

# INTRODUCTION AU RADAR

**Jean-Philippe OVARLEZ**  
[jean-philippe.ovarlez@onera.fr](mailto:jean-philippe.ovarlez@onera.fr)  
(ONERA DEMR/MATS)

**Cours M1 EESC — Ville Avray**  
*07 mars 2022*

**ONERA**

THE FRENCH AEROSPACE LAB

# Definition and Applications

**RADAR = RA**dio **D**etection **A**nd **R**anging

- ▶ transmit & receive E.M. waves
- ▶ detect the target
- ▶ provide localization (range, angle, velocity)
- ✚ can provide classification, identification of target

## Military

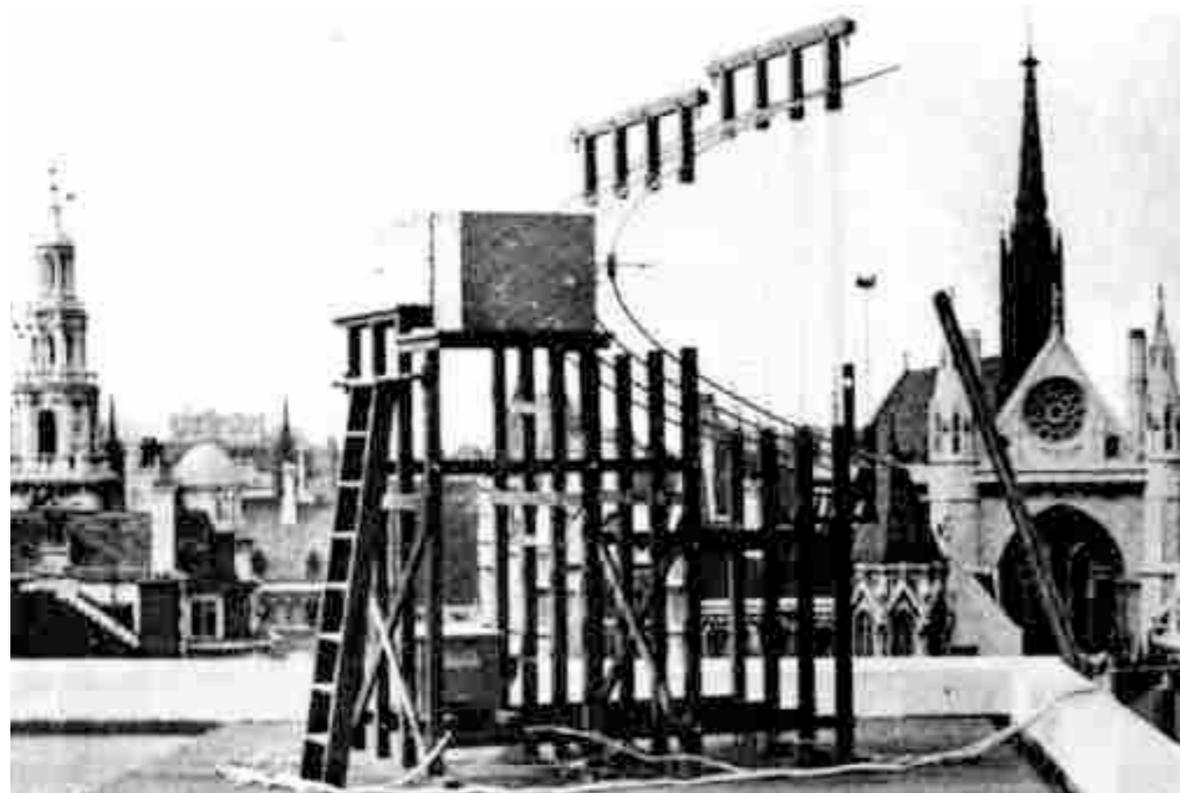
air surveillance (surveillance and tracking )  
maritime surveillance  
battlefield surveillance  
missile seeker  
guidance & interception  
imagery

## Civilian

air traffic control (ATC)  
maritime navigation control  
collision avoidance  
satellites tracking  
road traffic control & ERP  
archaeological & geologic research

# Historique (1)

- 1873**     **MAXWELL** (GB : théorie des ondes électromagnétiques)
- 1886**     **Heinrich HERTZ** (équivalence ondes radio/lumière ; concept réflexion EM ; premières ondes EM produites par décharge d'un condensateur ;)
1894.     **Oliver LODGE** (GB : 1er détecteur d'ondes EM)
- 1895**     **MARCONI** (IT/GB : transmission de signaux EM ; telegraphie sans fil)
- 1900**     **Nicolas TESLA** (Croatie : principes de la radiolocalisation)
- 1904**     **HULFSMEYER** (Allemagne : appareil de projection et d'interception)



antennes à réflecteur parabolique  
utilisées par la Compagnie Marconi  
pour sa station expérimentale à  
ondes courtes et ultra-courtes  
(toits de Londres 1930)



**Marconi**

## Historique (2)

**1922/1927** Ebauches expérimentales ; 1928 magnétron (Jap)  
**1930** USA - Naval Research Laboratory (Taylor, Young, Hyland)

1er écho d'avion "accidentel" en 1930 ( $\lambda = 9\text{m}$ )

**FRANCE** Mesny - David ( $\lambda = 1.8\text{m}$ )

Pierret - Gutton (magnétron  $\lambda = 0.16\text{m}$ )

**1930-1934** Développement de systèmes à ondes continues

NRL : détection avions à 80 kms (mauvaise précision distance)

DAVID (Fr) : barrage David

PONTE - GUTTON (Fr CSF) : détection à  $\lambda = 30\text{cm}$  (manque puissance)

ALLEMAGNE : détection navires  $\lambda = 50\text{cm}$  (idem)



Salle contrôle radar WWII EU



Maurice Ponte

# Historique (3)

**1935/1940**

## **PREMIERS RADARS A IMPULSIONS**

**GB :**      **Watson Watt (ondes métriques)**  
Réseau d'alerte sur les côtes sud et est  
Détection d'avions à 100 kms ( $\lambda = 10\text{m}$ )



**Radar du Normandie**

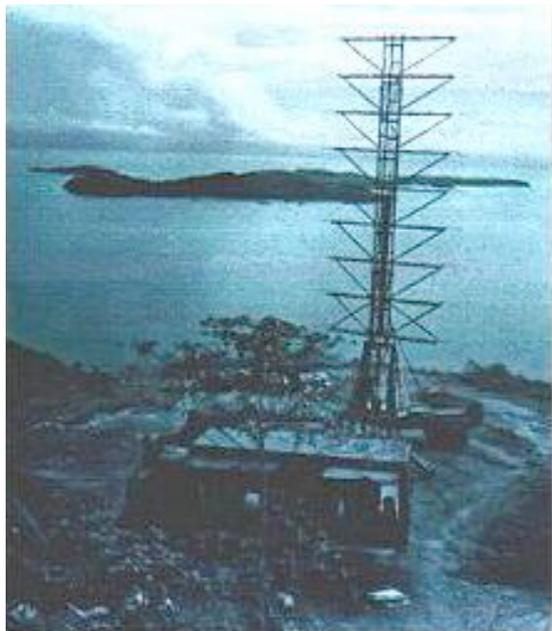
**FRANCE : équipement du Normandie**  
**Barrage David aux frontières**

Prototypes à impulsions/magnétrons  
Installation à bord du Richelieu, Jean-Bart



**Watson WATT**

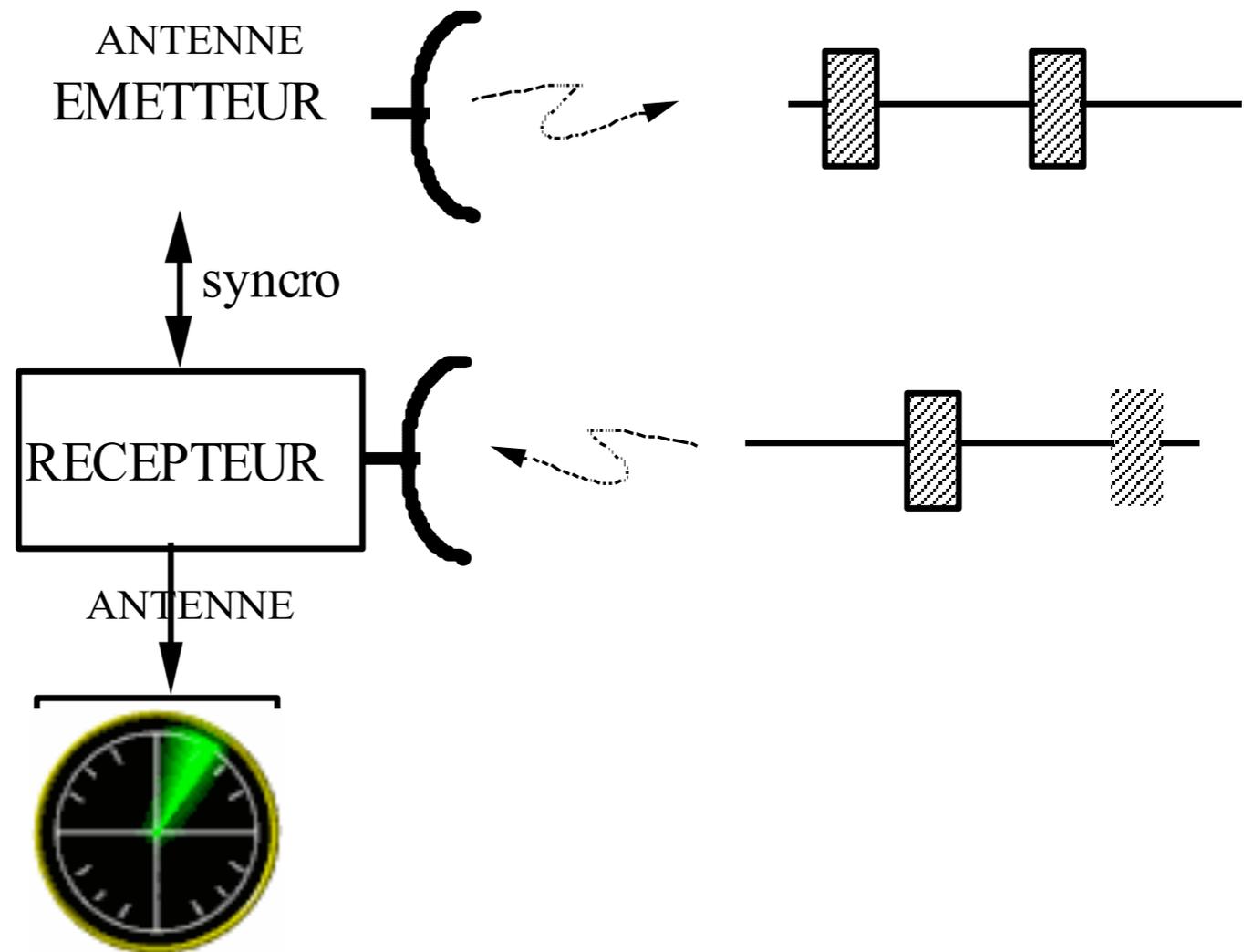
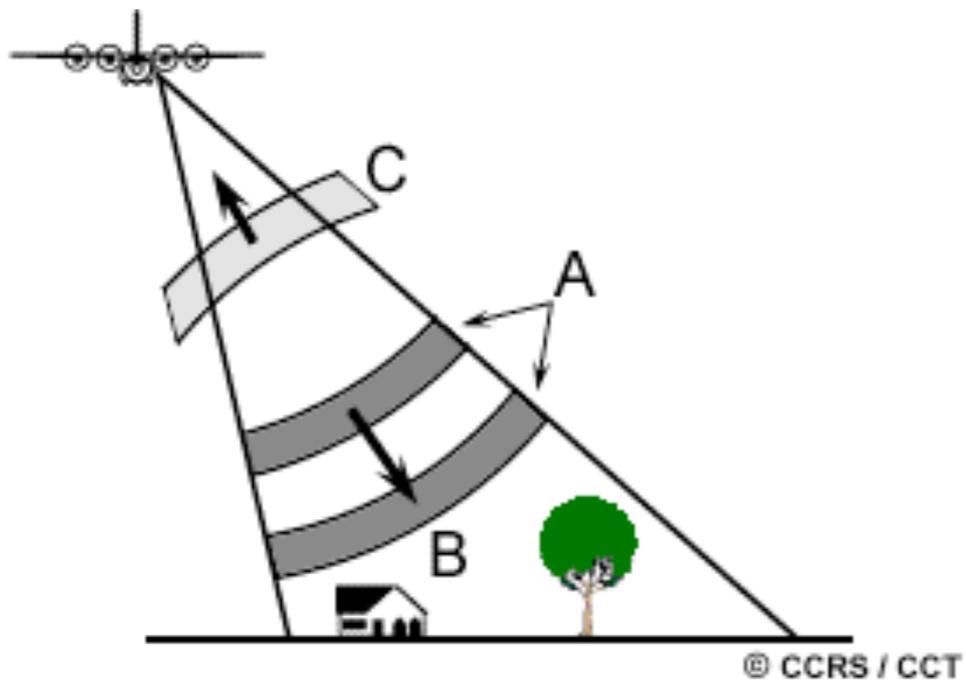
## **2nde GUERRE M<sup>dle</sup>**



**Mise en commun des efforts US/GB**  
**Fondation du Lincoln Lab**  
Progrès décisifs

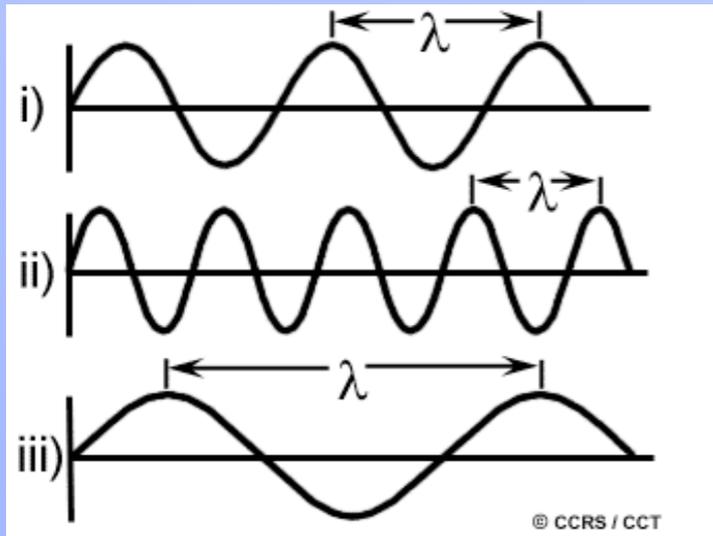
**Station radar Pearl Harbor 1941**

# Le radar classique : bloc diagramme



SCOPE PPI  
(Panoramic Plane Indicator)

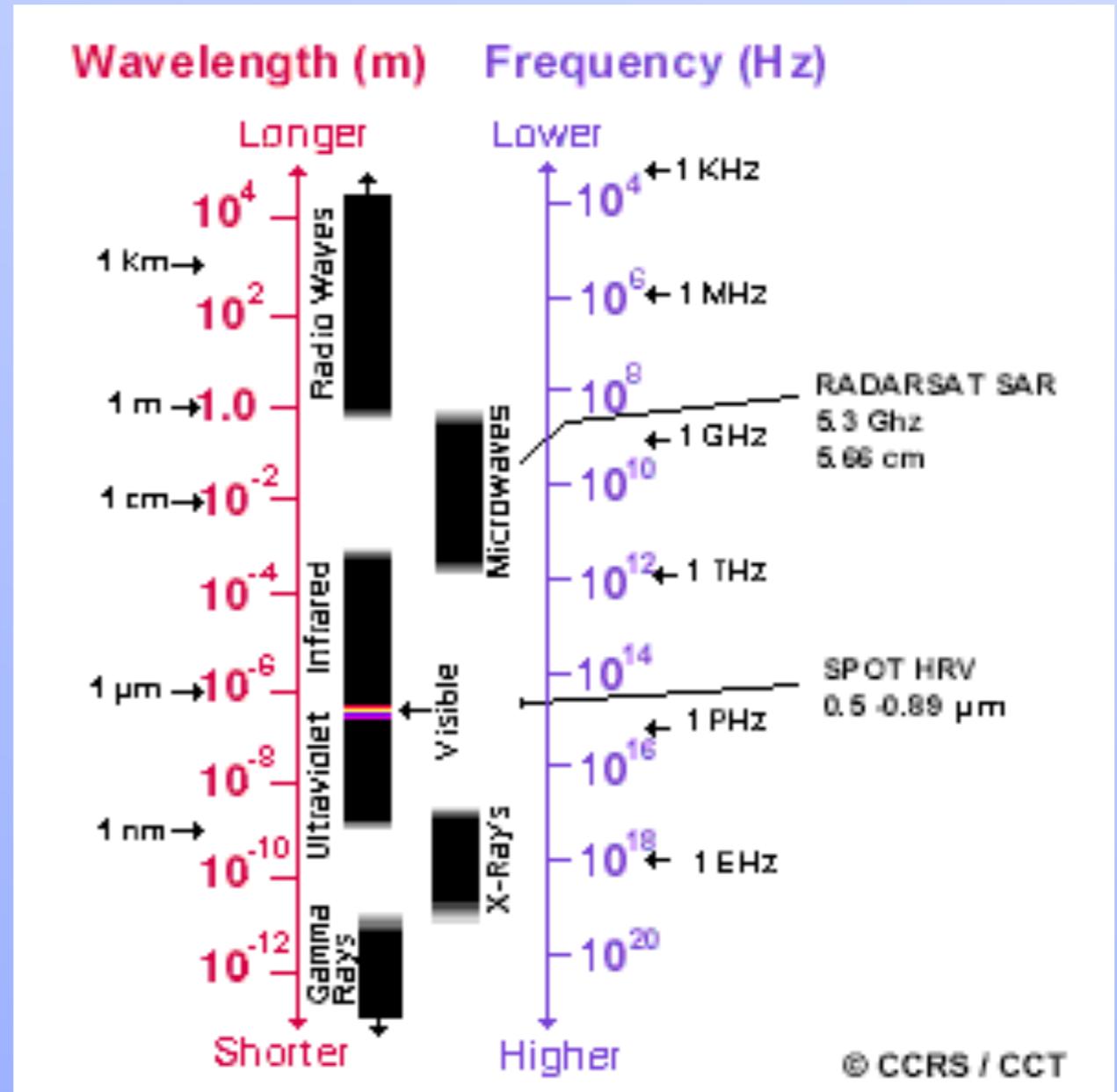
# Spectre électromagnétique



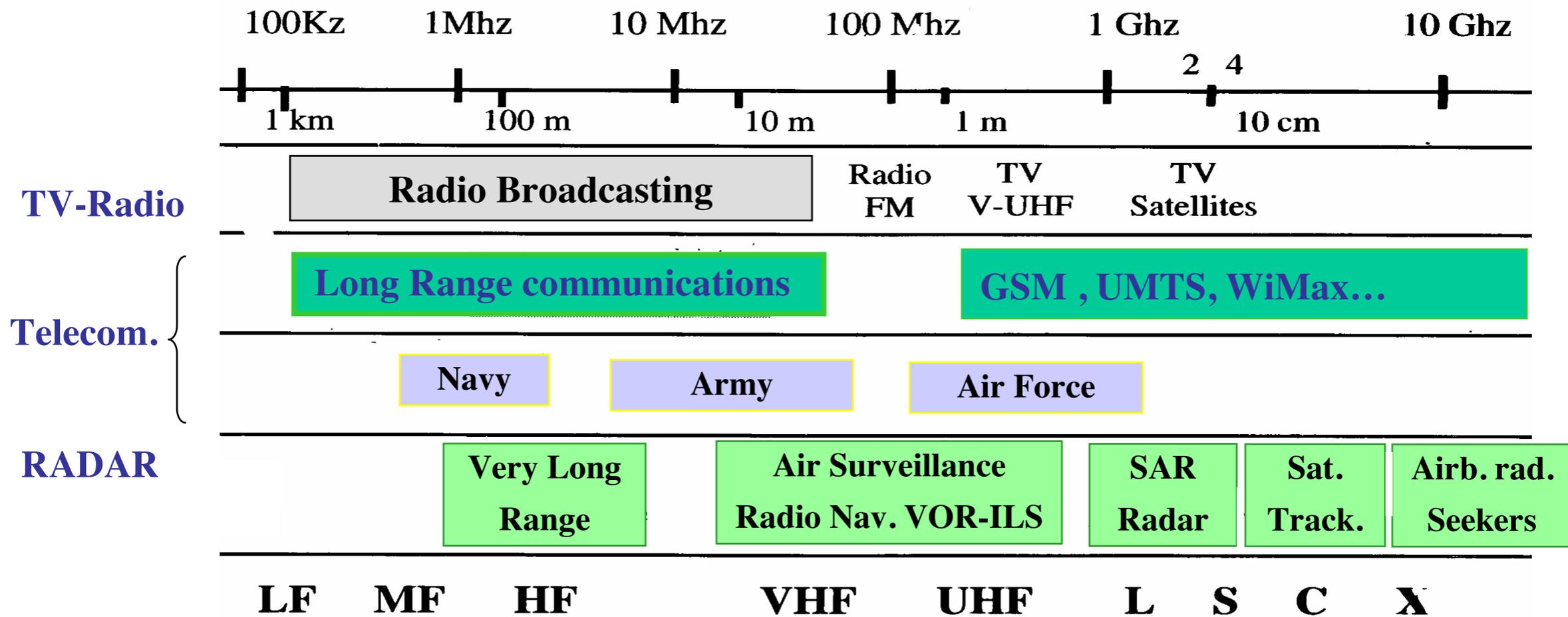
$$\lambda = \frac{c}{f}$$

Vitesse lumière

$$c \sim 3 \times 10^8 \text{ m/s}$$



# FREQUENCY BANDS



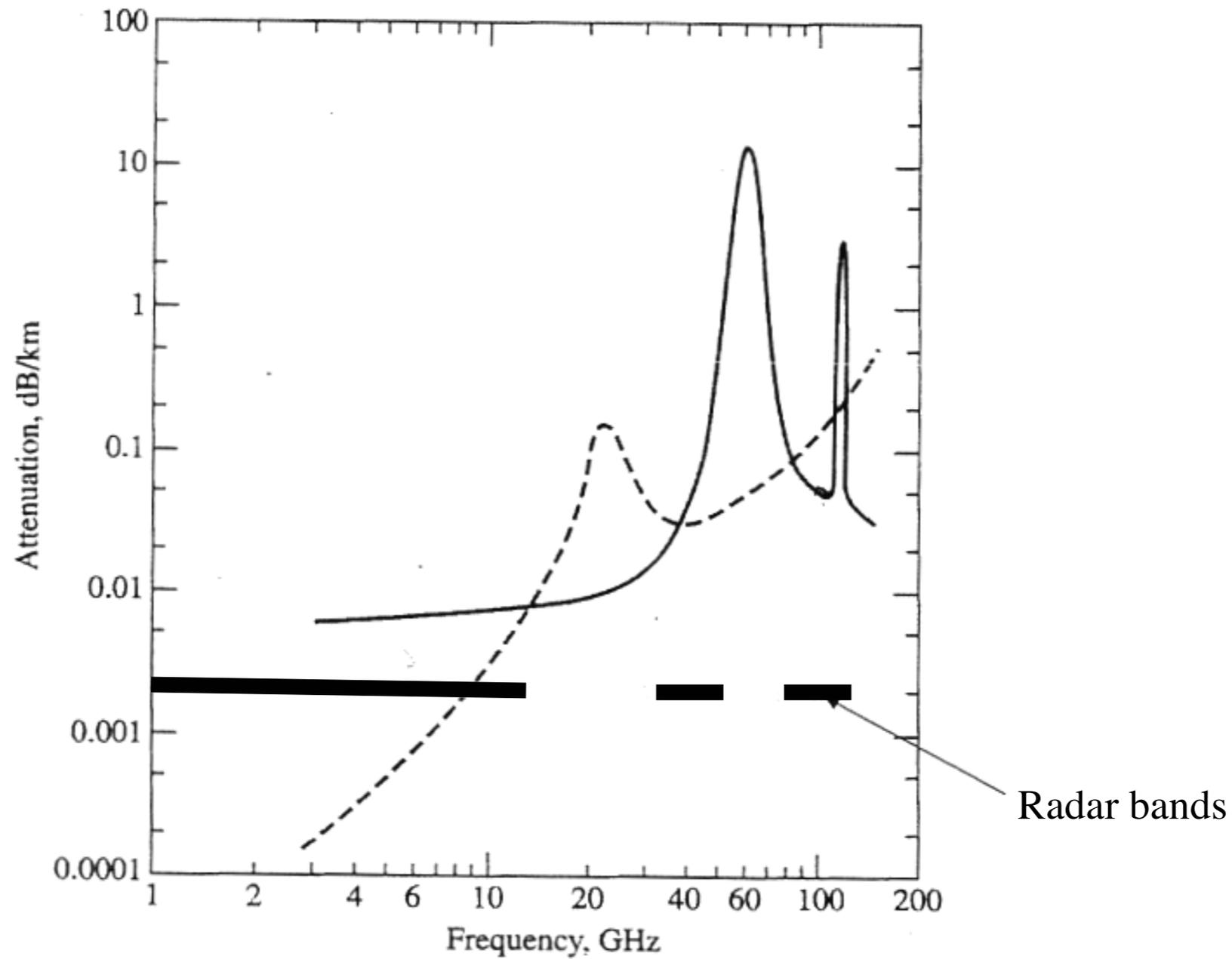
Band	Range (GHz)
L	1-2
S	2-4
C	4-8
X	8-12
P	12-18
K	18-26.5

*Counterstealth*

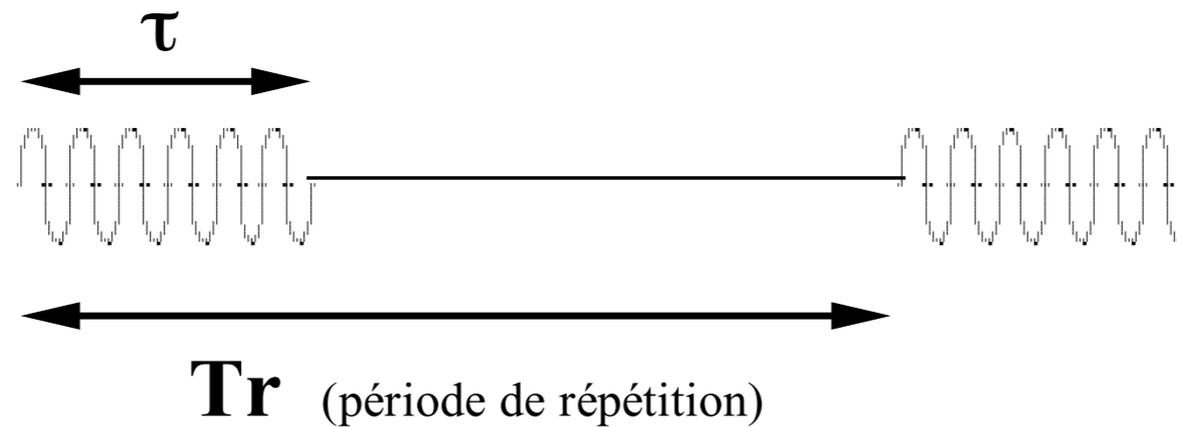
*Conventional radar*

# FREQUENCY BANDS

## Atmospheric absorption



# L'émetteur



- oscillateur de puissance (magnétron, triode) en CW
- amplification (klystron - TOP - Triode) en pulsé
- impulsions brèves de durée  $\tau$  ( $\sim 1$  à  $100 \mu\text{s}$ )
- impulsion répétitives, de période  $T_r$  ( $\sim 100 \mu\text{s}$  à  $10 \text{ ms}$ )
- puissance émise

puissance crête :  $P_c$  ( $\sim 1 \text{ kW}$  à  $1 \text{ MW}$ )

puissance crête :  $P_m$  ( $\sim 100 \text{ W}$  à  $10 \text{ kW}$ )

$$P_m = P_e \frac{t}{T_r} \times$$

- $F_r = 1/T_r$ , fréquence de récurrence  
(*P.R.F. Pulse Repetition Frequency*)

# ANTENNA

## Role of the antenna

transmit & receive radar signals

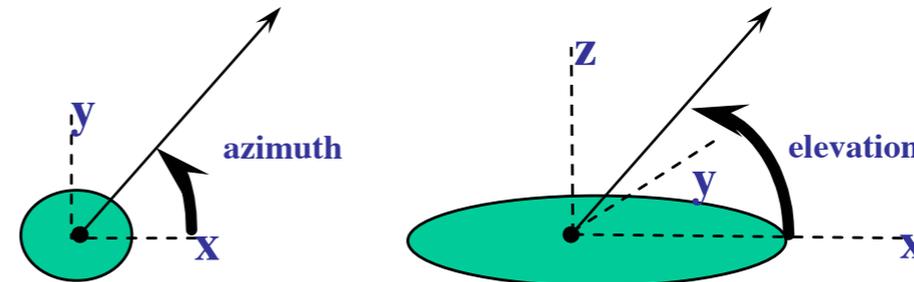
focusing the energy (beam  $\sim 1$  to  $3^\circ$ )

localisation of target in azimuth and elevation

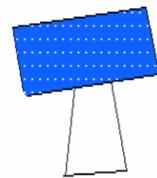
## Kinds of antennas

mechanical rotating

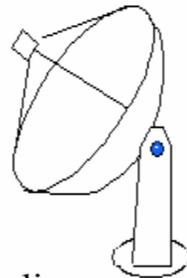
electronic, phased array



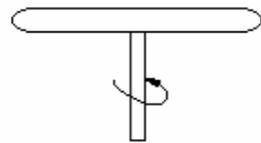
## Conventional radars



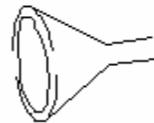
Air surveillance



Parabolic  
tracking, space appl.

