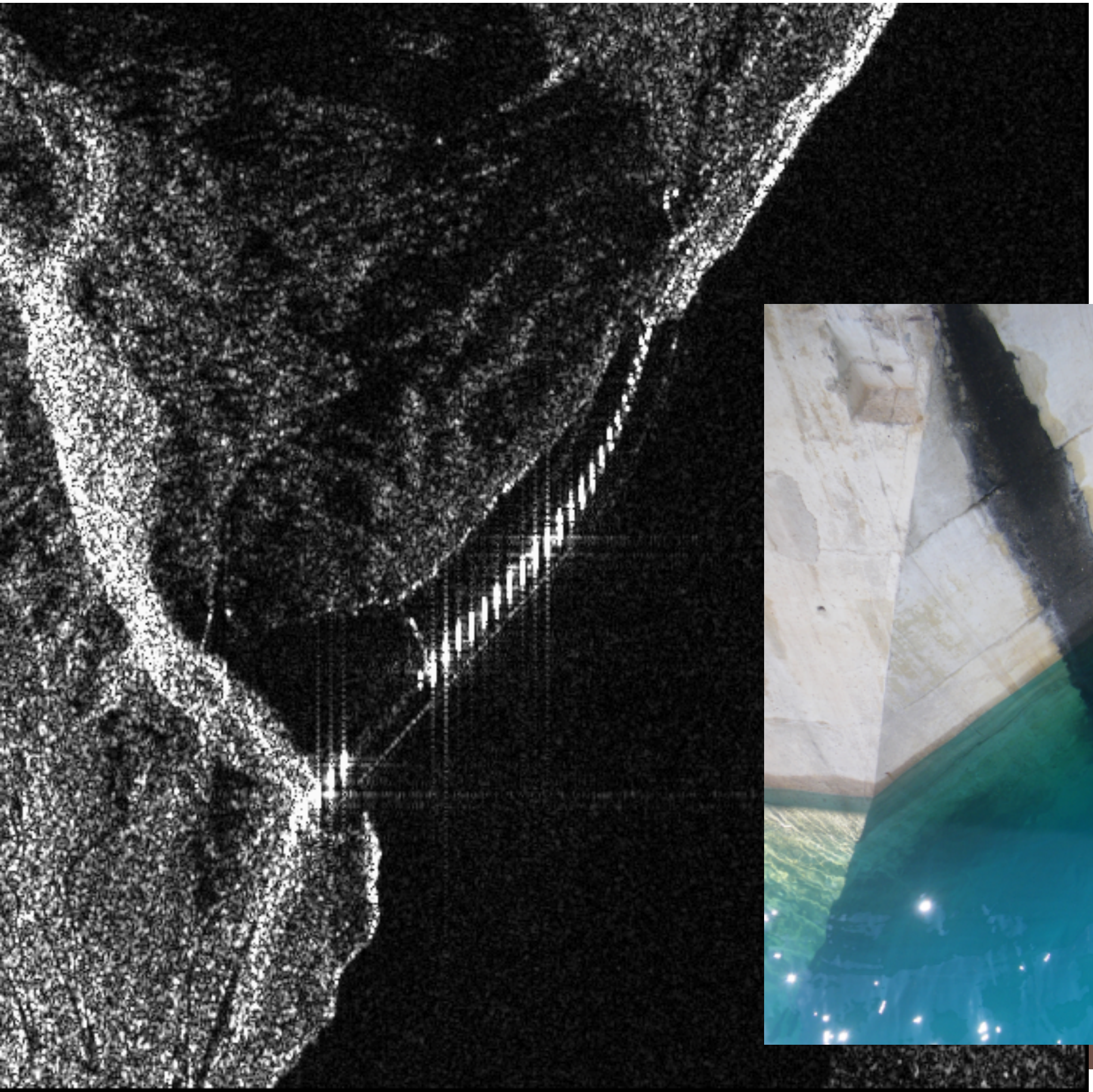
Ice tracking: artificial corner reflectors on the Glacier




ANR

Roseland lake (Terrasar-X): Black water and strong back-scatterers….



Targets and object visibility

- **Small isolated and isotropic object :**
  - Omnidirectionnal (sphere)
  - Trihedral configurations
- **Urban areas:**
  - Dihedral configurations (orientation influence)
- **Any target:**
  - Directivity effects
- **Many targets in a resolution cell:**
  - Speckle

Backscattering of a cell

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

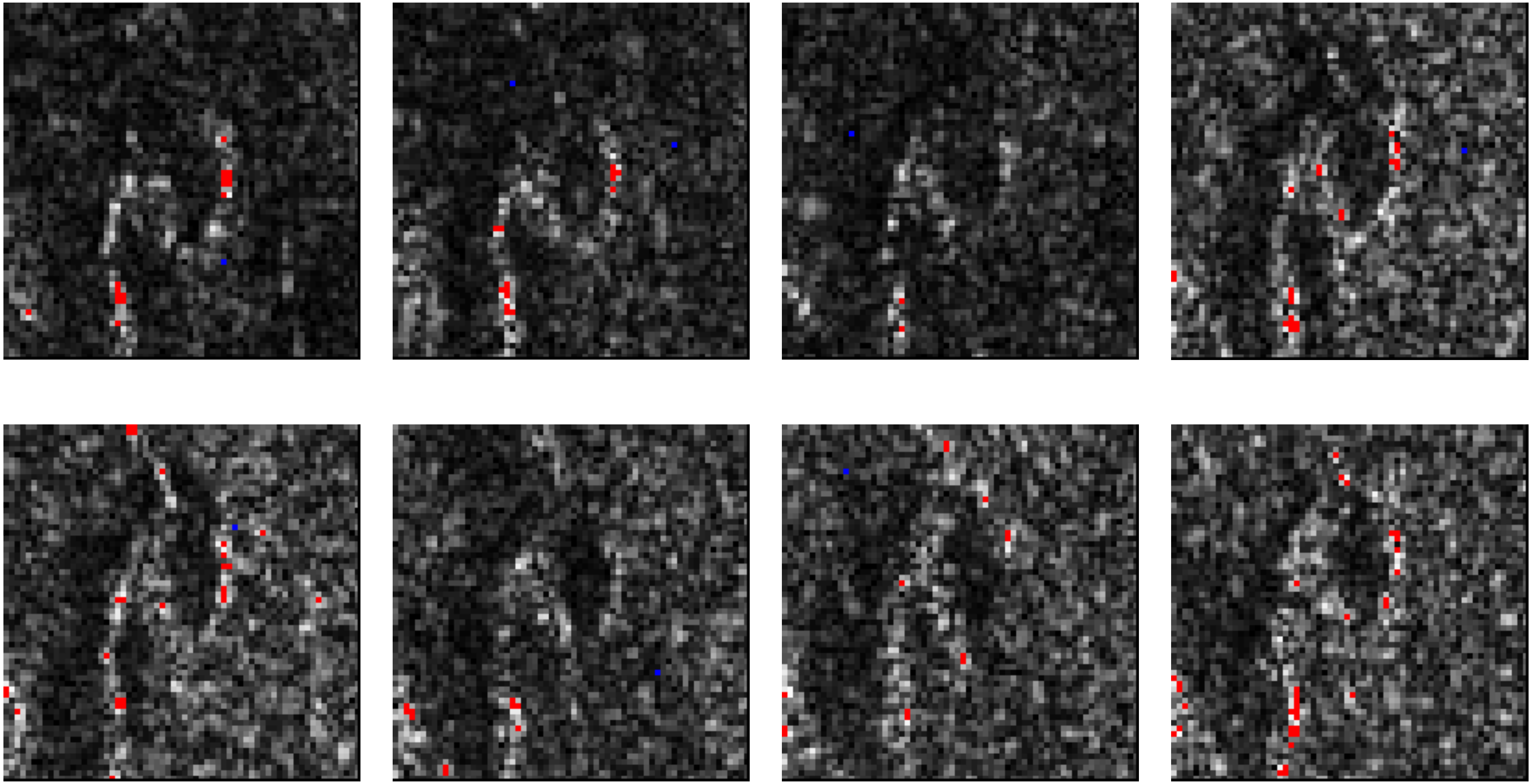
- **A(x,y) is characteristic of the imaged area**
- **A(x,y) can be complex :**
  - Amplitude: backscattering coefficient
  - Phase: delays or delocalisation inside the pixel
- **→Directivity of the backscattered signal : depends on A(x,y)**
  - The diagram of the local ground antenna is not known

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
  - Computed using calibration constant (corner reflector)