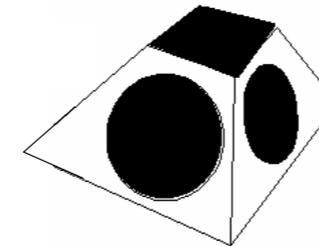


Early warning  
S, L bands

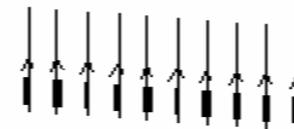


Missile seeker  
tracking, Ku band

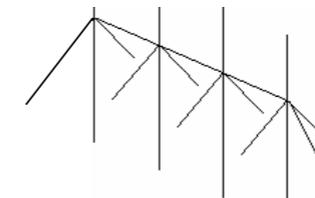
## Low frequency radars



Pyramidal antenna for ballistic target  
detection (very long range)

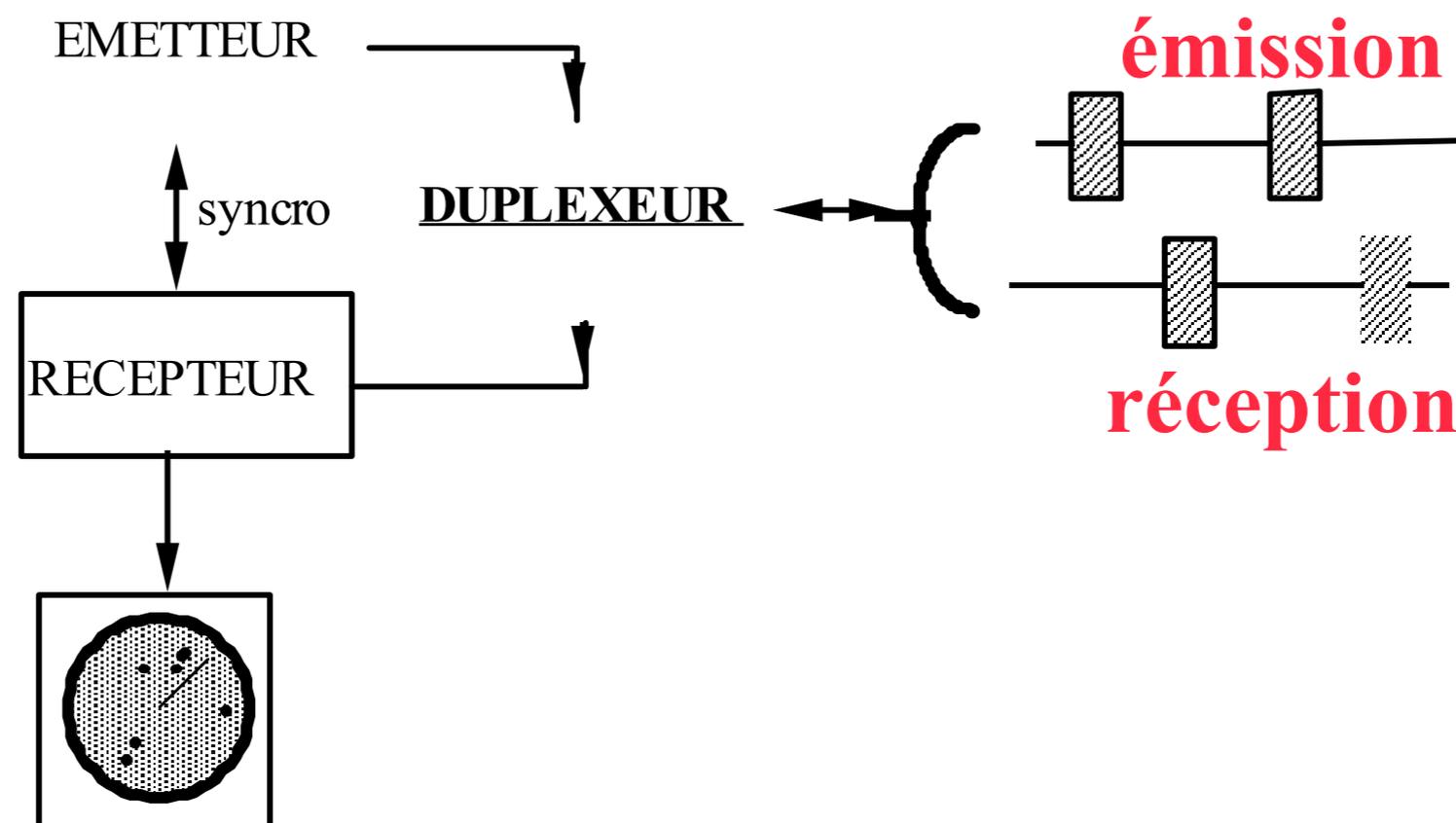


Dipole array - VHF band



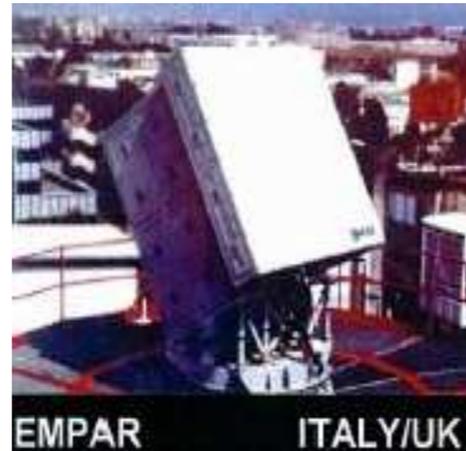
HF antennas - over the  
horizon sky wave or  
surface waves radar

# *L'antenne et le duplexeur*

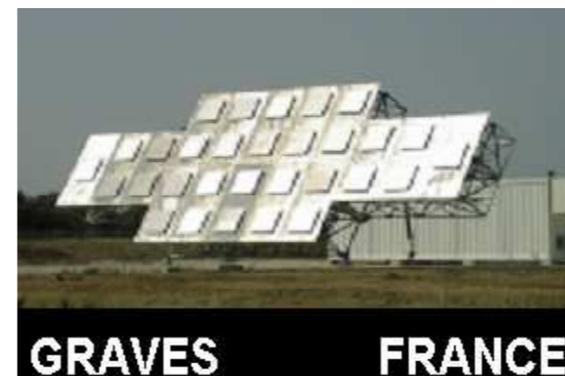
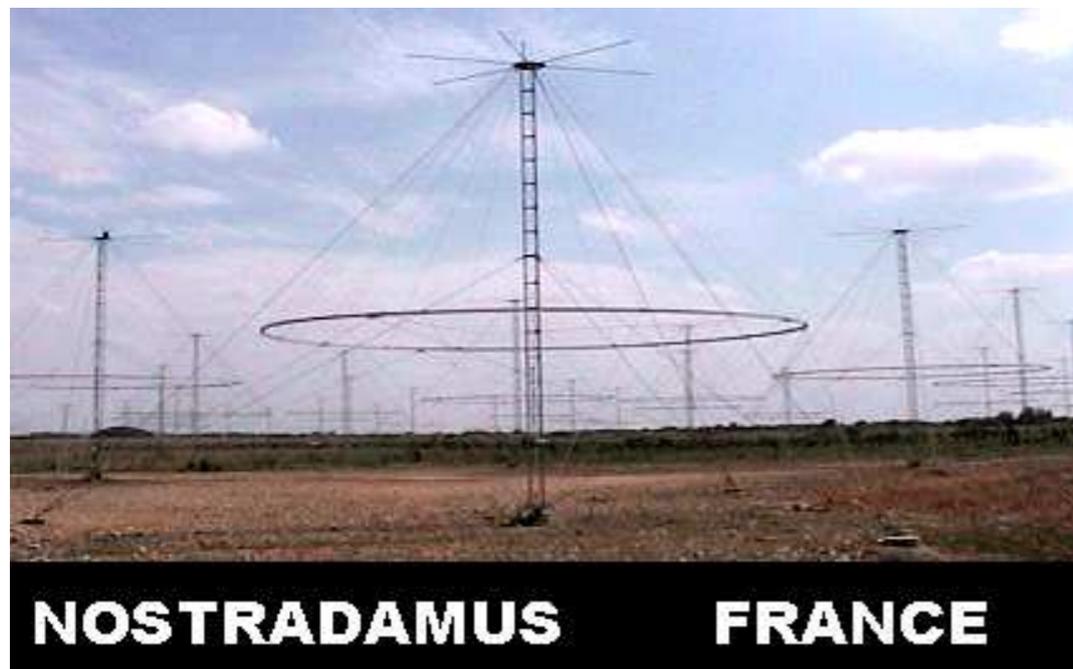


# ANTENNA

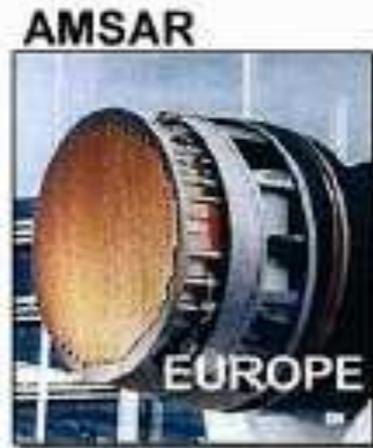
## « passive » Phased Array antenna



## « active » Phased Array antenna



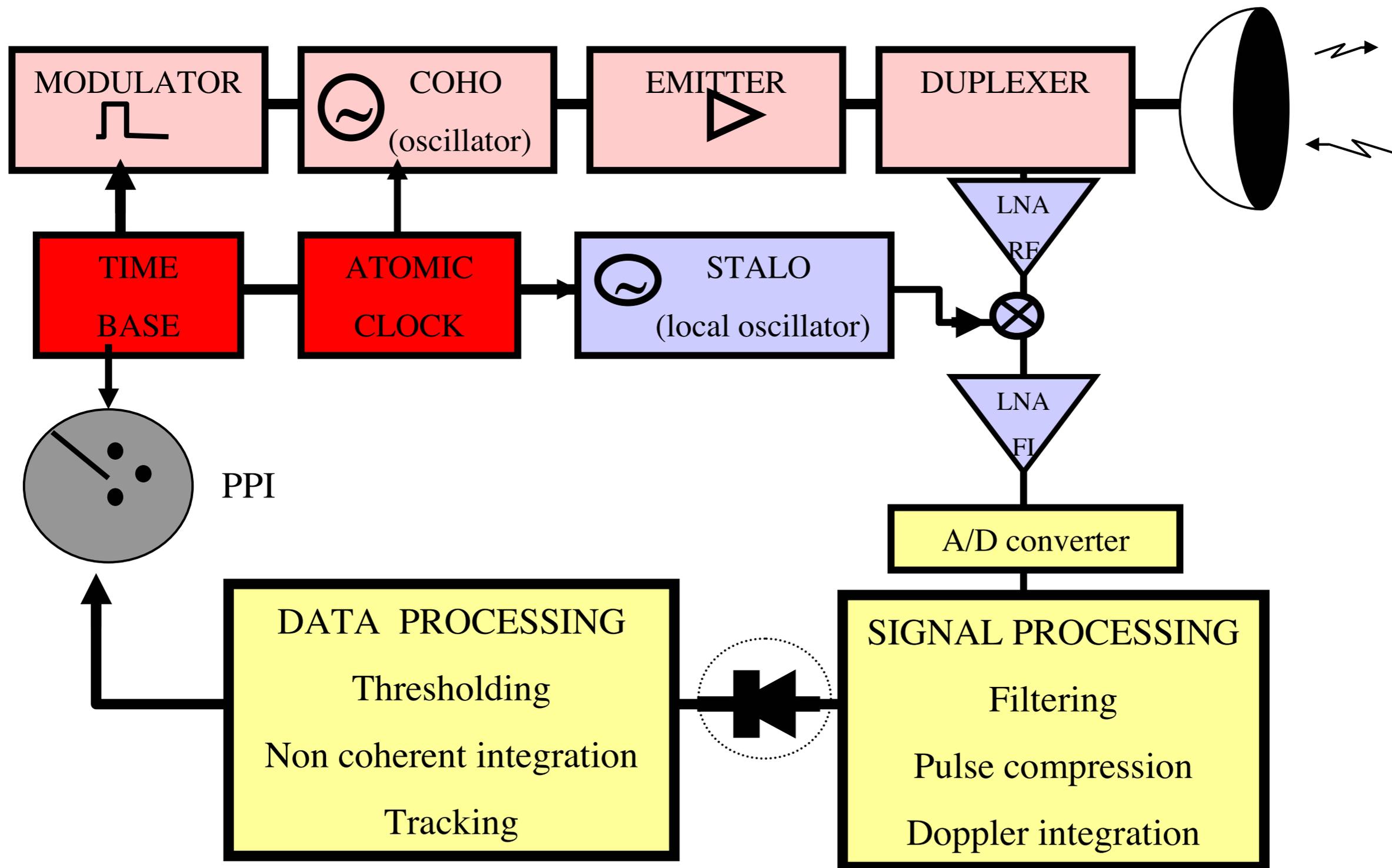
« active » Phased Array antenna using MMIC



*See : E. BROOKNER - Practical phased array antenna systems and adaptive arrays for radar and communication systems, Lecture series, Boston IEEE AESS, 2004*



# RADAR SYNOPSIS



# THREE KIND OF RADARS

## Surveillance / warning radar - **Primary Radar**

- panoramic (2D) surveillance, rate de 6 à 15 rn/mn
- PPI visualisation (panoramic plane indicator)
- elevation measurement capabilities (3D)

## **Tracking radar**

- high accuracy
- servo control systems

## Another kind of radar : **Secondary Surveillance Radar (SSR)**

- replies to each interrogation signal by transmitting its own response containing encoded data
- identification friend or foe (IFF) / **cooperative mode**

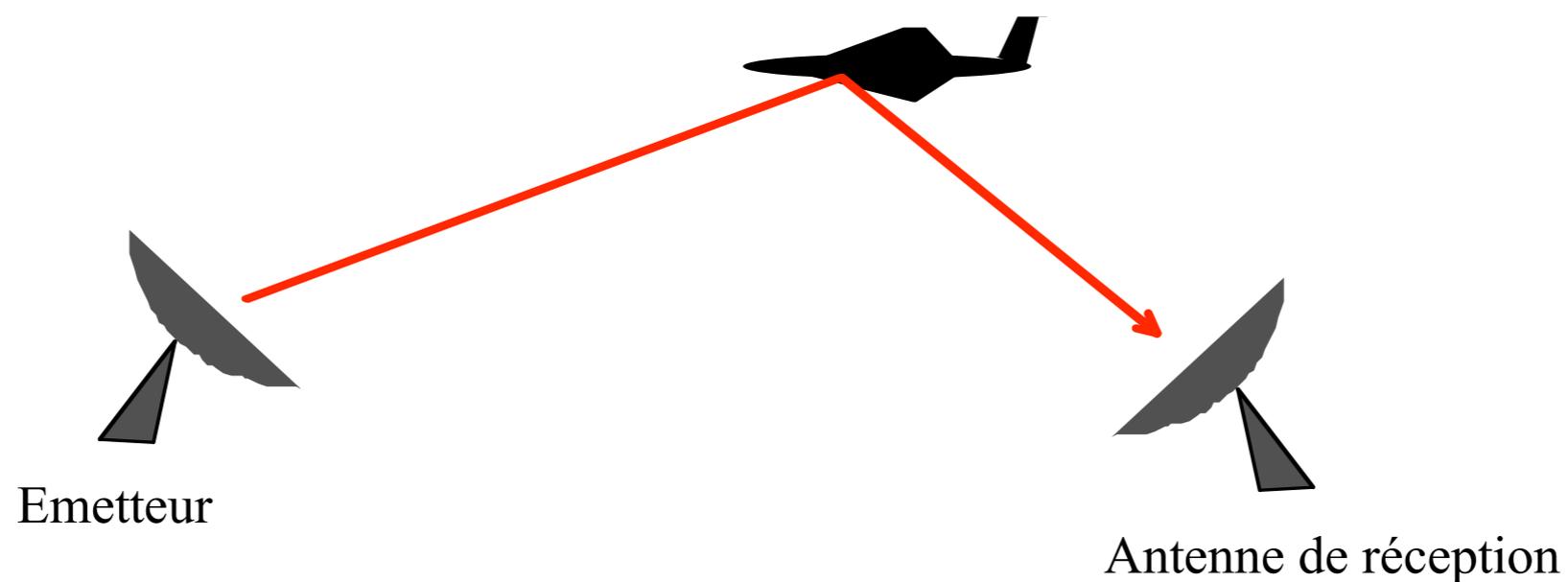
# *Nouveaux concepts radar (1)*

## **RADAR BISTATIQUE**

**antifurtivité**

**discrétion, survivabilité**

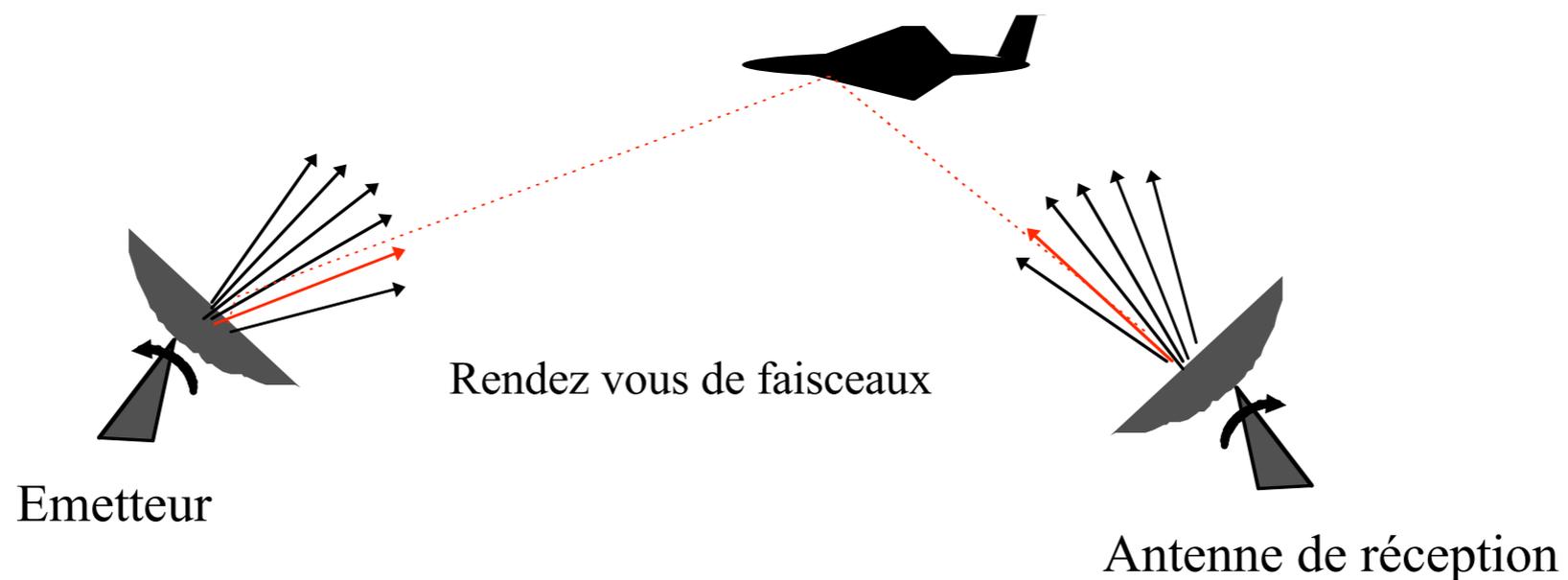
**utilisation d'émetteurs existants**



# *Nouveaux concepts radar (2)*

## **RADAR BISTATIQUE : fonctionnement**

**Problème du rendez vous de faisceaux (surveillance)**



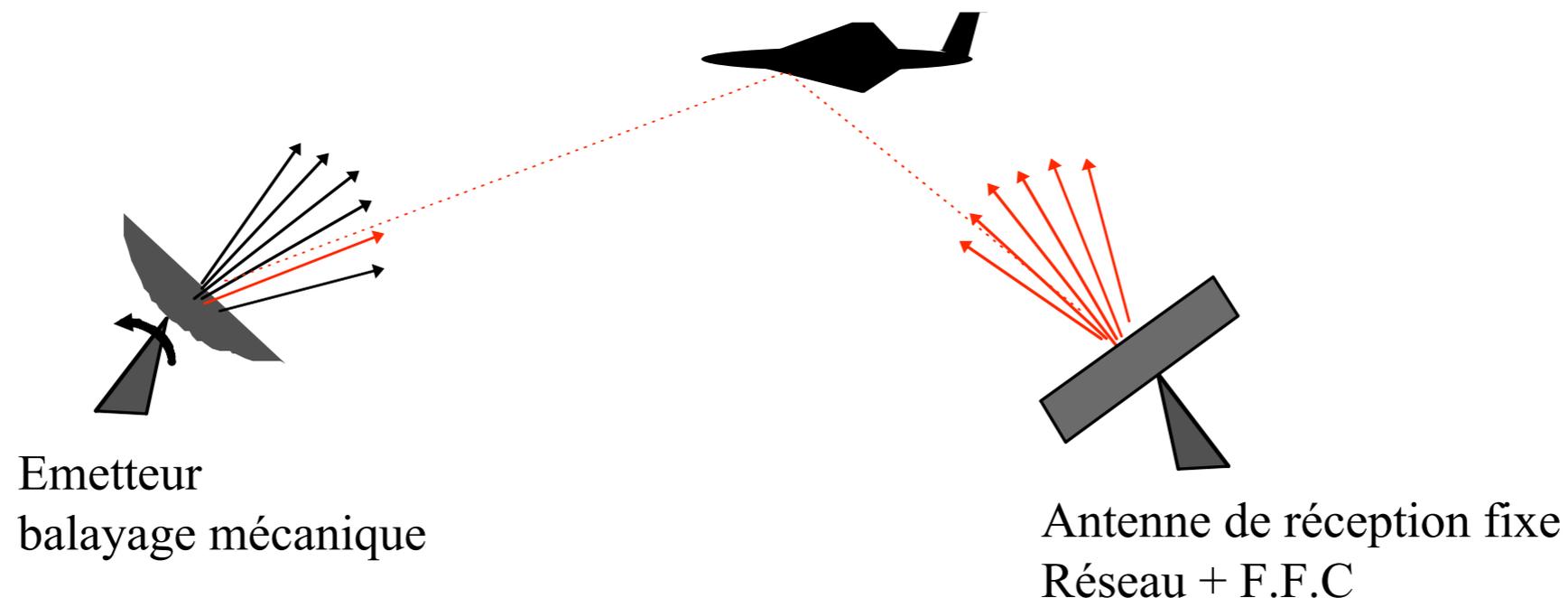
# *Nouveaux concepts radar (3)*

## RADAR BISTATIQUE

Utilisation d'une antenne réseau en réception

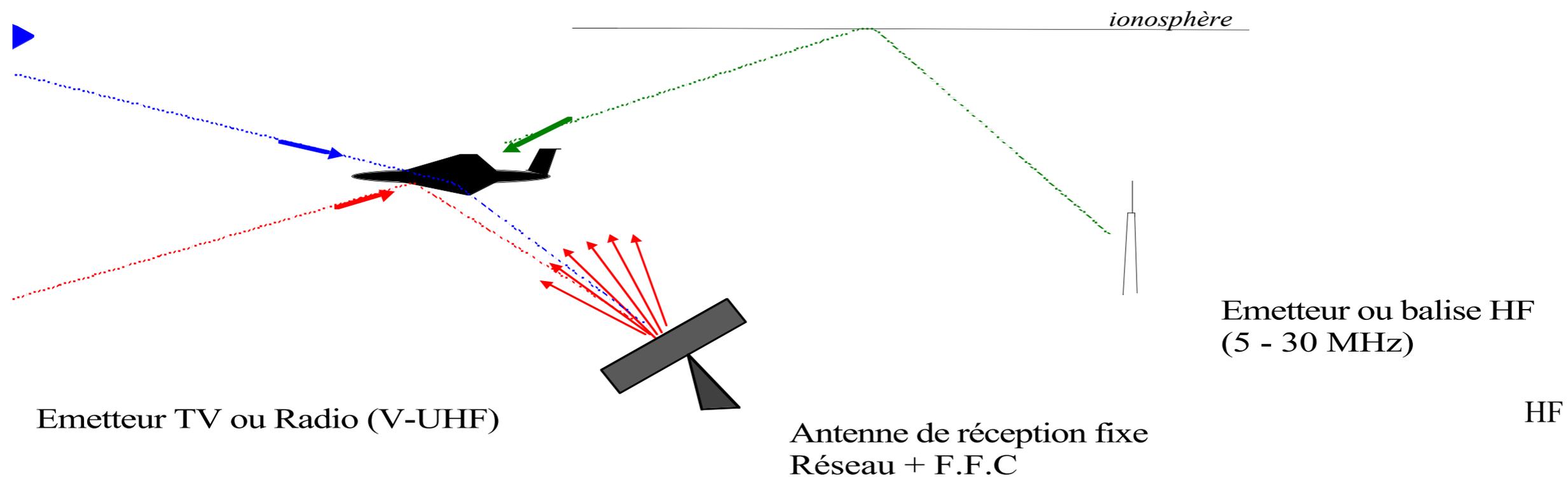
Formation de faisceaux par le calcul (F.F.C.)

Plus de problème de rendez vous des faisceaux



# Nouveaux concepts radar (6)

## RADAR PASSIF...



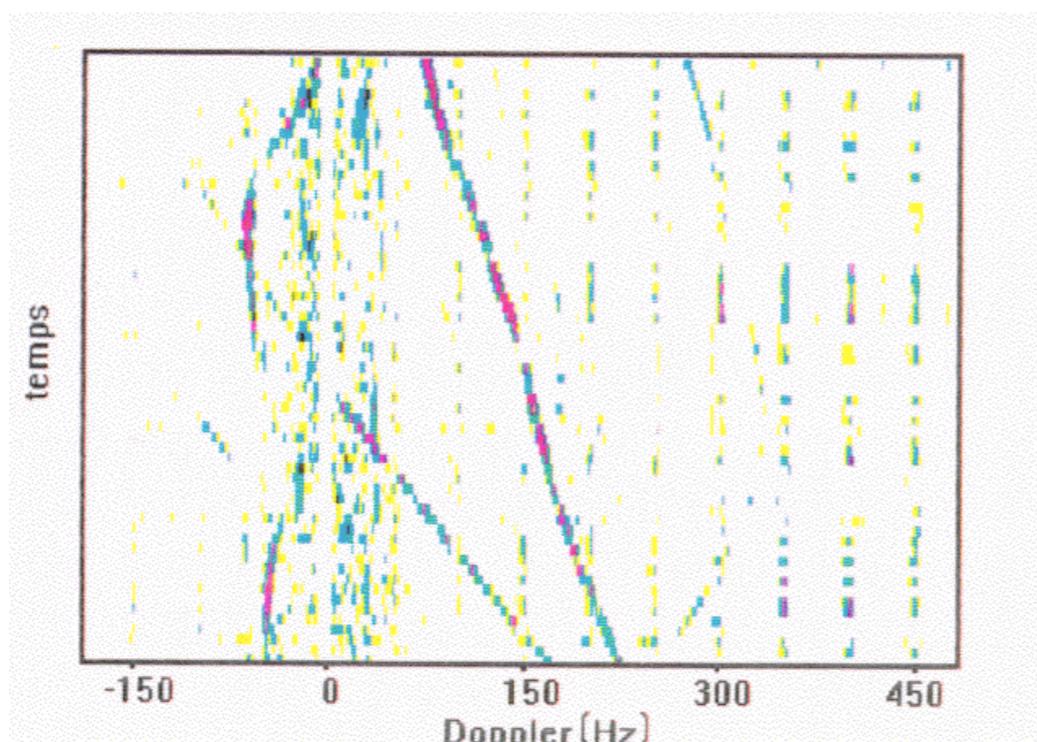
# *Nouveaux concepts radar (7)*

## EXEMPLE DE RADAR BISTATIQUE PASSIF

### Utilisation d'émetteurs de télévision (ONERA)

traitement Doppler sur porteuse image

localisation multistatique (1 site de réception + N émetteurs)



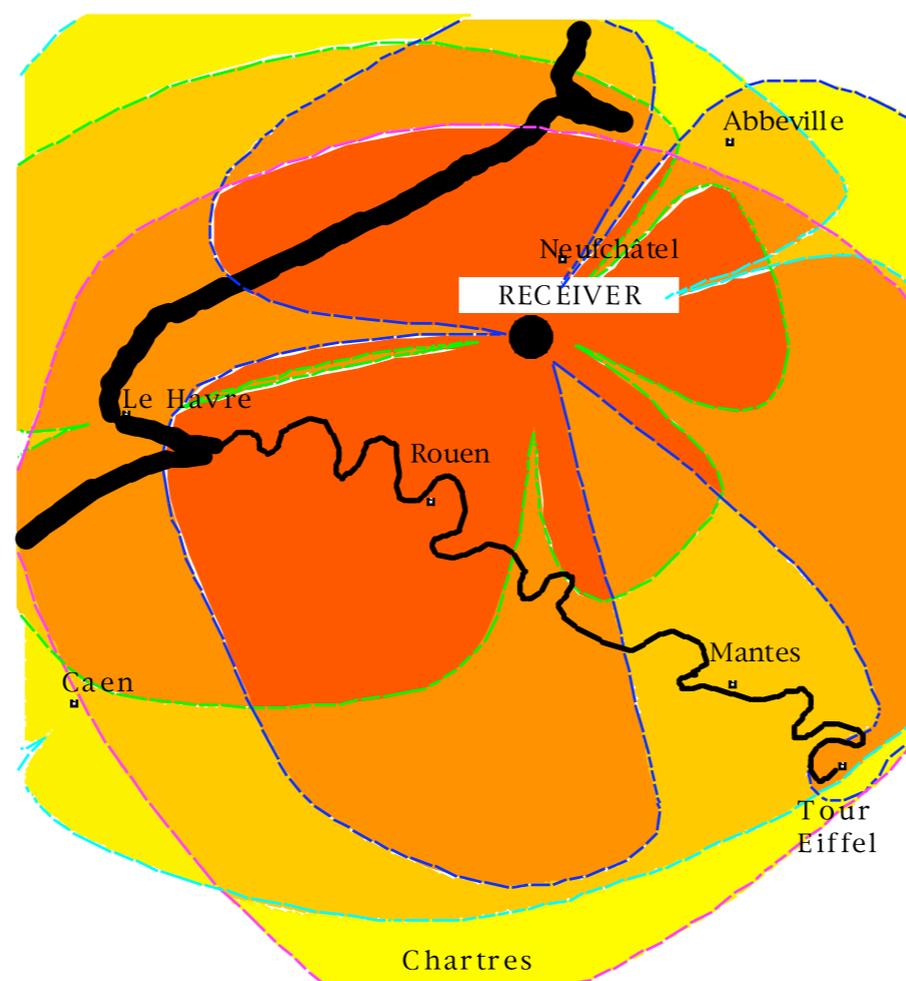
**Résultat de détection**



**Système expérimental  
(antenne multivoies, FFC)**

# *Nouveaux concepts radar (8)*

## **EXEMPLE DE COUVERTURE MULTISTATIQUE (ONERA)** (radar passif utilisant des émissions de télévision)



**Modélisation de la  
couverture**

**(Seine Maritime)**

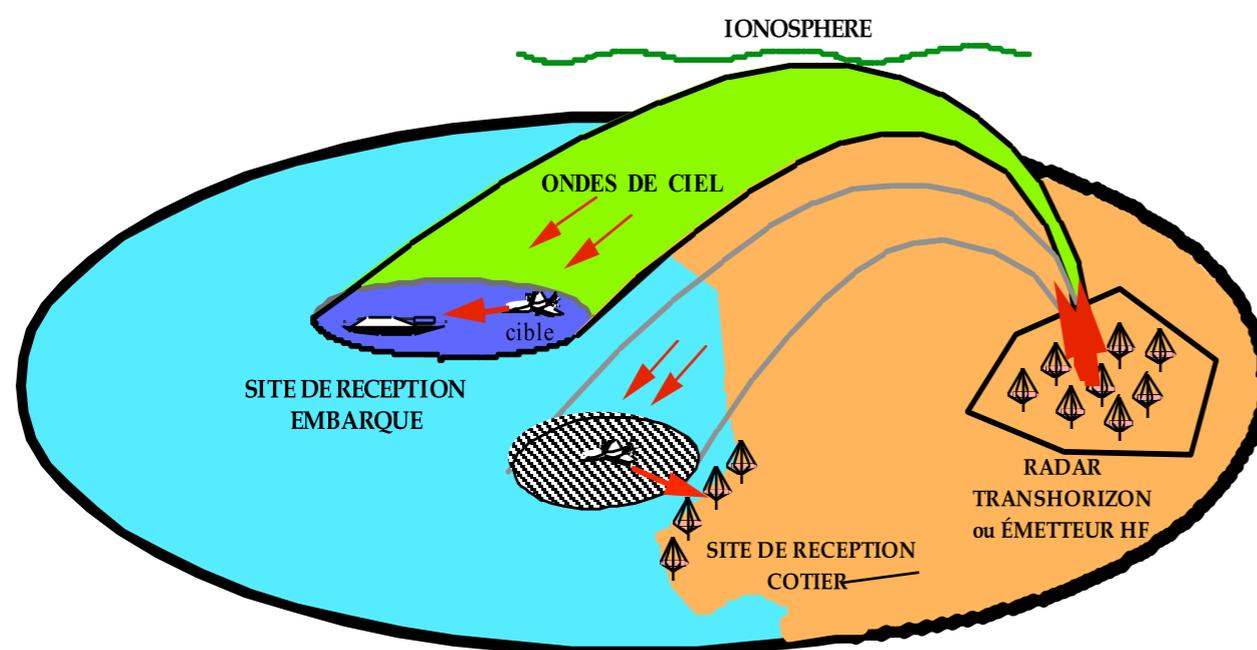
**4 émetteurs disponibles**

**bande UHF (450-800 MHz)**

# Nouveaux concepts radar (9)

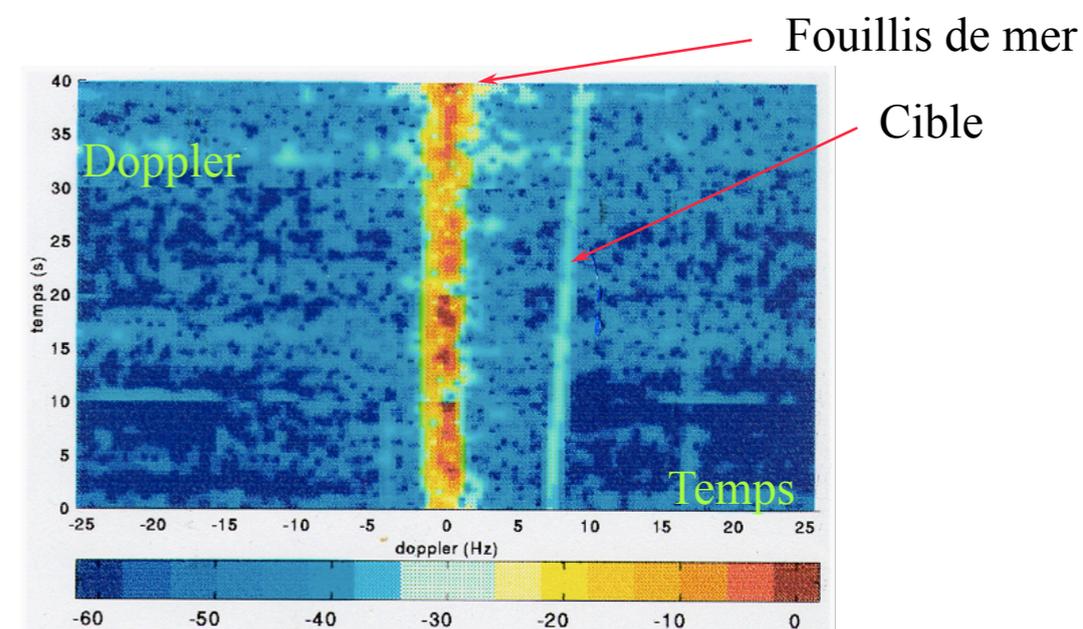
## EXEMPLE DE RADAR BISTATIQUE PASSIF

### Radar passif utilisant des émissions de radio HF



Concept

MHz)



Résultats expérimentaux

Emetteur de Kiev, (~15

( avion 100ft / 75 km )

Application : surveillance discrète basse altitude

# RADAR EXAMPLES



**2D surveillance radar**  
**L-band**  
(SIGNAAL)



**2&3 D air surveillance radar, S-band**  
(THALES)



**2D surveillance radar**  
**C-band**  
(THALES)

## **battlefield surveillance**



**PATRIOT**  
**X-band (Raytheon)**

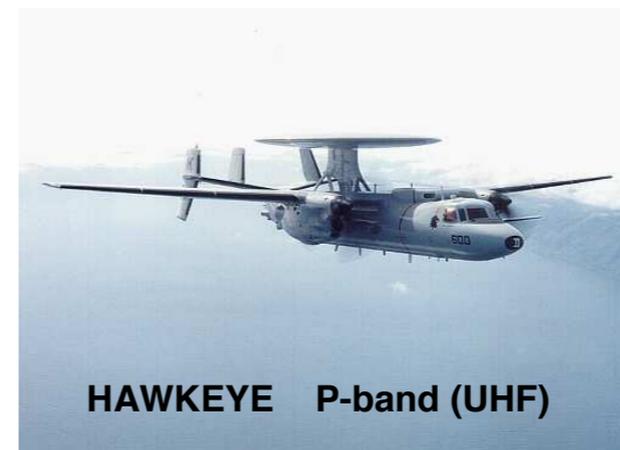


**CROTALE Ku-band**  
(Thales)

## **airborne surveillance radar**

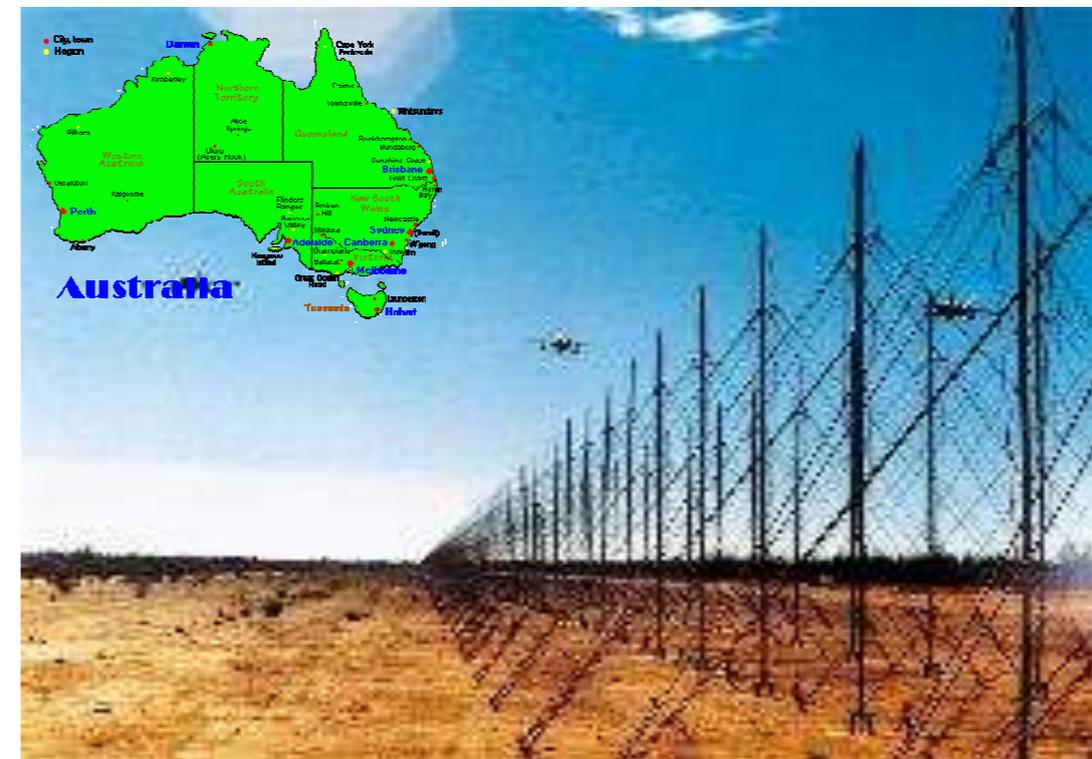
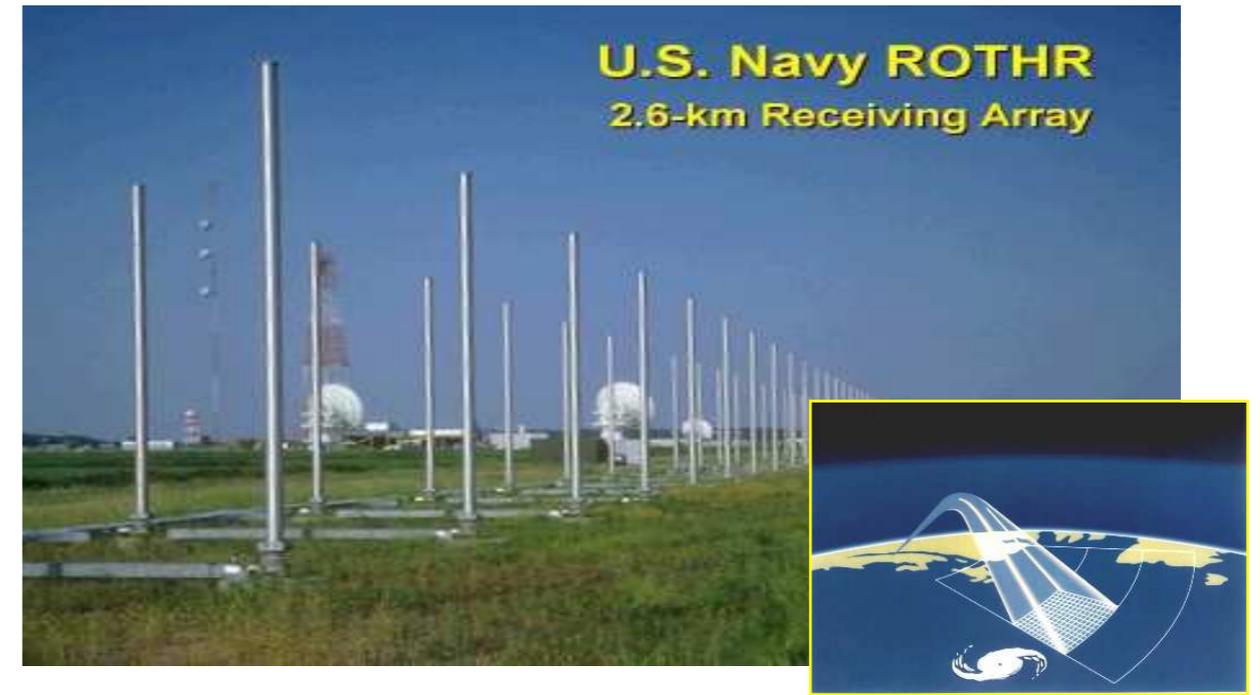
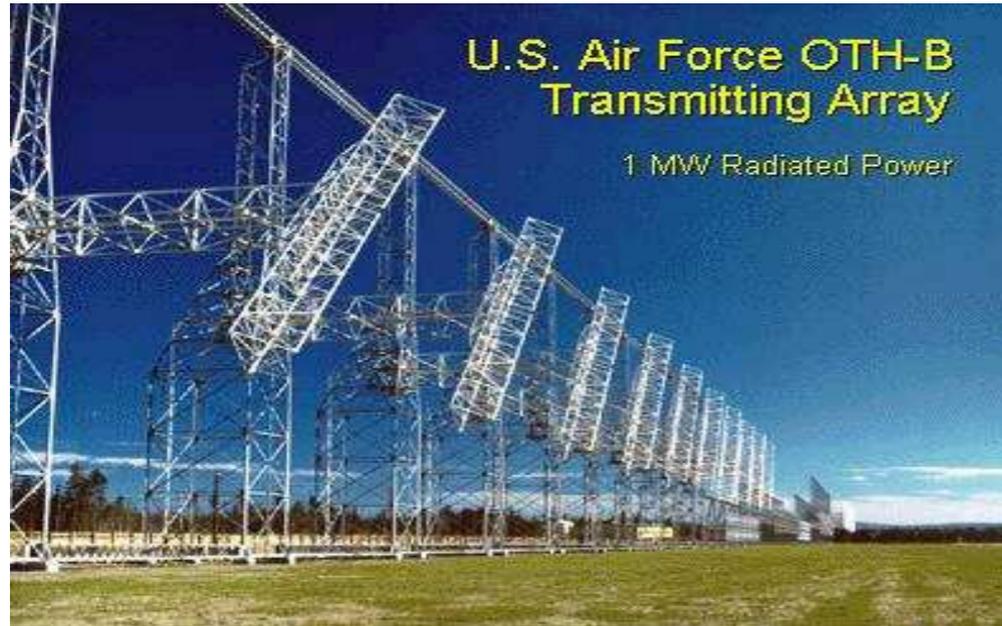


**AWACS S-band**



**HAWKEYE P-band (UHF)**

# LONG-RANGE RADAR



# FRENCH HFSW SYSTEM

## ROS - The French HFSWR

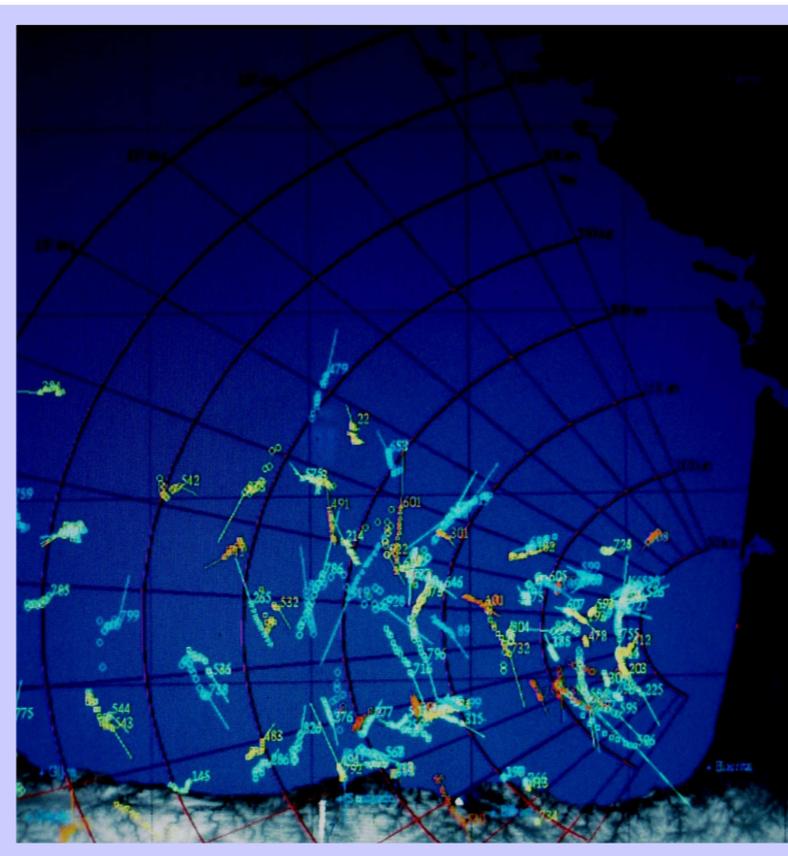
Maritime surveillance of atlantic ocean and mediterranean sea



Transmitting antenna



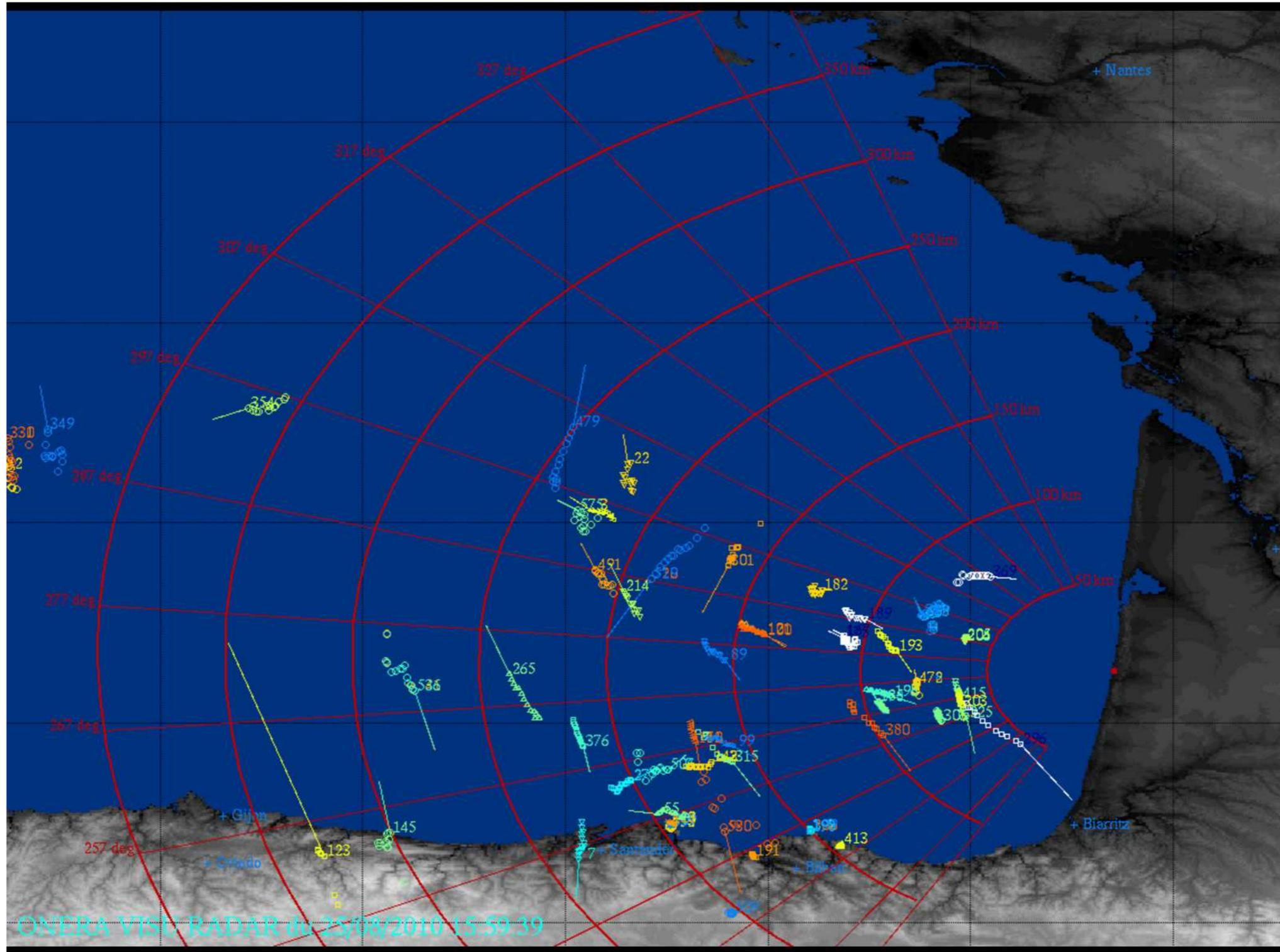
Receiving array



Ros.wmv



# FRENCH HFSW SYSTEM



# RADAR CLUTTER

## 🌐 La définition du fouillis (clutter) change selon l'applicatif :

- 🌐 dans le cadre d'une détection de cible par un radar, le fouillis représente "tout ce qui n'est pas la cible"
- 🌐 dans le cadre d'une cartographie de terrain, le fouillis est le signal d'intérêt

**Le fouillis est donc défini comme la réponse d'objets ou de groupes d'objets indésirables pour un applicatif donné.**

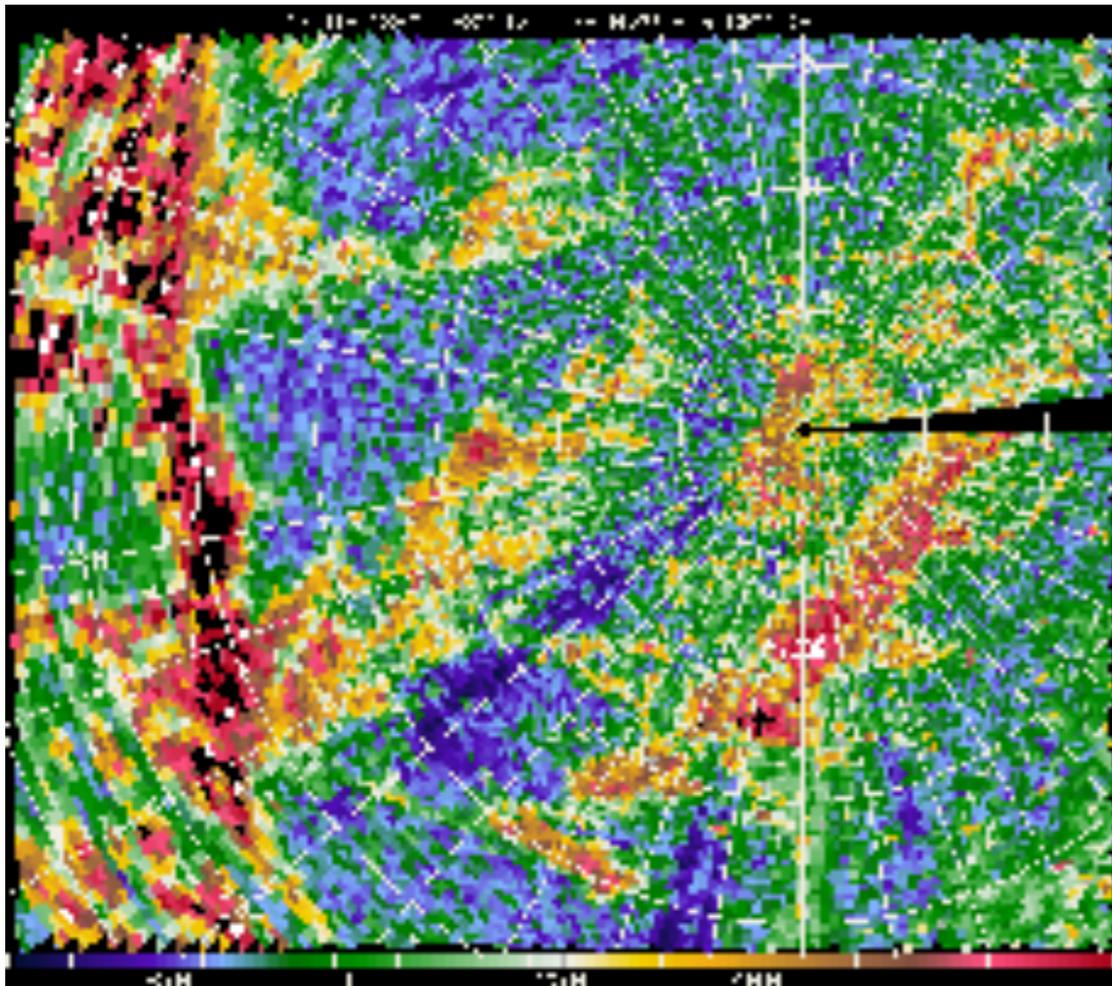
## **Le fouillis peut être caractérisé :**

- 🌐 par des sources distribuées sur une surface (terre ou mer),
- 🌐 dans un volume (pluie, neige, leurres),
- 🌐 par des ponctuels (structures, oiseaux, véhicules, pylônes, ...)