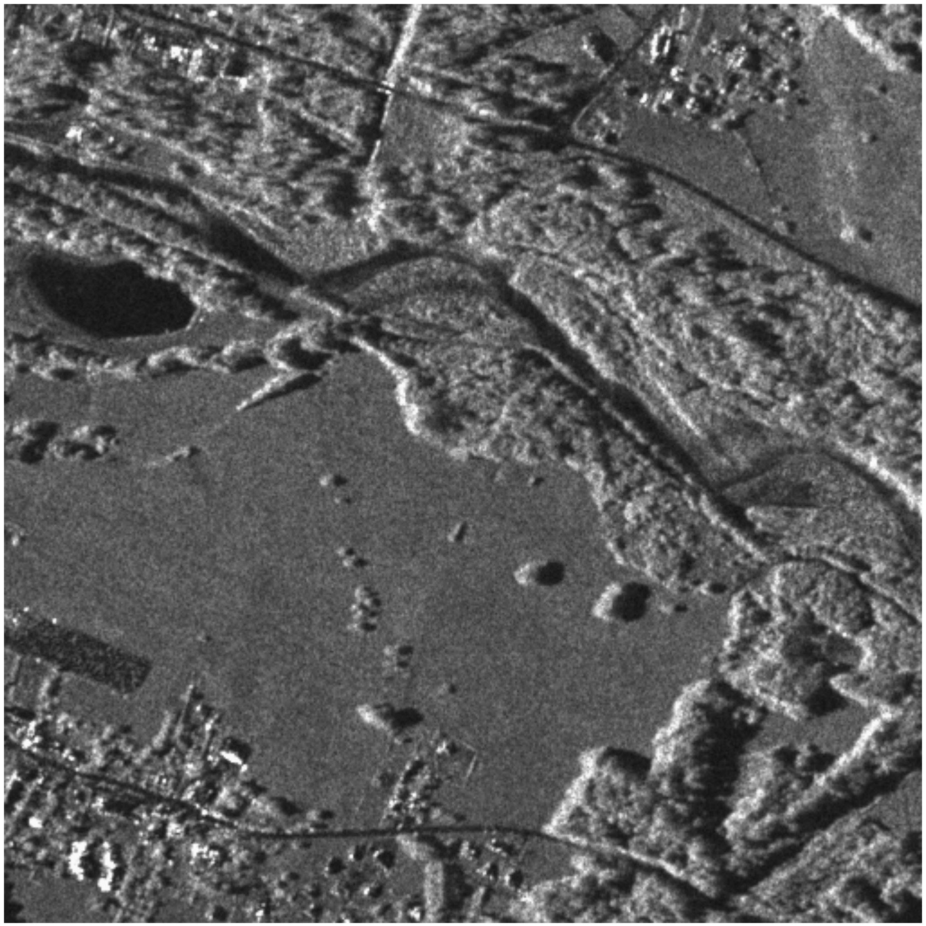
Argentière glacier: erratic block

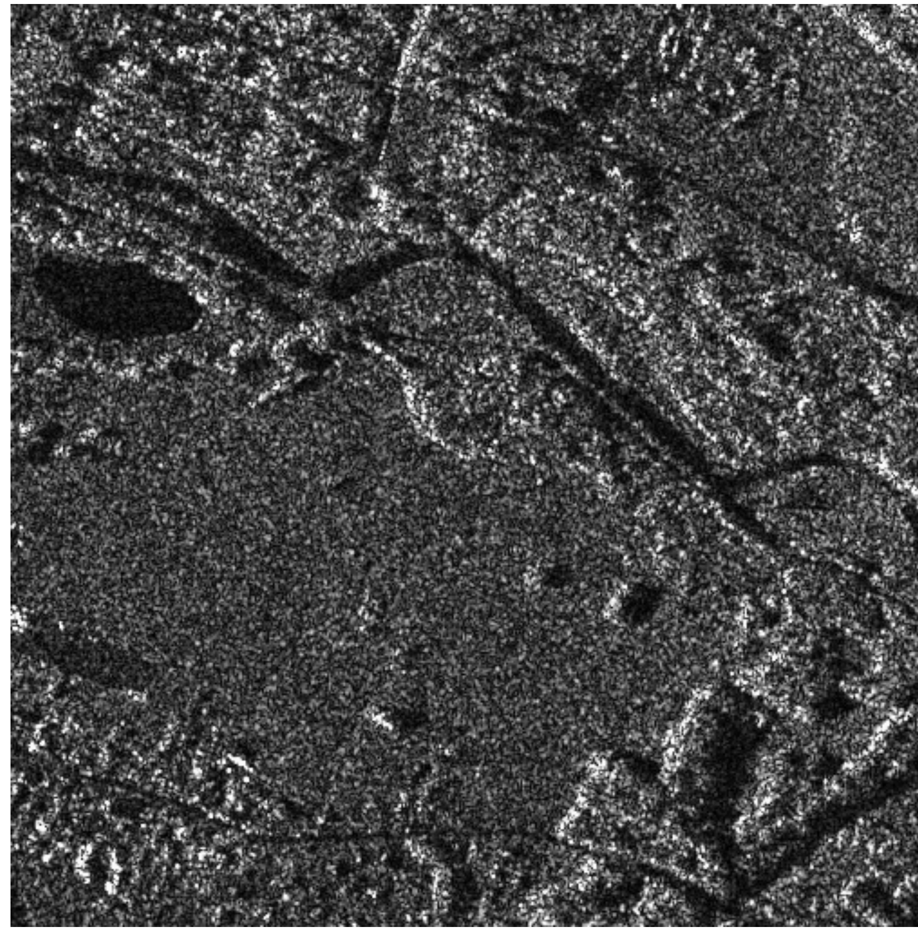


Same indidence angles
June 2009 to september 2009

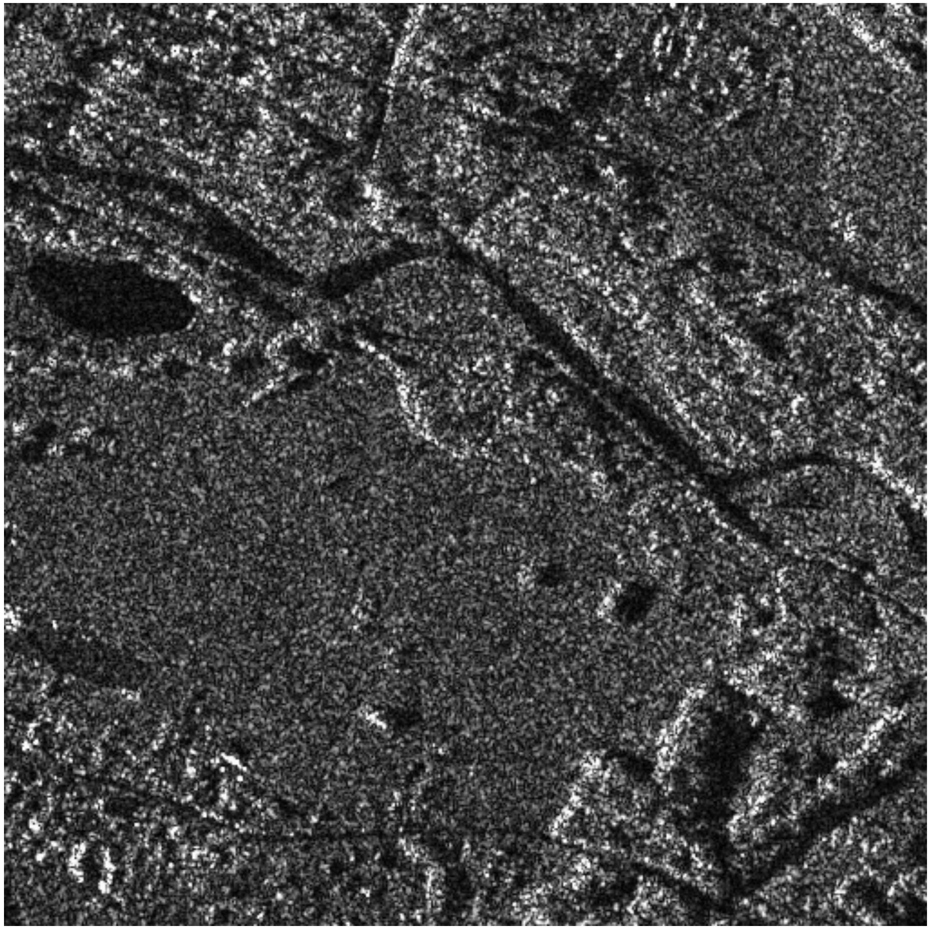
Speckle

TerraSAR-X image (~2m): speckle

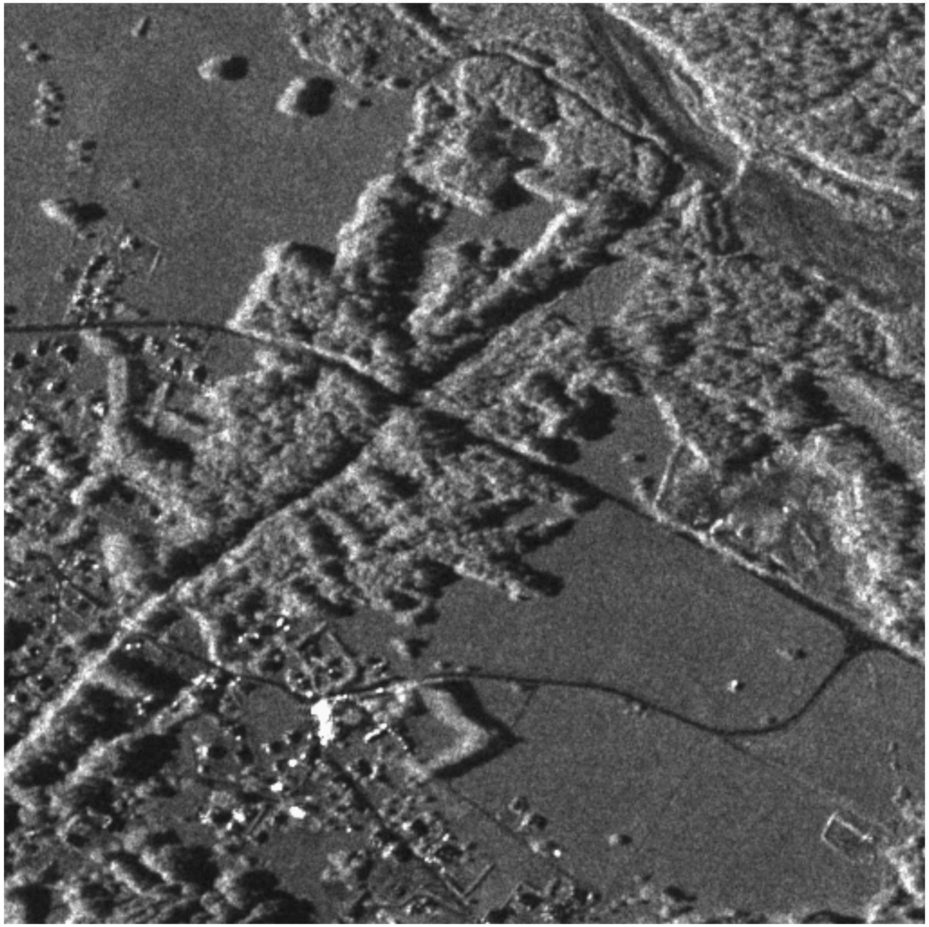


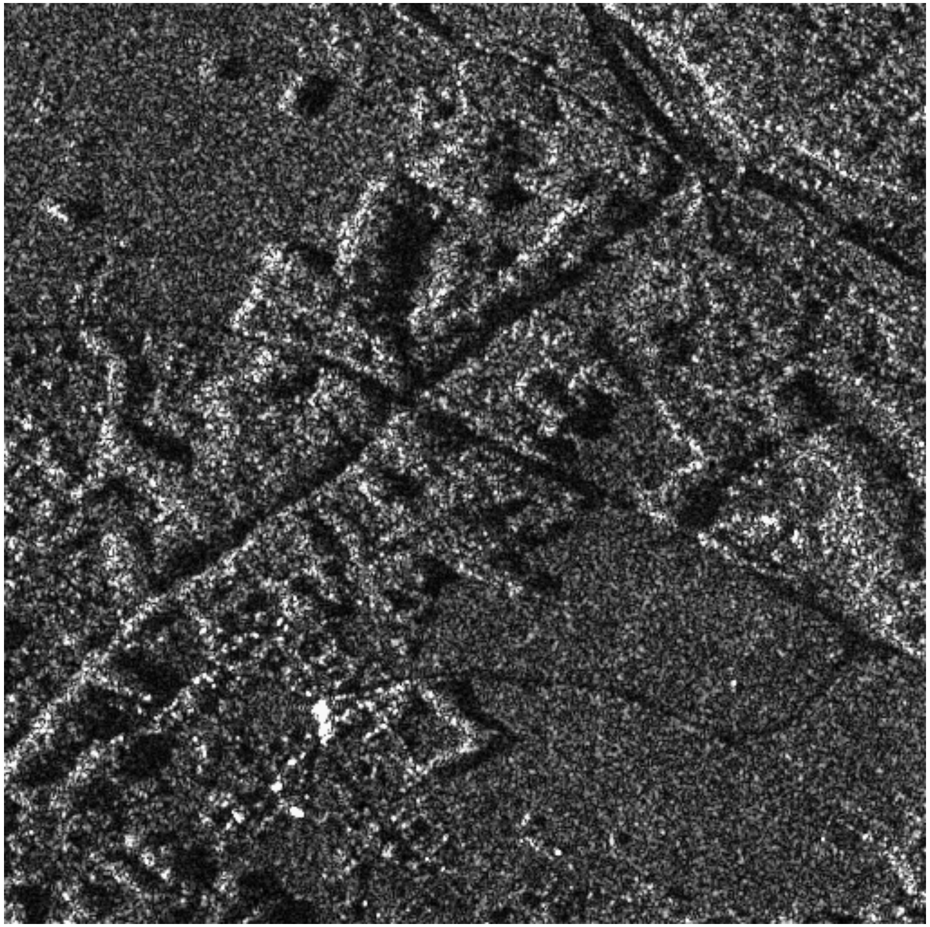


TerraSAR-X image (~2m): speckle

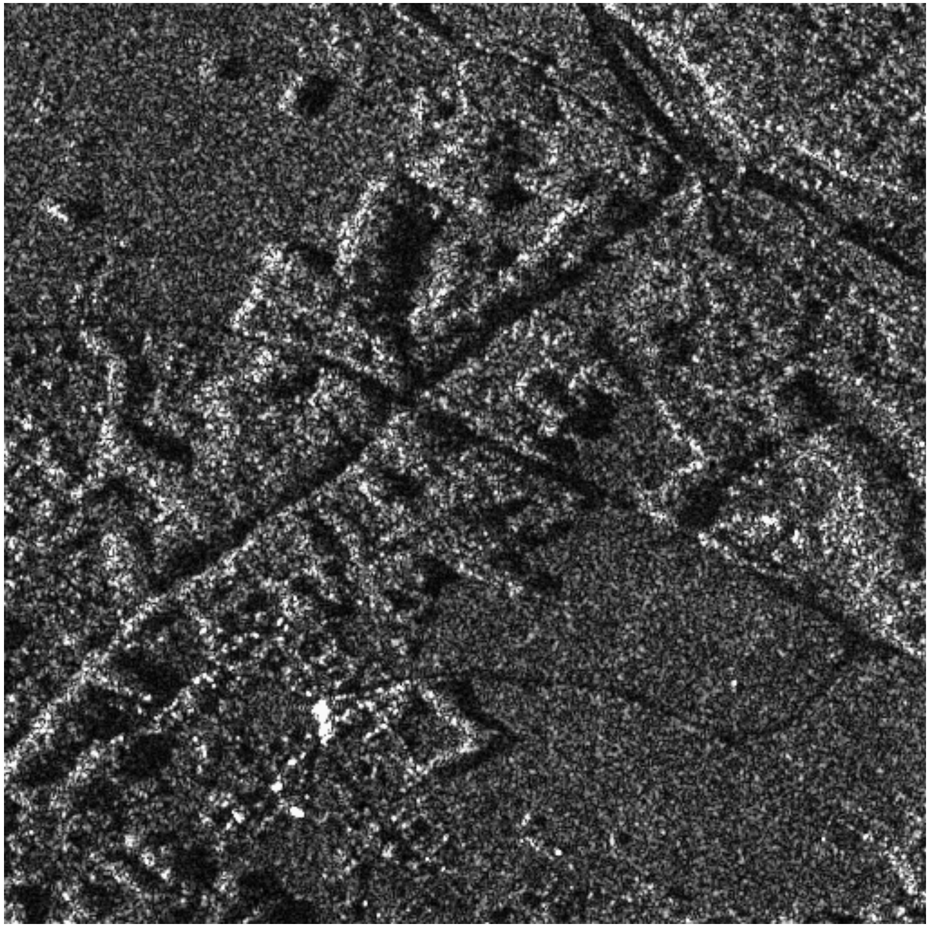


Speckle phenomenon

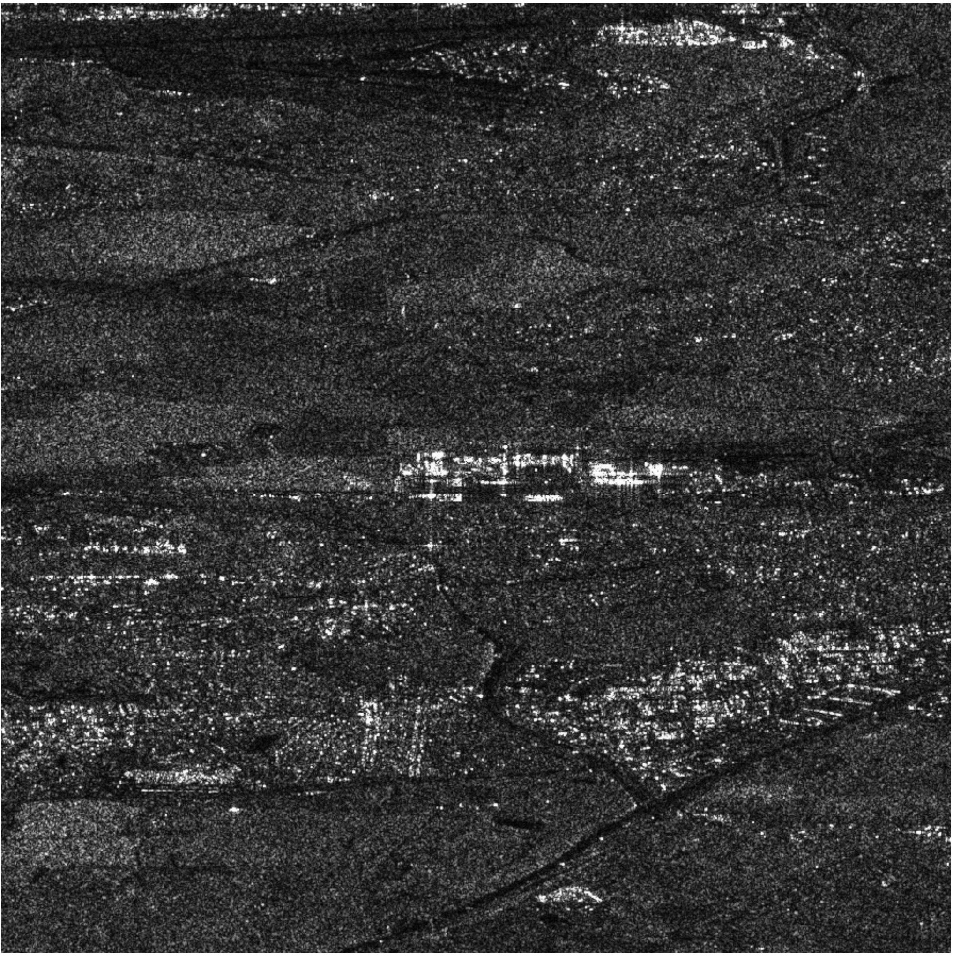




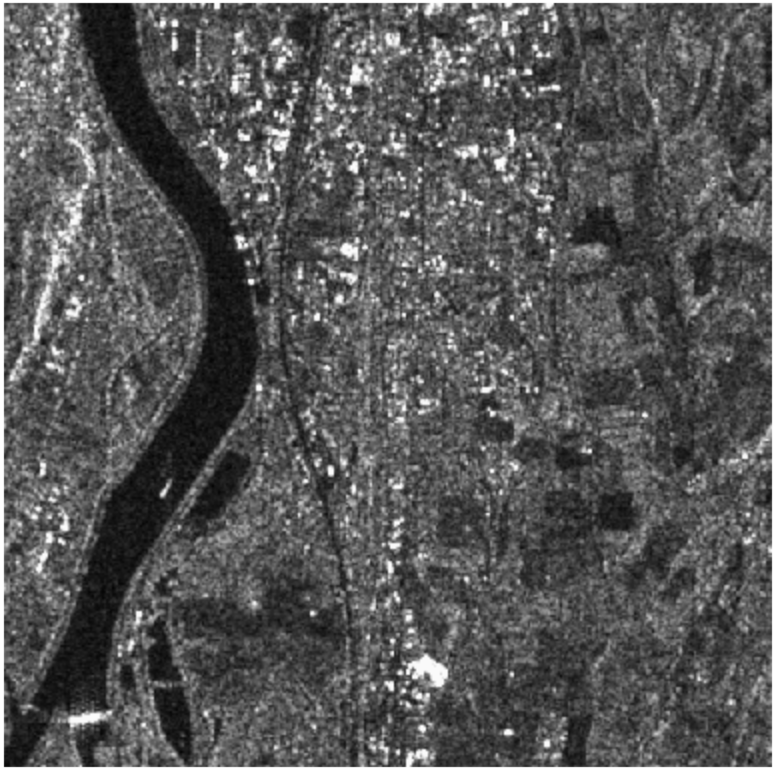
TerraSAR-X image (~2m): speckle



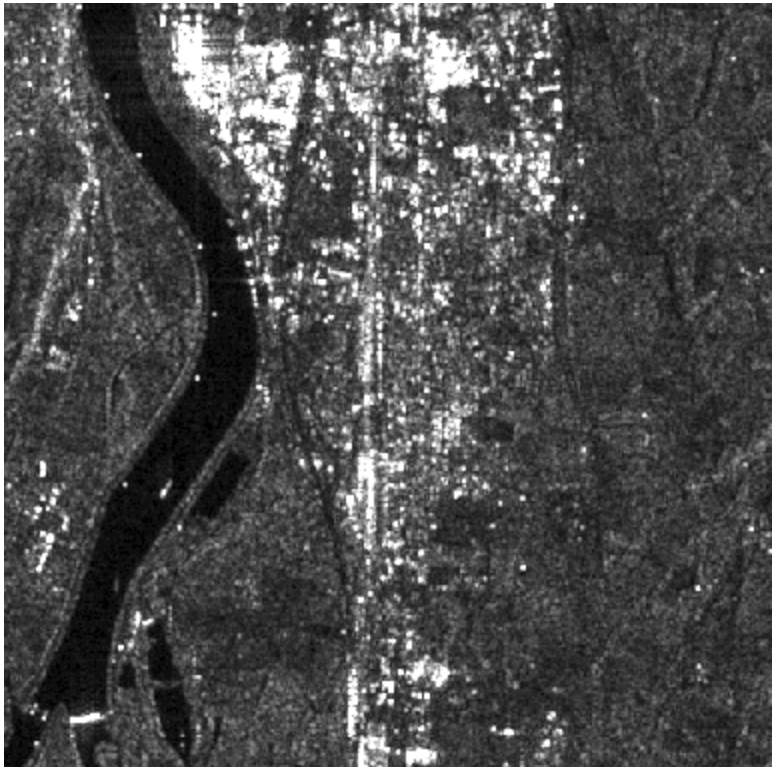
Speckle phenomenon (Sentinel)



Polarimetry (Sentinel)

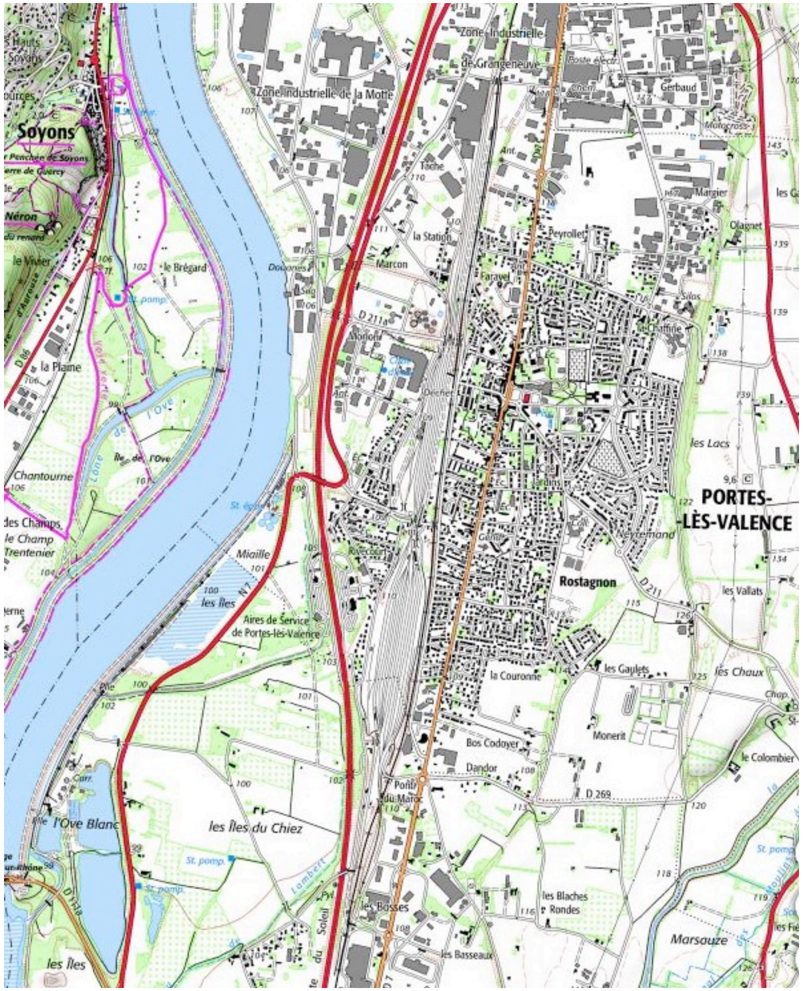


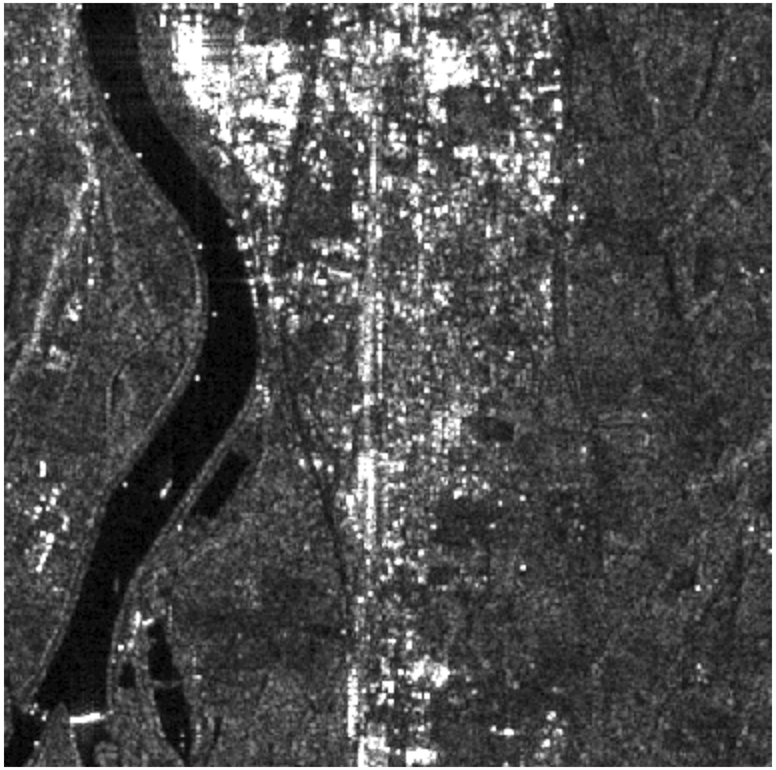
VH



VV

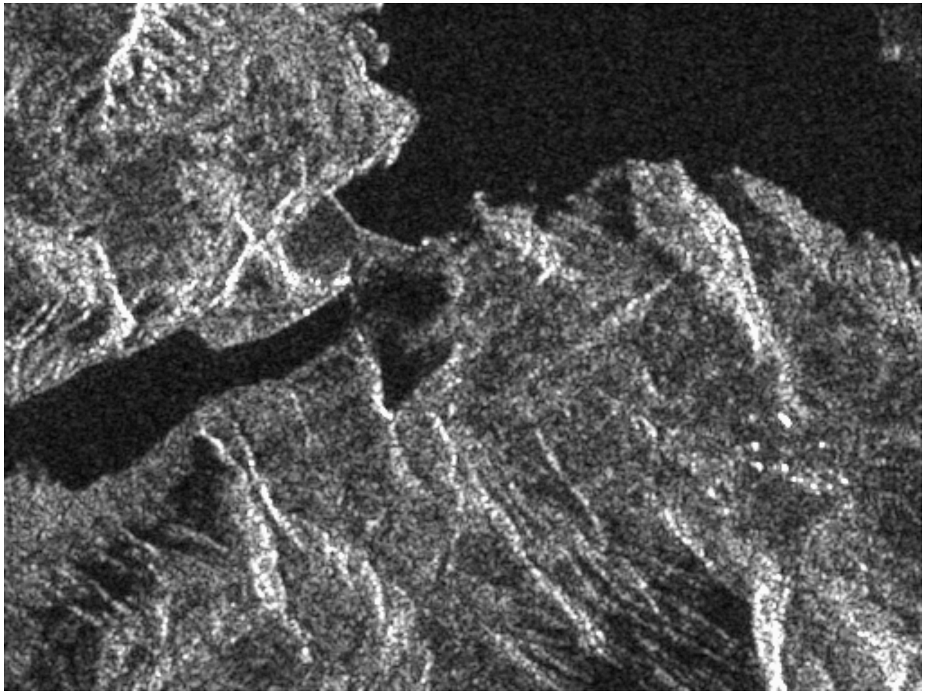
Polarimetry (Sentinel)

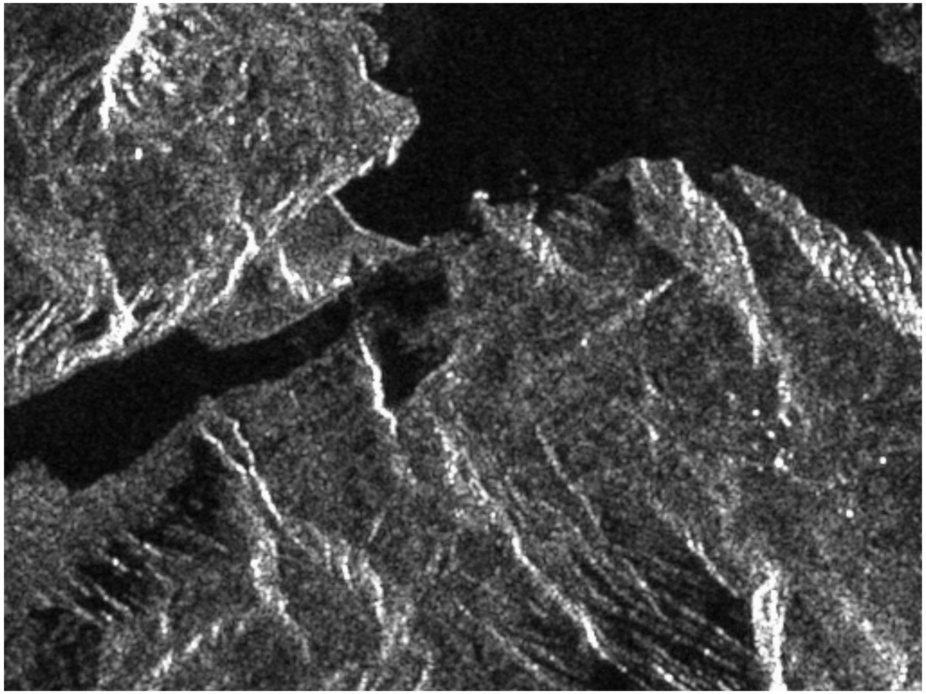




VV

Serre Ponçon: Sentinel





VH

VV

Overview of the session

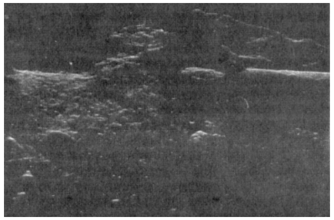
- **Principles of radar sensors**
- **Examples of SAR images**
- **SAR image acquisition**
  - Chirp and range direction
  - Synthetic aperture and azimuth direction
- **Some SAR systems and applications**

A few dates

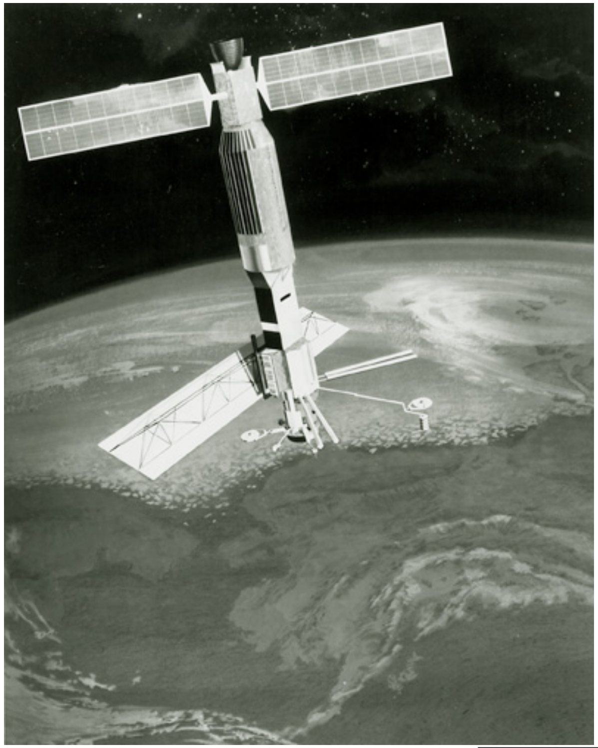
- Radar Invention:
C. Hülsmeyer (1904)

- Synthetic Aperture:
C. Wiley (1951)

- Apollo 17 (1972):
radar images of the moon



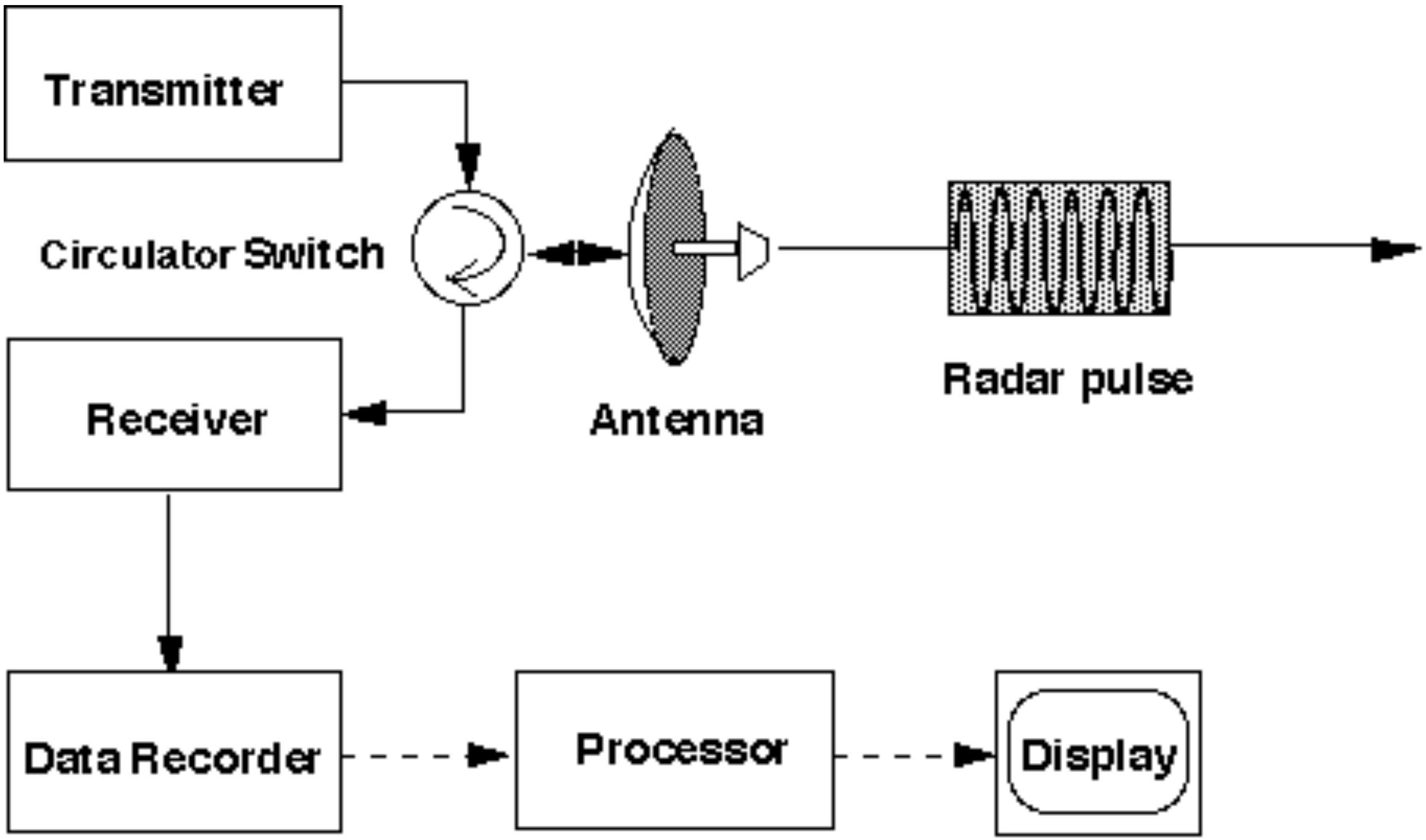
- First satellite:
SEASAT (1978, USA)



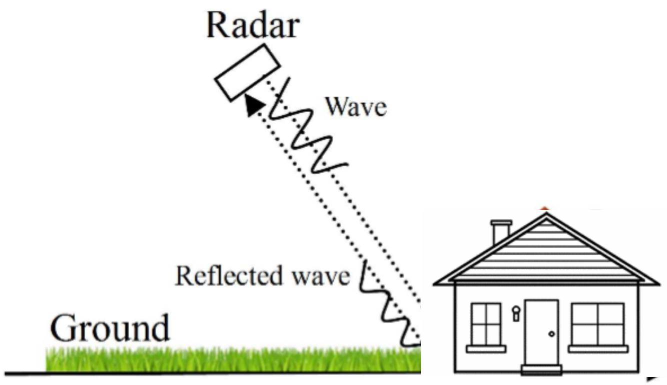
SAR history

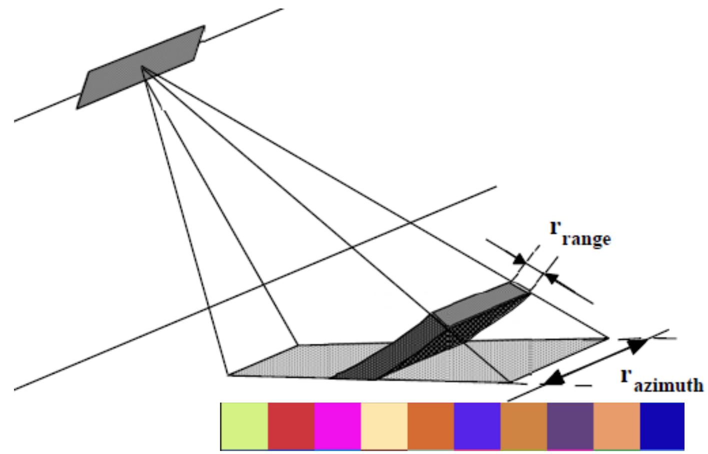
- Principles: Wiley (1951)
- First use to image the moon surface (Apollo 17)
- American SEASAT experiment (1978)
- Soviet satellite sensors (Kosmos et Almaz)
- Use of the Shuttle: SIR (1982, 1984 et 1994) and SRTM (2000)
- Europe: ERS (1991, 1995) et Envisat (2002)
- Japan (1992, 2006) and Canada (1995)

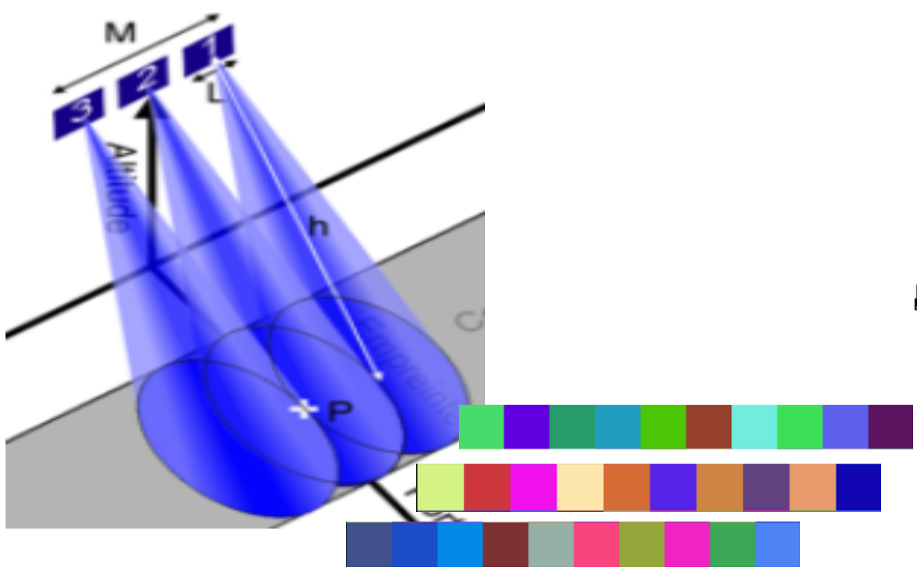
Principles of SAR : emission and recording