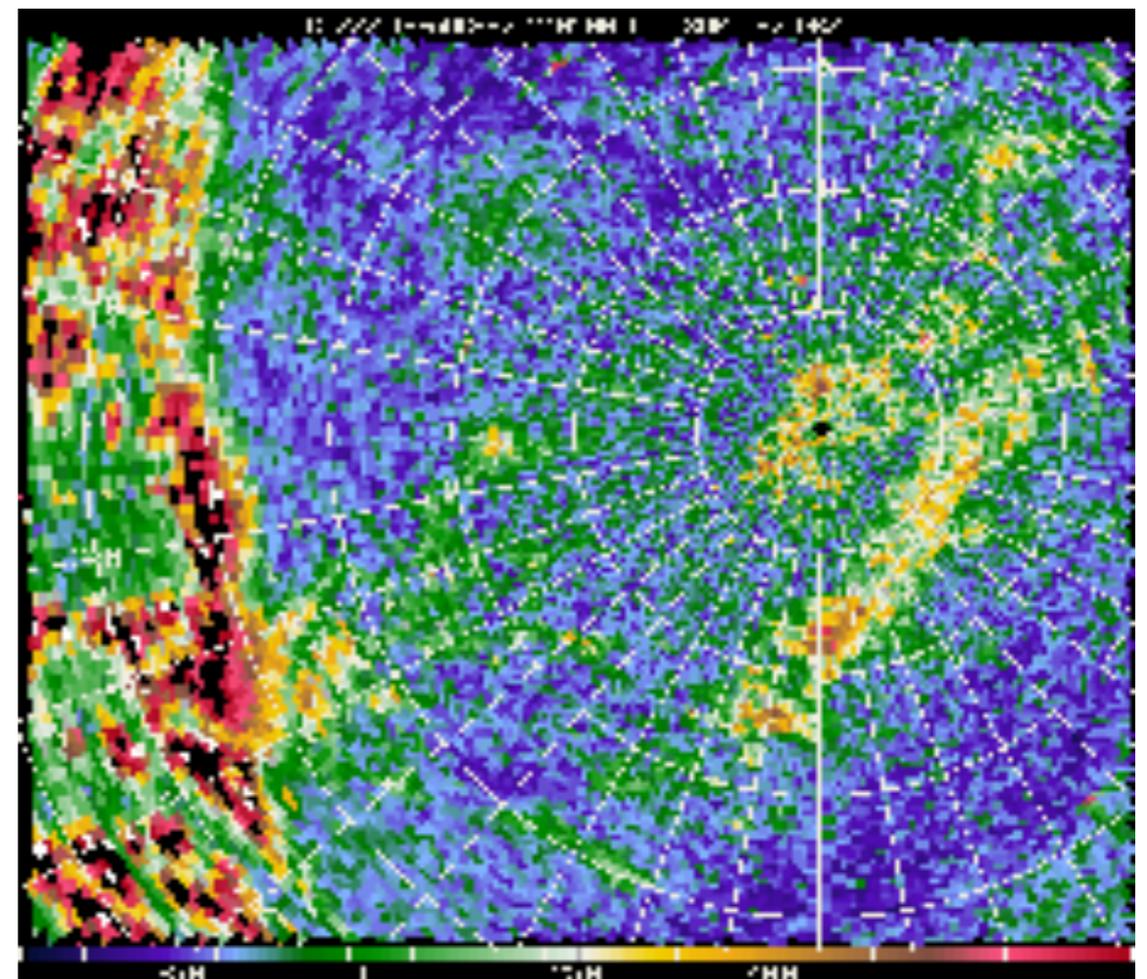
# EXAMPLES OF RADAR CLUTTER

Example of clutter map for different azimuth resolutions

resolution 3°

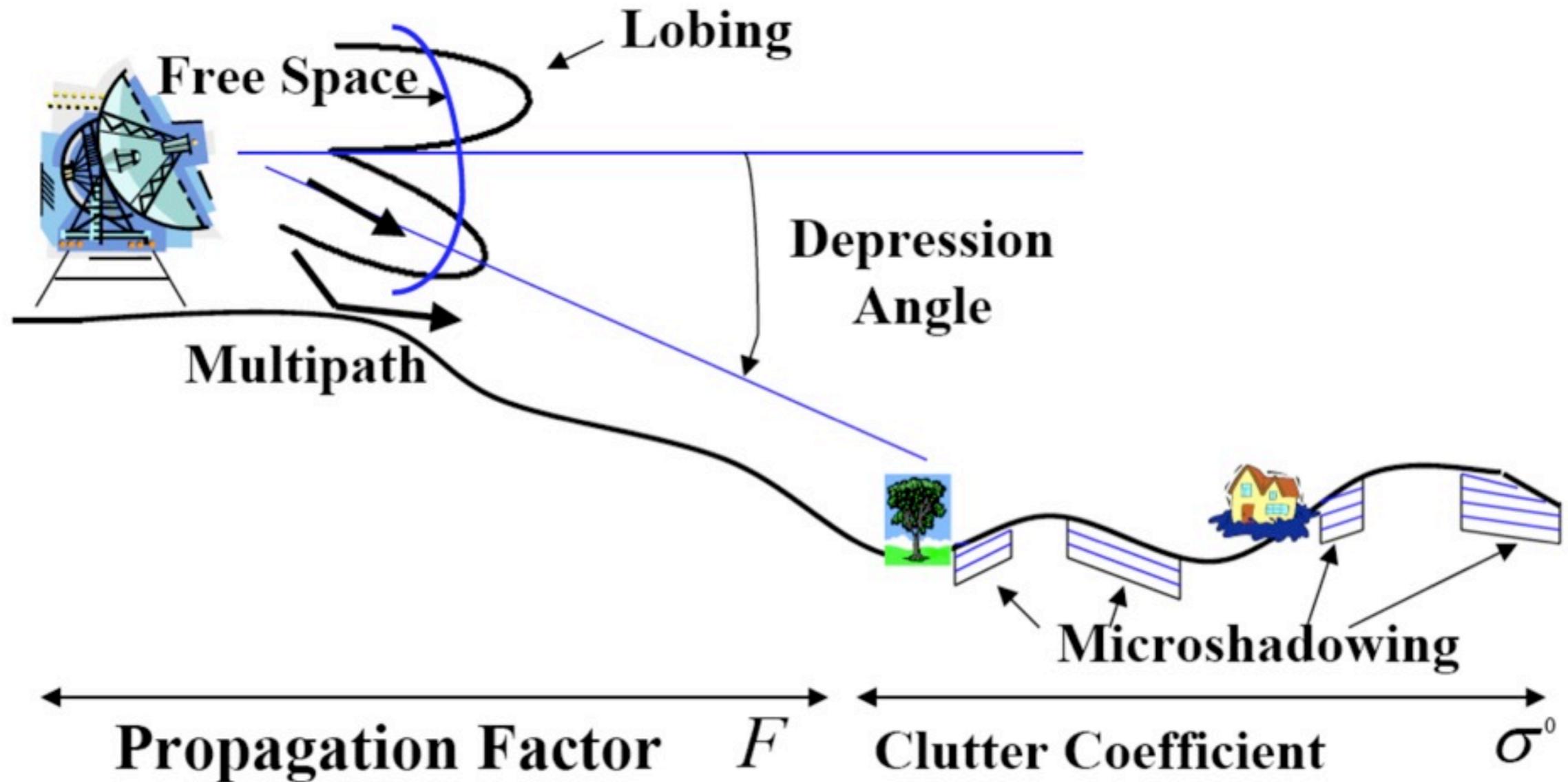


resolution 1°



*Antenna pattern has a strong impact on clutter return*

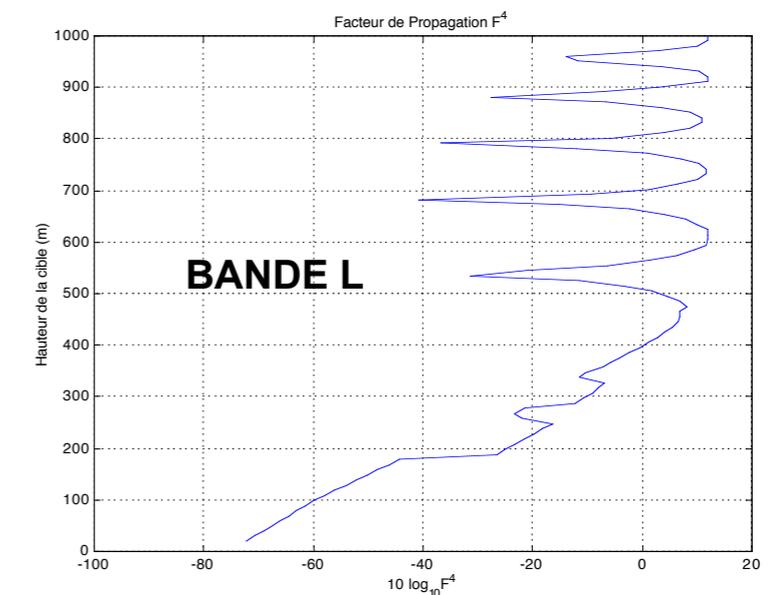
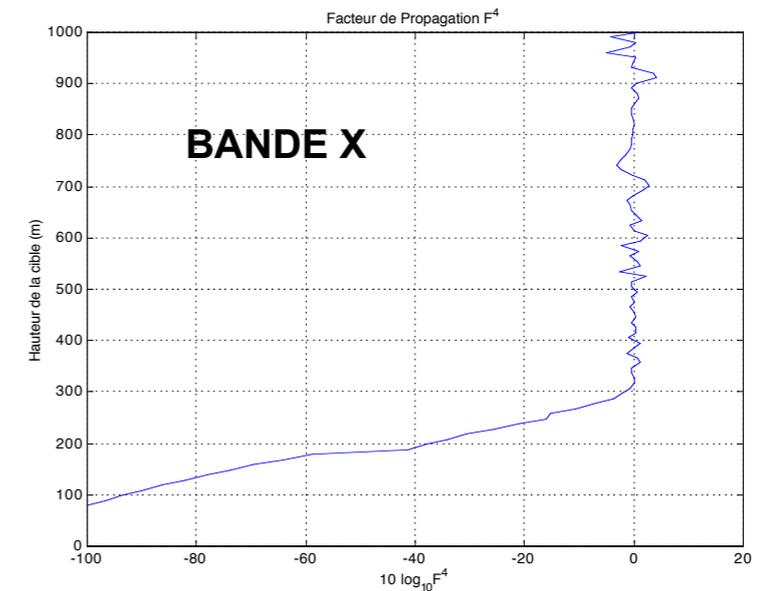
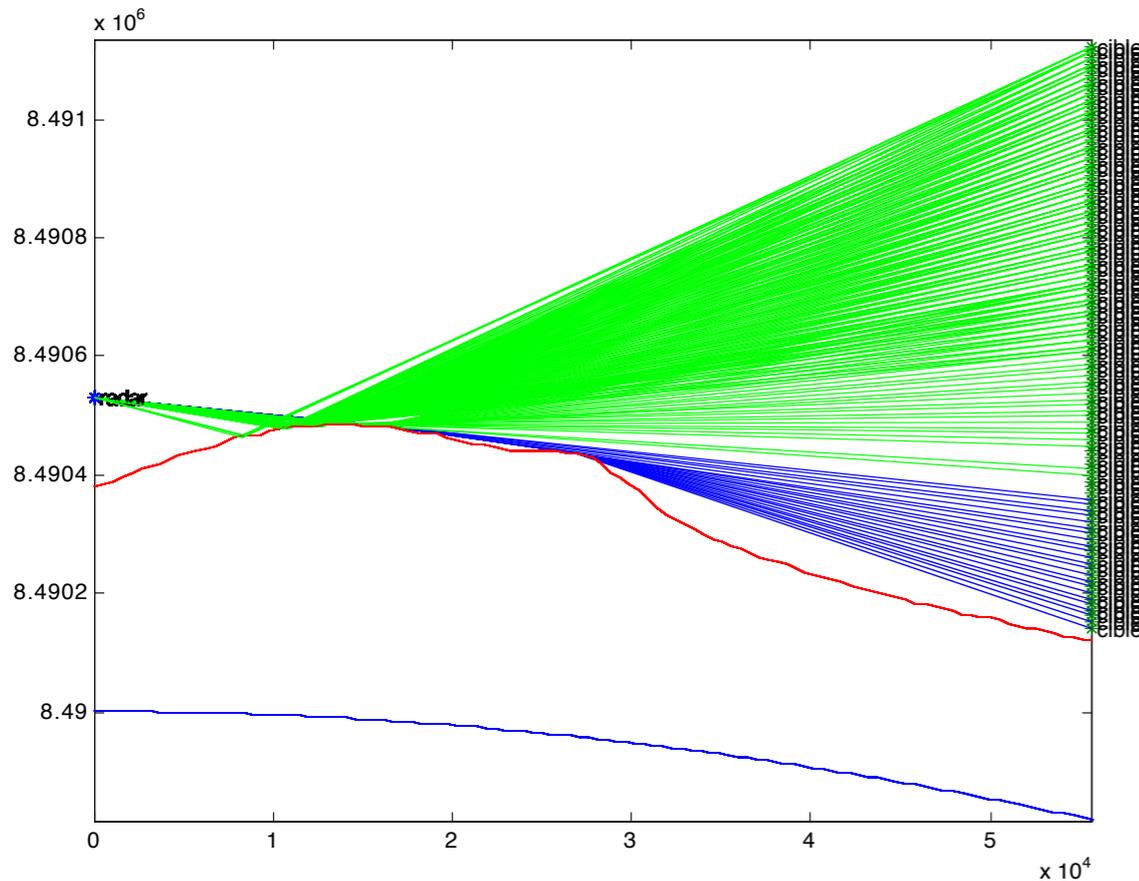
# CLUTTER AND PROPAGATION



$$\text{Clutter Strength} = \sigma^0 F^4$$

Difficulté de dissocier fouillis et propagation

# PATTERN PROPAGATION FACTOR



**Le Facteur de Propagation F tient compte de**

- de la réfraction (courbure des ondes électromagnétiques due au gradient d'indice de l'atmosphère)**
- de la réflexion spéculaire et diffuse (multitrajets) dans le plan vertical radar-cible,**
- de la diffraction d'arêtes multiples dans le plan vertical radar-cible,**
- de la diffraction sphérique due à l'horizon radioélectrique.**

# PATTERN PROPAGATION FACTOR

- **Cas classique sur Terre Sphérique et Lisse**

- le facteur de propagation est défini comme :

$$F = \left| 1 + \rho \sqrt{\frac{G_a (\theta_r + \theta_d)}{G_0}} e^{2i\pi(R_1 + R_2 - R_d)/\lambda} \right|$$

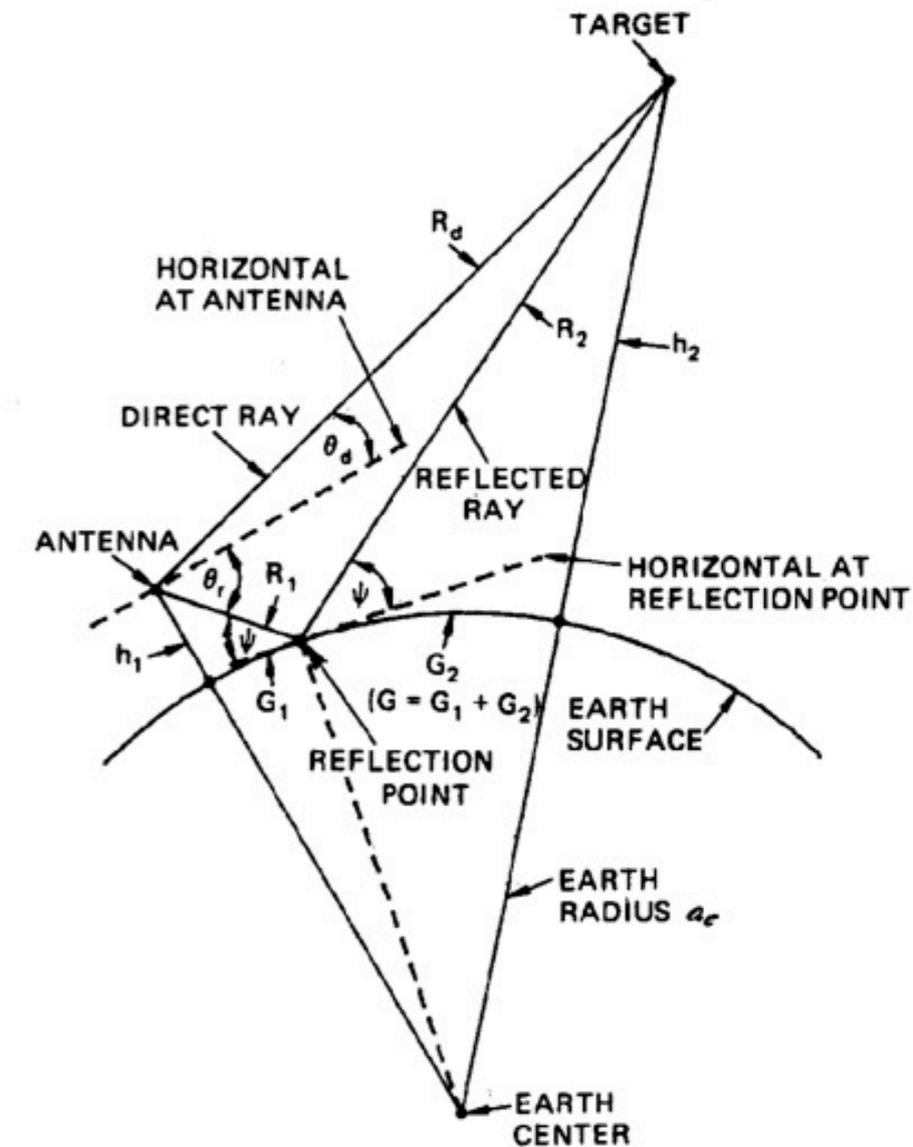
- avec  $\rho$  décomposable en produit de facteurs :

- réflexion spéculaire :  $\rho_S = \frac{\sin \psi - \sqrt{C_{H/V}}}{\sin \psi + \sqrt{C_{H/V}}}$

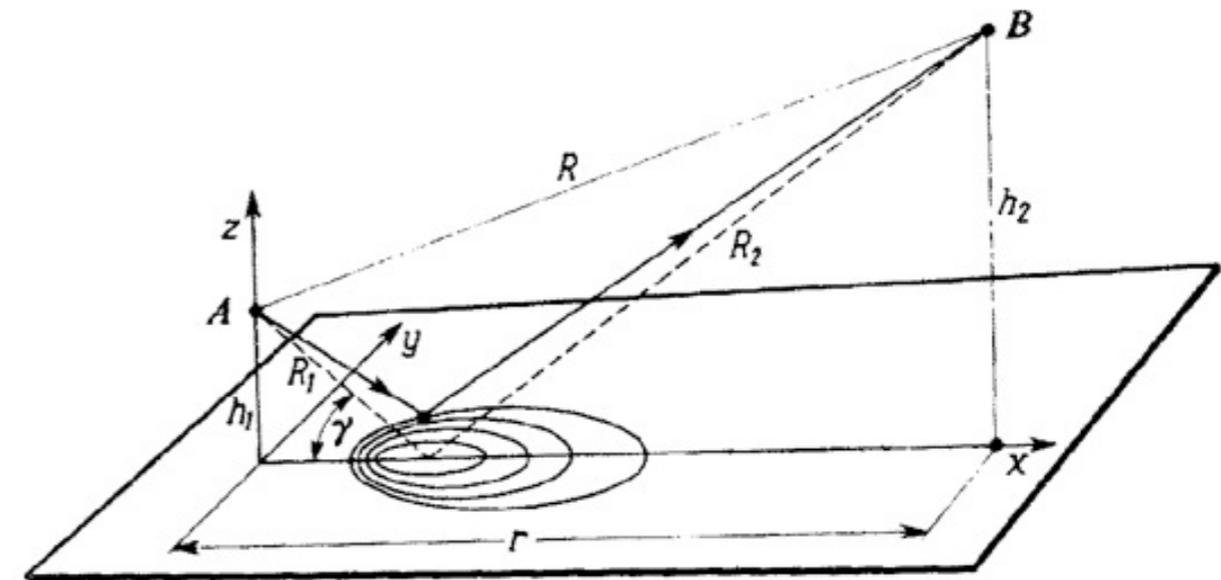
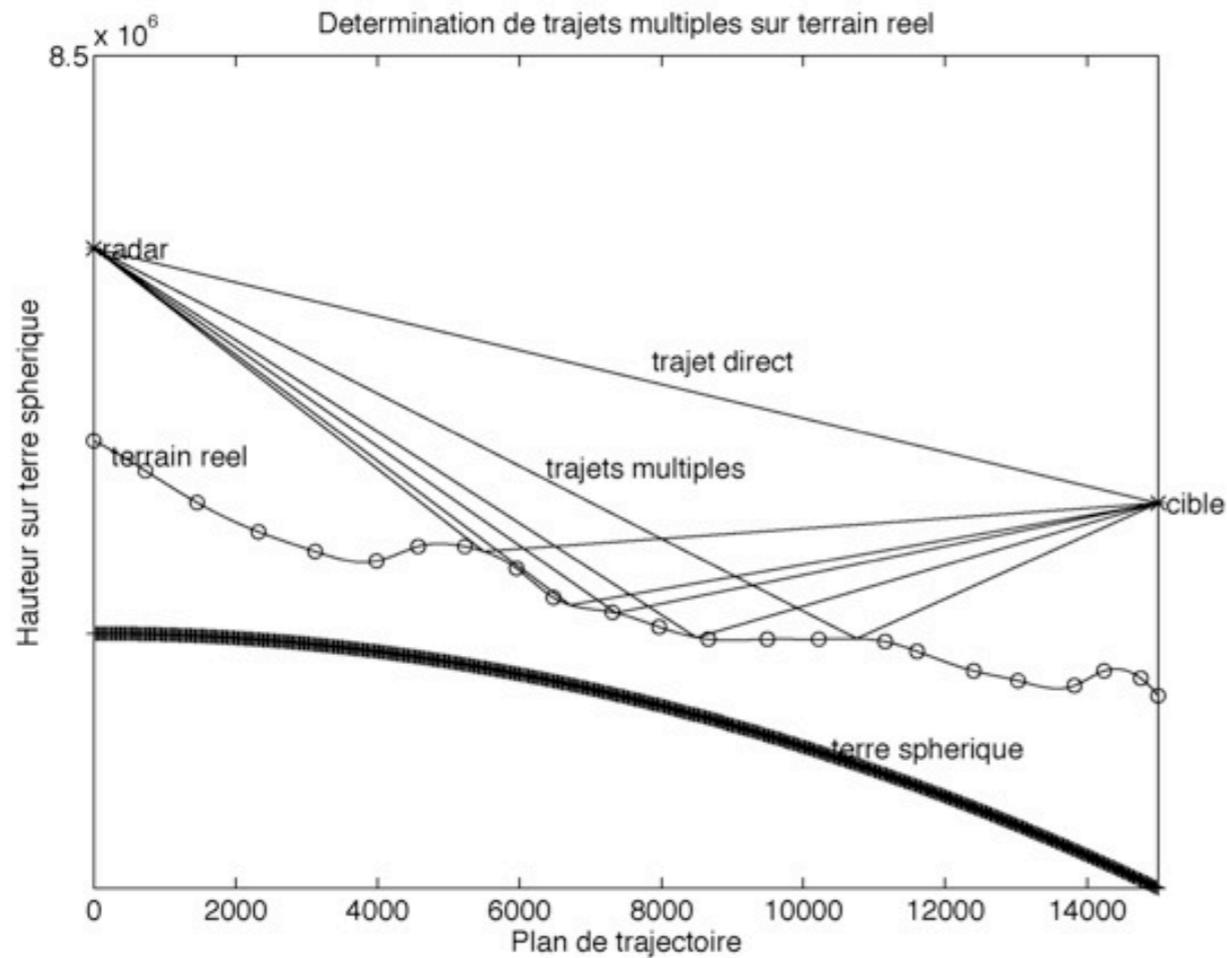
- rugosité  $r = \exp \left( -2 \left( \frac{2\pi \Delta_h \sin \psi}{\lambda} \right)^2 \right)$

- divergence  $\rho_{div} = \left( 1 + \frac{2G_1 (G - G_1)}{R G \sin \psi} \right)^{-1}$

- absorption due à la végétation :  $\rho_0$



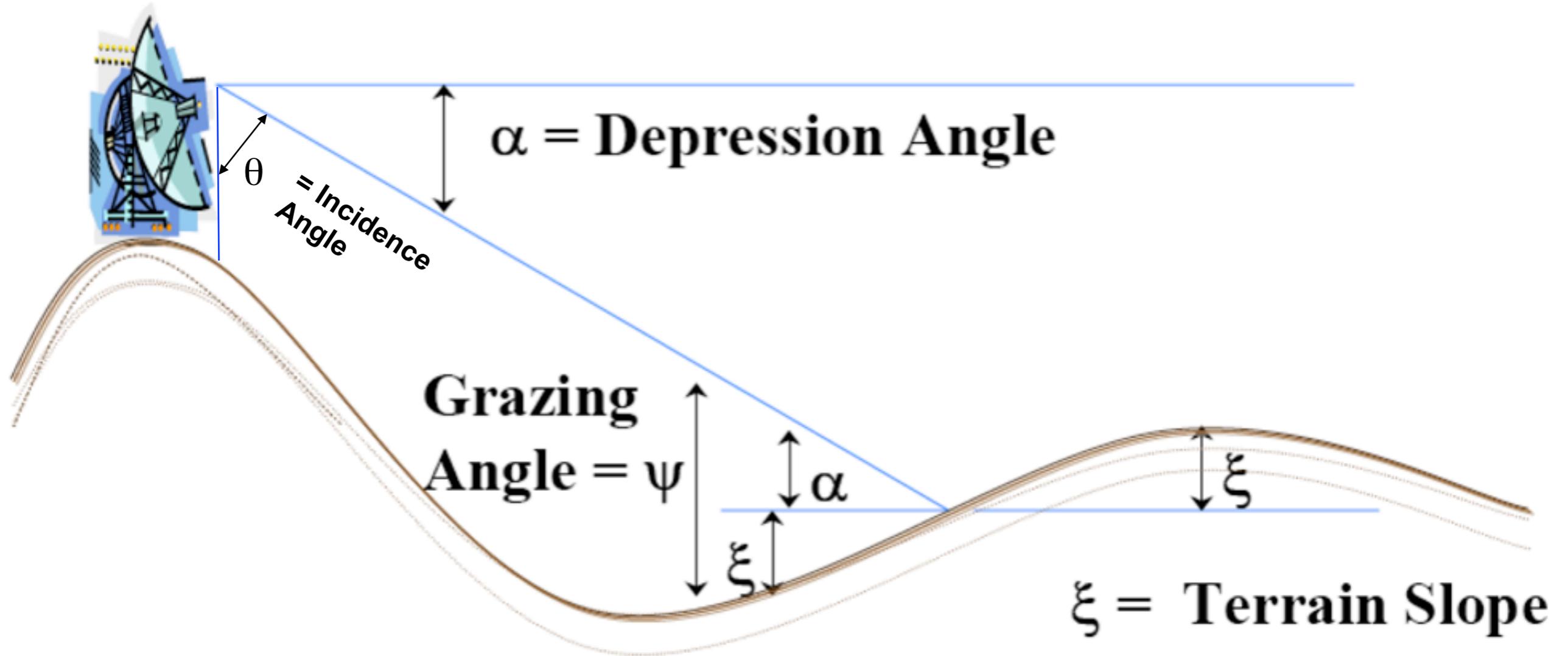
# PATTERN PROPAGATION FACTOR



**Sommation en phase de tous les points contenus dans la première zone de Fresnel**

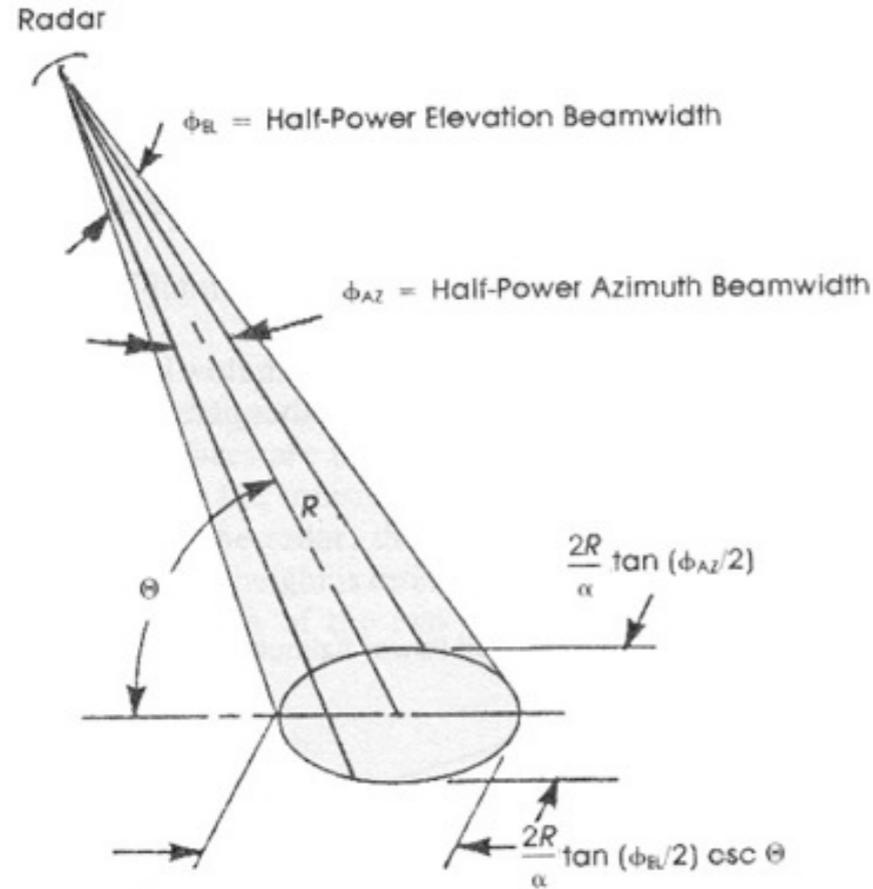
$$F = \left| 1 + \sum_{n=1}^N \rho_n \sqrt{\frac{G_a(\alpha_i)}{G_0}} \exp(2i\pi \Delta_n / \lambda) \right|$$

# GEOMETRY OF PROPAGATION



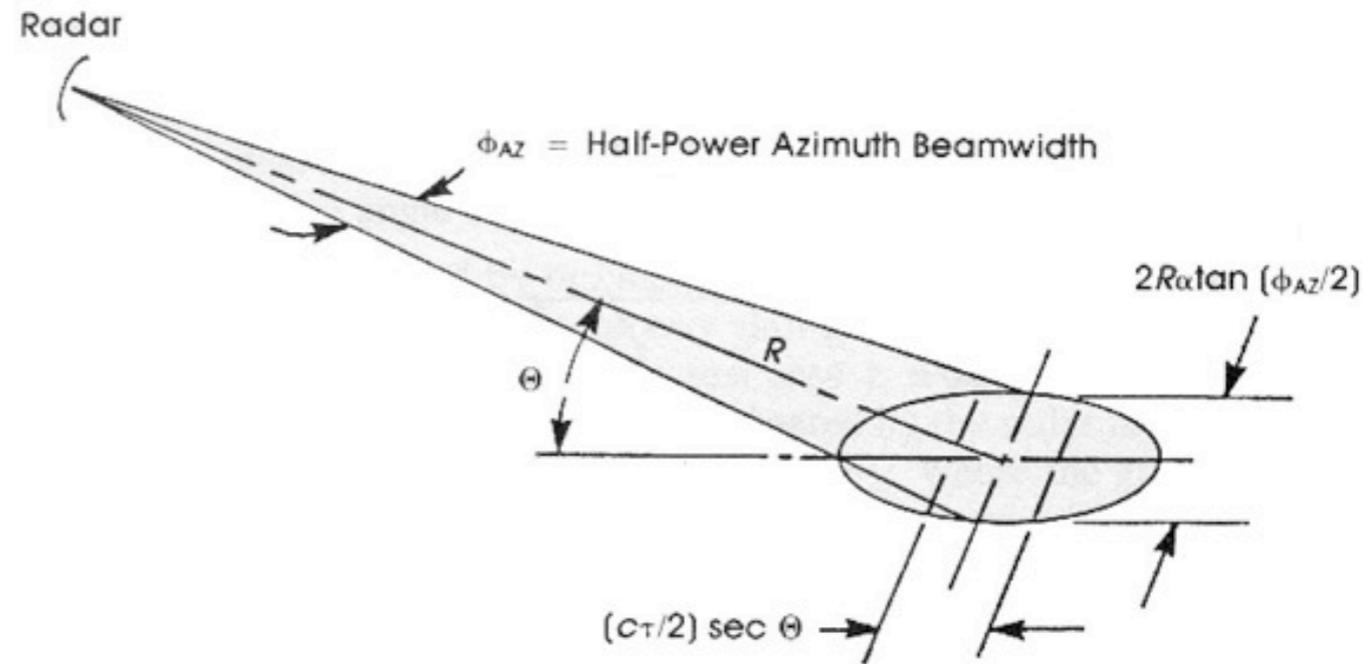
$$\text{Grazing Angle } \psi = \text{Depression Angle } \alpha + \text{Terrain Slope } \xi$$

# SURFACE OF CLUTTER REFLECTION



$$\tan \theta > \frac{2\pi R \tan(\phi_{EL}/2)}{\alpha(c\tau/2)}$$

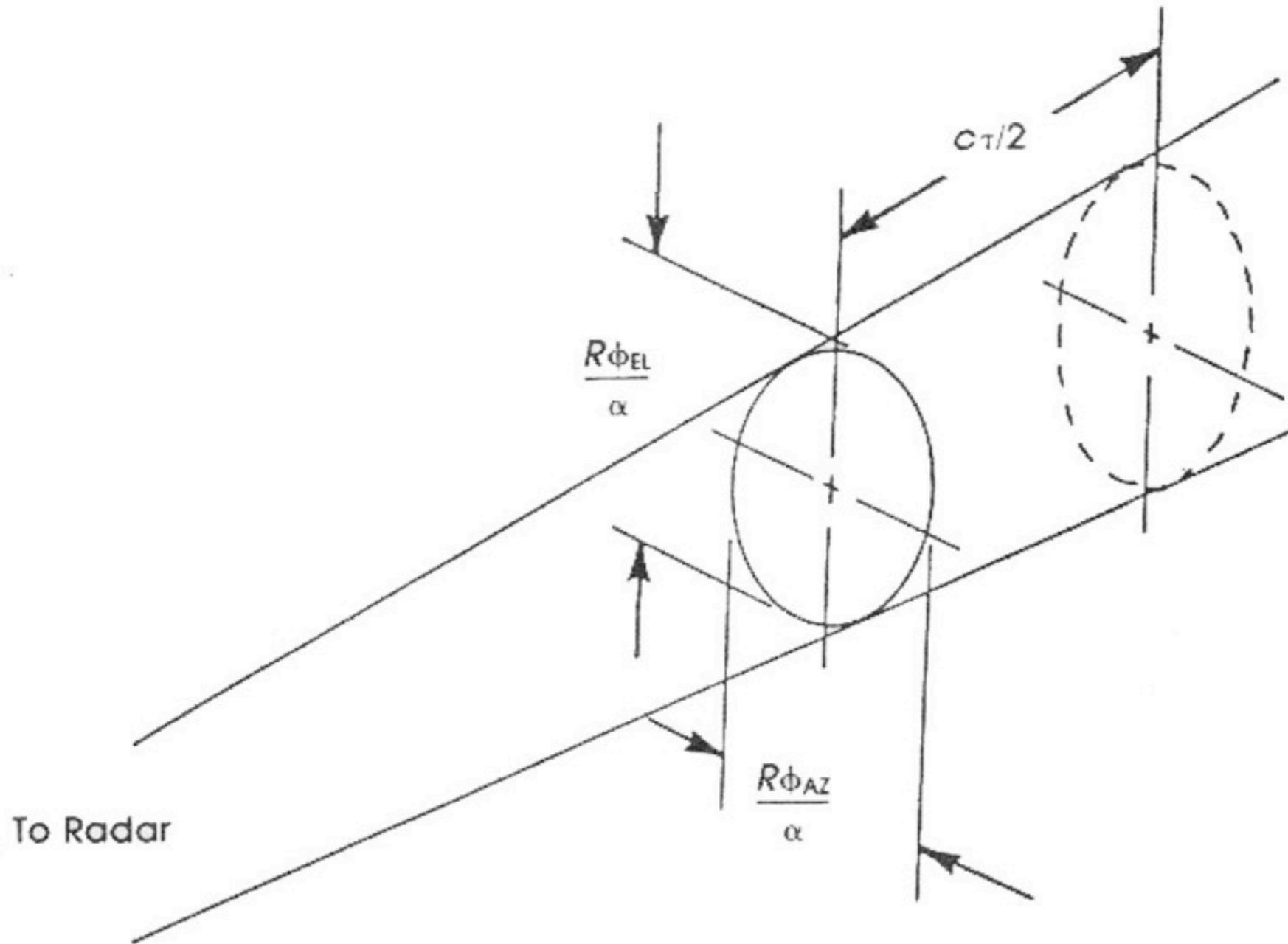
$$S = \frac{\pi R^2}{\alpha^2 \sin \theta} \tan\left(\frac{\phi_{az}}{2}\right) \tan\left(\frac{\phi_{el}}{2}\right)$$



$$\tan \theta < \frac{2\pi R \tan(\phi_{EL}/2)}{\alpha(c\tau/2)}$$

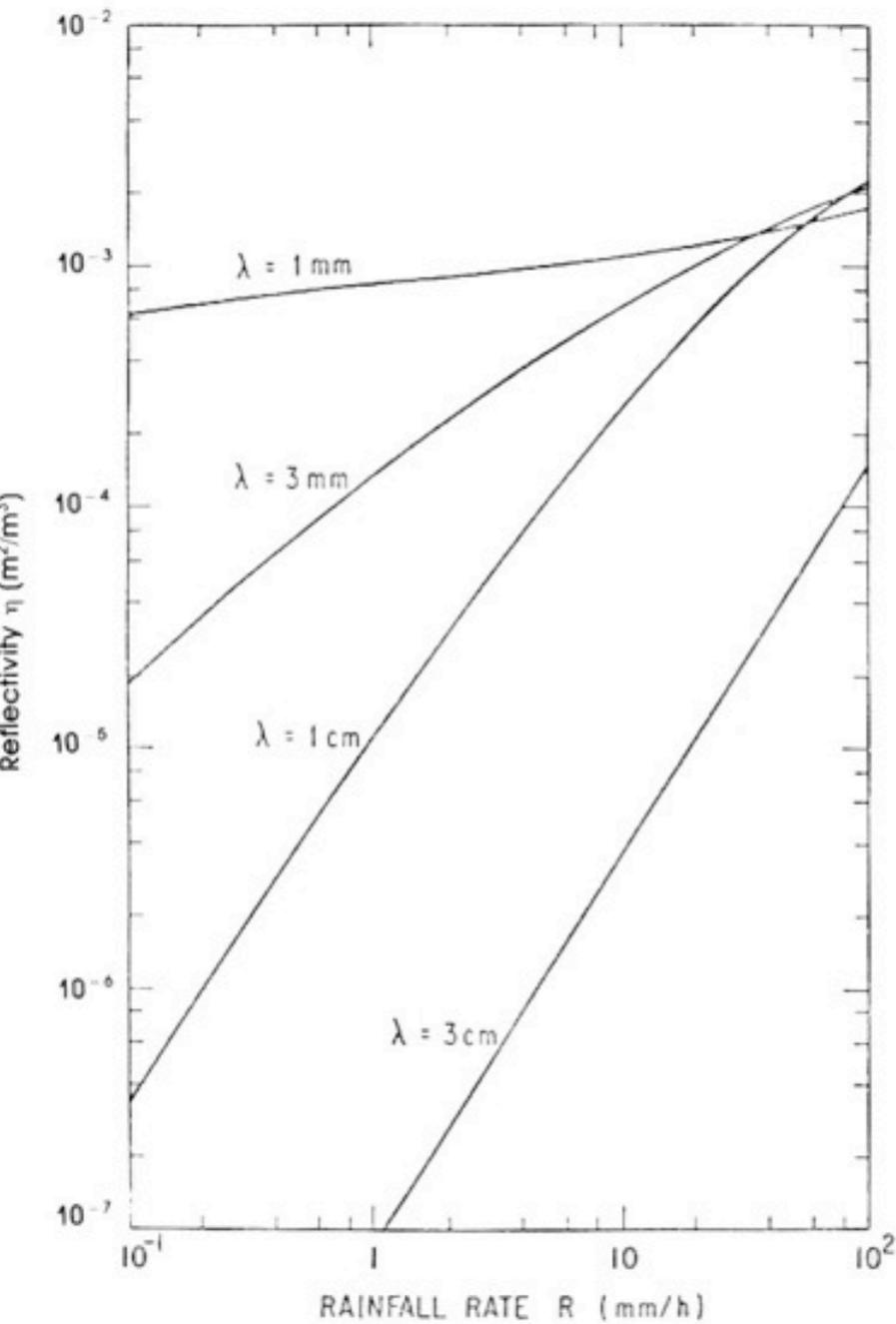
$$S = \frac{R c \tau}{\alpha \cos \theta} \tan\left(\frac{\phi_{az}}{2}\right)$$

# VOLUME OF CLUTTER REFLECTION



$$V = \frac{\pi R^2 \phi_{az} \phi_{el} c \tau}{8\alpha^2}$$

# ATMOSPHERIC CLUTTER



Modèle analytique du coefficient de rétrodiffusion du fouillis de pluie par unité de volume en fonction du taux de précipitation  $r$  en mm/h

$$\eta = A r^B \quad (\text{m}^2/\text{m}^3)$$

Fréquence (GHz)	A	B
9.4	$1.3 \cdot 10^{-8}$	1.6
35	$1.2 \cdot 10^{-6}$	1.6
70	$4.2 \cdot 10^{-5}$	1.1
95	$1.5 \cdot 10^{-5}$	1.0

# SPECTRAL PROPERTIES OF CLUTTER

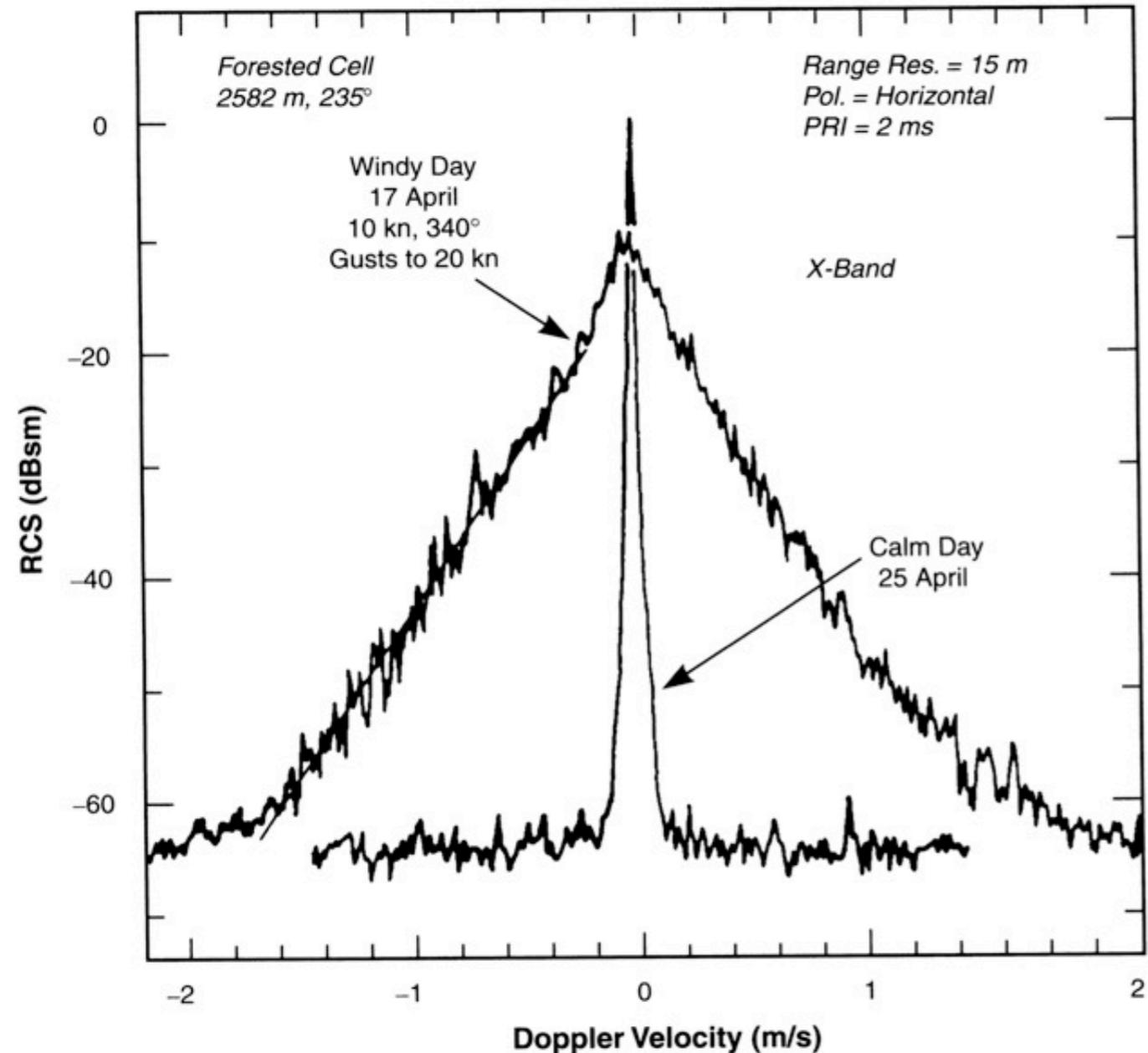


FIGURE 4.23 Power spectra of X-band radar returns from windblown trees.

## Modèles de Densité Spectrale de Puissance

$$\Phi(f) = \Phi_0 \exp\left(-\frac{(f - f_0)^2}{2\sigma_{fc}^2}\right)$$

$$\Phi(f) = \Phi_0 \frac{1}{1 + \left(\frac{f}{f_0}\right)^n}$$

pour  $\left\{ \begin{array}{l} -\frac{1}{2T_r} \leq f \leq \frac{1}{2T_r} \\ -\frac{\lambda}{4T_r} \leq v \leq \frac{\lambda}{4T_r} \end{array} \right.$

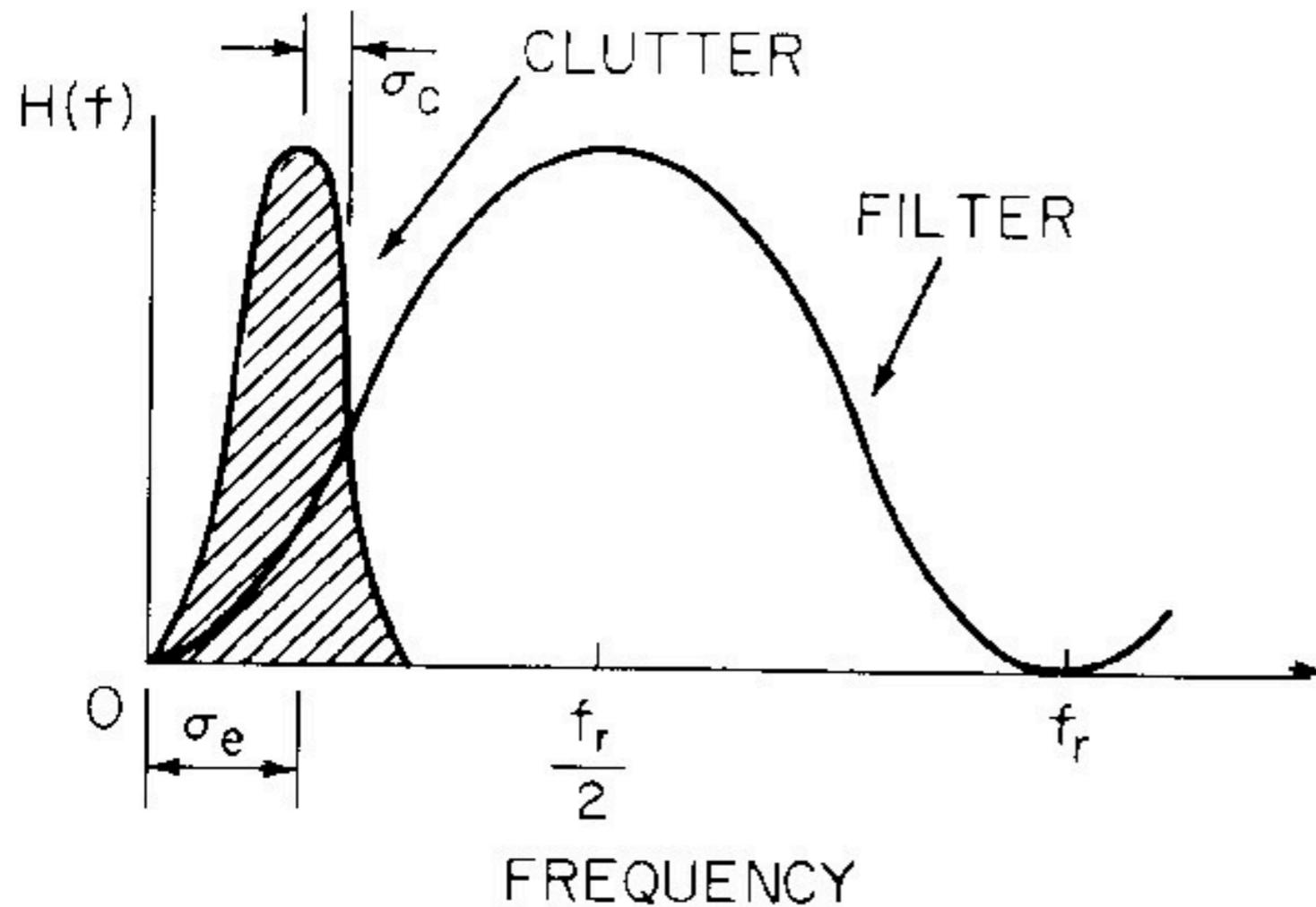
## Fonction d'Autocorrélation

$$\rho(\tau) = \int_{-\infty}^{+\infty} \Phi(f) e^{2i\pi f \tau}$$

## Matrice de Covariance

$$M = \begin{pmatrix} \rho_0 & \rho_1 & \dots & \rho_{N-1} \\ \vdots & \vdots & \vdots & \vdots \\ \rho_k & \rho_{k+1} & \dots & \rho_{N-k-1} \\ \vdots & \vdots & \vdots & \vdots \\ \rho_{N-1} & \rho_{N-2} & \dots & \rho_0 \end{pmatrix}$$

# MTI RADAR PROCESSING



## FILTRE MTI

$$|H(f)|^2 = (2 \sin(\pi f T_r))^{2m}$$

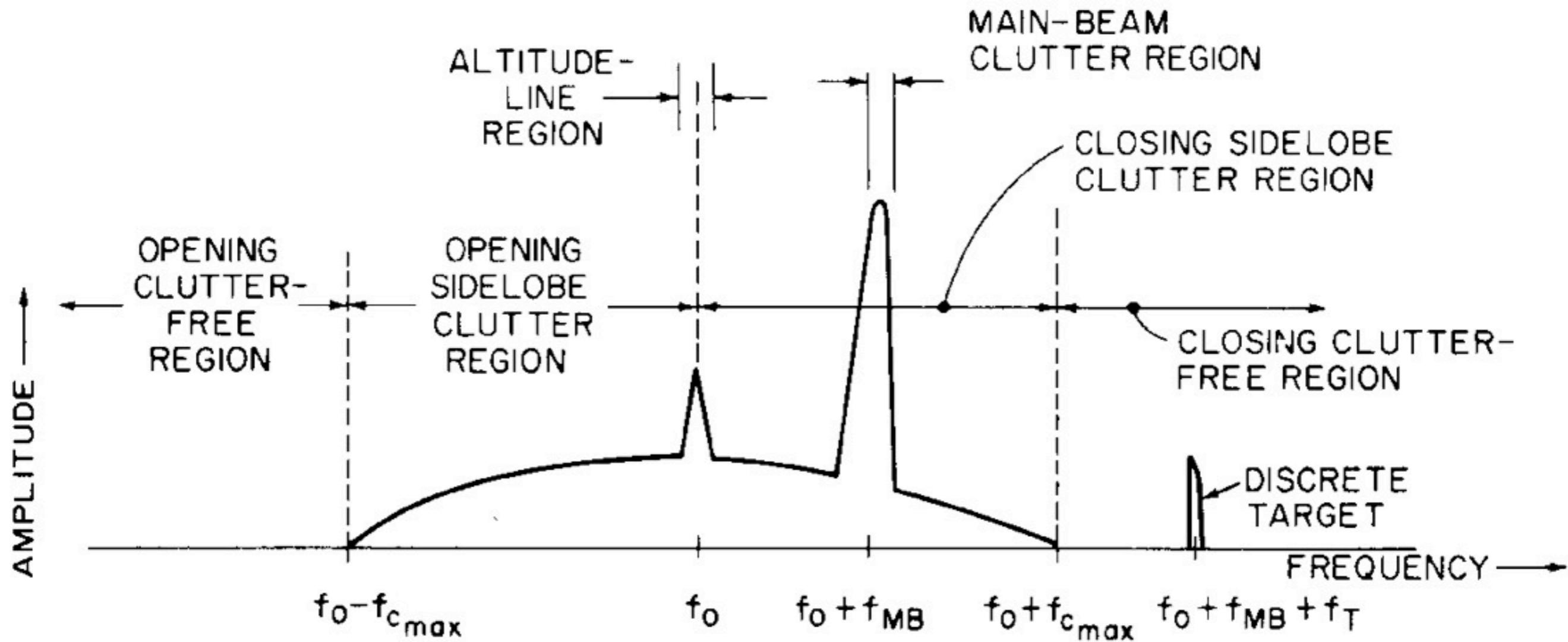
## FILTRE FFT

$$|H(f)|^2 = \left| \frac{\sin\left(\pi N \left(T_r f - \frac{N_0}{N}\right)\right)}{N \sin\left(\pi \left(T_r f - \frac{N_0}{N}\right)\right)} \right|^2$$

## TAUX D'ANNULATION DU FOUILLIS

$$I_m = \frac{\int_0^{\frac{1}{T_r}} \Phi(f) df}{\int_0^{\frac{1}{T_r}} \Phi(f) |H(f)|^2 df}$$