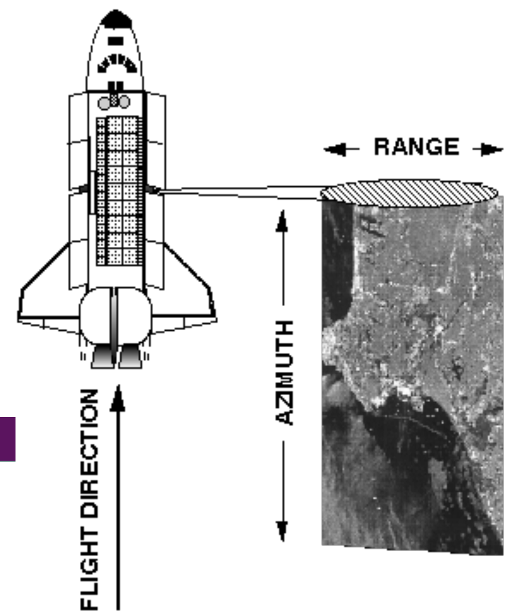


Principles of SAR: wave emission and recording





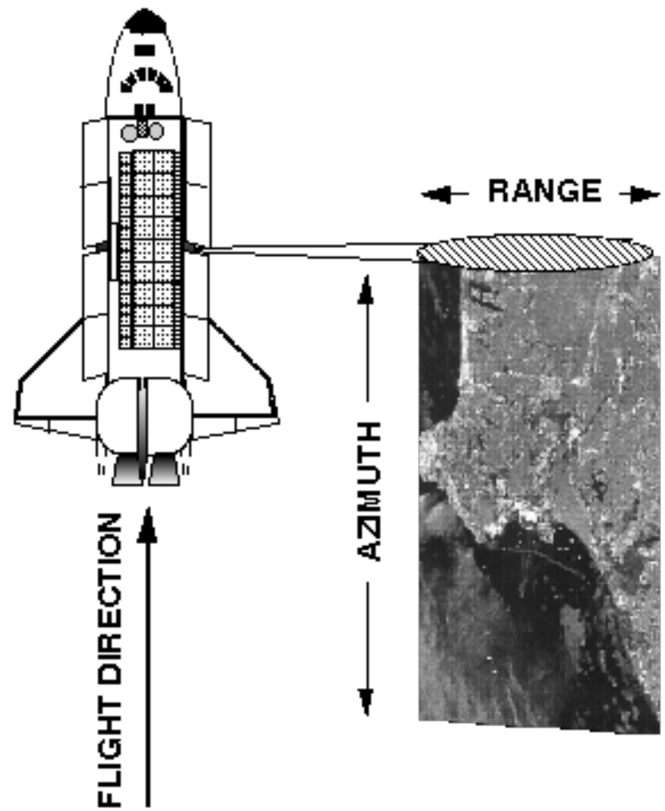




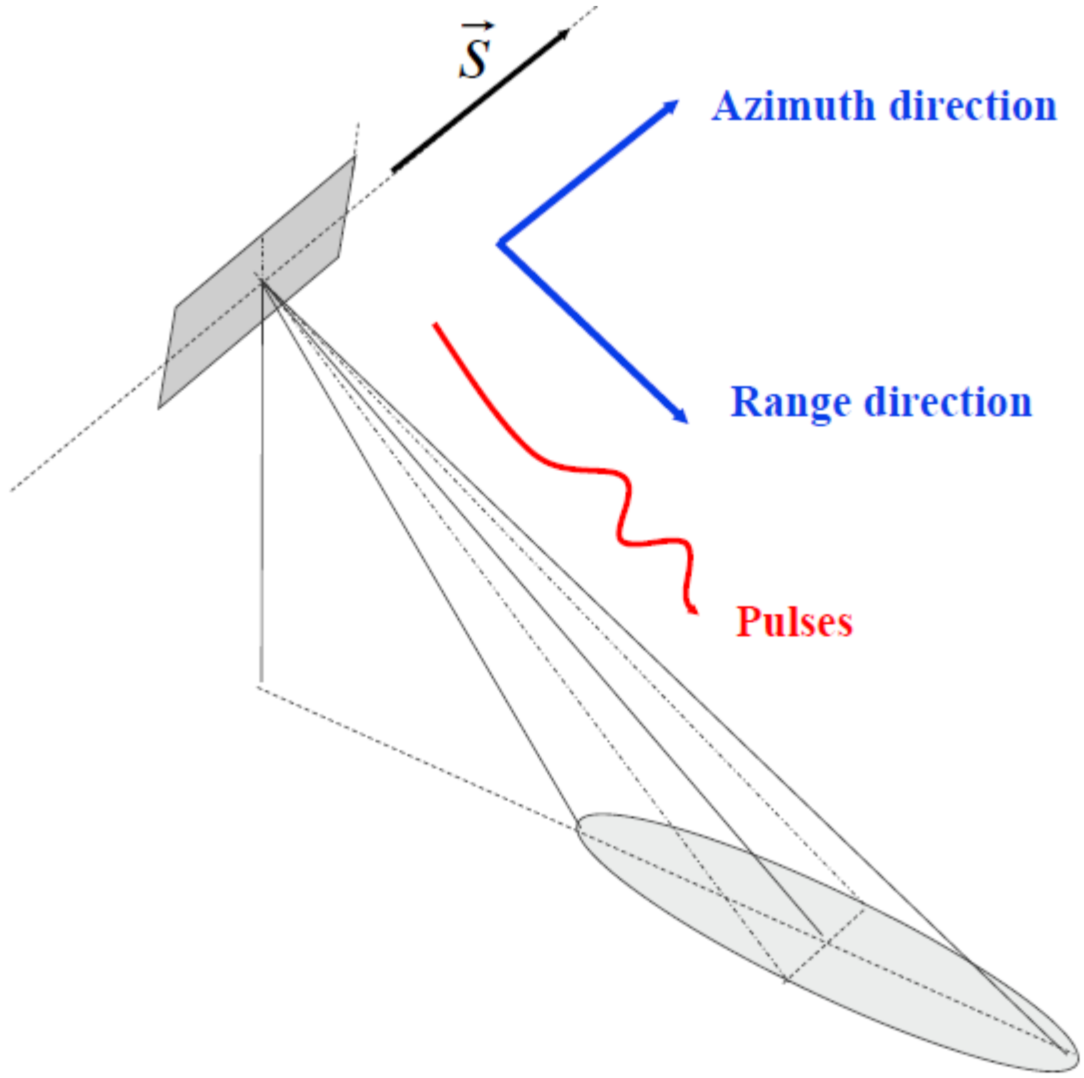
The two main principles of SAR

- **Flight time measurements: range direction**
- **Antenna resolution: azimuth direction**

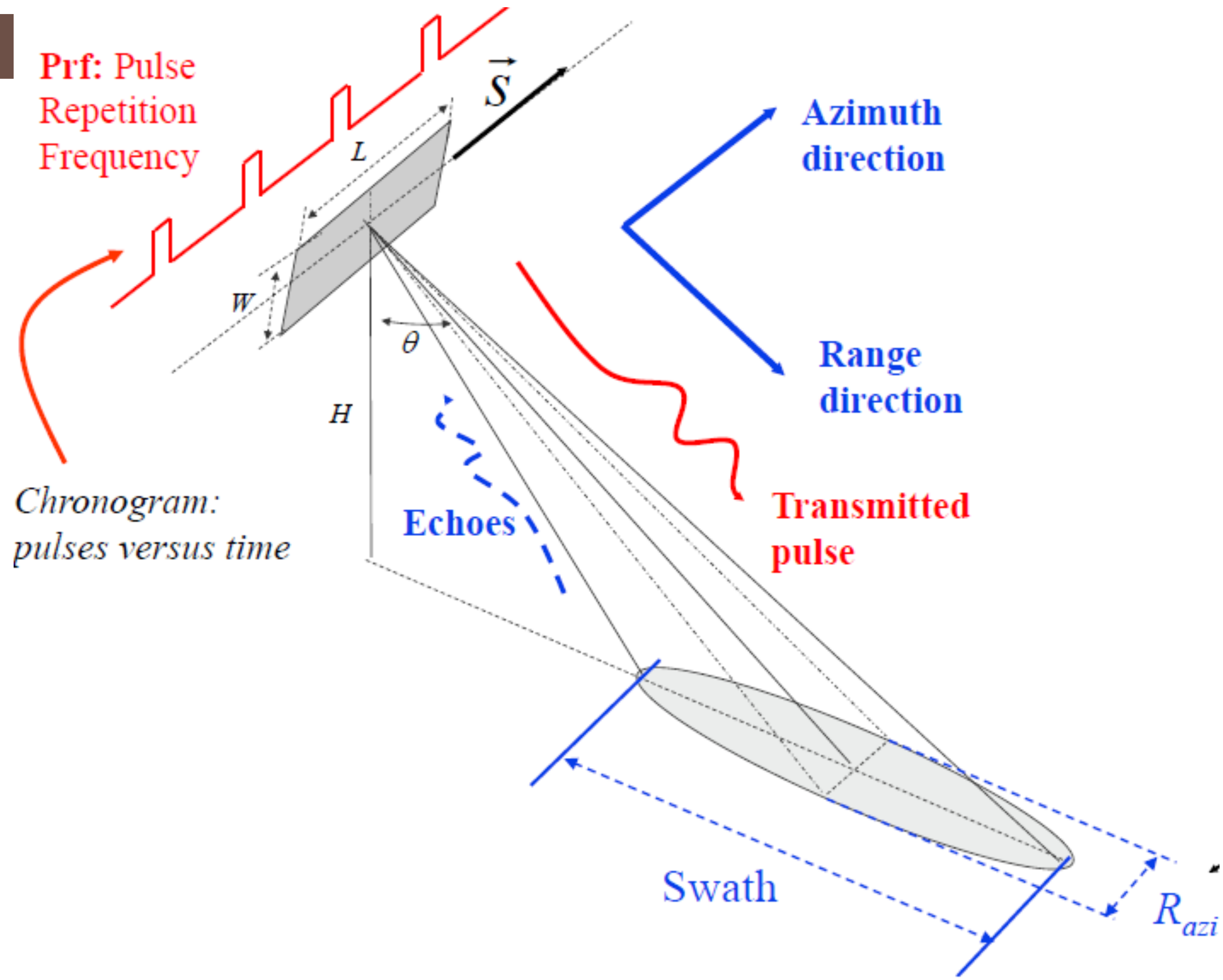
- **Two dimensions:**
  - 1 pulse in range = 1 line
  - Time sampling = columns



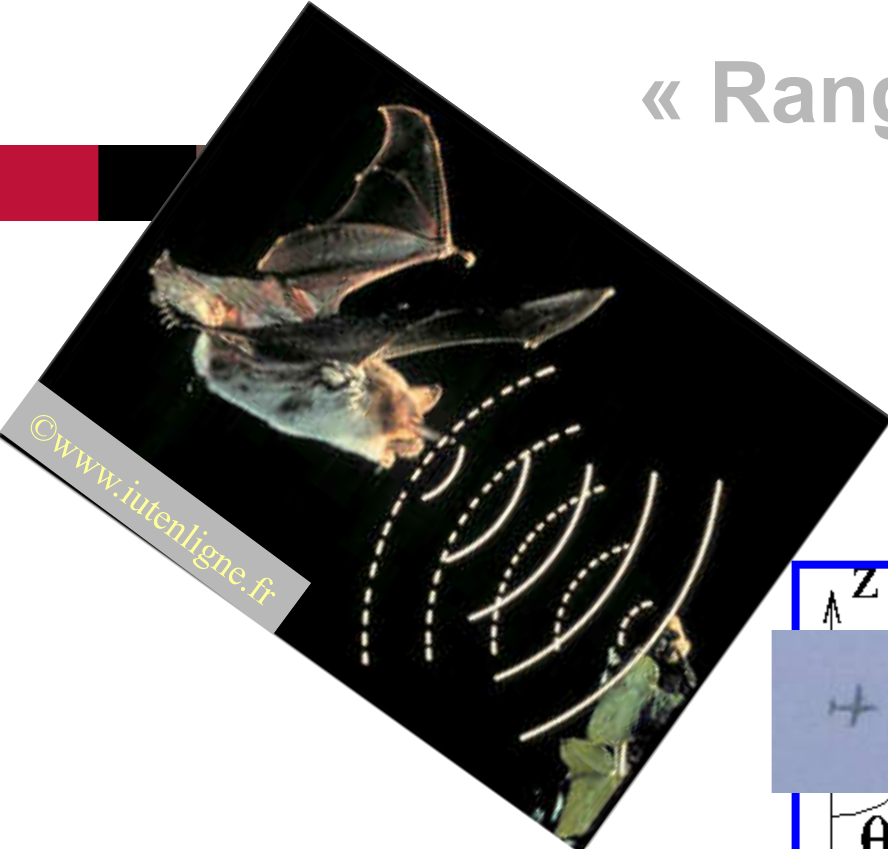
Equivalence between time and range : c=R/T (c light velocity)



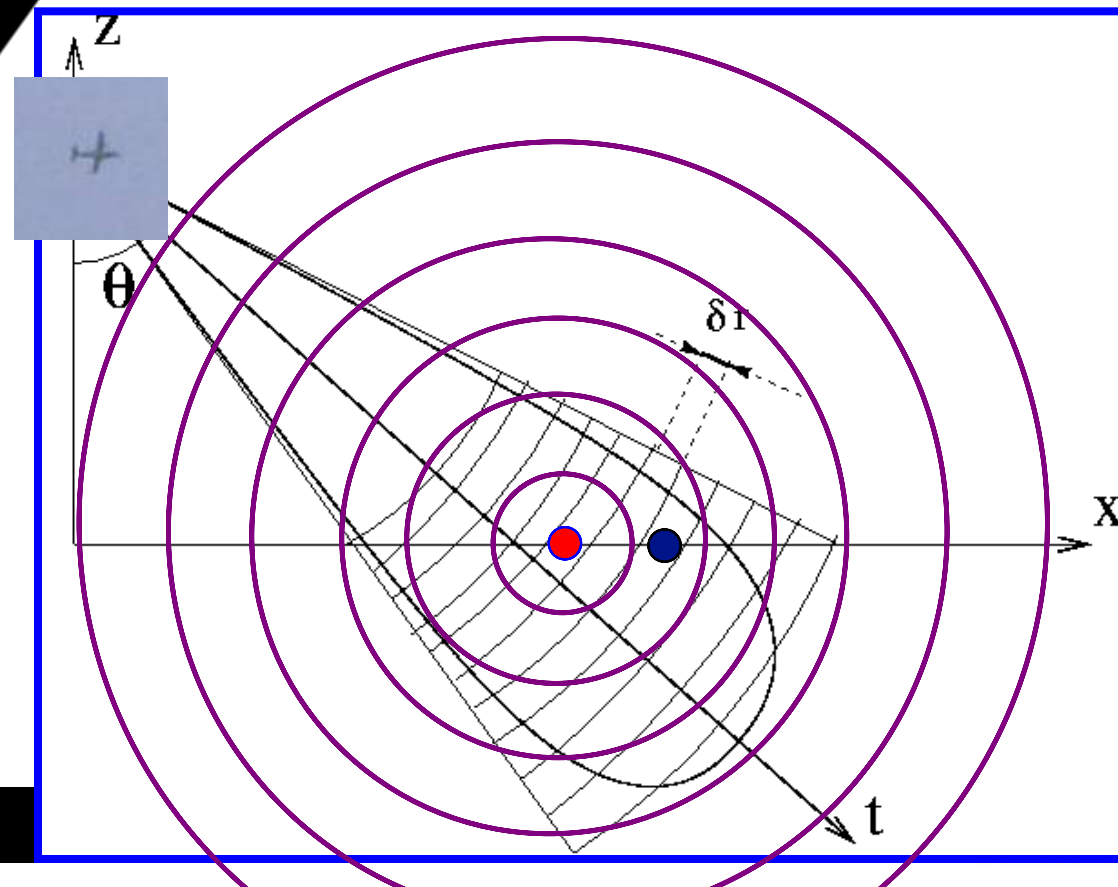
$\vec{S}$
Azimuth direction
Range direction
Pulses


Prf: Pulse
Repetition
Frequency
$\vec{S}$
L
W
θ
H
Azimuth
direction
Range
direction
Chronogram:
pulses versus time
Echoes
Transmitted
pulse
Swath
R_{azi}

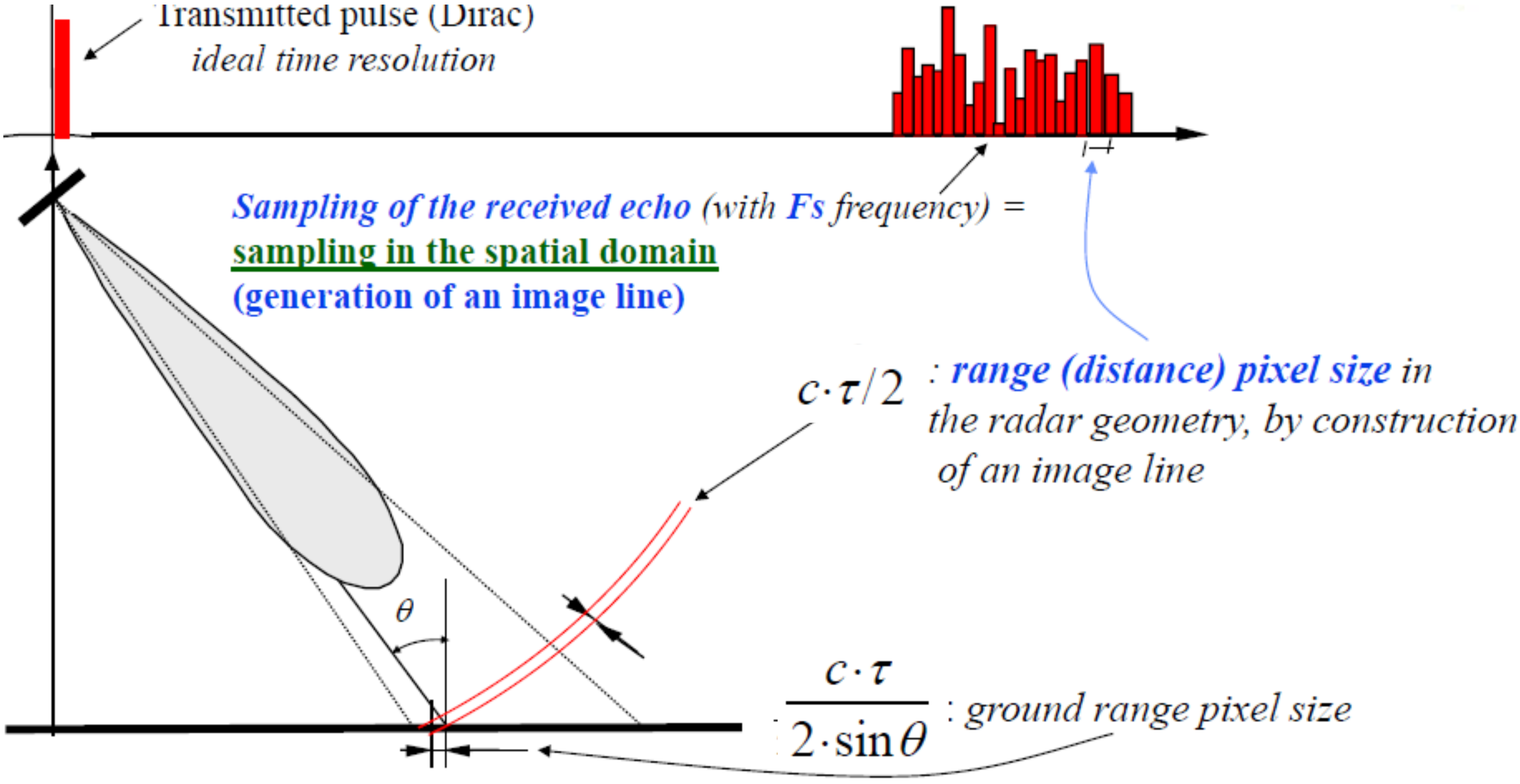
« Ranging » : Echolocation



- Lateral viewing
- between 20° et 50°

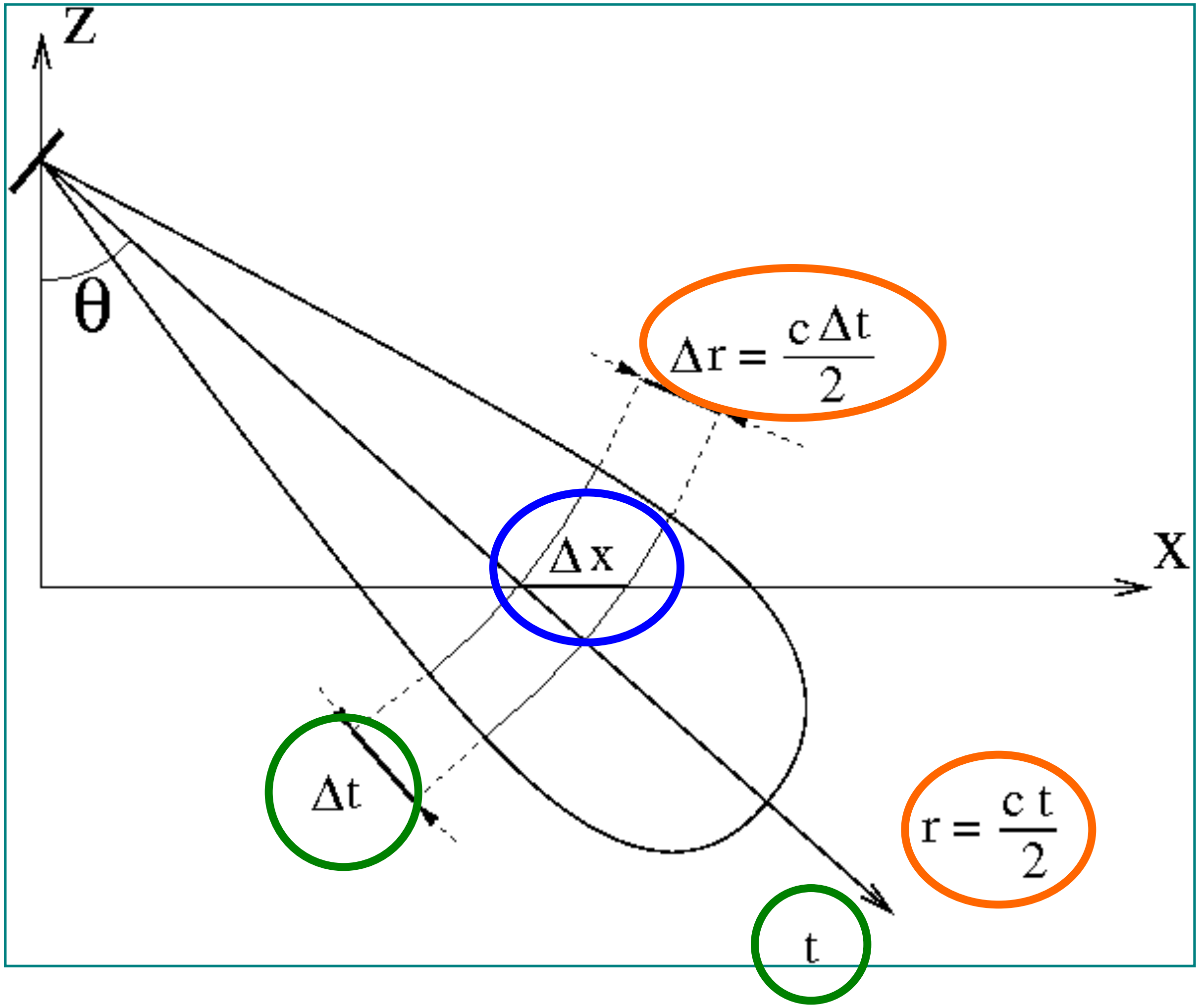


Range cell= Image column


Transmitted pulse (Dirac)
ideal time resolution
Sampling of the received echo (with Fs frequency) =
sampling in the spatial domain
(generation of an image line)
$c \cdot \tau / 2$
: range (distance) pixel size in the radar geometry, by construction of an image line
θ
$\frac{c \cdot \tau}{2 \cdot \sin\theta}$
: ground range pixel size

©ESA/CNES

Sampling (time, range, ground) $\Delta t \leftrightarrow \Delta r \leftrightarrow \Delta x$



- **Time cell:**

$$\Delta t$$

- **Range cell:**

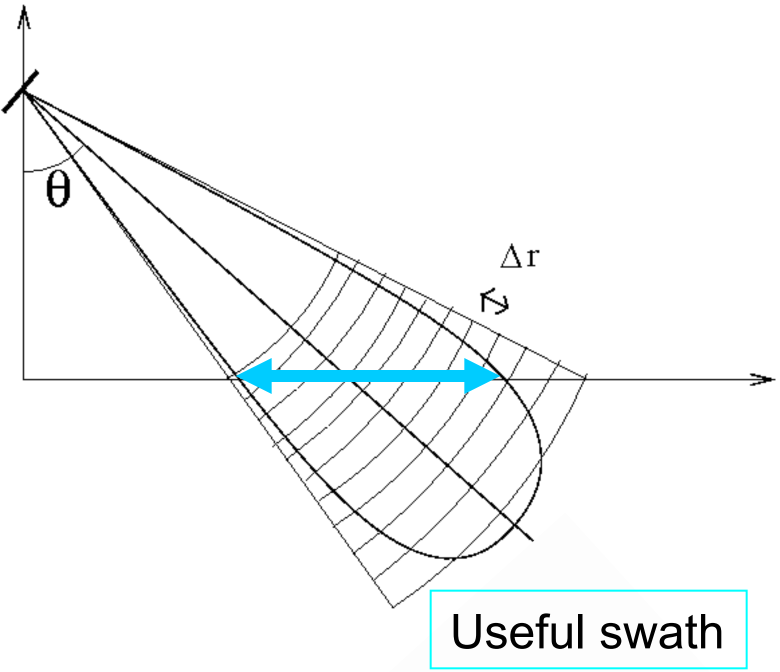
$$\Delta r = \frac{c\,\Delta t}{2}$$

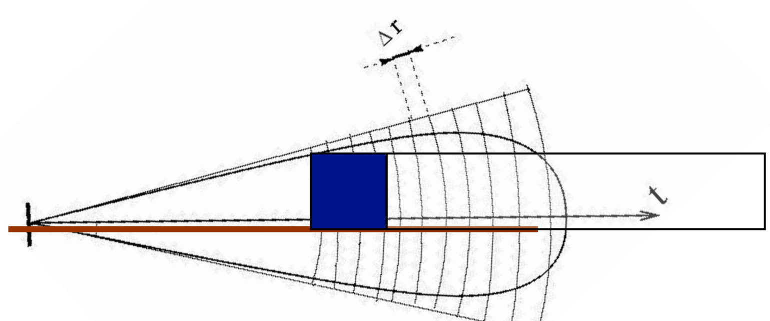
- **Ground range cell**

$$\Delta x = \frac{\Delta r}{\sin\theta}$$

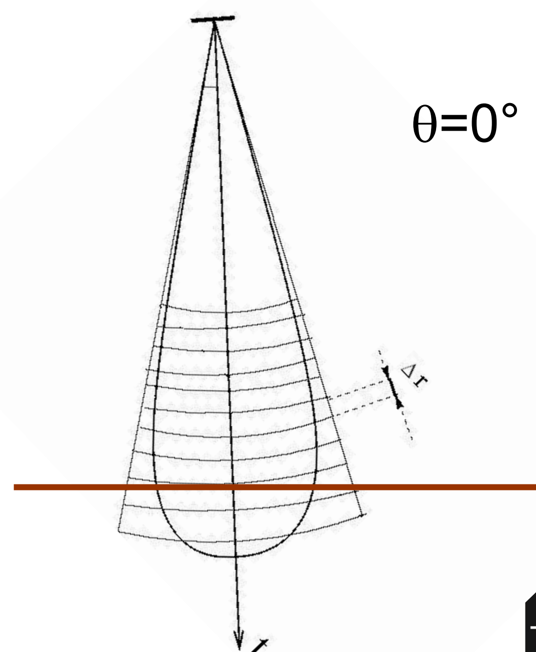
Lateral viewing: incidence angle

- Object location through time
- « range cell »
- Nadir viewing no possible : 1 cell!
- Horizontal viewing: shadows