# AIRBORNE CLUTTER SPECTRAL PROPERTIES



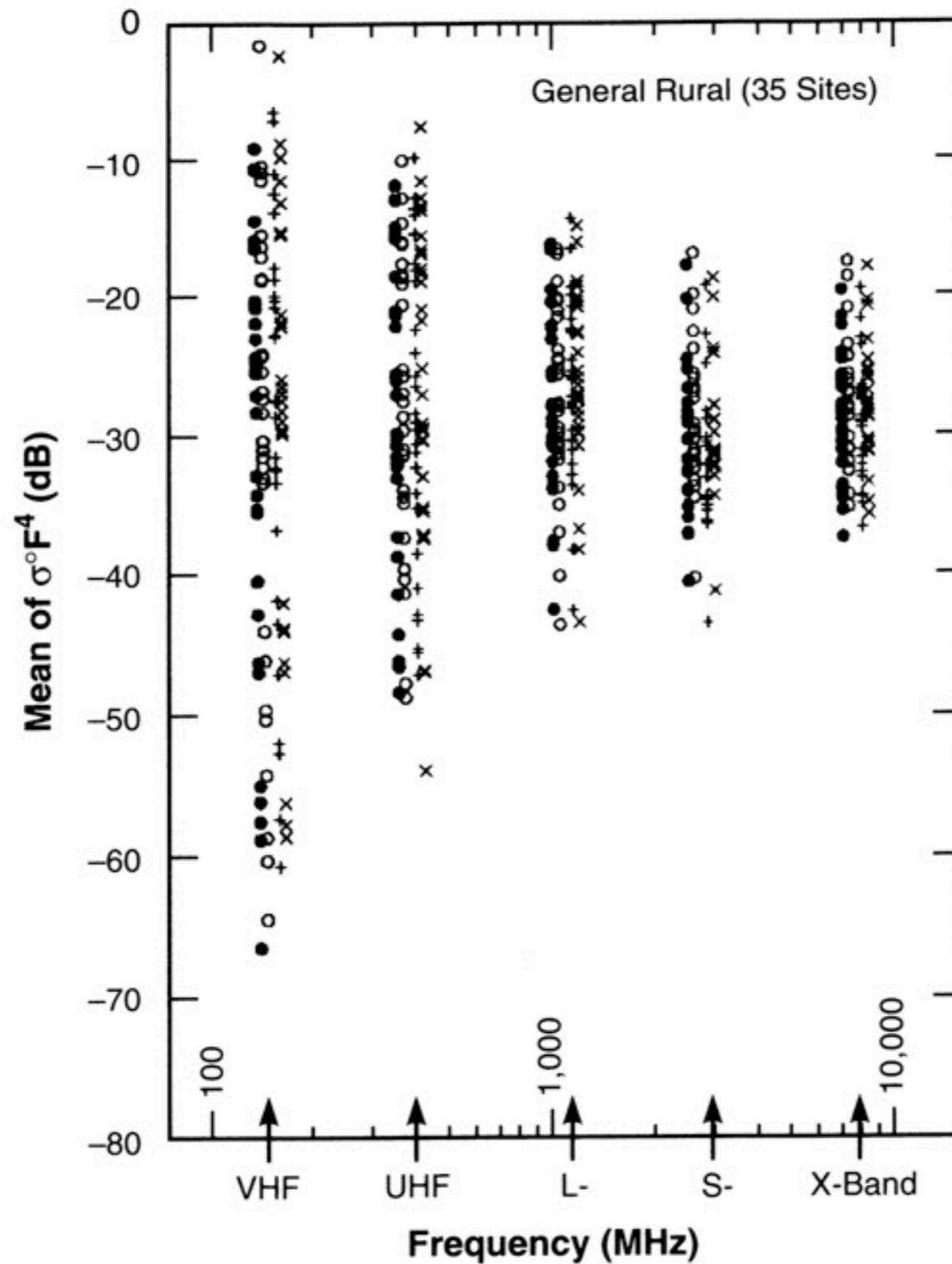
$$f_c = \frac{2V_R}{\lambda} \cos \psi$$

$$f_{MB} = \frac{2V_R}{\lambda} \cos \psi_0$$

$$f_{c_{max}} = \frac{2V_R}{\lambda}$$

$$f_T = \frac{2V_T}{\lambda} \cos \psi_T$$

# DISPERSION OF CLUTTER MEAN VALUE



Key	
Range	Pol.
150	H ●
150	V ○
15/36	H +
15/36	V x

# RADAR CROSS SECTION

The RCS notion quantifies the reflection of radar signals by the target

The target is similar to an antenna , with a more complex structure

Scattering, diffraction and absorption contribute to a complex mechanism

**Definition ( $\sigma$ )**

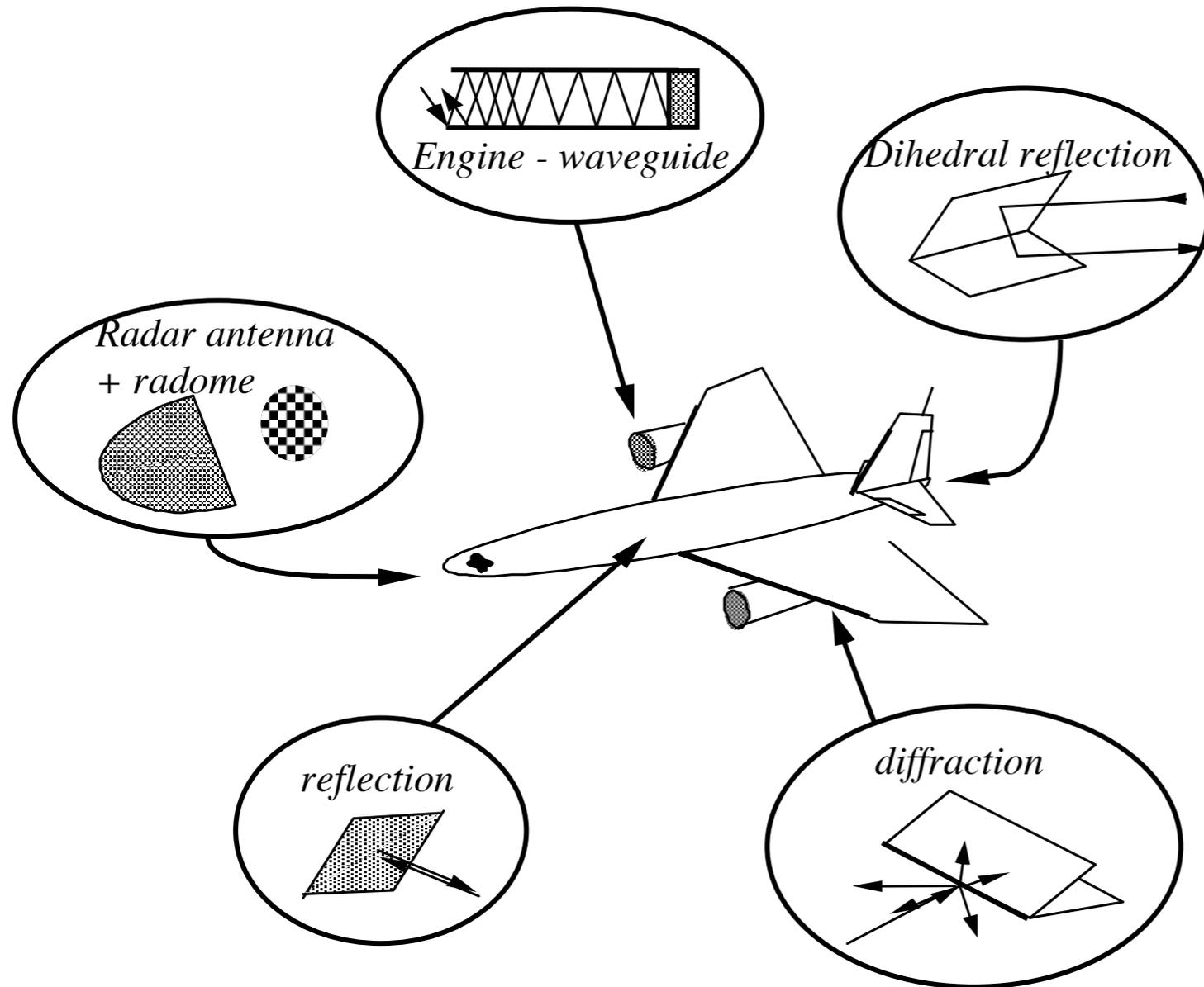
$$\sigma(\theta, \phi) = \frac{\text{scattered energy in the radar direction } \theta, \phi \text{ ( J )}}{\text{target incident energy density ( J / m}^2 \text{ )}}$$

## Important properties

- non physical area **RCS unit : m<sup>2</sup>**
- fluctuating (up to 10 or 20 dB of magnitude in X-band)
- RCS depends both on aspect angle ( $\theta, \phi$ ) and frequency
- RCS is complex to estimate : computation or measurements

Fighter	0.5 à 3 m <sup>2</sup>
Propeller	10 à 20 m <sup>2</sup>
B737, A320	30 à 50 m <sup>2</sup>
Ship	1000 à 100000 m <sup>2</sup>
Bird	0.01 m <sup>2</sup>

# INTERACTIONS CONTRIBUTING TO RCS



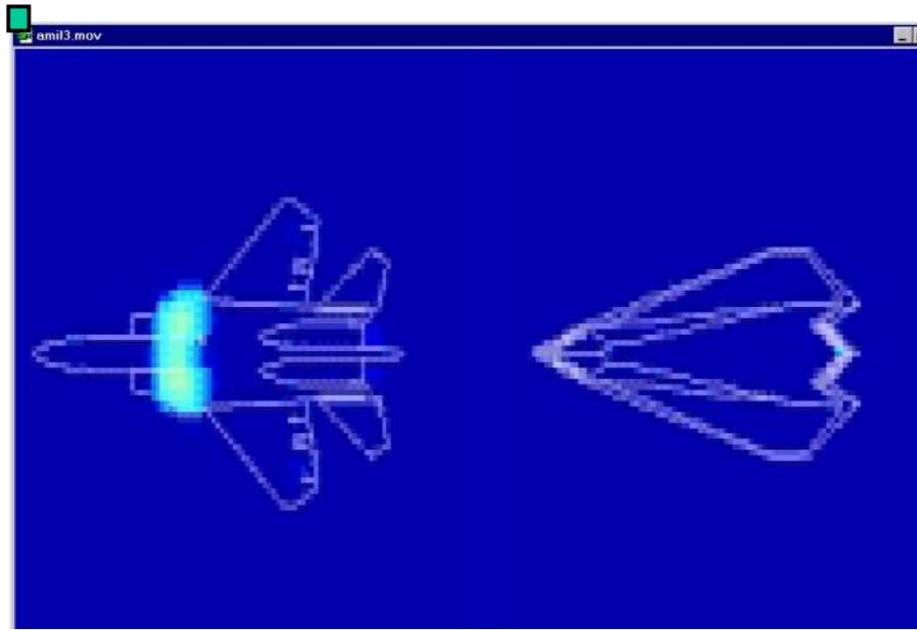
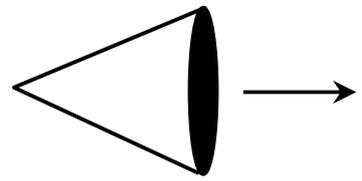
Specular reflections  
Diffraction  
Wave guide effects  
Dihedral, triedrals effects  
....



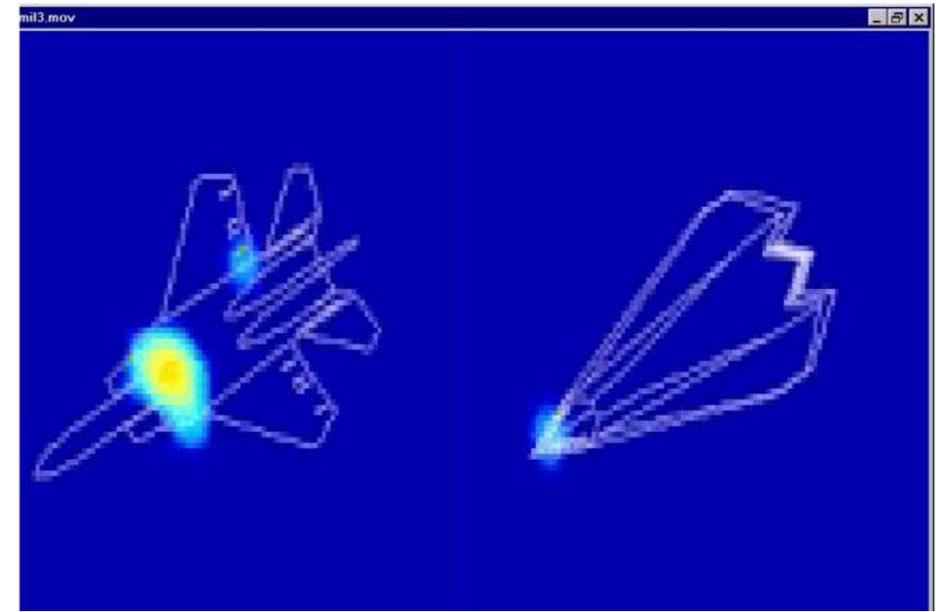
RCS is **polarization-dependent**... 4 terms RCS matrix :

$$[\Sigma] = \begin{bmatrix} \sigma_{hh} & \sigma_{hv} \\ \sigma_{vh} & \sigma_{vv} \end{bmatrix}$$

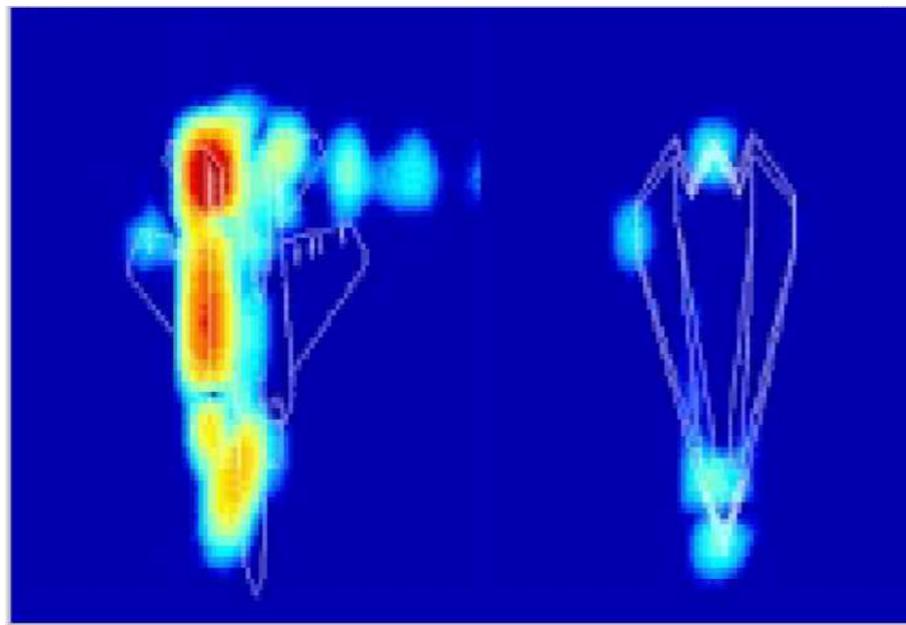
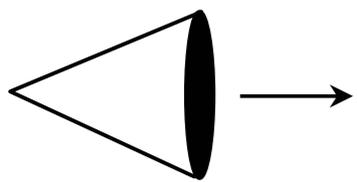
# RCS AND STEALTH



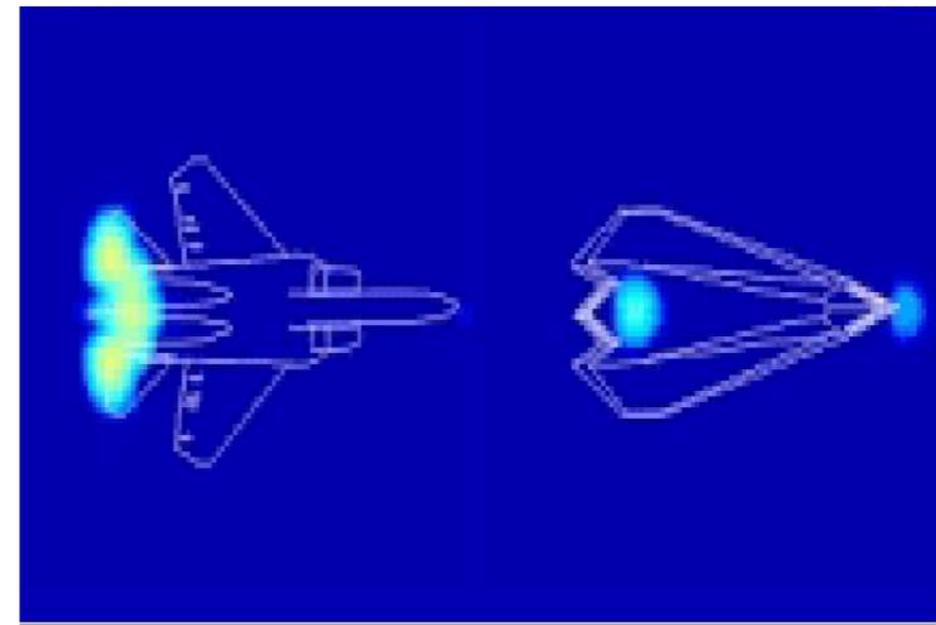
$\theta = 0^\circ$



$\theta = 45^\circ$



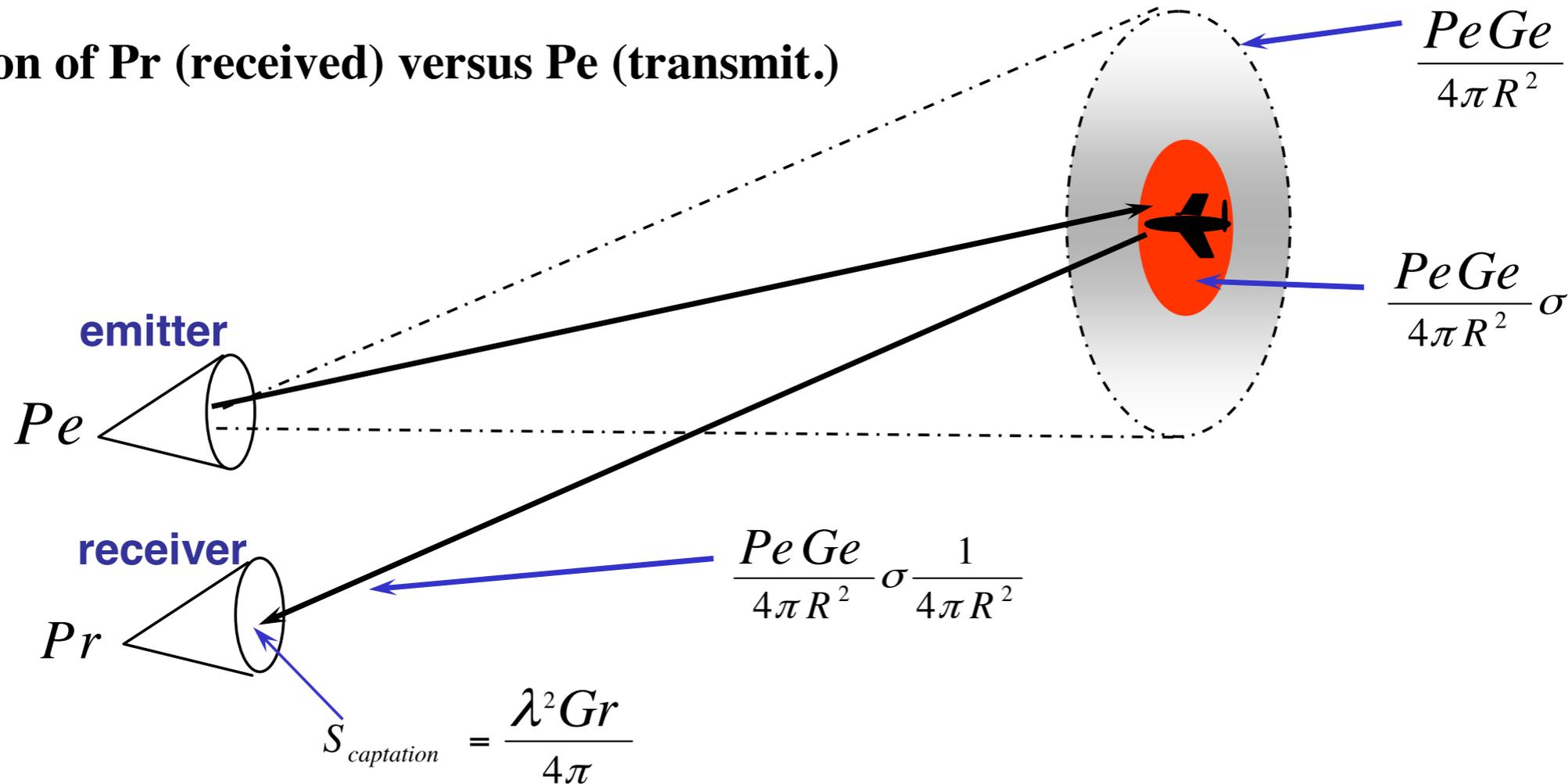
$\theta = 90^\circ$



$\theta = 180^\circ$

# RADAR POWER BUDGET

Calculation of  $P_r$  (received) versus  $P_e$  (transmit.)



$$\rightarrow P_r = \frac{P_e G_e}{4\pi R^2} \sigma \frac{1}{4\pi R^2} S_{\text{captation}} = \frac{P_e G_e G_r \sigma \lambda^2}{(4\pi)^3 R^4}$$

$$P_r = \frac{P_e G_e G_r \sigma \lambda^2}{L (4\pi)^3 R^4}$$

$L$  = losses (circuits, propagation..)

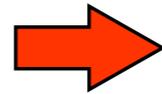
$G_e, G_r$  : Tx,Rx antenna gains

$R$  : target to radar range

$\sigma$  = radar cross section

# SNR (one single pulse)

**SNR calculation**



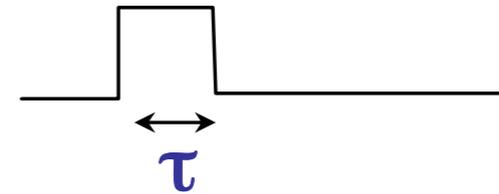
$$\frac{S}{N} = SNR = \frac{P_{rec \text{ .signals}}}{P_{noise}} = \frac{P_s}{P_n}$$

$$\left\{ \begin{array}{l} P_s = \frac{P_e G_e G_r \sigma \lambda^2}{L (4\pi)^3 R^4} \\ P_n = F_{radar} K T_0 \Delta F \end{array} \right.$$

with

$$\Delta F = \frac{1}{\tau}$$

(Uncoded pulse)



$$\left[ \frac{S}{B} \right] = \frac{P_e G_e G_r \lambda^2 \sigma \tau}{(4\pi)^3 R^4 L F K T_0}$$

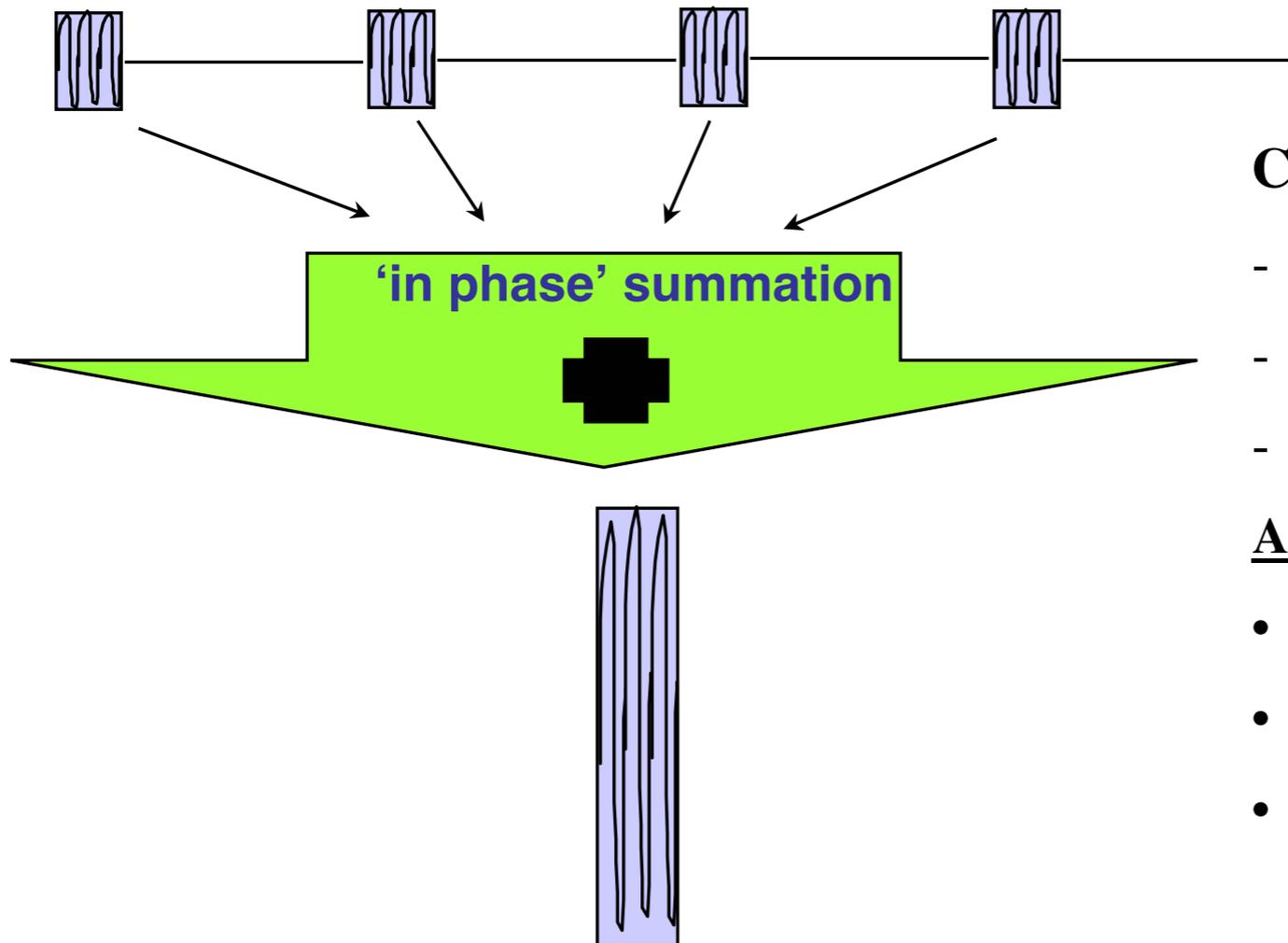
<b><math>P_e</math></b>	<b>Watt</b>	<b>( dBW)</b>
<b><math>G_e, G_r</math></b>		<b>( dB)</b>
<b><math>\lambda</math></b>	<b>m</b>	<b>( dBm)</b>
<b><math>\tau</math></b>	<b>s</b>	<b>( dBs)</b>
<b><math>R</math></b>	<b>m</b>	<b>( dBm)</b>
<b><math>F K T_0</math></b>	<b>Joule</b>	<b>( dBJ)</b>
<b><math>L</math>(losses)</b>		<b>( dB)</b>

(decibel)

$$10 \log_{10} [K T_0] = -204 \text{ dBJ}$$

$$10 \log_{10} [(4\pi)^3] = 33 \text{ dB}$$

## Coherent integration of N pulses (Doppler radar)



### Consider :

- N number of periods
- a magnitude of individual pulse
- $b^2$  noise variance of each pulse

### AFTER COHERENT INTEGRATION

- magnitude  $\implies N a$
- power  $\implies (Na)^2$
- noise power  $\implies N b^2$

$$\left[ \frac{S}{B} \right]_N = \frac{N^2 a^2}{N b^2} = \frac{N a^2}{b^2} = N \left[ \frac{S}{B} \right]_1$$

$$\left[ \frac{S}{B} \right]_N = N \frac{P_e G_e G_r \lambda^2 \sigma \tau}{(4\pi)^3 D^4 L F K T_0}$$