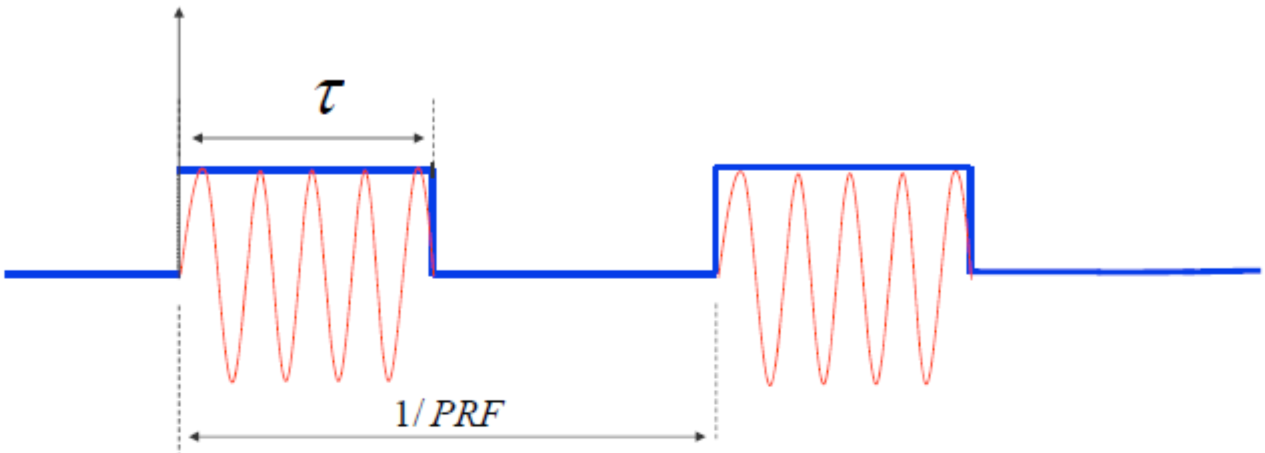


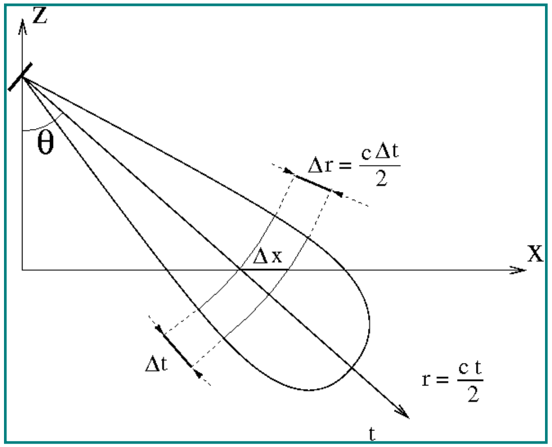
θ=0°



θ=90° : shadow behind the objects

Range resolution





$$t_1 = 2\frac{R_1}{c}$$

$$t_2 = 2\frac{R_2}{c}$$

$$t_2 - t_1 > \tau \iff R_2 - R_1 > \frac{c\tau}{2}$$

- **Resolution:** $\dfrac{c \cdot \tau}{2 \cdot \sin\theta}$
- **ERS :** $\tau \approx 37\ \mu s$ **resolution: a few km (5 km)**

➡ **Improvement of the resolution by chirp emission**

TELECOM ParisTech

Backscattering of a target

- **Emitted signal:** $s_e(t)$
- **Target at distance** ***d*** **:**
  - *Outward :* $$\delta\left(t-\frac{d}{c}\right)$$
- **Target backscattering :** ***R(t)***
- **Target at distance** ***d*** **:**
  - *Backward:* $$\delta\left(t-\frac{d}{c}\right)$$
- **Backscattered signal :** $s_r(t)$

$$s_r(t)=\delta\left(t-\frac{2d}{c}\right)*R(t)*s_e(t)$$

Backscattering of a target

- Target at distance *d*
- Backscattering of the target : *R(t)*

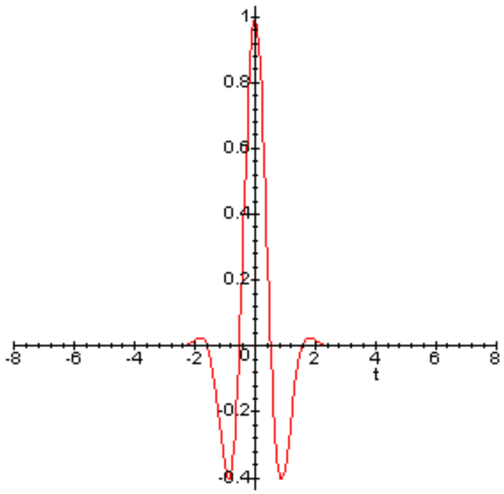
$$s_r(t) = \delta\left(t - \frac{2d}{c}\right) * R(t) * s_e(t)$$

- Other target at distance *d’*
- Backscattering of the target : *R’(t)*

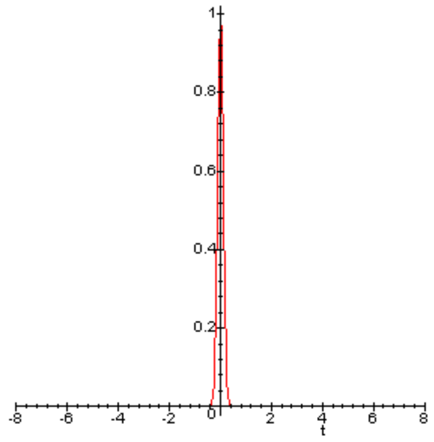
$$s'_r(t) = \delta\left(t - \frac{2d'}{c}\right) * R'(t) * s_e(t)$$

Signal and backscattering

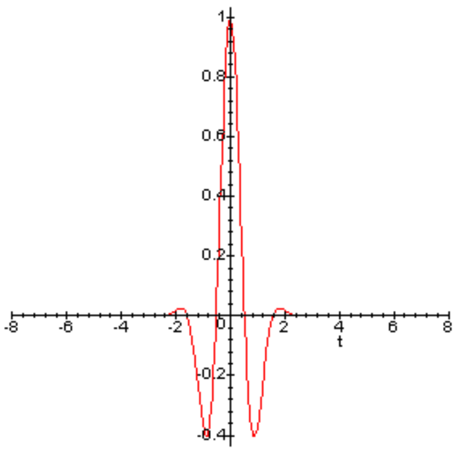
- Example of « ideal » emitted signal



- Example of « ideal » target

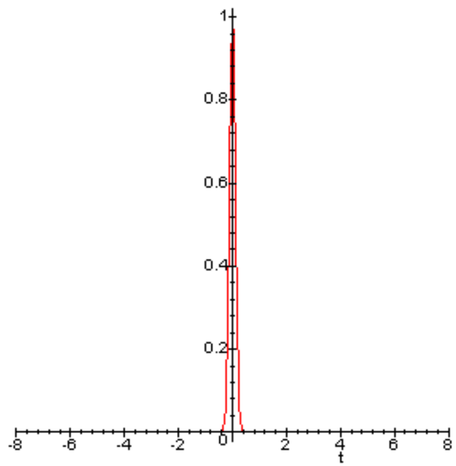


Signal reçu : convolution



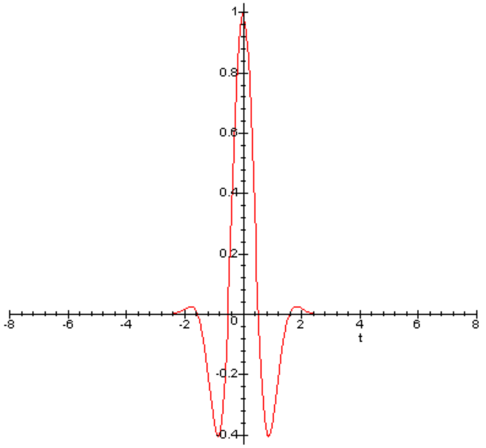
$s_e(t)$

*



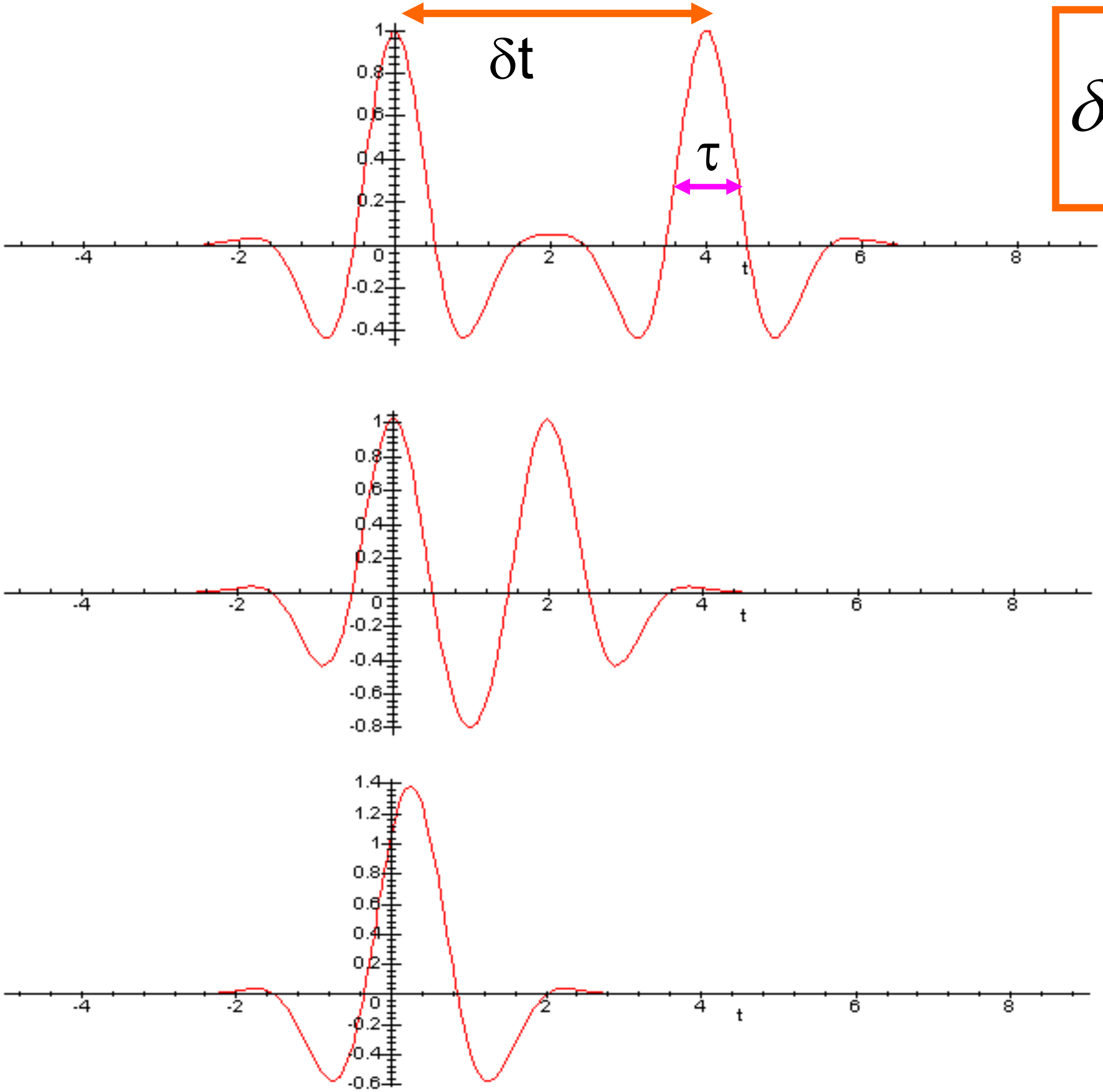
$R(t)$

=



$s_r(t)$

Two targets: radial resolution

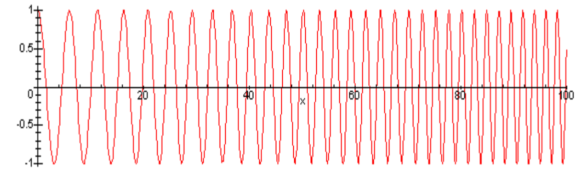


$$\delta t = 2\frac{\delta r}{c}$$

Signal :
choose the shortest τ

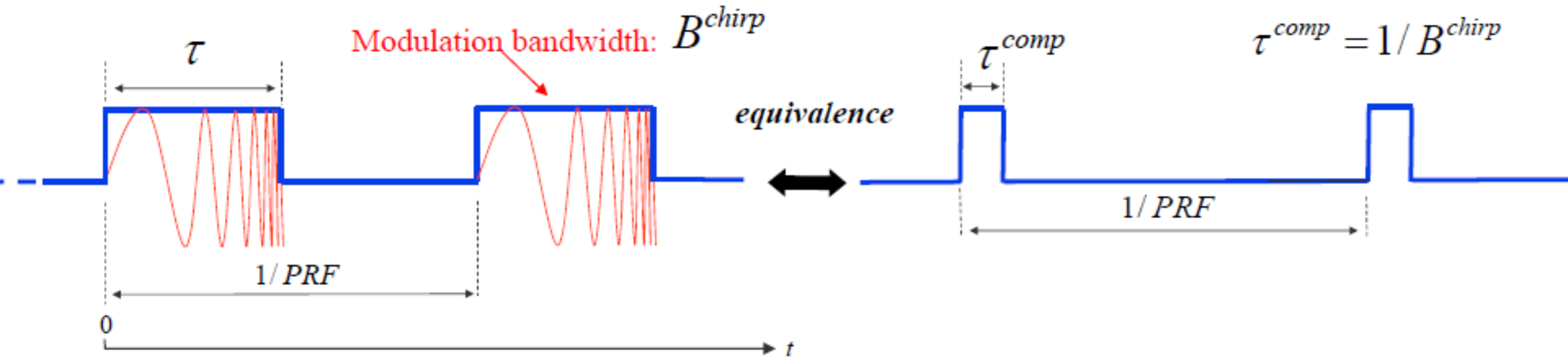
Pulse compression

- **Linearly varying frequency around fo: « modulated frequency» :**
  - Linear term in frequency : f_0
  - Quadratic term in phase : K
- **« *chirp* » of duration T**



$$e^{j2\pi f_0 t} \; e^{j\pi K t^2} \qquad t \in \left[-\frac{T}{2}, \frac{T}{2}\right]$$

Pulse compression



- **Matched filter: short apparent pulse**

$$f_i = \frac{1}{2j\pi}\frac{\partial \varphi}{\partial t} = f_0 + Kt$$

B=KT

$$f_i \in \left[f_0 - K\frac{T}{2}, f_0 + K\frac{T}{2} \right]$$

Frequency modulation

- **Fourier transform**

$$\mathrm{TF}\left[e^{j\pi K t^2}\right] \approx \sqrt{\frac{j}{K}}\, e^{-j\pi\frac{1}{K}f^2} \qquad f \in \left[-\frac{KT}{2}, \frac{KT}{2}\right]$$

- **Frequential matched filter**

$$\left[\sqrt{\frac{j}{K}}\, e^{-j\pi\frac{1}{K}f^2}\right] \cdot \left[\sqrt{\frac{j}{K}}\, e^{-j\pi\frac{1}{K}f^2}\right]^* = \frac{1}{K} \qquad f \in \left[-\frac{KT}{2}, \frac{KT}{2}\right]$$

- **Inverse Fourier transform**

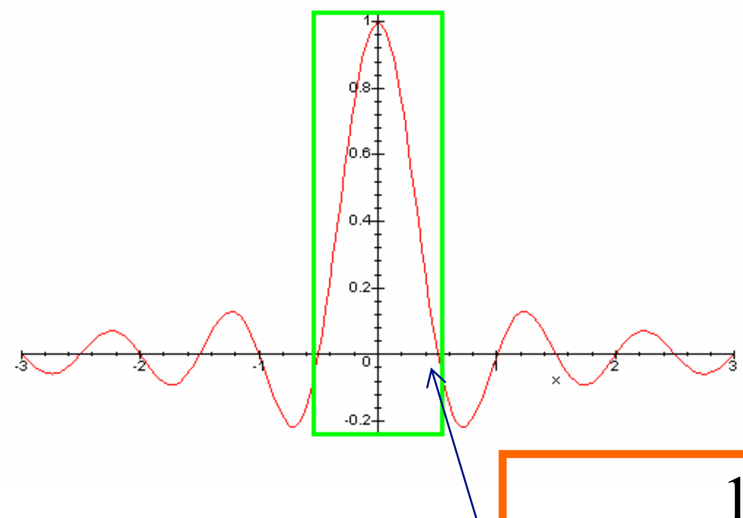
$$\mathrm{TF}^{-1}\left[\mathrm{Id}\right]_{f\in[-0.5,0.5]} = \frac{\sin(2\pi x)}{2\pi x}$$

Result of the matched filter

$$e^{j2\pi f_0 t}\ e^{j\pi K t^2} \qquad t \in \left[-\frac{T}{2}, \frac{T}{2}\right]$$

- **Chirp of duration *T*, of bandwith B=*KT*, « sinc » :**

$$\propto \frac{\sin(\pi KT\,t)}{\pi KT\,t}$$



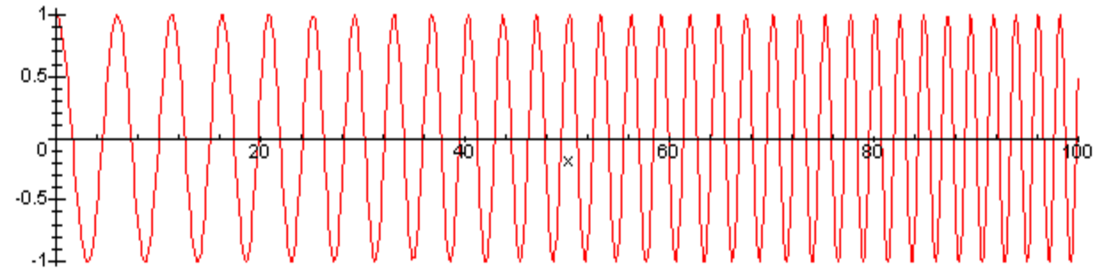
$$\tau = \frac{1}{KT} = \frac{1}{KT^2}T$$

$$\tau_0 = \pm\frac{1}{KT}$$

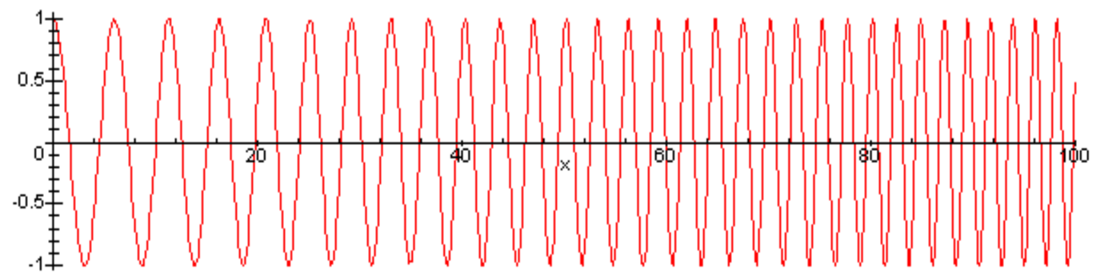
Compressed pulse and chirp

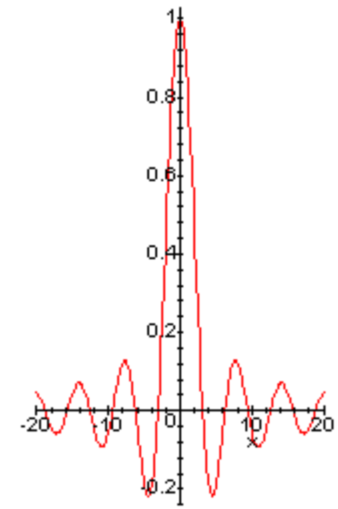
- **Emission of a linearly modulated frequency with Bandwith B=KT**
- **Equivalent to a duration τ**
- **Compression factor KT^2**

$$s_r(t) * s_e^*(-t) = \delta\left(t - \frac{2d}{c}\right) * R(t) * s_e(t) * s_e^*(-t)$$
$$= \delta\left(t - \frac{2d}{c}\right) * R(t) * \text{sinc}$$



*





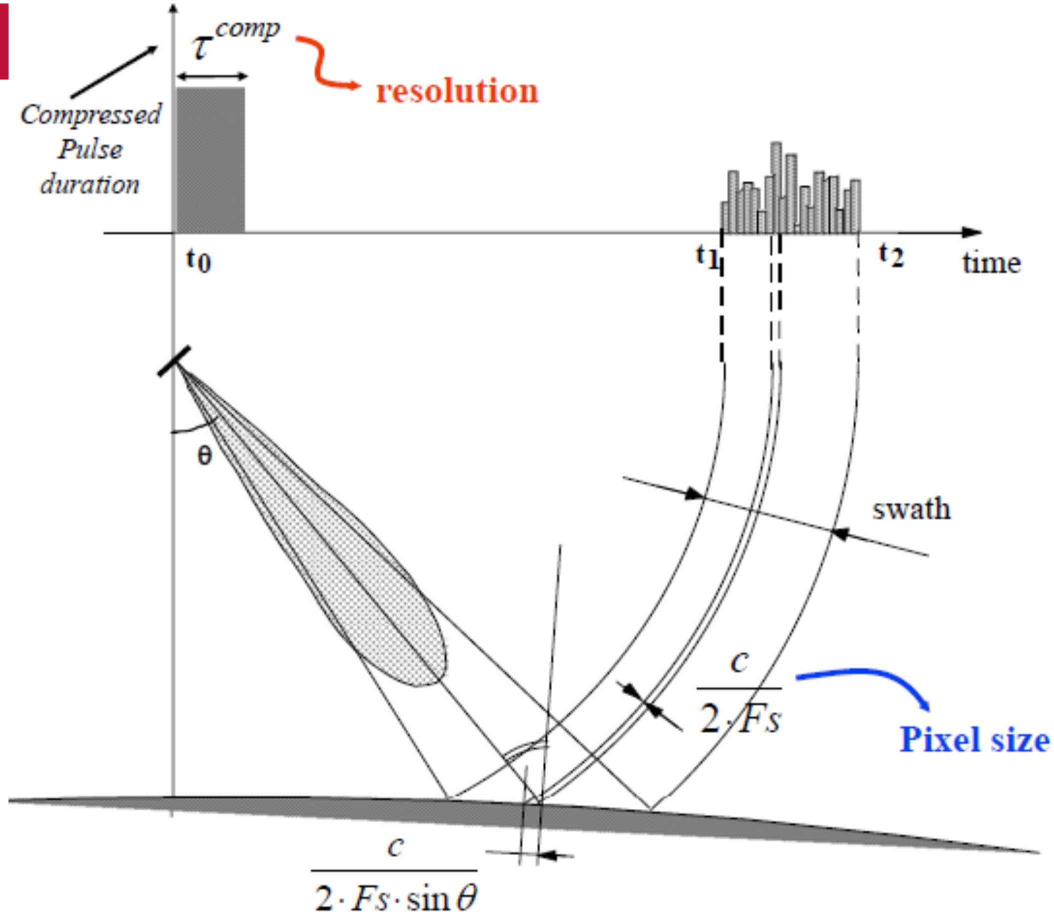
Conclusion on range resolution

- **The radial resolution of a SAR sensor depends on the bandwith**

$$B = \frac{1}{\tau}$$

	Bandwith	« range » resolution
ERS	15.55 MHz	9,6m
Radarsat 1	30 MHz	5m
Terrasar-X	150 MHz	1m

$$\delta r = \frac{c\tau}{2} = \frac{c}{2B}$$



- The pixel size is defined by the sampling frequency Fs
- The range resolution is defined by the modulation Bandwidth B^{chirp}

Numerical example: ERS

$$Fs = 18.96\,MHz$$

$$Pixel_{slant\_range} = 7{,}9\ m$$

$$Pixel_{ground\_range} = 26\ to\ 18\ m$$

$$B = 1/\tau^{comp} = 15.5\,MHz$$

$$Res_{slant\_range} = 9.7\ m$$

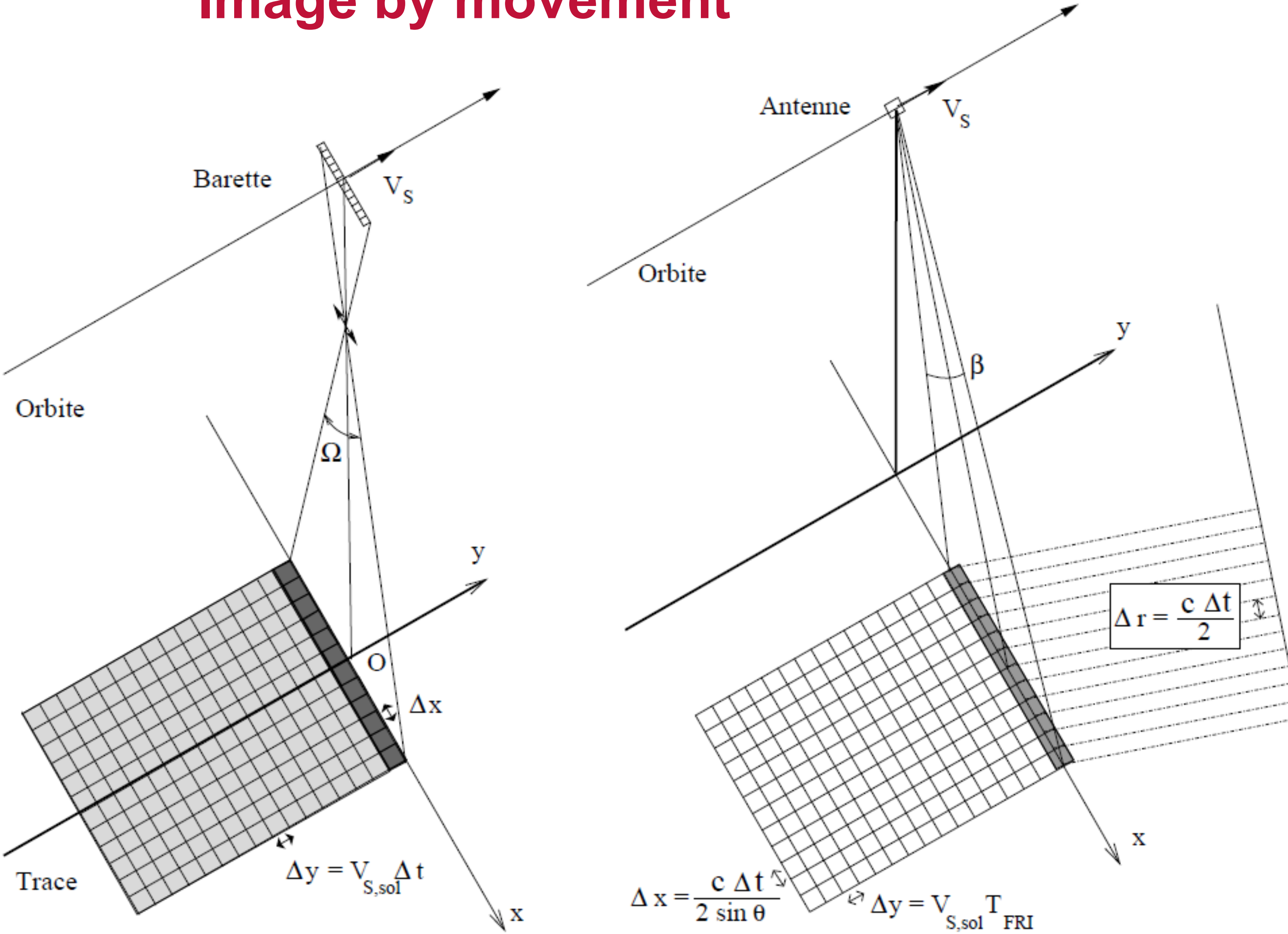
$$Res_{ground\_range} = 22\ to\ 32\ m$$

The pixel size is generally "built" slightly smaller than the resolution: Fs≥Bchirp

Overview of the session

- **Principles of radar sensors**
- **Examples of SAR images**
- **SAR image acquisition**
  - Chirp and distance direction
  - Synthetic aperture and azimuth direction
- **Some SAR systems and applications**

Image by movement



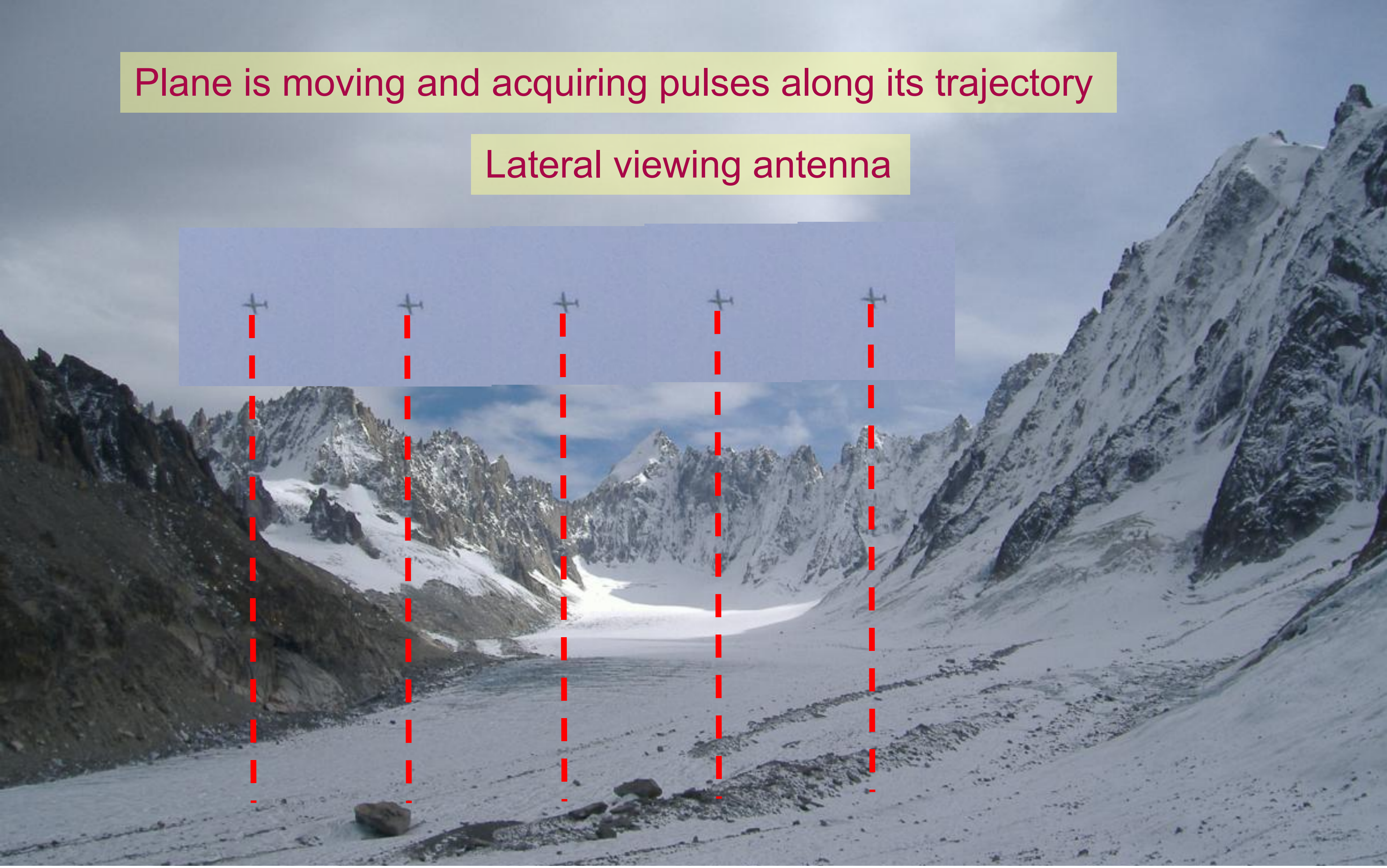
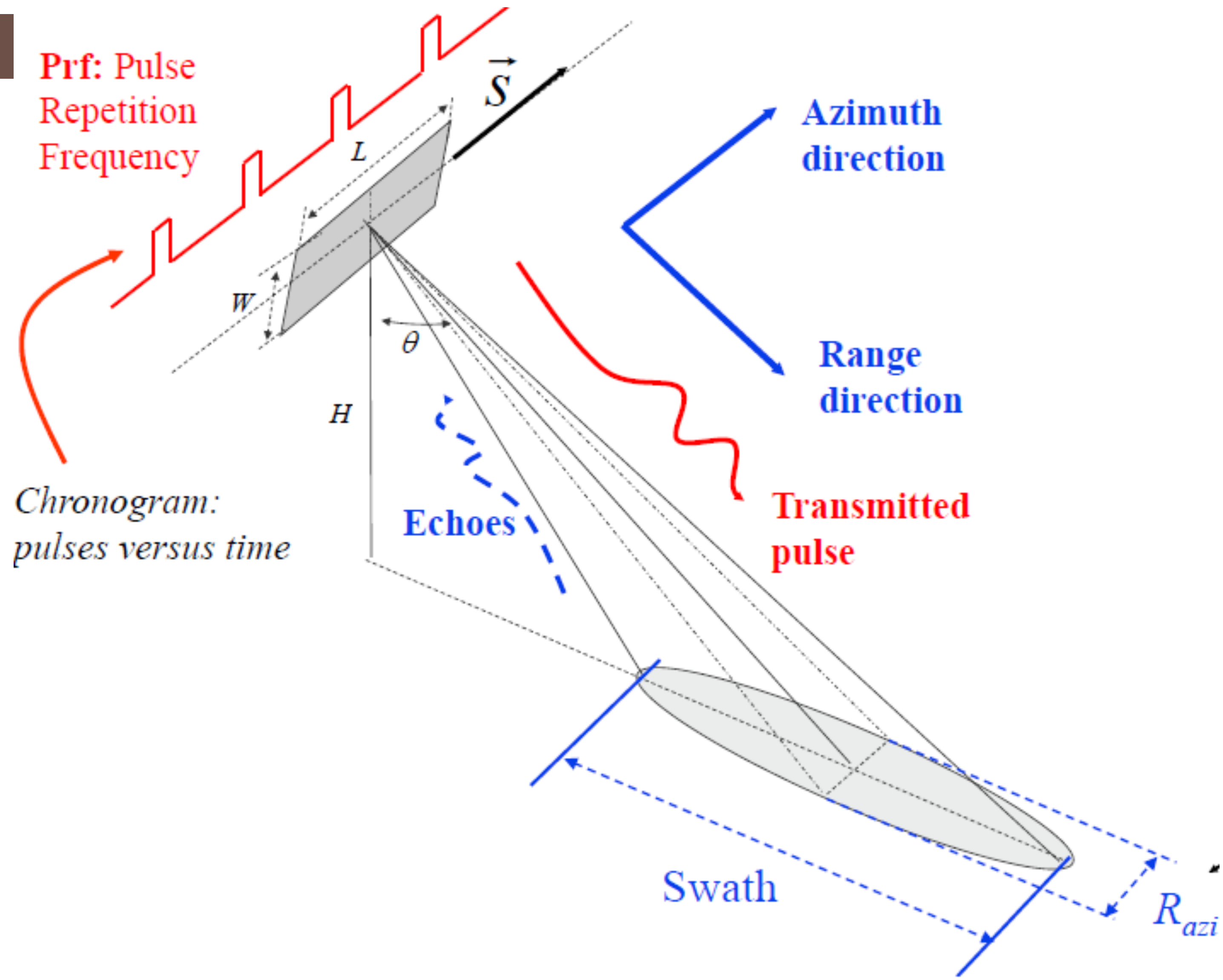
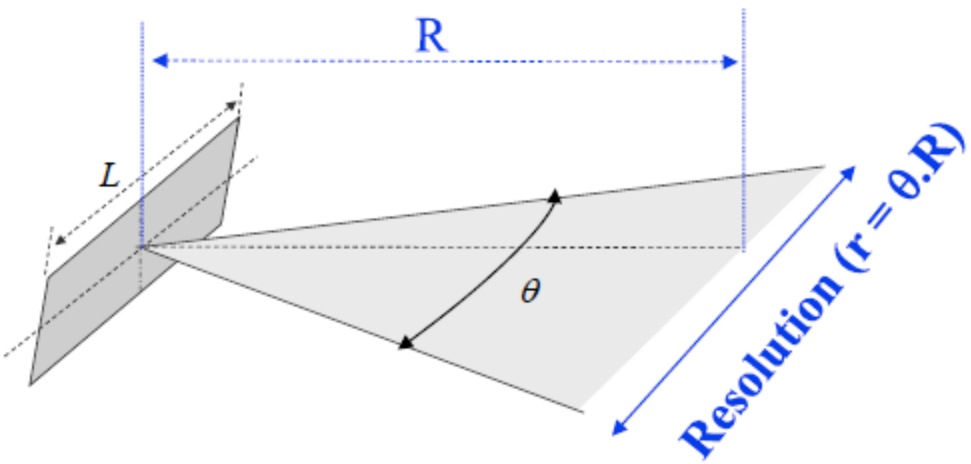

Plane is moving and acquiring pulses along its trajectory
Lateral viewing antenna

Image lines


Prf: Pulse Repetition Frequency
$\vec{S}$
L
W
θ
H
Azimuth direction
Range direction
Transmitted pulse
Echoes
Chronogram: pulses versus time
Swath
R_{azi}

Antenna and swath

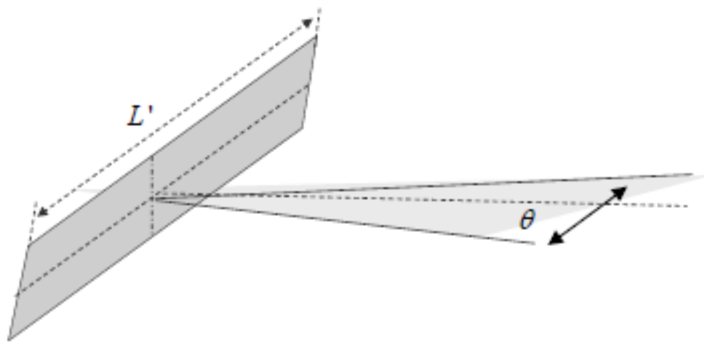


$$\theta = \frac{\lambda}{L}$$

Wavelength

Angular aperture (horizontal plane)

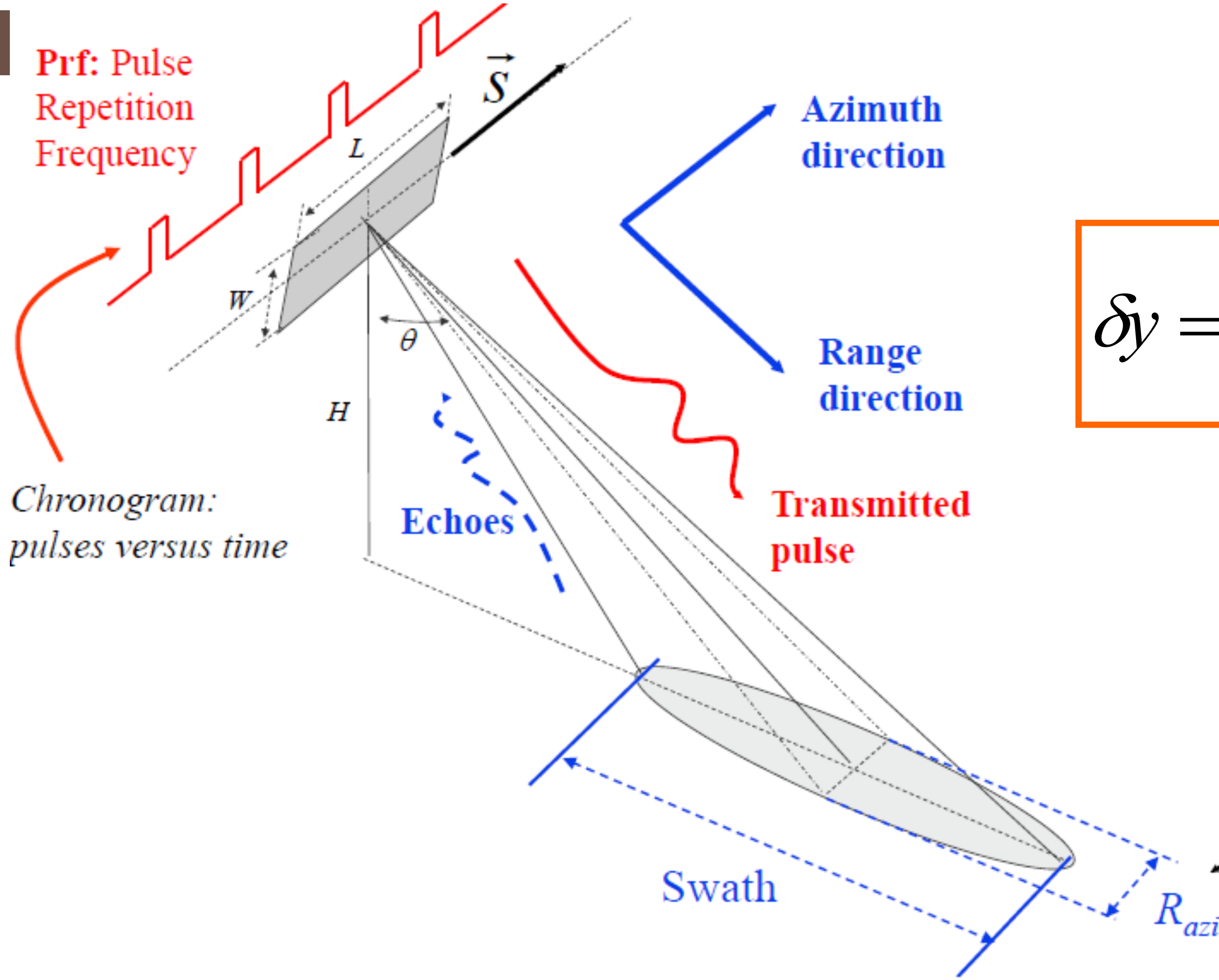
Antenna length (horizontal direction)



➡ The larger the antenna, the narrower the aperture (resolution ↘)

Numerical example:

L ≈ 4m, R ≈ 4 km (airborne radar), λ ≈ 3 cm (X band) ➔ **resolution ≈ 30 m**

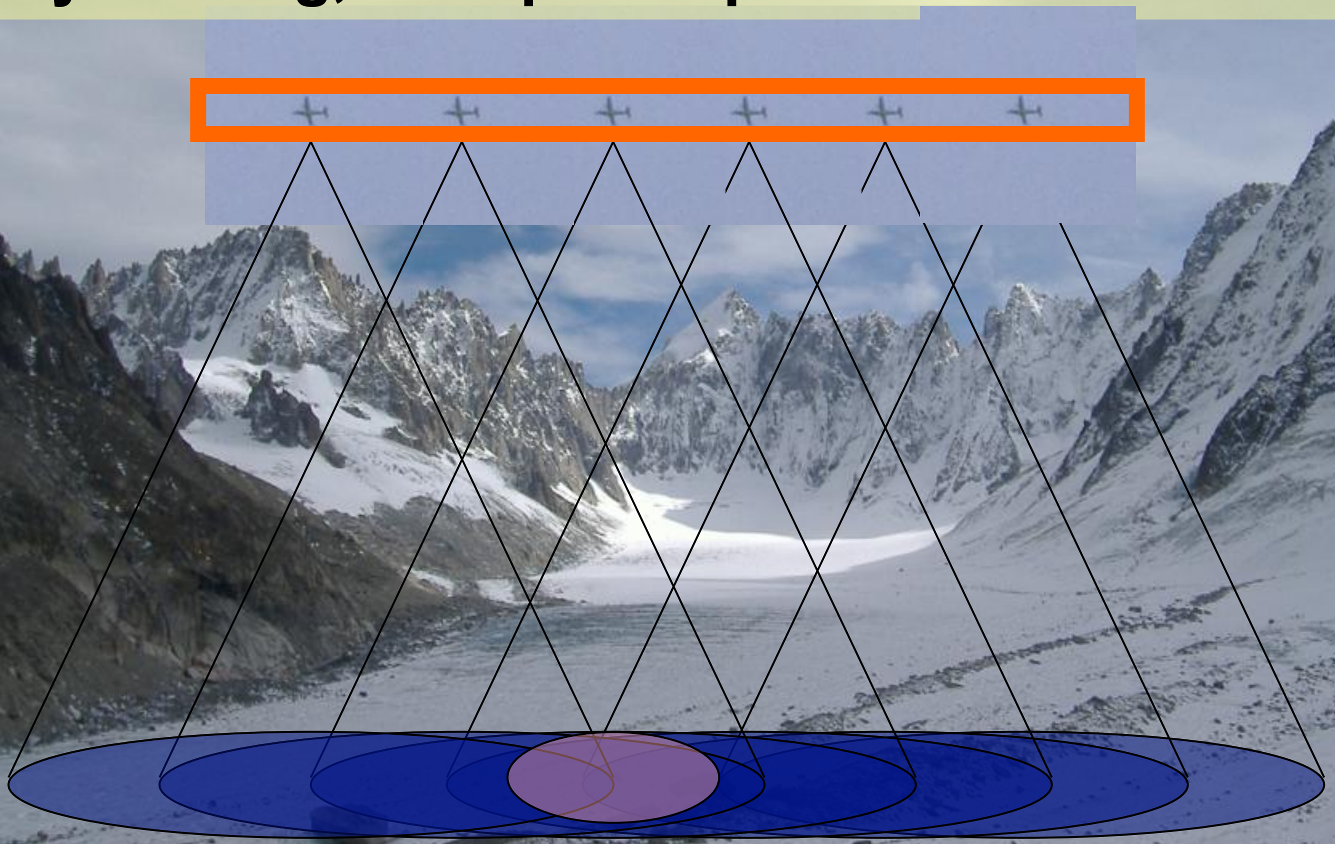


$$\delta y = \frac{\lambda R}{L}$$

Real antenna is too small

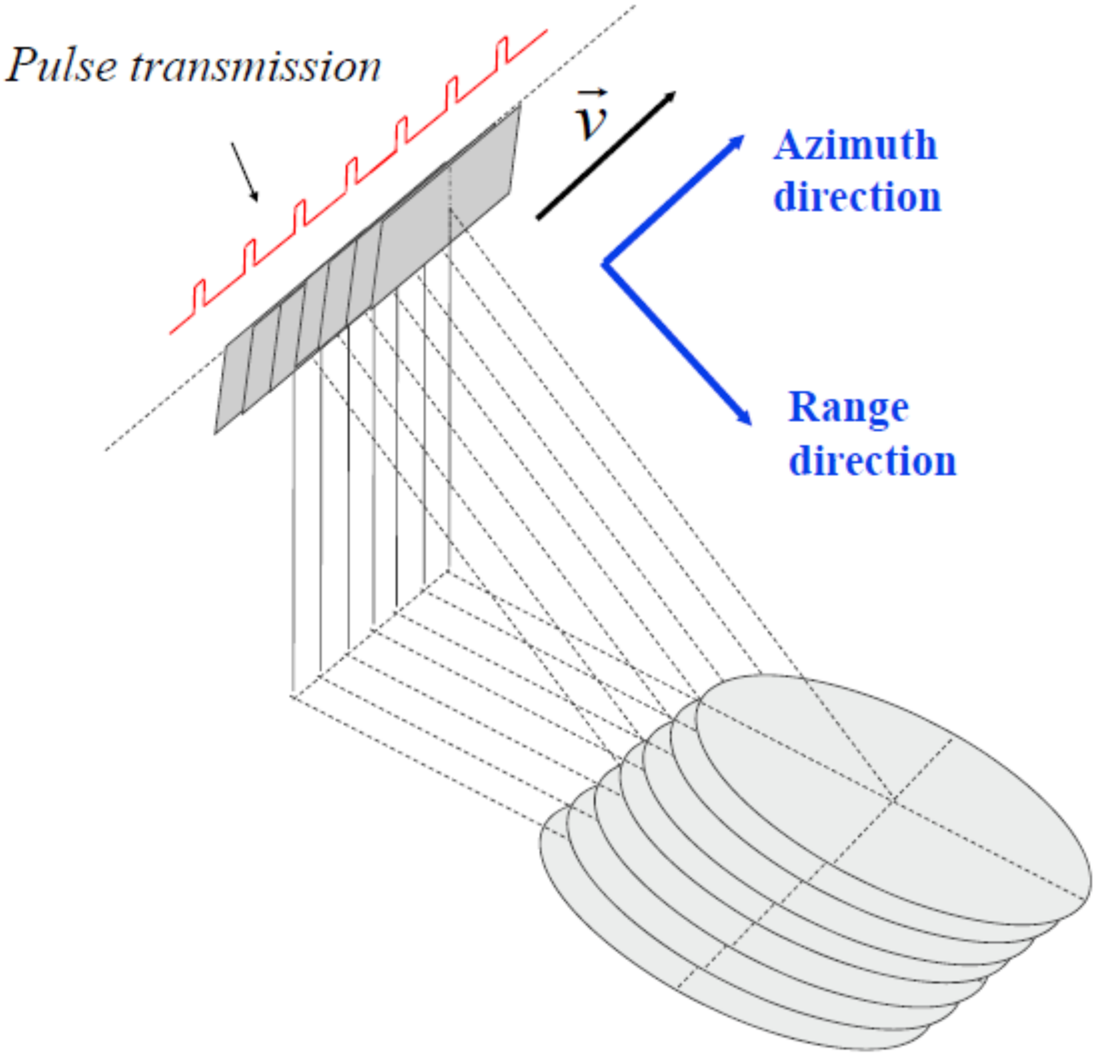
→ It measures a too big area

By moving, multiple acquisitions of the same point



A same point is seen by different antenna positions

The synthetic antenna « sees » a small area

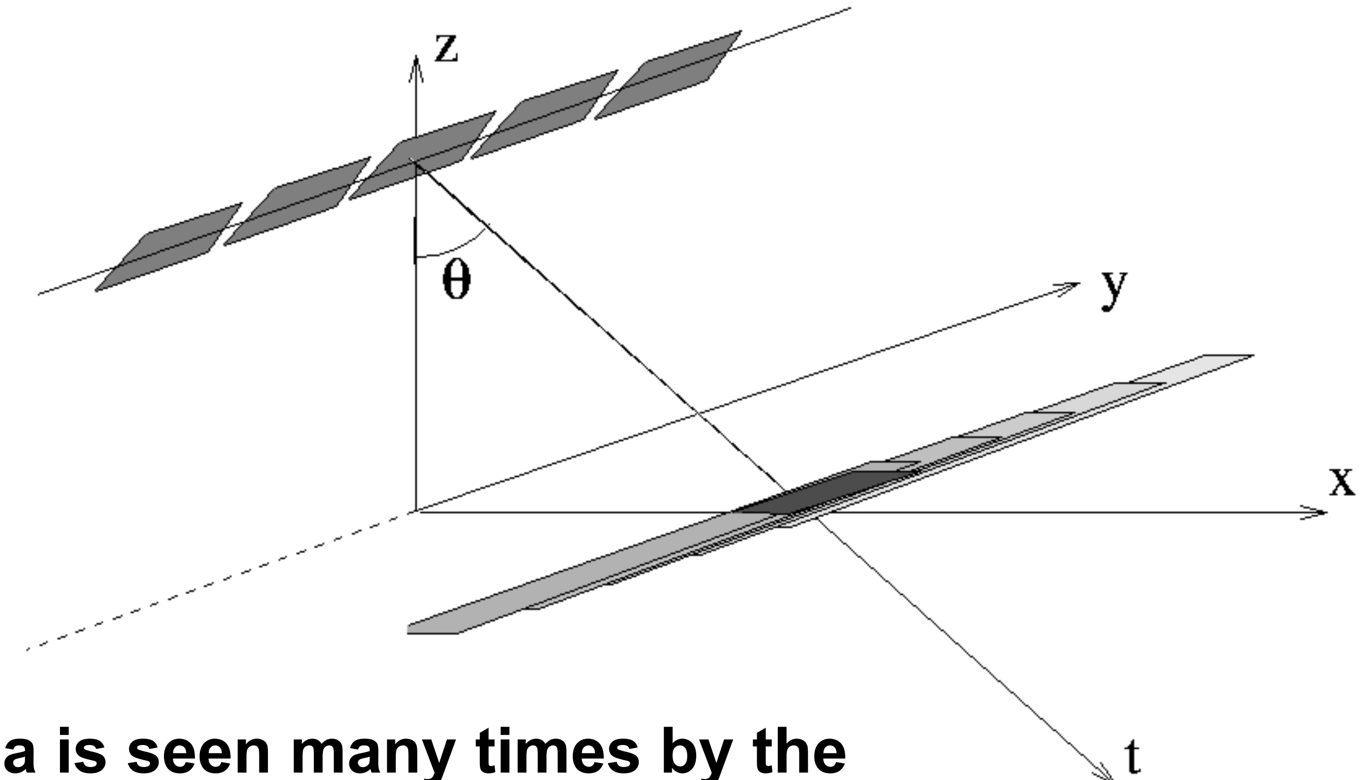


The antenna progression along the orbit allows to observe **each given point at different times**