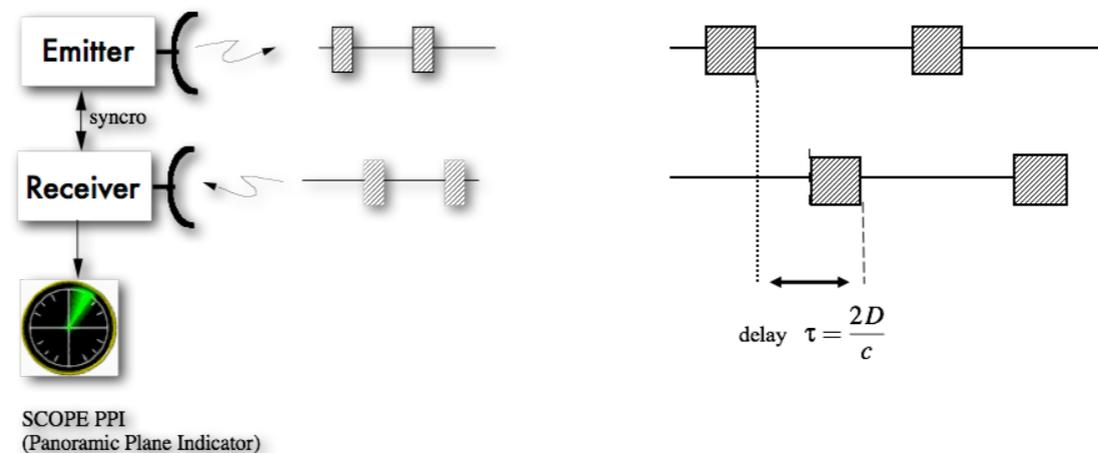
# RADAR EQUATION

Puissance de cible	Puissance de fouillis	Puissance de Bruit thermique
$P_s = \frac{P_{ce} \lambda^2 G_0^2 F^4}{(4\pi)^3 D^4 L} \sigma_{cible}$	$P_c = \frac{P_{ce} \lambda^2 G_0^2(\alpha)}{(4\pi)^3 D^4 L I_m} \sigma_{sol}$	$P_b = F_b k T_0 \frac{1}{N T_r},$

Rapport Signal à Bruit :  $SNR = \frac{P_s}{P_c + P_b}$

# RANGE MEASUREMENT

Electromagnetic wave propagates with speed light  $c$ . The two-way propagation delay up to the distance  $D$  is  $\tau = \frac{2D}{c}$



- Radar emitted signal:  $s_e(t) = u(t) \exp(2i\pi f_0 t)$  where  $f_0$  is the carrier frequency, and  $u(\cdot)$  the baseband signal,
- Radar received signal:  $s_r(t) = \alpha s_e(t - \tau) + b(t)$  where  $\alpha$  is the backscattering amplitude of the target and  $b(\cdot)$  is an additive noise.

$$s_r(t) = \alpha s_e \left( t - \frac{2D}{c} \right) + b(t).$$

# RANGE RESOLUTION

Let us suppose  $N$  targets with amplitude  $\{\alpha_i\}_{i \in [1, N]}$  located in range space at distance  $\left\{d_i = \frac{c \tau_i}{2}\right\}_{i \in [1, N]}$ . The received signal  $s_r(t)$  is:

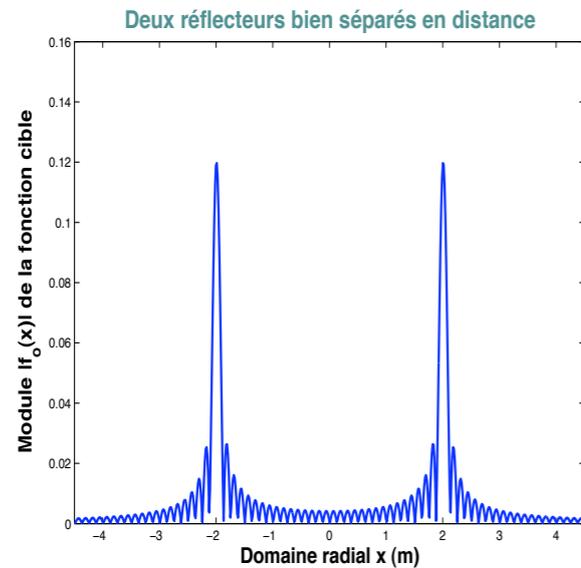
$$s_r(t) = \sum_{i=1}^N \alpha_i s_e(t - \tau_i) \xrightarrow{t \rightarrow f} S_r(f) = \sum_{i=1}^N \alpha_i S_e(f) e^{-2i \pi f \tau_i}.$$

The radar processing leads to evaluate for all  $\tau$ , the following expression:

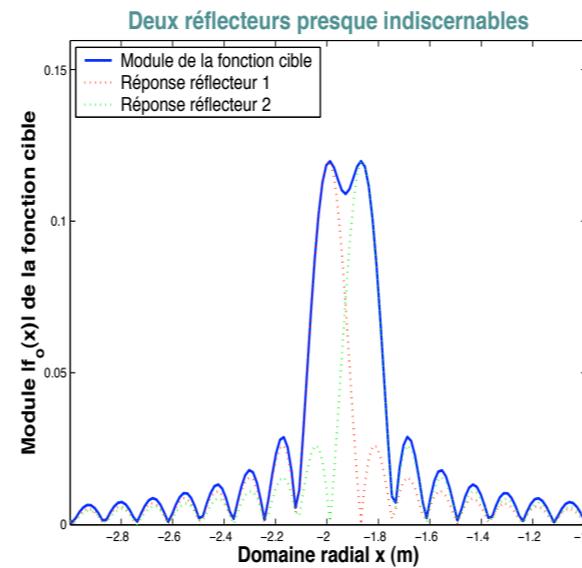
$$R(\tau) = \int_{-\infty}^{+\infty} s_r(t) s_e^*(t - \tau) dt \xrightarrow{t \rightarrow f} R(\tau) = \sum_{i=1}^N \alpha_i \int_{-\infty}^{+\infty} |S_e(f)|^2 e^{2i \pi f (\tau - \tau_i)} df.$$

- When  $S_e(f) = 1$  for  $f \in ]-\infty, +\infty[$ ,  $R(\tau) = \sum_{i=1}^N \alpha_i \delta(\tau - \tau_i)$ ,
- When  $S_e(f) = 1$  for  $f \in [B/2, +B/2]$ ,  $R(\tau) = \sum_{i=1}^N \alpha_i \frac{\sin(\pi B (\tau - \tau_i))}{\pi B (\tau - \tau_i)}$ .

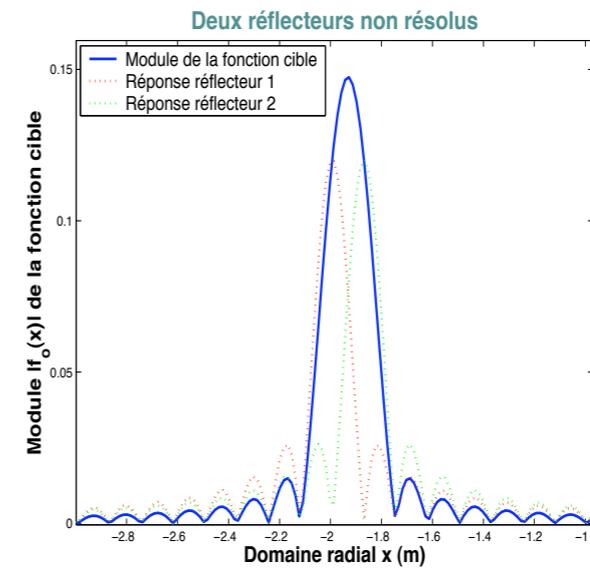
# RANGE RESOLUTION



(a) Distance réflecteurs : 4 m



(b) Distance réflecteurs : 13 cm



(c) Distance réflecteurs : 12.5 cm.  
(à la limite de résolution  $\delta x = 12.5$  cm)

The range resolution  $\delta D$  is proportional to the inverse of the emitted signal bandwidth  $B$ :

$$\delta D = \frac{c}{2} \frac{1}{B}$$

# VELOCITY MEASUREMENT

Let us consider an illuminated moving target located for time  $t$  at range  $D(t) = D_0 + v t$  where  $v$  is the radial target velocity.

If  $\tau(t)$  is the two-way delay of the received signal at time  $t$ , the signal has been reflected at time  $t - \tau(t)/2$  and the range  $D(t)$  has to verify the following equation:

$$c \tau(t) = 2 D \left( t - \frac{\tau(t)}{2} \right).$$

We obtain  $\tau(t) = 2 \frac{D_0 + v t}{c + v}$  and the model relative to signal return is:

$$s_r(t) = \alpha s_e \left( \frac{c - v}{c + v} t - \frac{2 D_0}{c + v} \right) + b(t).$$

The moving target is characterized in the signal return by a time-shift-compression/dilation of the emitted signal: action of Affine Group

# VELOCITY MEASUREMENT

Under the so-called *narrow-band* assumptions:

- $f_0 \gg B$ , where  $B$  is the bandwidth of baseband signal  $u(\cdot)$ ,
- $v \ll c$ ,
- $2 B T \ll c/v$ ,

then

$$\begin{aligned} s_r(t) &= \alpha s_e \left( \frac{c-v}{c+v} t - \frac{2D_0}{c+v} \right) + b(t), \\ &= \alpha \exp(i\phi) u \left( t - \frac{2D_0}{c} \right) \exp(2i\pi f_0 t) \exp \left( -2i\pi \frac{2v}{c} f_0 t \right) + b(t). \end{aligned}$$

$$s_r(t) = \alpha' s_e \left( t - \frac{2D_0}{c} \right) \exp(-2i\pi f_d t) + b(t).$$

where  $|\alpha'| = |\alpha|$  and where  $f_d = \frac{2v}{c} f_0$  is called the **Doppler frequency** corresponding to moving target. The moving target is so characterized in the signal return by a time-shift/frequency shift of the emitted signal: action of Heisenberg Group

# VELOCITY RESOLUTION

Let us suppose  $N$  targets with amplitude  $\{\alpha_i\}_{i \in [1, N]}$  with Doppler  $\left\{ \nu_i = \frac{2 \nu_i}{c} f_0 \right\}_{i \in [1, N]}$ .

The received signal  $S_r(f)$  is:

$$S_r(f) = \sum_{i=1}^N \alpha_i S_e(f - \nu_i) \xrightarrow{f \rightarrow t} s_r(t) = \sum_{i=1}^N \alpha_i s_e(t) e^{2i \pi \nu_i t}.$$

The radar processing leads to evaluate for all  $\nu$ , the following expression:

$$R(\nu) = \int_{-\infty}^{+\infty} S_r(f) S_e^*(f - \nu) df \xrightarrow{t-f} R(\nu) = \sum_{i=1}^N \alpha_i \int_{-\infty}^{+\infty} |s_e(t)|^2 e^{-2i \pi t (\nu - \nu_i)} dt.$$

The velocity resolution  $\delta V$  is proportional to the inverse of the emitted signal duration (or integration time)  $T$ :

$$\delta V = \frac{c}{2 f_0} \frac{1}{T}.$$

# DOPPLER EFFECT



# EXAMPLES OF DOPPLER

## Equation du Doppler

La fréquence Doppler est égale à la variation de  $d$  (distance) exprimée en longueurs d'onde

$$f_d = -\frac{1}{\lambda} \cdot \frac{\delta d}{\delta t}$$

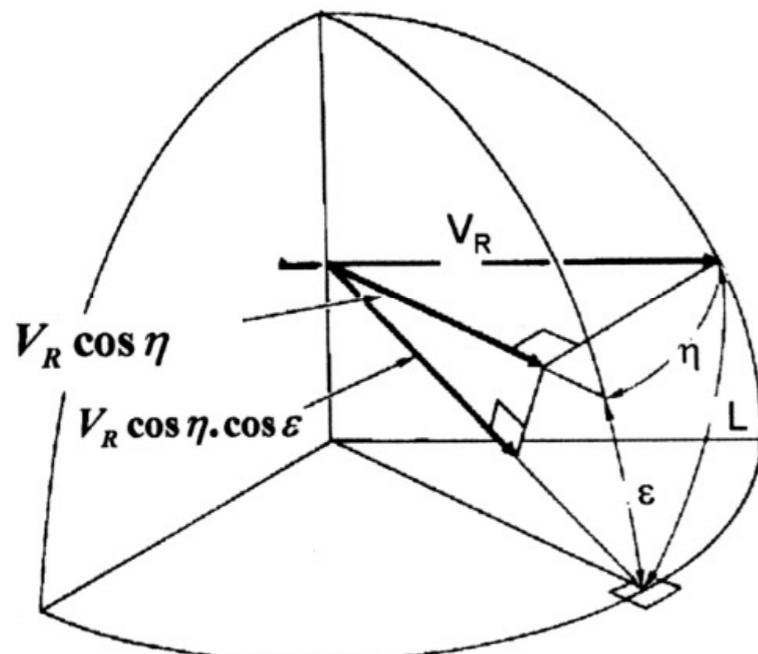
$$d = 2R$$

$$f_d = -\frac{2}{\lambda} \cdot \frac{\delta R}{\delta t}$$

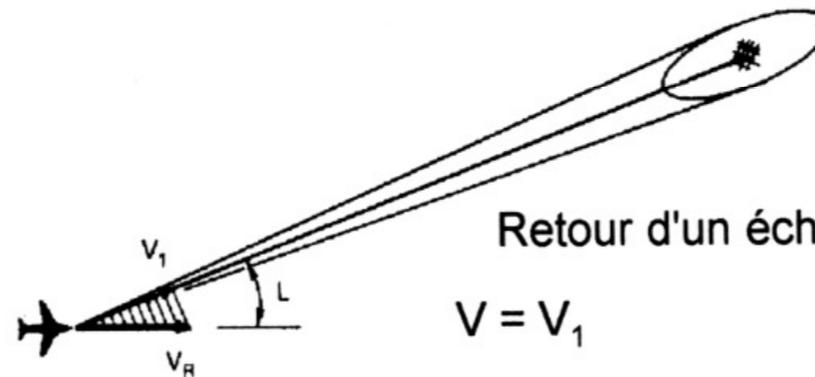
$$\frac{f_d}{f} = \frac{2V}{c}$$

$f_d$  fréquence Doppler,  
 $\delta R/\delta t = V$  vitesse relative entre  
 le radar et la cible,  
 $\lambda$  porteuse transmise.

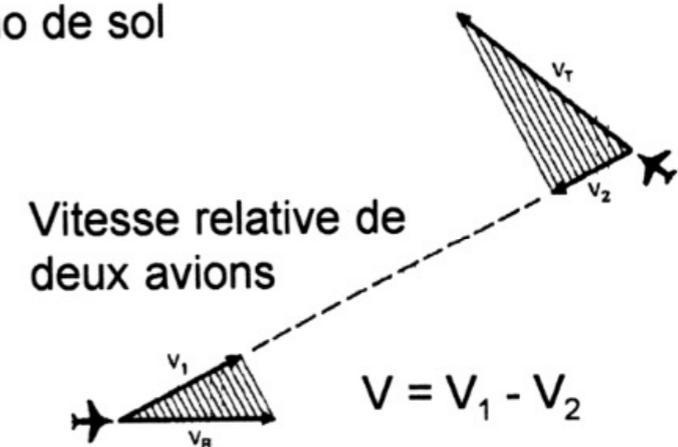
$$V = V_R + V_T$$



Vitesse relative du sol  
 $V_1 = V_R \cos \eta \cdot \cos \epsilon$



Retour d'un écho de sol  
 $V = V_1$



Vitesse relative de  
 deux avions  
 $V = V_1 - V_2$

# AMBIGUITY FUNCTION

One of the most important problem arising in radar theory is to separate targets in range and Doppler spaces. A  $\mathcal{L}^2(\mathbb{R})$  distance  $R$  between two signals  $X$  and  $Y$  can be defined:

$$R^2 = \int_{-\infty}^{+\infty} |X(t) - Y(t)|^2 dt.$$

Minimizing this distance leads to maximize the inner product between  $X$  and  $Y$ :

$$\int_{-\infty}^{+\infty} X(t) Y^*(t) dt.$$

According to the physical transformation of  $X$ , we obtain the so-called Ambiguity functions [Woodward, 1953, Kelly and Wishner, 1965]:

- Example:  $Y(t) = X(t - \tau) e^{2i\pi\nu t}$ :  $A(\tau, \nu) = \int_{-\infty}^{+\infty} X(t) X^*(t - \tau) e^{-2i\pi\nu t} dt,$
- Example:  $Y(t) = \frac{1}{\sqrt{a}} X(a^{-1}t - b)$ :  $A(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} X(t) X^*(a^{-1}t - b) dt.$

# JOINT RANGE AND VELOCITY RESOLUTION

Let us suppose  $N$  targets with amplitude  $\{\alpha_i\}_{i \in [1, N]}$  moving at velocity  $\{v_i\}_{i \in [1, N]}$  and located in range space at distance  $\left\{d_i = \frac{c \tau_i}{2}\right\}_{i \in [1, N]}$ . The received signal  $S_r(f)$  is:

$$s_r(t) = \sum_{i=1}^N \alpha_i s_e(t - \tau_i) e^{2i \pi v_i t}.$$

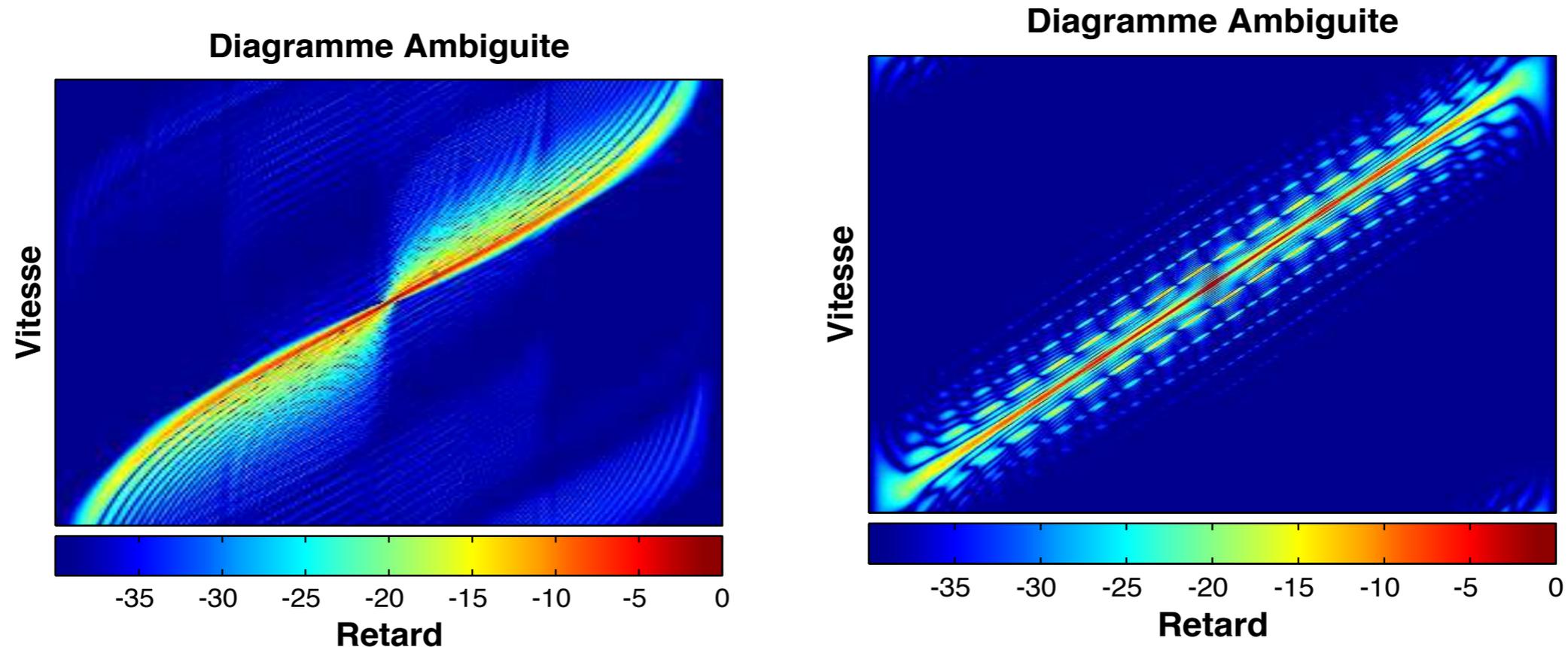
The radar processing leads to evaluate for all  $(\tau, \nu)$ , the following expression:

$$R(\tau, \nu) = \int_{-\infty}^{+\infty} s_r(t) s_e^*(t - \tau) e^{-2i \pi \nu t} dt.$$

This last equation is the superposition of the ambiguity functions [Rihaczek, 1969] centered at  $\{(\tau_i, \nu_i)\}_{i \in [1, N]}$

$$R(\tau, \nu) = \sum_{i=1}^N \alpha_i A(\tau - \tau_i, \nu - \nu_i).$$

# EXAMPLES OF AMBIGUITY FUNCTION



- Best radar waveforms are those which look like a *thumbtack* form ( $A(\tau, \nu) = \delta(\tau) \delta(\nu)$ ) but they definitely don't exist :-)
- Range and Doppler sidelobes can be troublesome for high density targets detection because of their superposition at different ranges and Doppler [Rihaczek, 1969].

# PERFORMANCE ANALYSIS

- Let us define the second order moments of the signal  $\sigma_t^2 = \int_{-\infty}^{+\infty} |s_e(t)|^2 dt \approx T^2$ ,  
 $\sigma_f^2 = \int_{-\infty}^{+\infty} |S_e(f)|^2 df \approx B^2$  and the modulation index  $m = \frac{-1}{2\pi} \text{Im} \int_{-\infty}^{+\infty} t s_e(t) \frac{ds_e^*(t)}{dt} dt$ .

Under white Gaussian noise with variance  $\sigma^2$ , range and doppler accuracies are given by the following Cramer-Rao bounds [Kay, 1993]:

$$E [(\nu - \hat{\nu})^2] = \frac{\sigma^2}{4 \pi^2 \alpha^2} \frac{\sigma_f^2}{\sigma_f^2 \sigma_t^2 - (m - t_0 f_0)^2} \geq \frac{\sigma^2}{4 \pi^2 \alpha^2} \frac{1}{\sigma_t^2}, \quad (1)$$

$$E [(\tau - \hat{\tau})^2] = \frac{\sigma^2}{4 \pi^2 \alpha^2} \frac{\sigma_t^2}{\sigma_f^2 \sigma_t^2 - (m - t_0 f_0)^2} \geq \frac{\sigma^2}{4 \pi^2 \alpha^2} \frac{1}{\sigma_f^2}, \quad (2)$$

$$E [(\nu - \hat{\nu})(\tau - \hat{\tau})] = \frac{\sigma^2}{4 \pi^2 \alpha^2} \cdot \frac{m - t_0 f_0}{\sigma_f^2 \sigma_t^2 - (m - t_0 f_0)^2} \quad (3)$$

- Radar uses to emit signal characterized with high time-bandwidth product  $B T$ .

# RANGE DOPPLER RADAR PROCESSING

- The cross-correlation operation is closely related to the so-called *Matched Filter* (filter which maximizes the SNR at its output). This is also known as the *pulse compression* processing. This matched filter offers the gain  $B T$  on the noise power  $\sigma^2$  (SNR improvement),
- The Doppler resolution is inversely proportional to the integration time. For monostatic radar (both emission and reception on the same antenna), radar prefers to cut off this long integration time into  $m$  pulses of duration  $T$  with Pulse Repetition Frequency (PRF)  $F_r = 1/T_r$  (total integration time  $m T_r$ ):

$$s(t) = \sum_{k=0}^{m-1} s_e(t - k T_r).$$

Considering the signal return  $s_r(t)$ , the radar processing consists in evaluating the following expression:

$$\begin{aligned} R(\tau, \nu) &= \int_{-\infty}^{+\infty} s_r(t) s_r^*(t - \tau) e^{-2i \pi \nu t} dt, \\ &= \sum_{n=0}^{m-1} e^{-2i \pi \nu n T_r} \int_0^{T_r} s_r(u + n T_r) s_r^*(u - \tau) e^{-2i \pi \nu u} du. \end{aligned}$$

# RANGE DOPPLER RADAR PROCESSING

- Coherent Doppler processing brings an improvement of  $m$  on the Doppler resolution with regards to the one pulse processing ( $\delta v = 1/(m T_r)$ ) as well as a gain  $m$  in SNR.
- Range resolution does not change. Always related by the pulse bandwidth,
- Appearance of the range ambiguities at ranges  $c k T_r/2$ ,
- Appearance of the Doppler ambiguities at Doppler frequency  $k/T_r$ .

Radar users have to choose the swath (range domain  $c (k - 1) T_r/2 \leq d_i < c k T_r/2$ ) relative the potential presence of targets and the Doppler support relative to the velocity of targets ( $-c/(4 T_r f_0) \leq v_i < c/(4 T_r f_0)$ ).

Unfortunately, a large non-ambiguous swath and large non-ambiguous Doppler support cannot be chosen simultaneously.

	Range	Velocity
Resolution	$\frac{c}{2 B}$ (depends on the signal)	$\frac{c}{2 f_0 m T_r}$ (does not depend on signal)
Ambiguity	$\frac{c T_r}{2}$	$\frac{c}{2 f_0 T_r}$

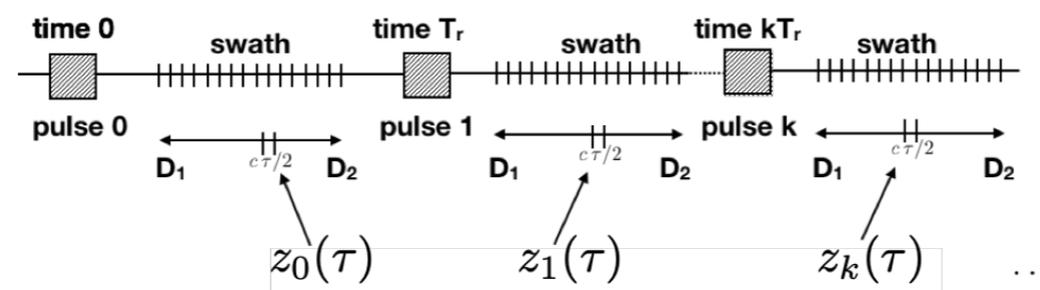
Characteristics of  $m$  pulses train with duration  $T$ , bandwidth  $B$ , PRF  $1/T_r$  and carrier frequency  $f_0$

# RANGE DOPPLER RADAR PROCESSING

When supposing non migrating target (target stays in the same range bin during the duration  $T$  of the pulse, i.e.  $BT \leq \frac{c}{2v}$ ) and neglecting the Doppler variation in the pulse, we can rewrite the processing as:

$$\begin{aligned}
 R(\tau, \nu) &= \sum_{n=0}^{m-1} e^{-2i\pi\nu n T_r} \int_0^{T_r} s_r(u + n T_r + \tau) s_e^*(u) du, \\
 &= \sum_{n=0}^{m-1} z_n(\tau) e^{-2i\pi\nu n T_r} = \mathbf{p}^H \mathbf{z},
 \end{aligned}$$

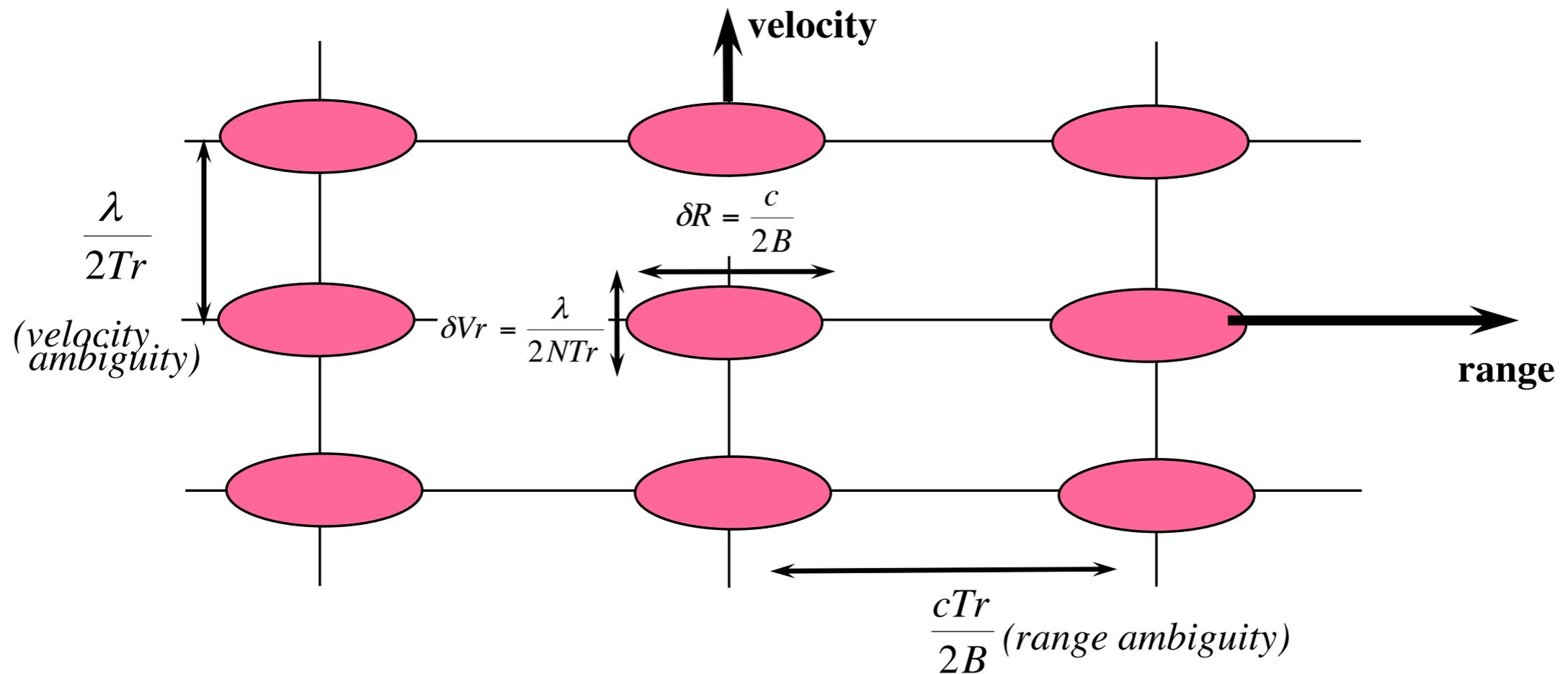
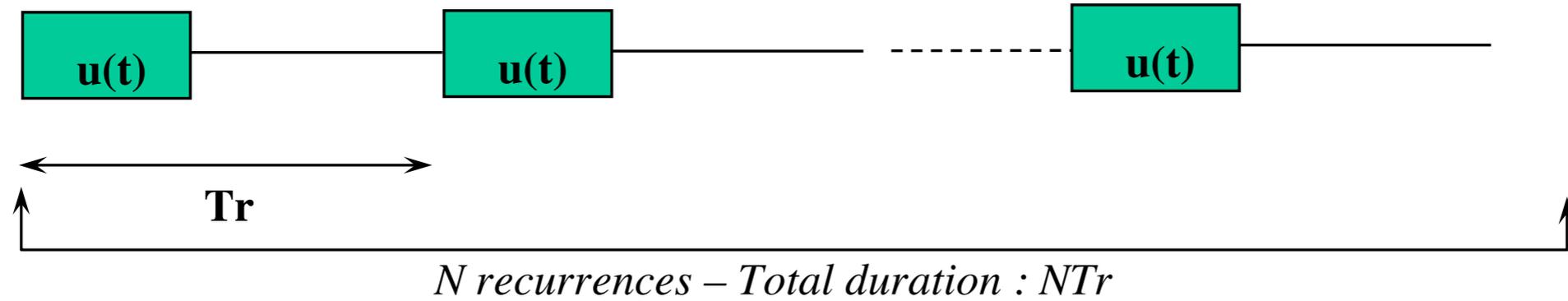
where  $\mathbf{z} = (z_0(\tau), z_1(\tau), \dots, z_{m-1}(\tau))^T$  and  $\mathbf{p} = (1, e^{2i\pi\nu T_r}, \dots, e^{2i\pi\nu (m-1) T_r})^T$ .