⬇

Resolution improvement in the **azimuth** direction

Synthetic aperture



- A same area is seen many times by the sensor
- Visibility length= synthetic aperture

$$L' = 2\left(\frac{\lambda R}{L}\right)$$

SAR resolution

- Depends only on the antenna size L

$$\text{Resolution :} \quad \boxed{\delta y = \frac{L}{2}}$$

- Does not depend on the distance to the target !!
- Does not depend on the wavelength

- Illumination time depends on L et λ

Size of the synthetic antenna

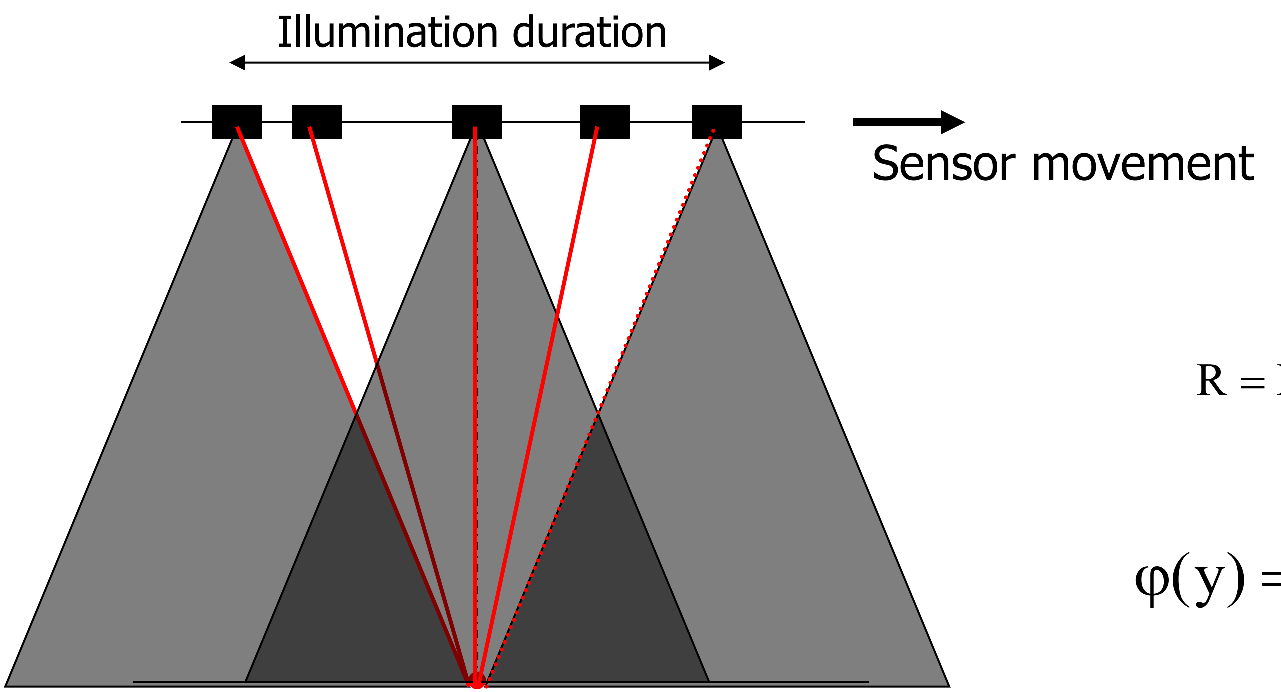
$$L_S = \frac{2\lambda R}{L}$$

$$\omega = \frac{2\lambda}{L}$$

	L (m)	λ (cm)	ω	R (km)	L_S (km)
ENVISAT (θ=30°)	10	5,66	0,324°	912	10,32
CSK (θ=30°)	5,7	3,1	0,311°	714	7,76
TSX (θ=30°)	4,8	3,1	0.370°	593	7,65
ALOS (θ=30°)	8,9	23,5	1.513°	799	42,2

Synthetic aperture and signal processing

Sensor trajectory, target plan



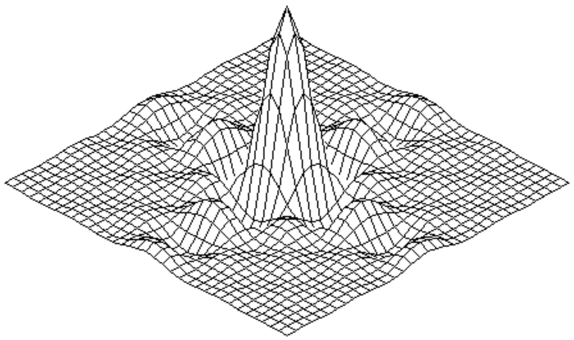
$$R = R_0 + \frac{y^2}{2R_0}$$

$$\varphi(y) = \frac{2\pi y^2}{\lambda R_0} + k$$

$$f(y) = \frac{2y}{\lambda R_0}$$

Linearly varying frequency: « modulated frequency» !
« natural » chirp in azimuth direction : matched filter

Summary of SAR imaging: chirp + synthetic aperture



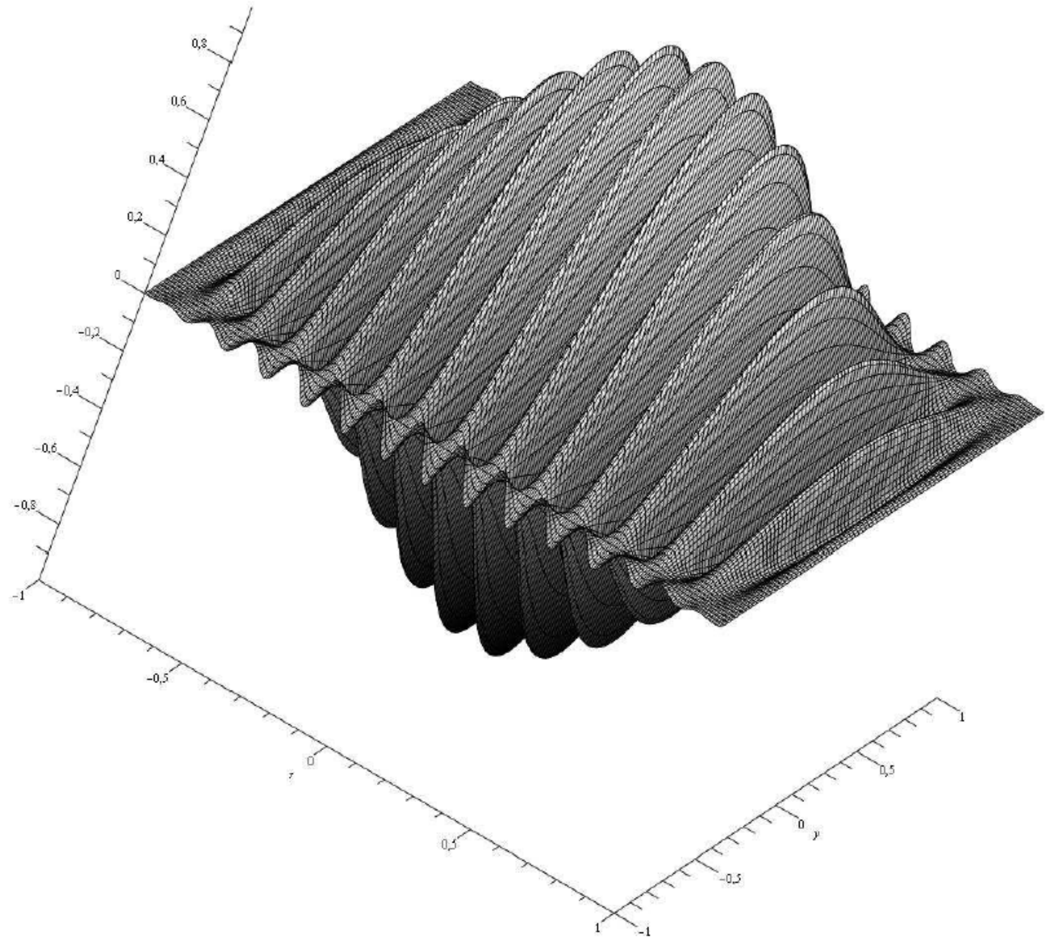
- **Range: pulse compression and matched filter**
- **Azimuth: natural chirp and matched filter = big synthetic aperture**
- **PSF :**
  - Cardinal sinus in range
  - Cardinal sinus in azimuth

$$PSF \propto \frac{\sin(\pi B t)}{\pi B t} \frac{\sin(\pi B_y y)}{\pi B_y y} \propto \frac{\sin(\pi B_r r)}{\pi B_r r} \frac{\sin(\pi B_y y)}{\pi B_y y}$$

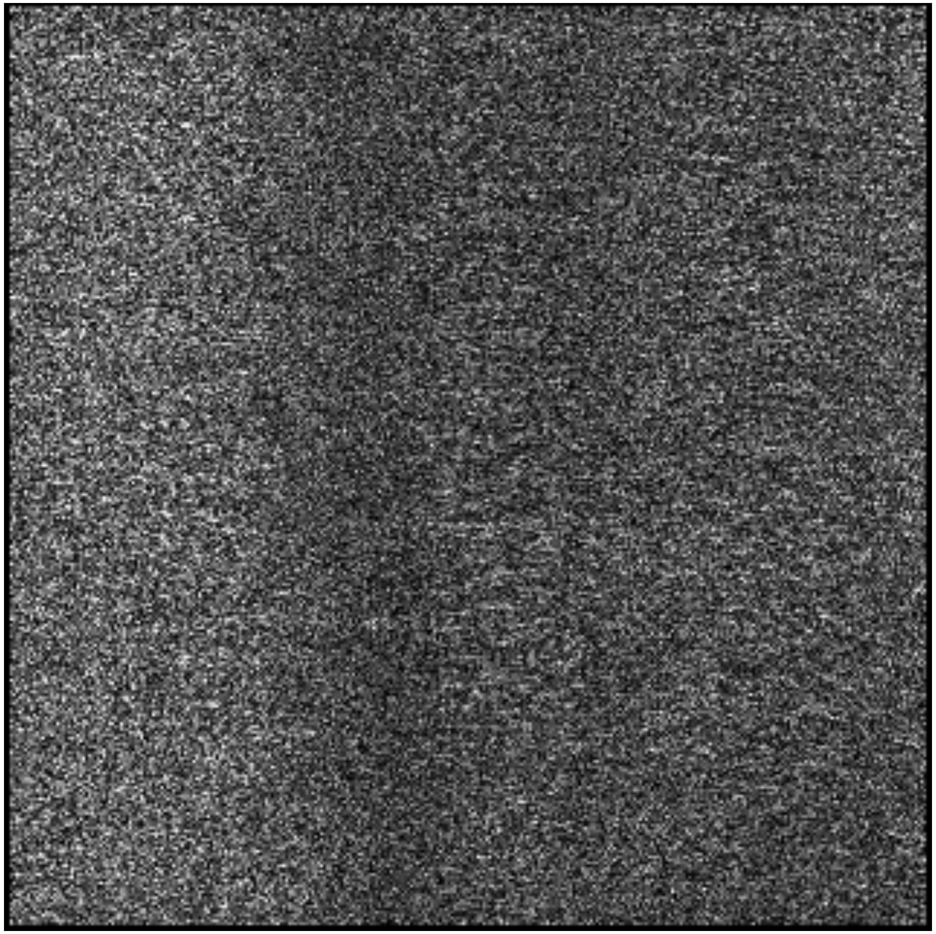
$$B_r = \frac{2B}{c}$$

$$B_y = \frac{2\lambda}{L_S}$$

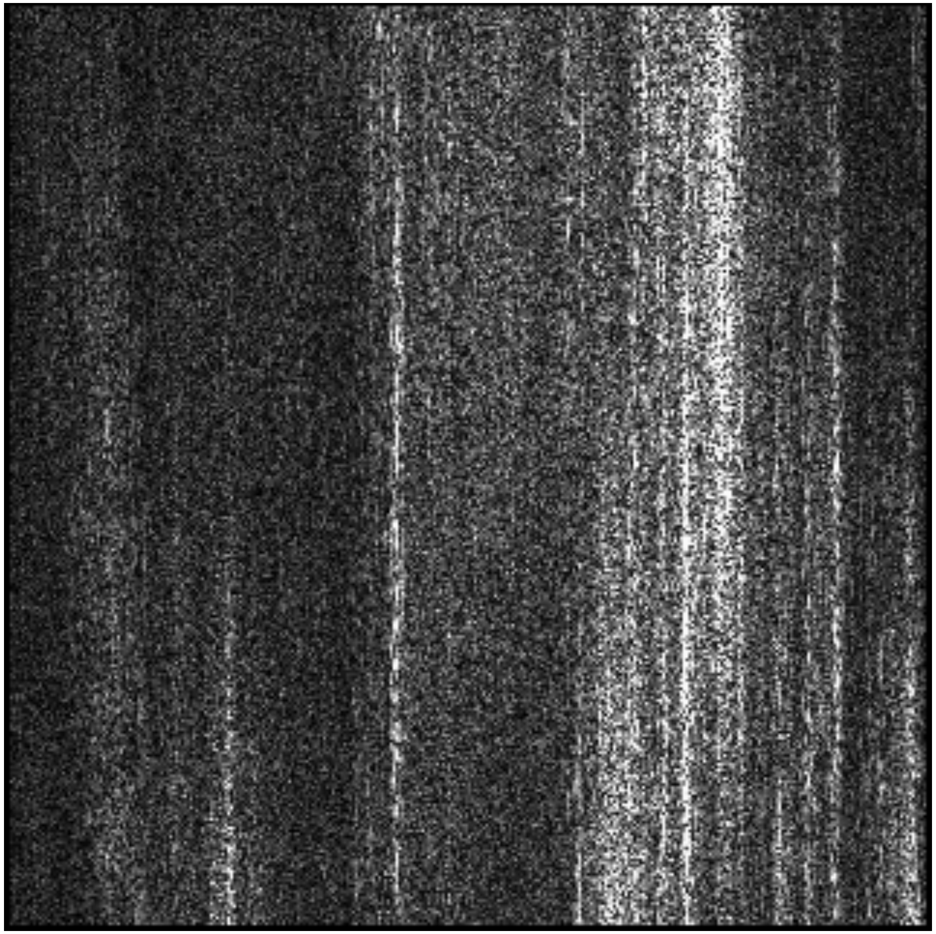
Carrier frequency + cardinal sinus (Ox et Oy)



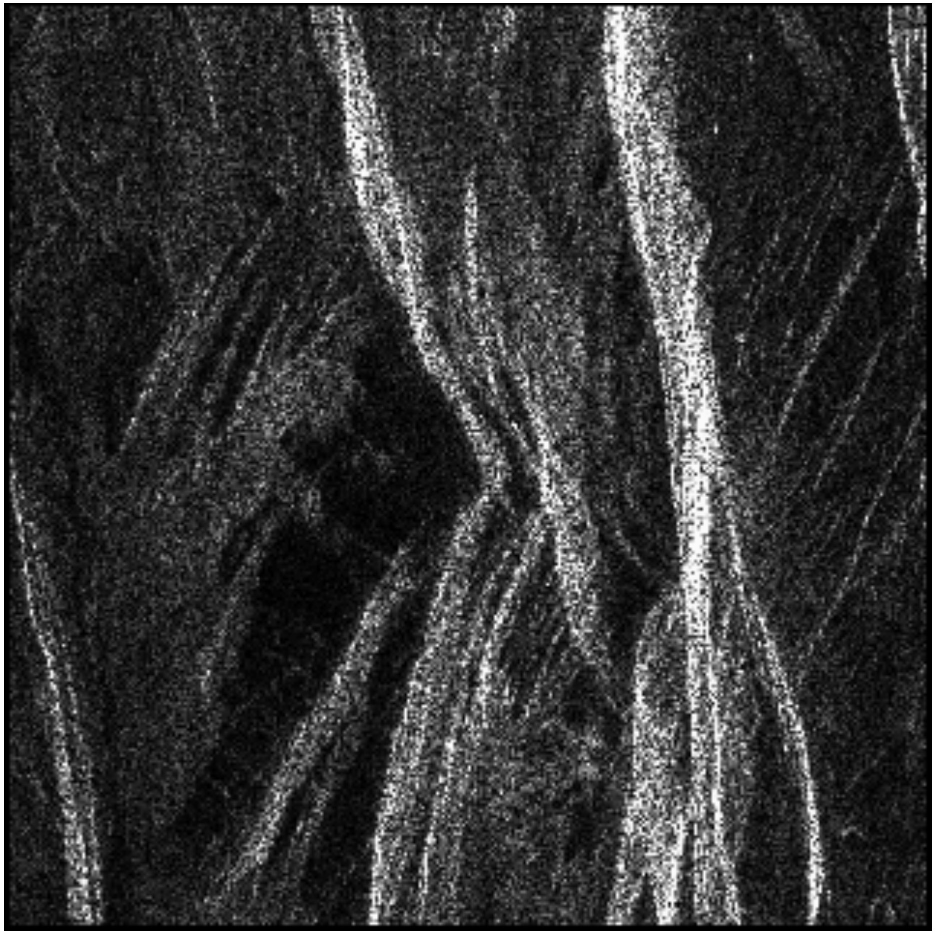
Example of SAR data : RAW data (km res)



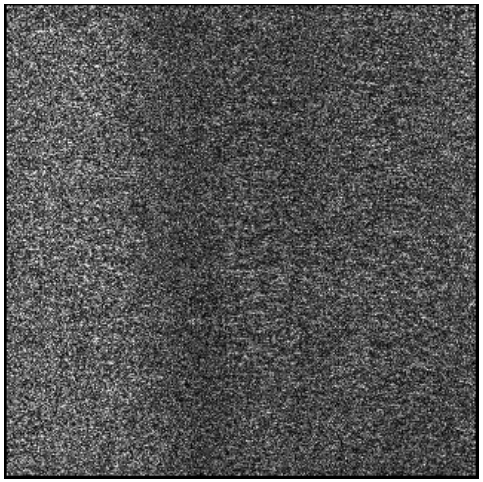
Matched filter in range direction (chirp)

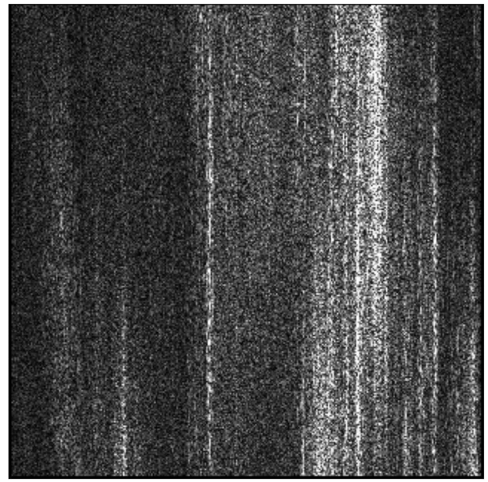


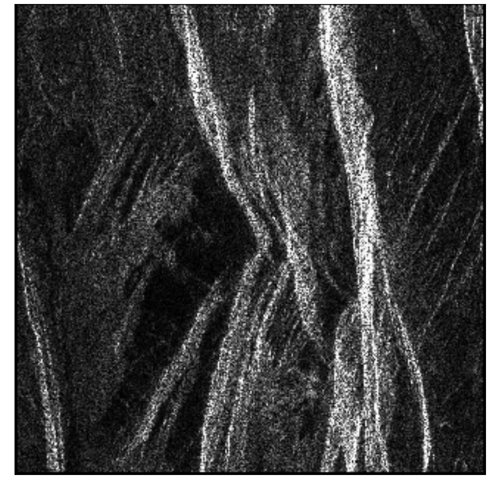
Matched filter in azimuth direction (synt. aperture



Signal processing to improve resolution…

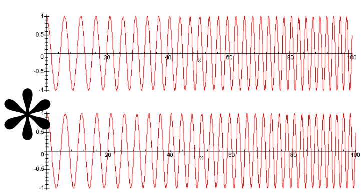


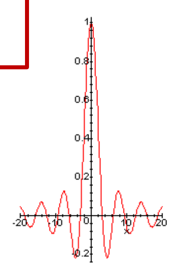


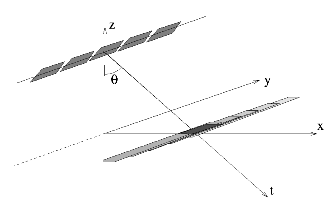


Range direction
- Chirp
- Matched filter

Azimuth direction
- Synthetic aperture
- Matched filter

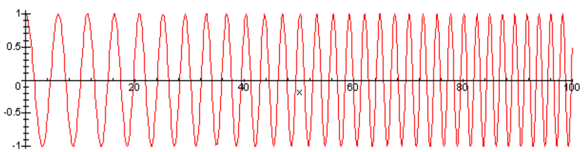


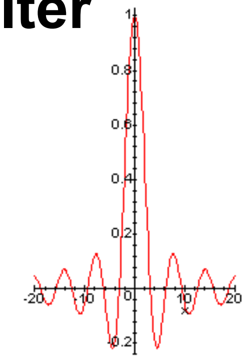


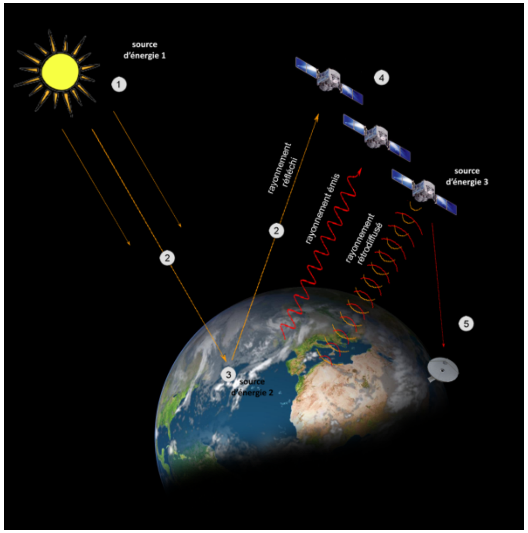


SAR acquisition (summary)

- **Range: chirp and matched filter**

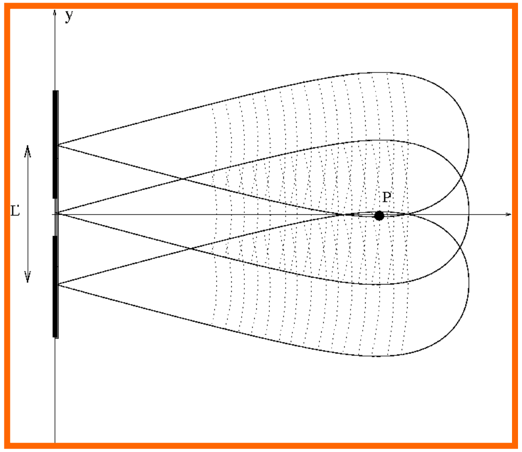


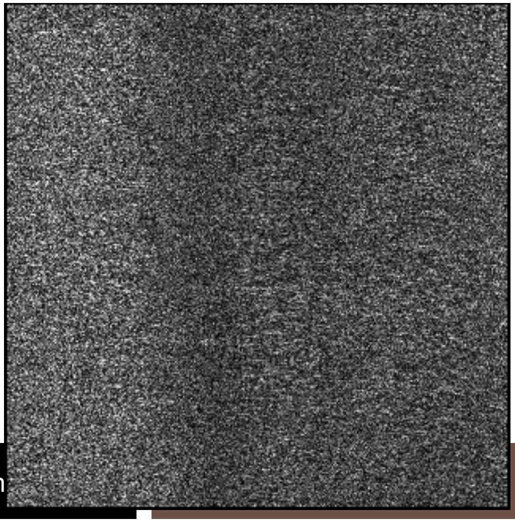


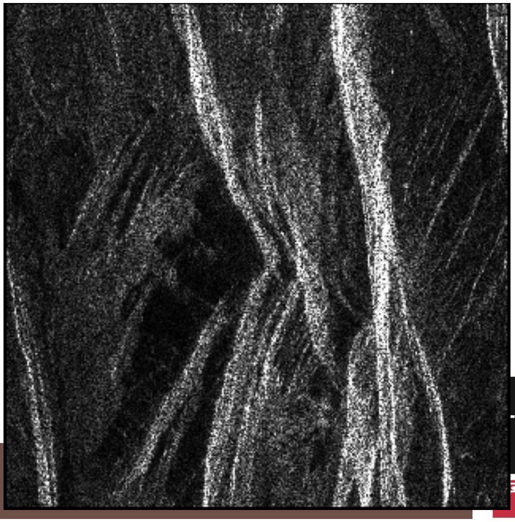


- **Azimuth: synthetic aperture**

« geometric chirp » and matched filter







Overview of the session

- **Principles of radar sensors**
- **Examples of SAR images**
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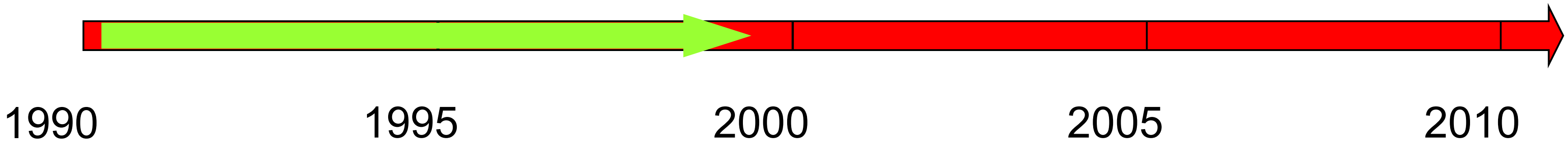
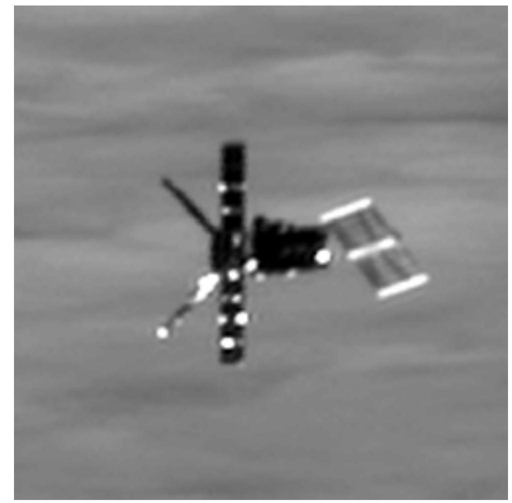
  - Chirp and distance direction
  - Synthetic aperture and azimuth direction
- **Some SAR systems and applications**

ERS-1 (ESA) 1991

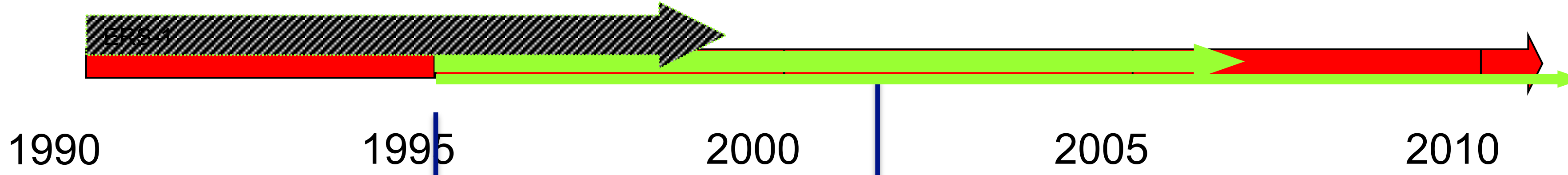




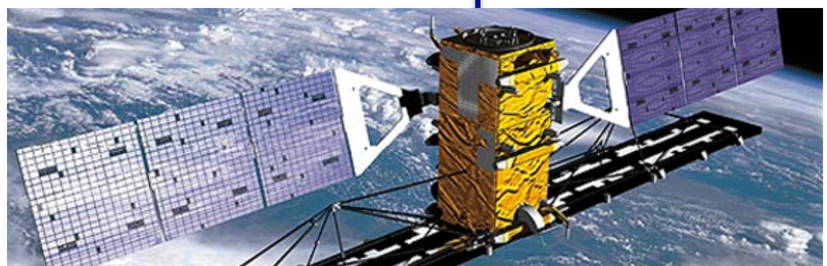
- C-Band (5.6 cm)
- 15.5 MHz bandwidth
- 35 day repeat polar orbit
- Initiated cross track and along track SAR interferometry

Paris seen from ERS-1

First generation



ERS-2



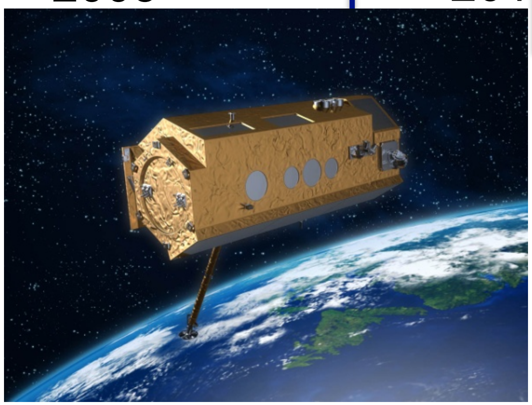
Radarsat-1

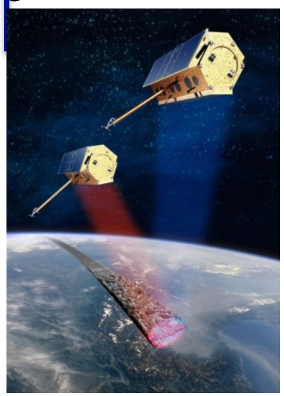
ENVISAT (ASAR)

Second generation (2007-)

2007 2014

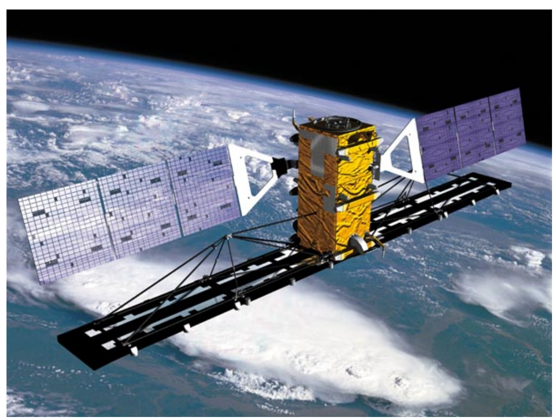
2005 2010 2015 2020 2025





TerraSAR-

CSK

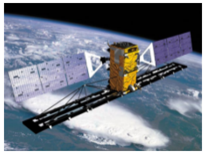


Radarsat-2

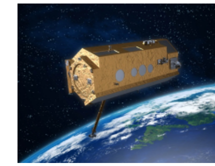
Sentinel-1

Golden age of SAR sensors: improved *spatial*, *polarimetric* and *temporal* resolutions

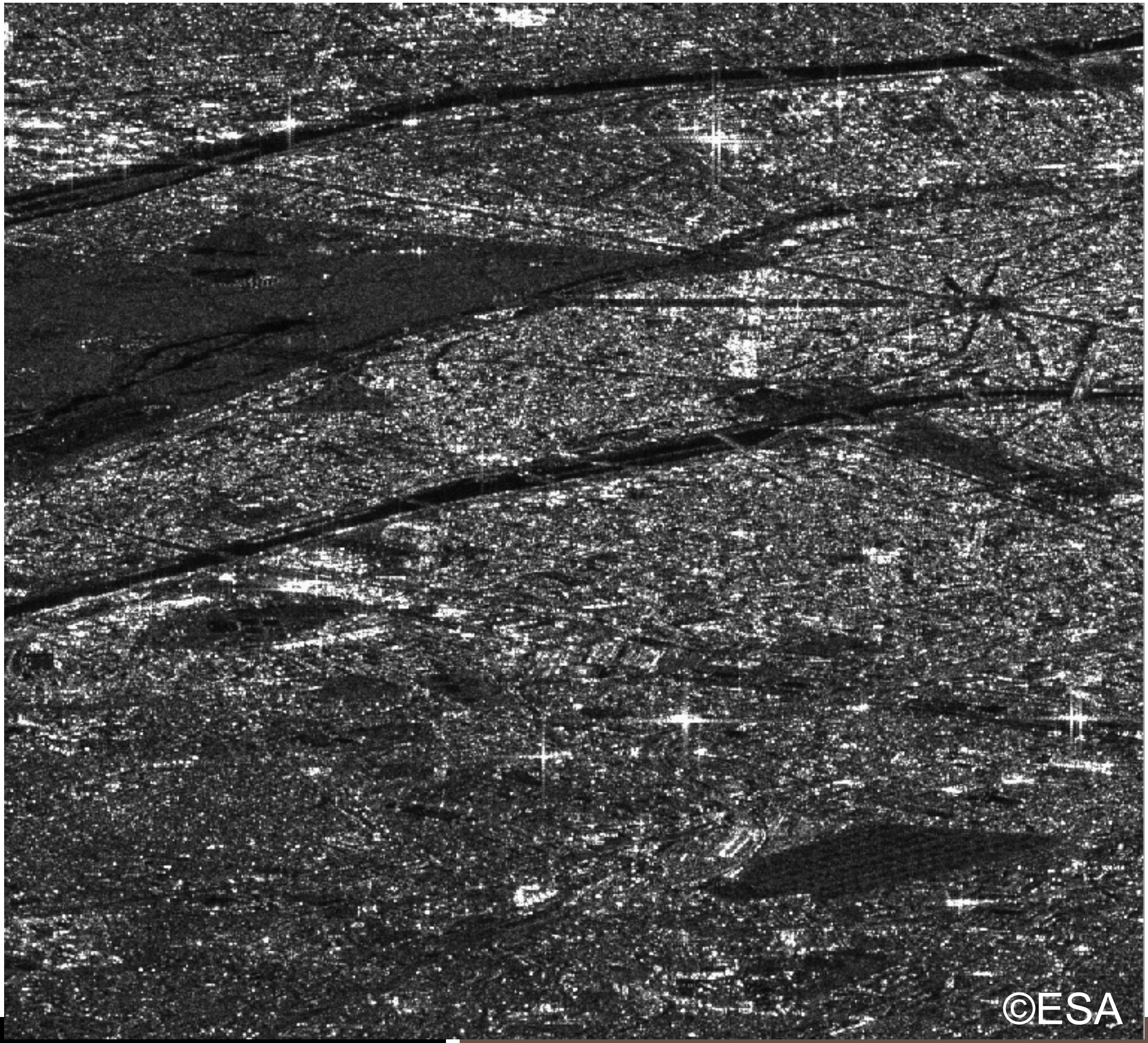
Paris seen from Radarsat-2



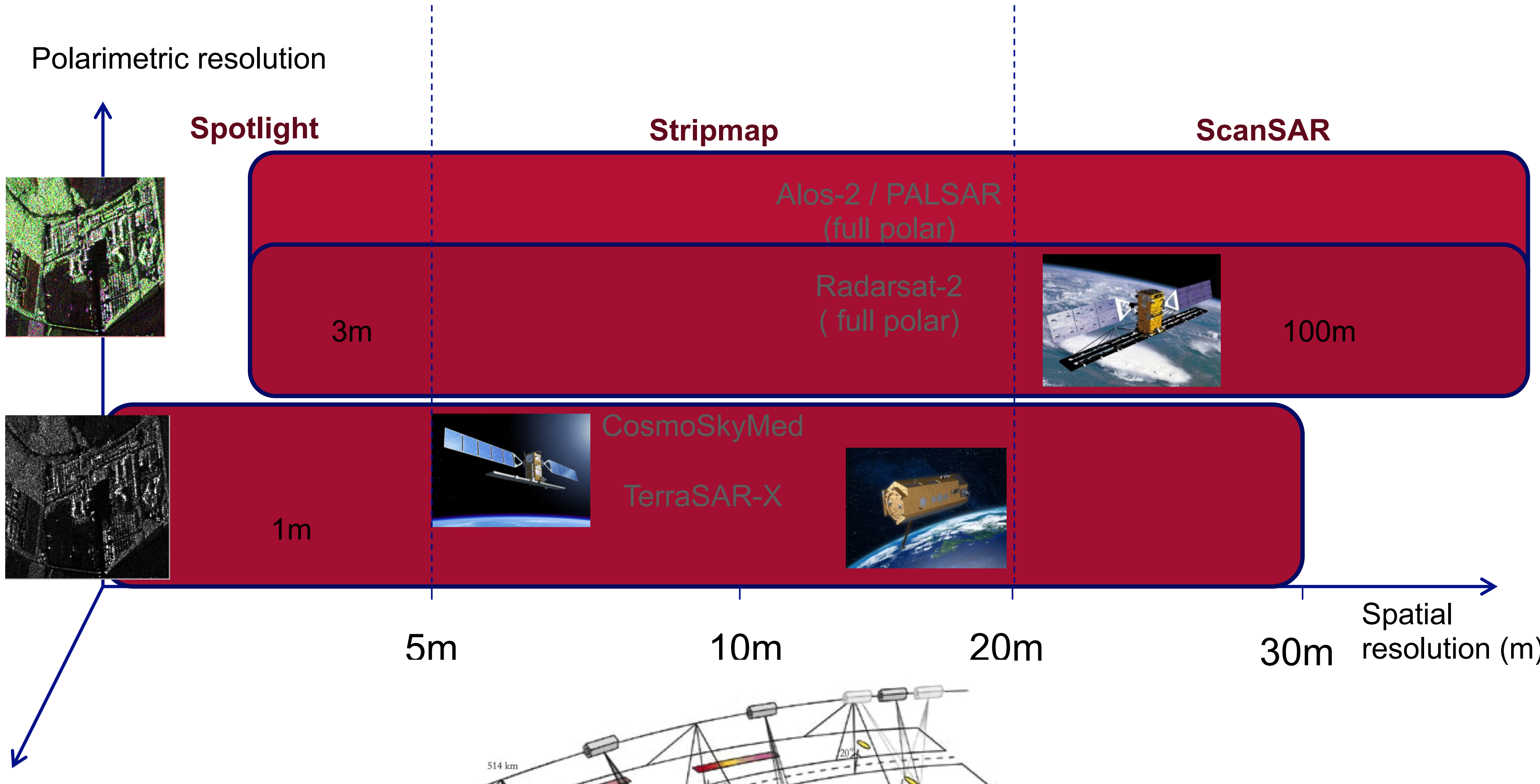
Paris seen from TerraSAR-X

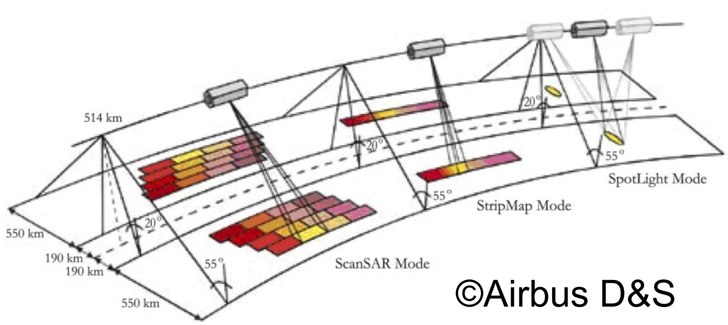


Paris seen from Sentinel-1



SAR sensors – resolutions





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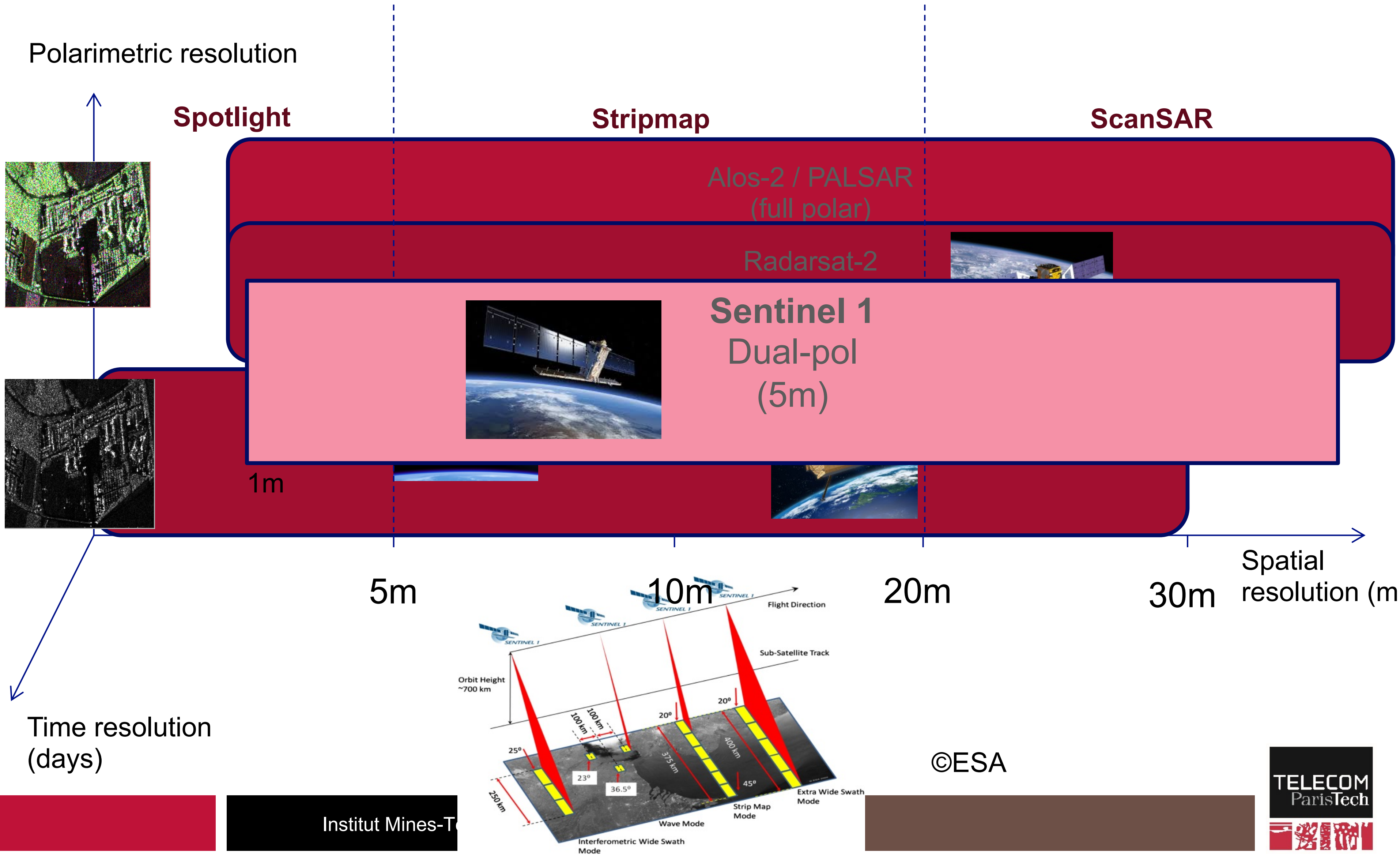
SAR sensors – resolutions



SAR sensors – revisiting time

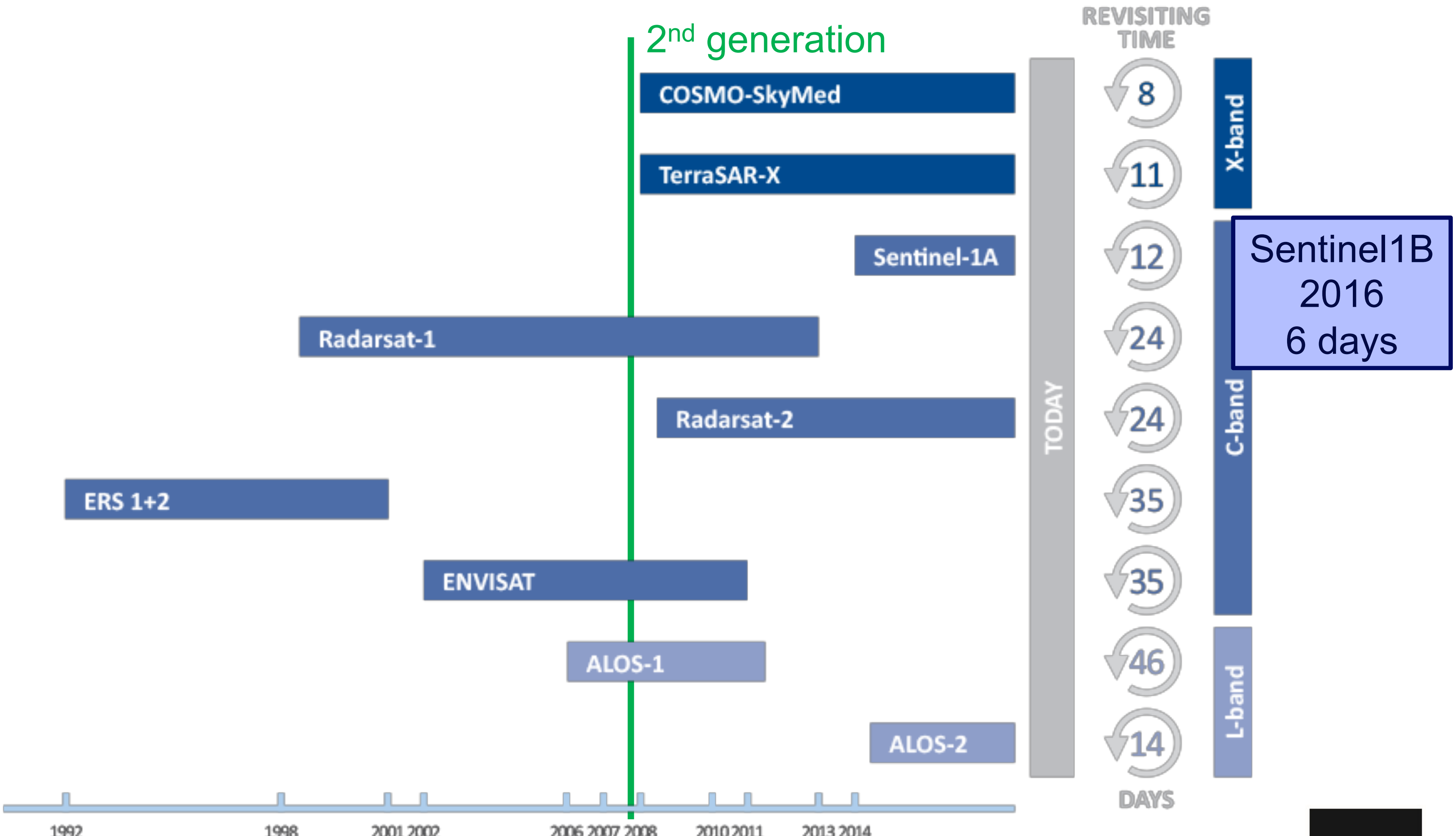
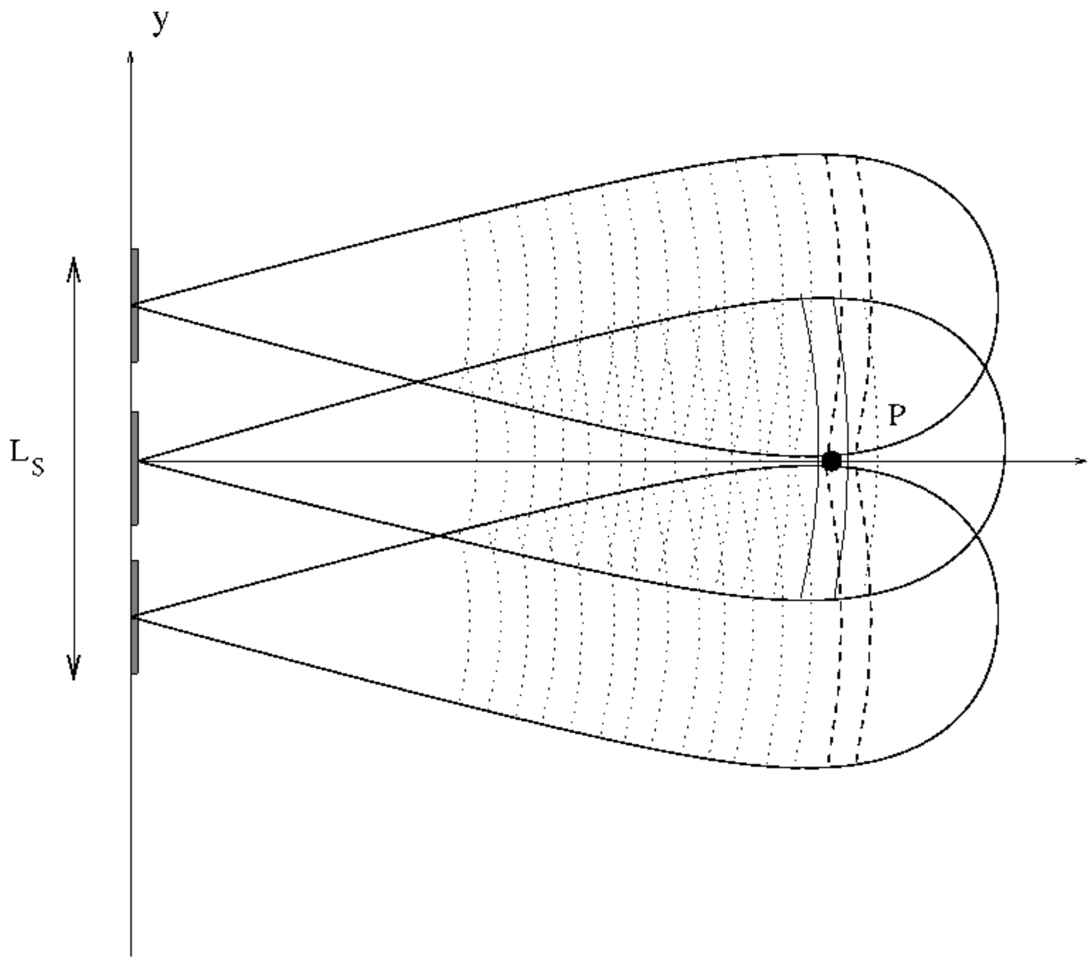
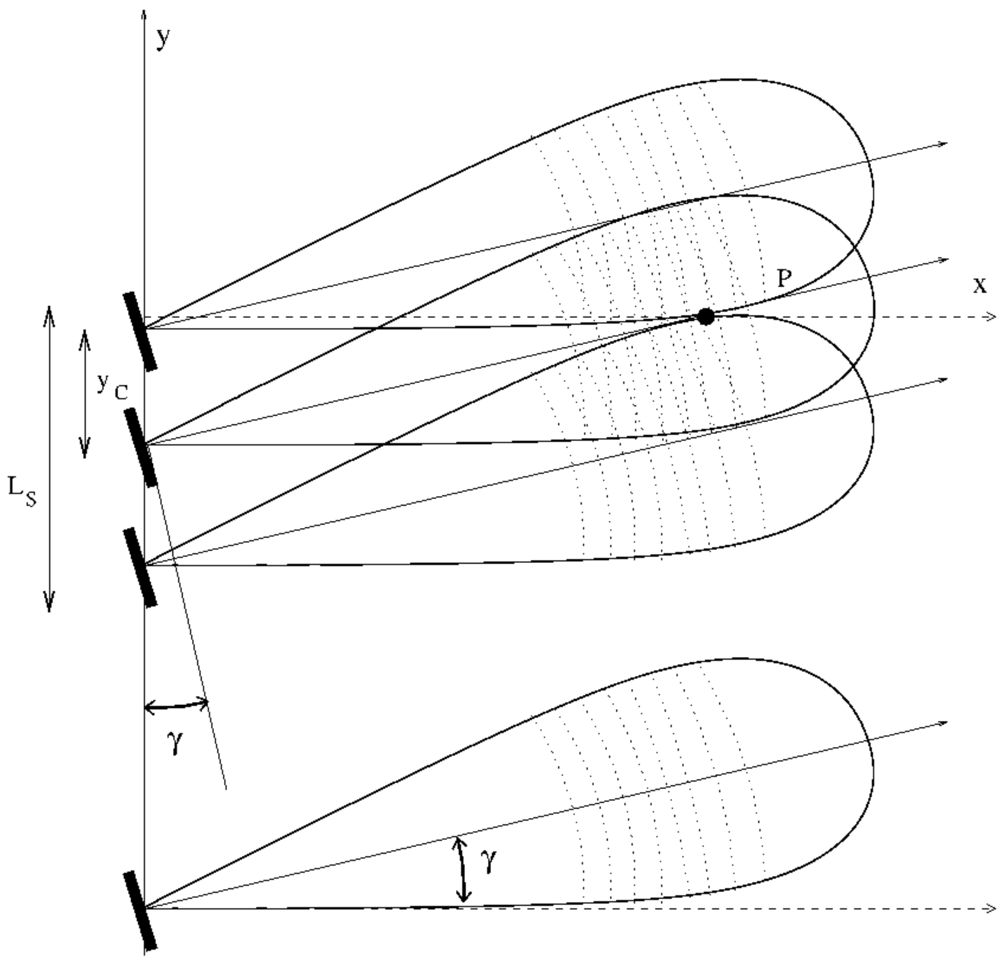


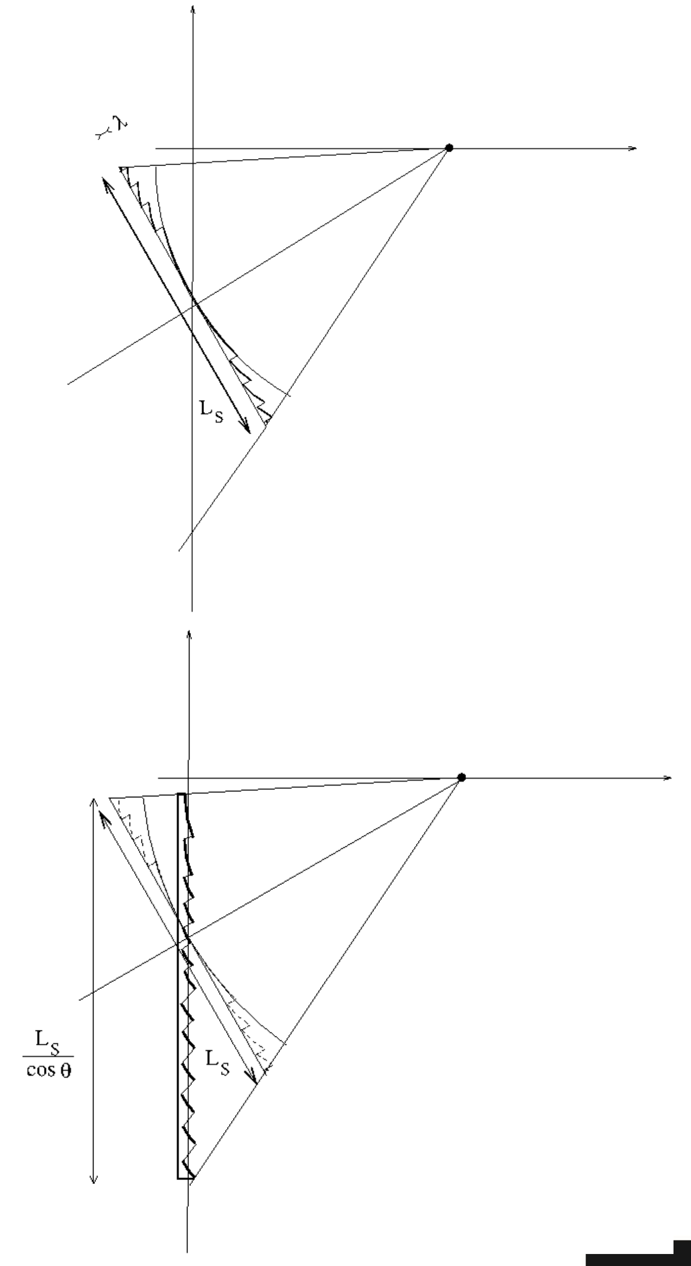
Figure from http://www.treuropa.com

StripMap mode

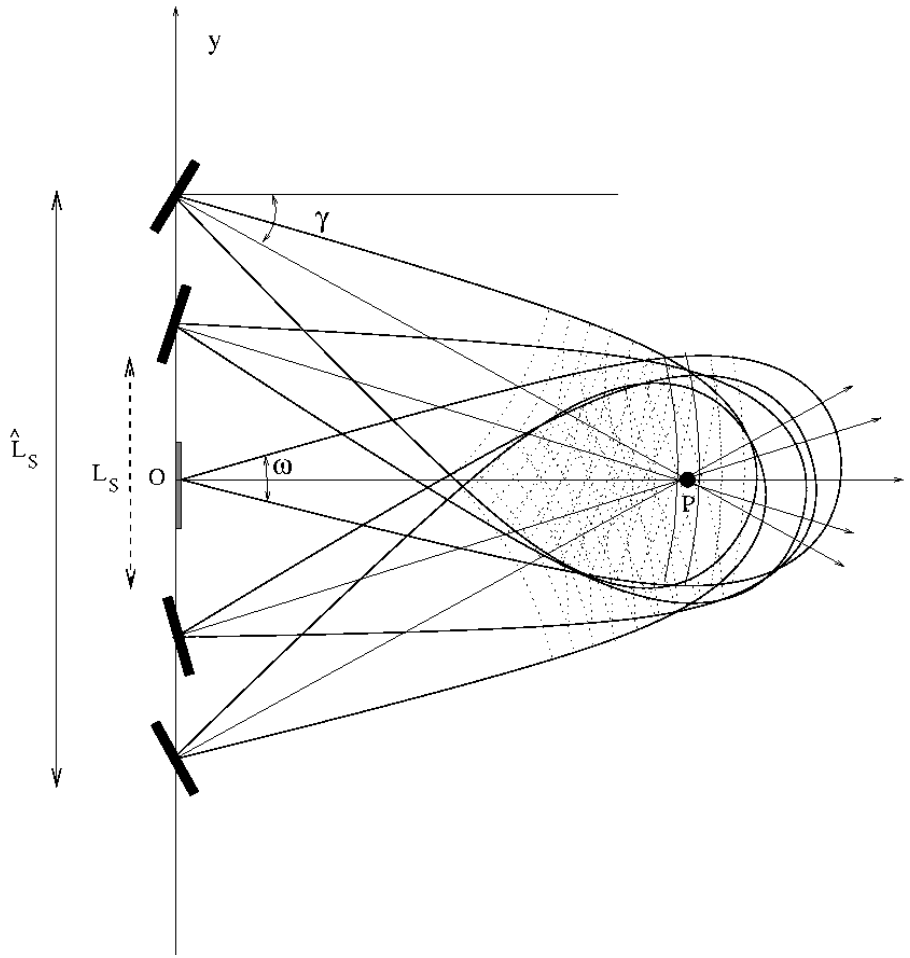


Squint

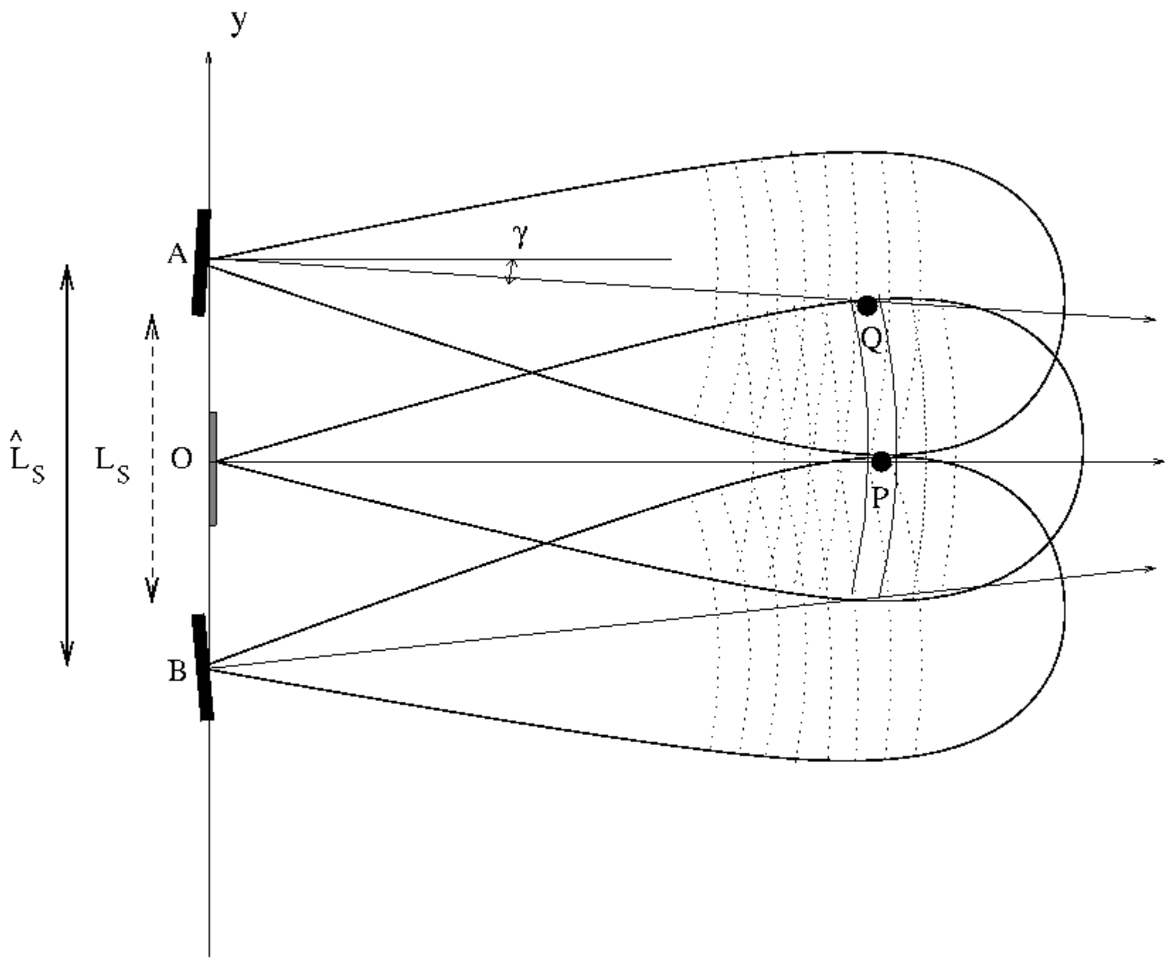




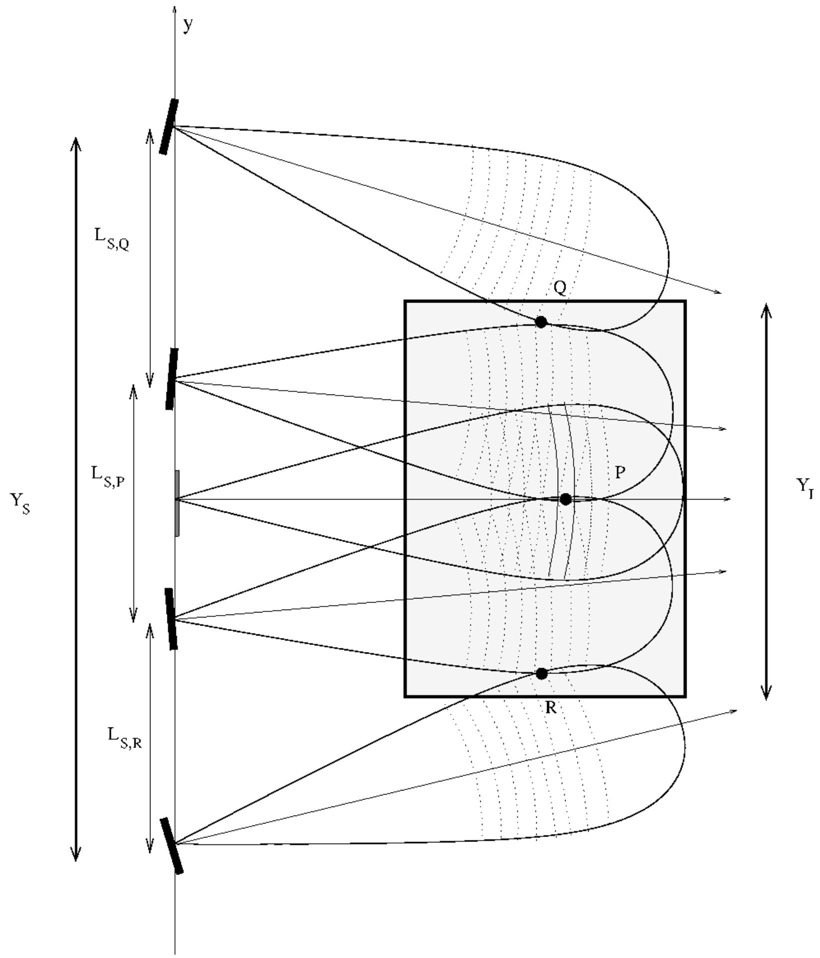
Starring SpotLight mode

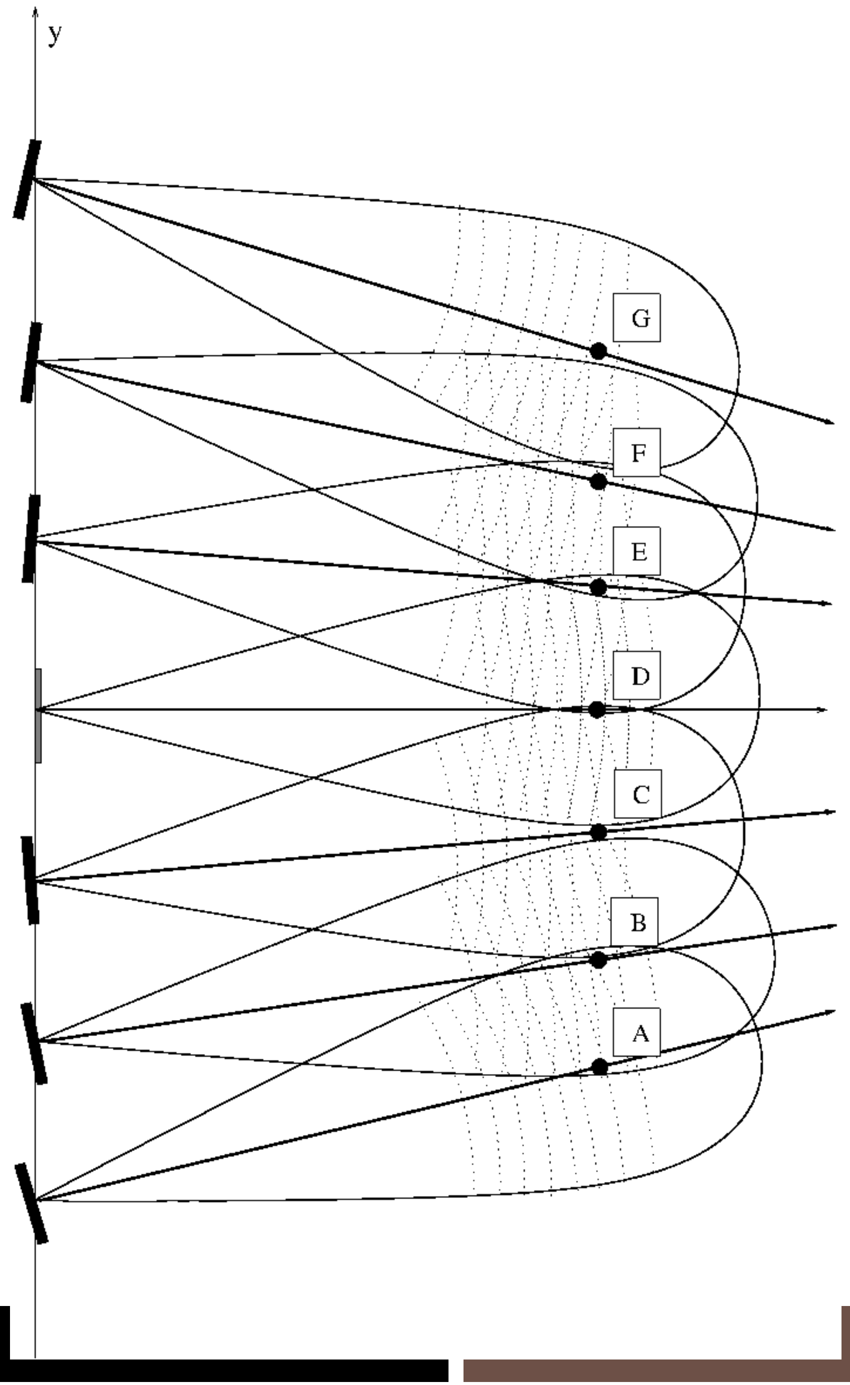


SpotLight mode for P



SpotLight

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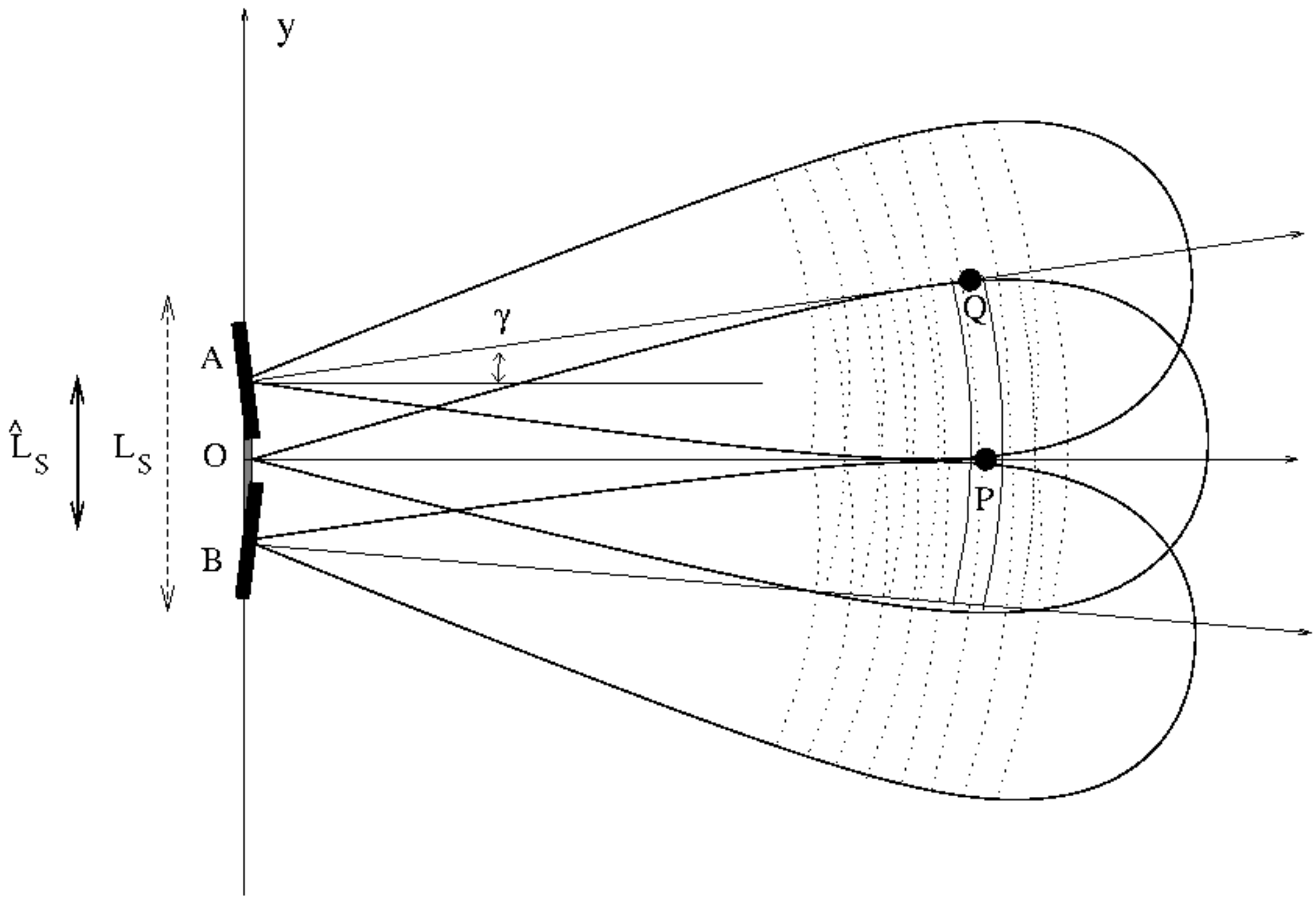
ScanSAR mode



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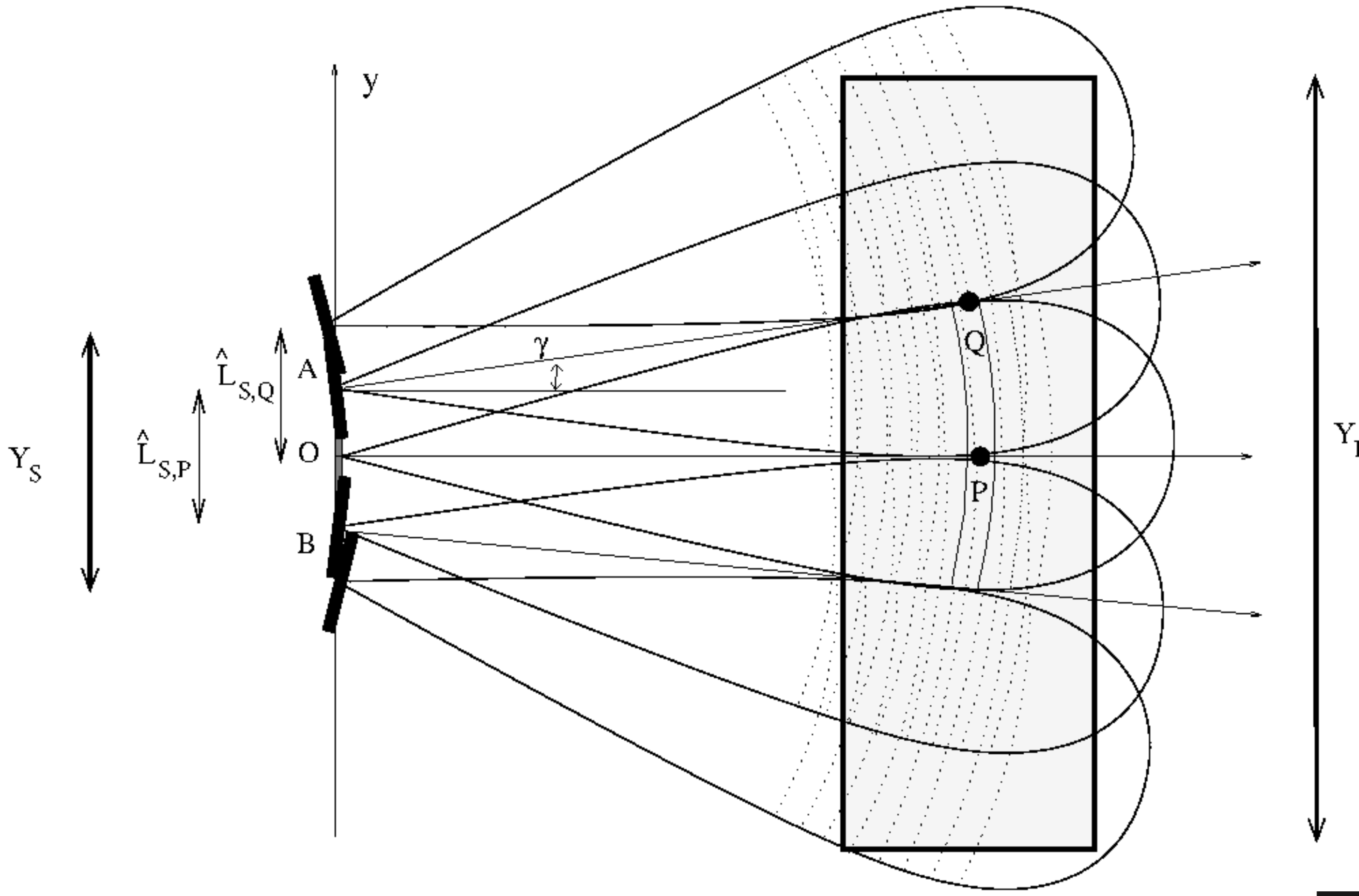
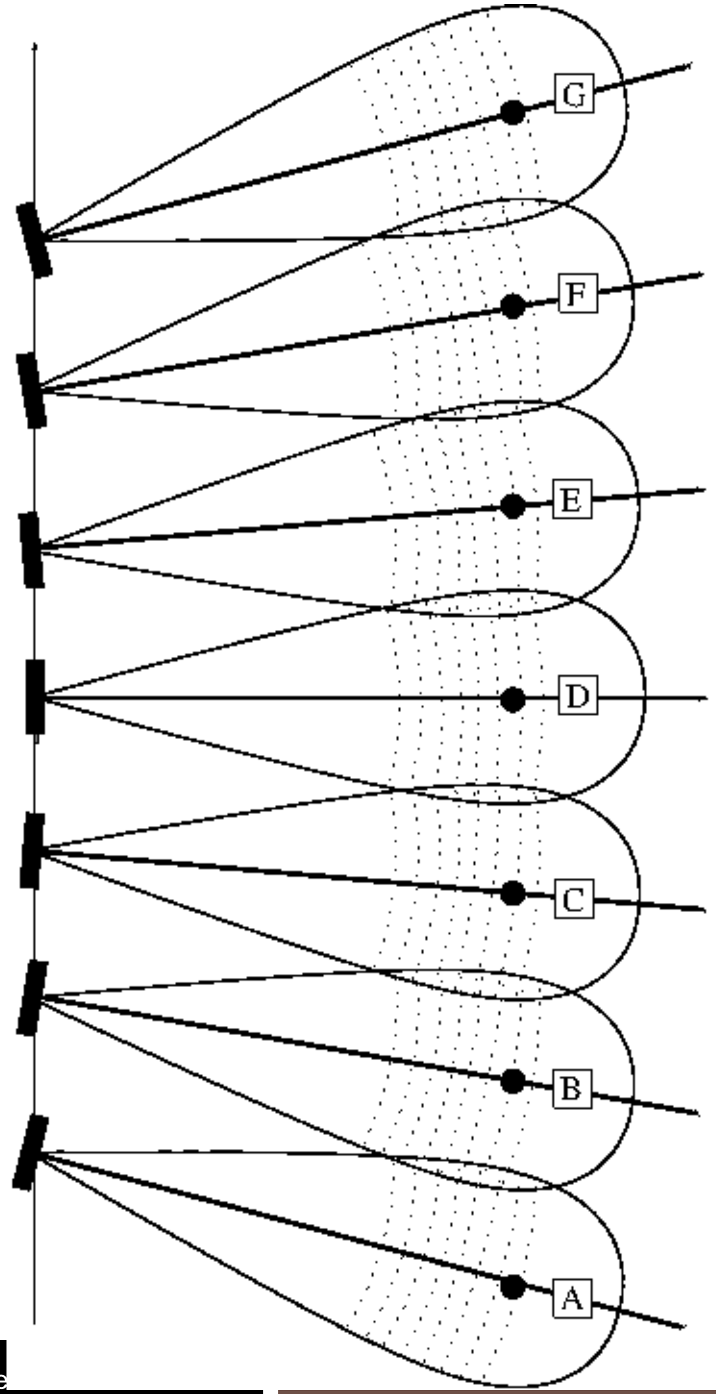
ScanSAR mode

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Sentinel mode