- For each range bin  $c\tau/2$  (time  $T_r$  can be sampled at resolution  $\delta\tau = 1/B$ ) on the range support  $[D_1, D_2]$  of the analyzed swath, compute  $z_n(\tau)$  corresponding to the time correlation between received signal and emitted pulse  $s_e(t)$  at time  $n T_r$ ,

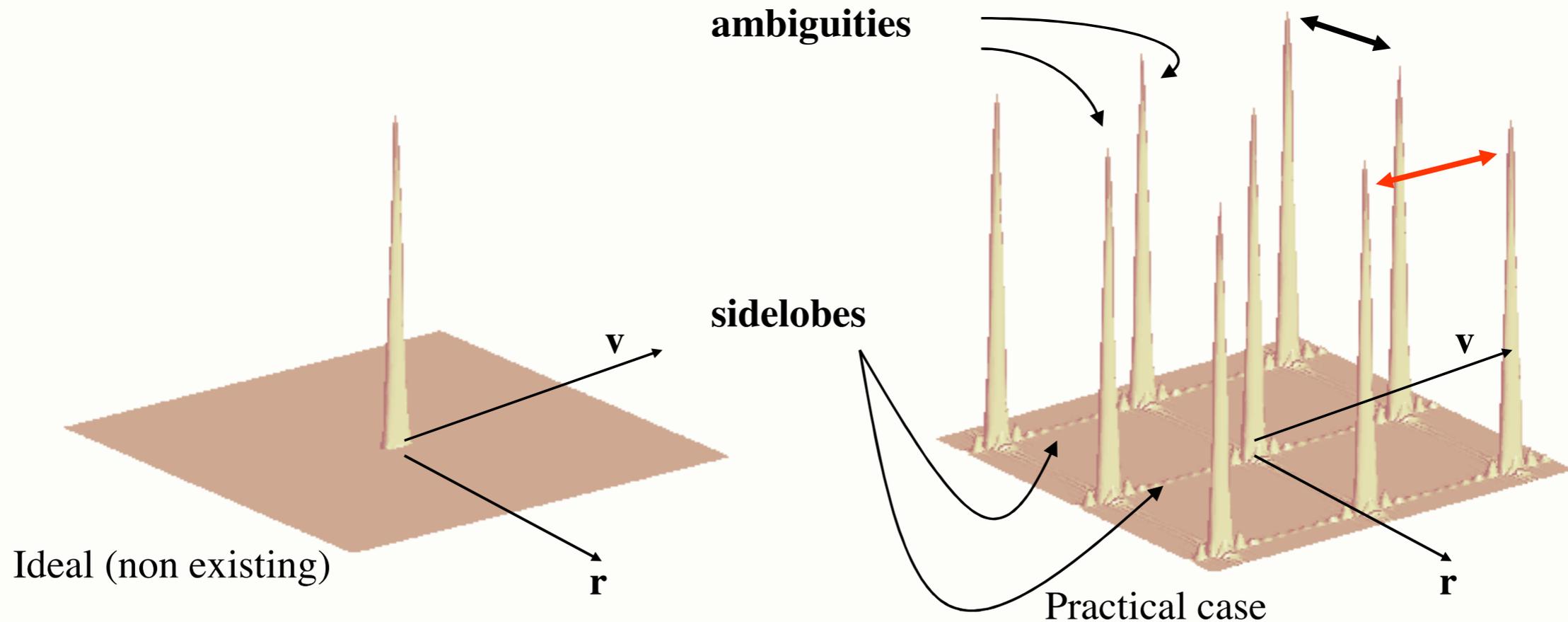
# RANGE DOPPLER RADAR PROCESSING

Modulation code of bandwidth  $B$ , repetition over  $N$  réurrences



# RANGE DOPPLER RADAR PROCESSING

## 3D representation – Ideal and real ambiguity function



$B$  = modulation bandwidth

$N$  = number of recurrences

$Tr$  = repetition period

$$\text{Range resolution} = \frac{c}{2B}$$

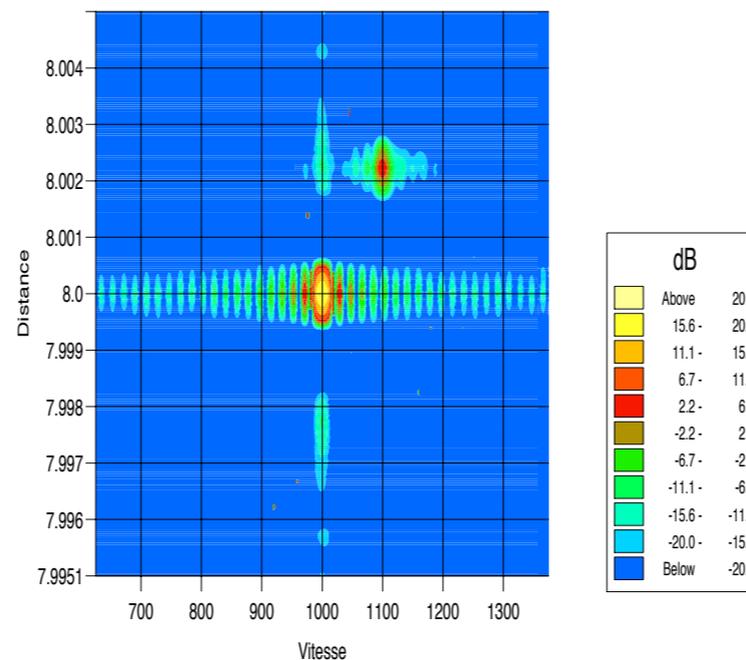
$$\text{Velocity resolution} = \frac{\lambda}{2NTr}$$

$$\text{Range ambiguity} = \frac{cTr}{2}$$

$$\text{Velocity ambiguity} = \frac{\lambda}{2Tr}$$

# RANGE DOPPLER RADAR PROCESSING

- For each range bin  $c\tau/2$ , compute the Discrete Fourier Transform over the  $m$  coefficients  $\{z_n(\tau)\}_{n \in [0, m-1]}$  to characterize Doppler spectrum in the domain  $\nu \in [0, 1/T_r]$ .
- For non fluctuating target, the coefficients  $\{z_n(\tau)\}_{n \in [0, m-1]}$  are generally constant over pulse train. This constant will be denoted by  $A$  in the following,  $A$  being the amplitude of the target over the burst.



Example of the so-called Range-Doppler map of the processing data.

# FORMULATION OF THE RANGE DOPPLER RADAR DETECTION PROBLEM

## Set of two binary hypotheses

$$\begin{cases} H_0 : \mathbf{y} = \mathbf{b} \\ H_1 : \mathbf{y} = A\mathbf{p} + \mathbf{b} \end{cases} ,$$

where

- $\mathbf{y}$  is a  $m$ -vector of data collected in the same given range bin  $c\tau/2$  and characterizing the reflected signal for each emitted pulse of the burst.
- The complex amplitude  $A$  is considered here deterministic.
- The  $m$ -vector  $\mathbf{b}$  represents the additive noise (thermal noise, clutter, jam, etc.) characterized by a known (or unknown) PDF.
- The  $m$ -vector  $\mathbf{p}$  represents the so-called *steering vector*: here  $\mathbf{p} = (1, \exp(2i\pi\nu T_r), \exp(2i\pi\nu 2T_r), \dots, \exp(2i\pi\nu(m-1)T_r))^T$ , where the Doppler frequency  $\nu$  is unknown and has to be estimated.

The problem here consists in choosing between  $H_1$  hypothesis and  $H_0$  hypothesis.

# PROBLEM STATEMENT

- When the noise parameters are known:

In a  $m$ -vector  $\mathbf{z}$  of observation, detecting a complex deterministic signal  $\mathbf{s} = A\mathbf{p}$  embedded in an additive noise  $\mathbf{b}$  can be written as the following set of binary hypotheses test:

$$\begin{cases} \text{Hypothesis } H_0: & \mathbf{z} = \mathbf{b}, \\ \text{Hypothesis } H_1: & \mathbf{z} = \mathbf{s} + \mathbf{b}. \end{cases}$$

- When the noise parameters are unknown: (covariance, mean, etc.):

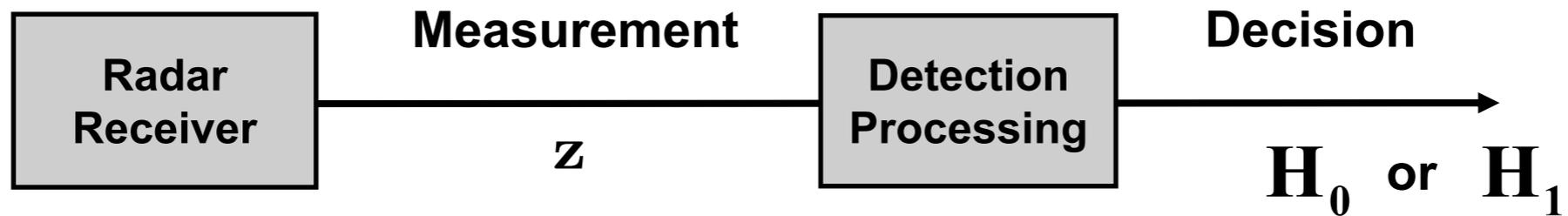
In a  $m$ -vector  $\mathbf{z}$ , detecting a complex deterministic signal  $\mathbf{s} = A\mathbf{p}$  embedded in an additive noise  $\mathbf{b}$  can be written as the following set of binary hypotheses test:

$$\begin{cases} \text{Hypothesis } H_0: & \mathbf{z} = \mathbf{b}, & \mathbf{z}_i = \mathbf{b}_i, & i = 1, \dots, n, \\ \text{Hypothesis } H_1: & \mathbf{z} = \mathbf{s} + \mathbf{b}, & \mathbf{z}_i = \mathbf{b}_i, & i = 1, \dots, n. \end{cases}$$

where the  $\mathbf{z}_i$ 's are  $n$  "signal-free" independent secondary data used to estimate the noise parameters.

⇒ **Neyman-Pearson criterion** [Kay, 1993, Kay, 1998]

# HYPOTHESIS TESTING



For each measurement  
There are two possibilities:

	Measurement	Probability Density
Target absent hypothesis, $H_0$ Noise only	$z = b$	$p_{z/H_0}(z)$
Target present hypothesis, $H_1$ Signal plus noise	$z = s + b$	$p_{z/H_1}(z)$

For each measurement  
There are four decisions:

		Decision	
		$H_0$	$H_1$
Truth	$H_0$	Don't Report	False Alarm
	$H_1$	Missed Detection	Detection

# DETECTION THEORY

When all parameters (noise, target) are known

- **Detection test:** comparison between the Likelihood Ratio  $\Lambda(\mathbf{z})$  and a detection threshold  $\lambda$ :

$$\Lambda(\mathbf{z}) = \frac{p_{\mathbf{z}/H_1}(\mathbf{z})}{p_{\mathbf{z}/H_0}(\mathbf{z})} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda ,$$

where  $\lambda$  is set for a given *PFA* (set by the user):

- Probability of False Alarm (type-I error):

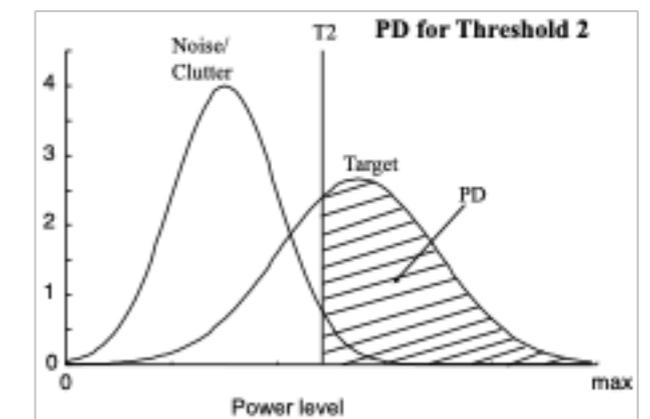
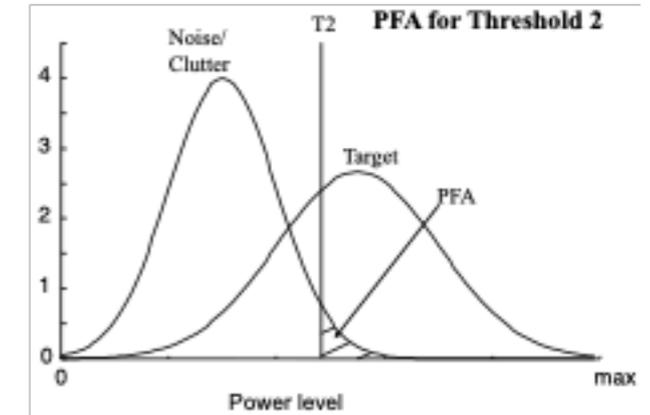
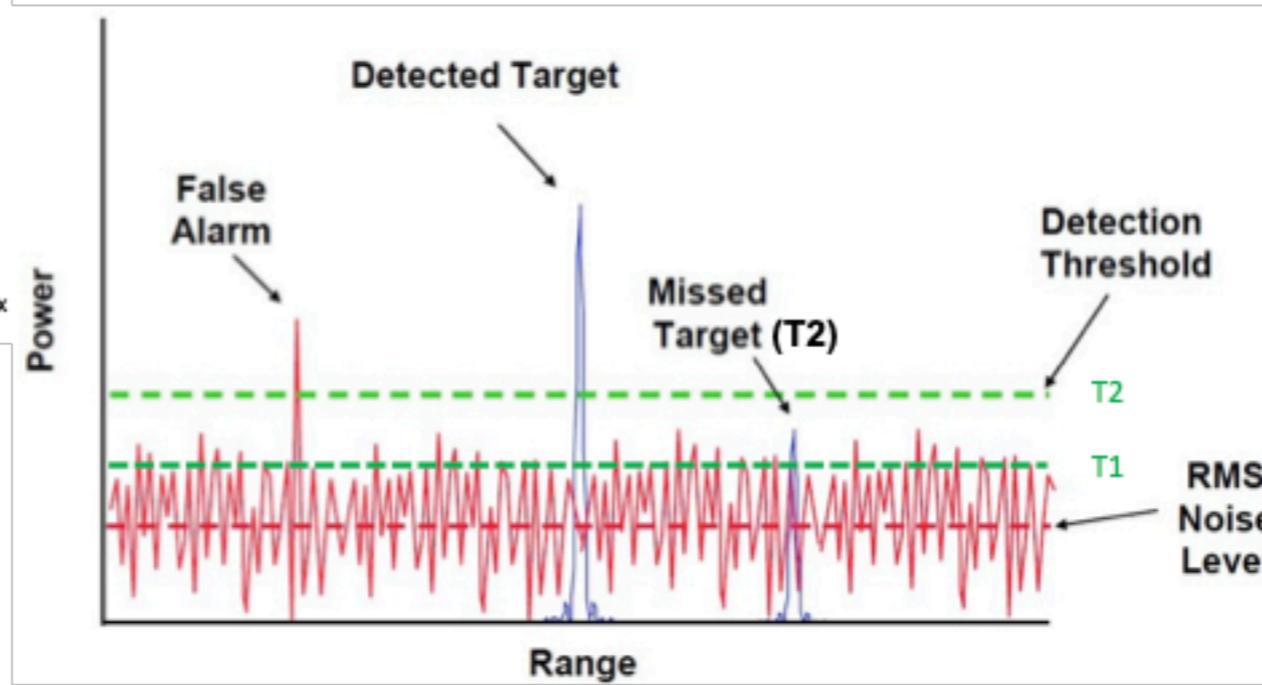
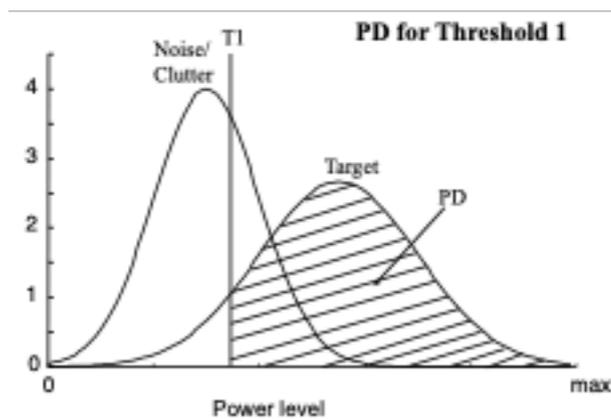
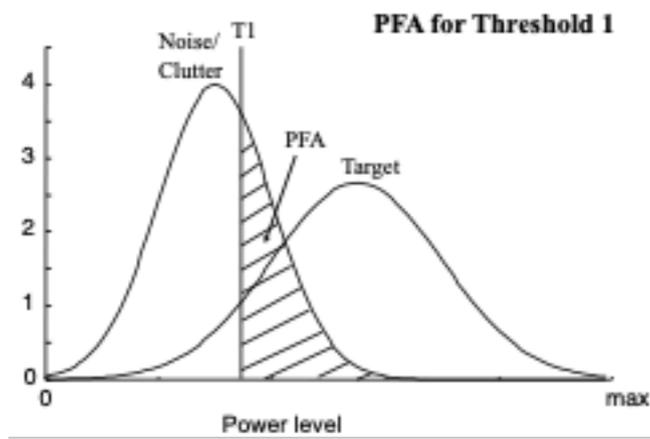
$$P_{fa} = \mathbb{P} (\Lambda(\mathbf{z}) > \lambda / H_0) .$$

- Probability of Detection (to evaluate the performance):

$$P_d = \mathbb{P} (\Lambda(\mathbf{z}) > \lambda / H_1) ,$$

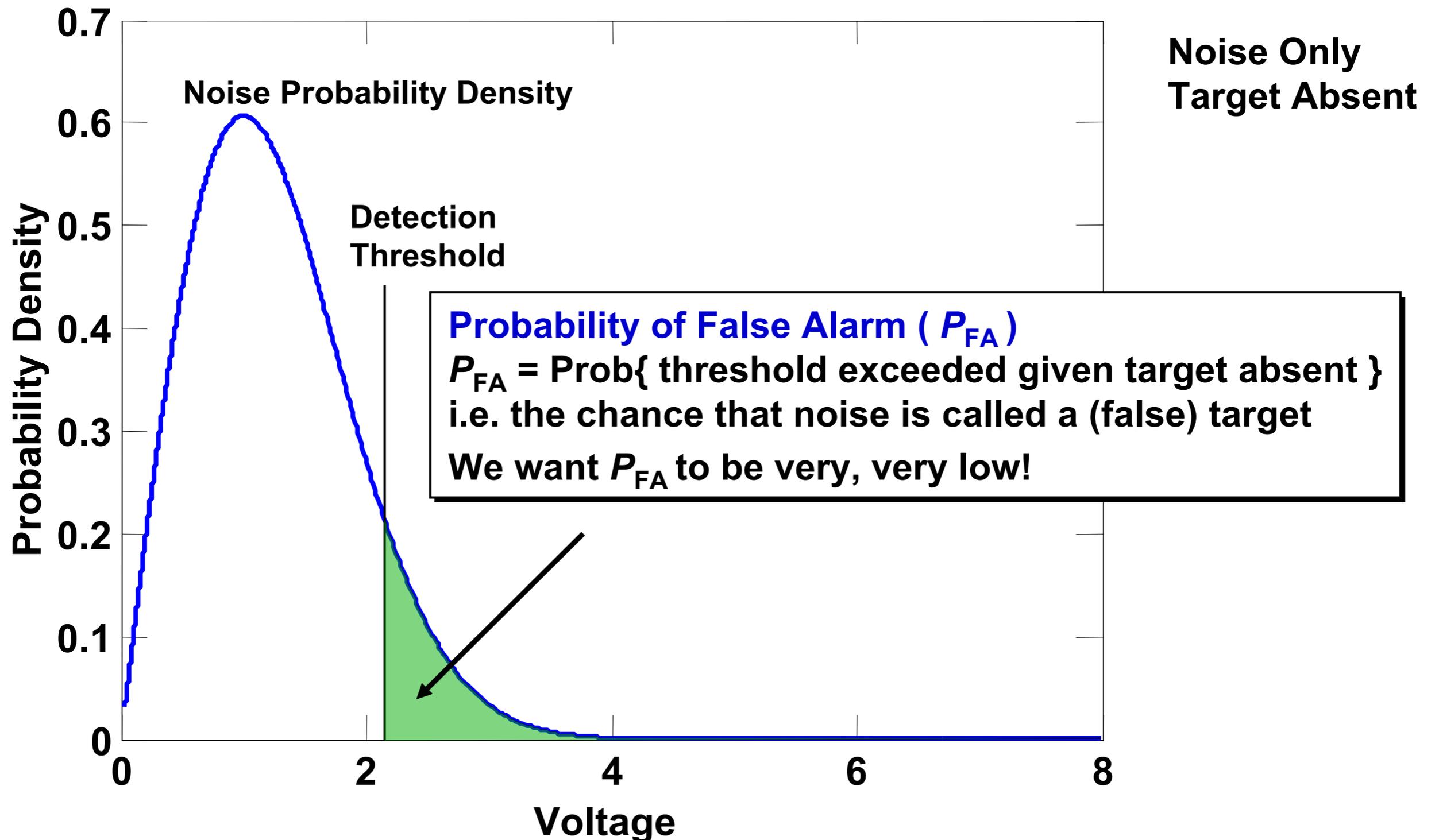
for different Signal-to-Noise Ratios (SNR).

# Pd/Pfa

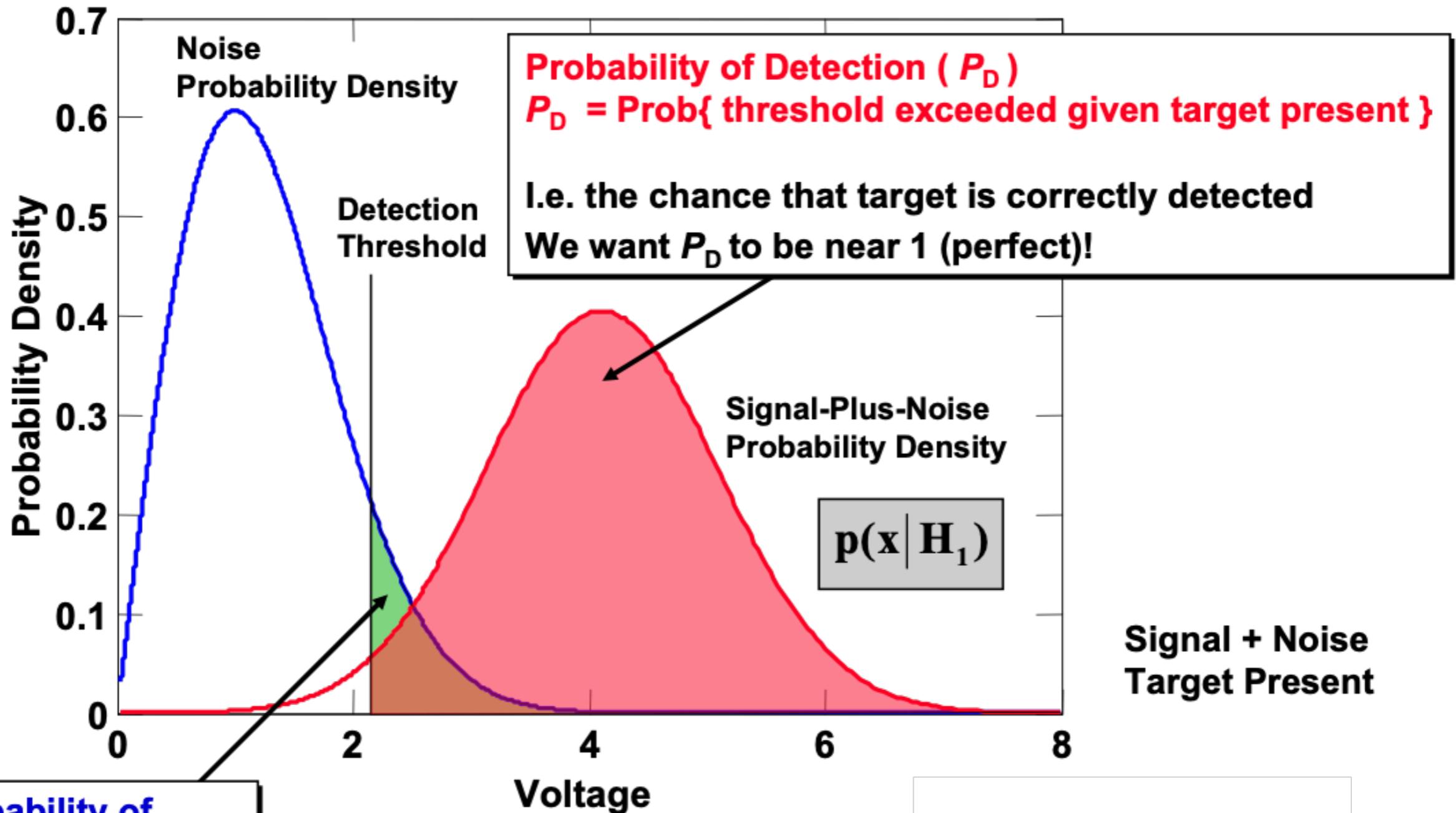


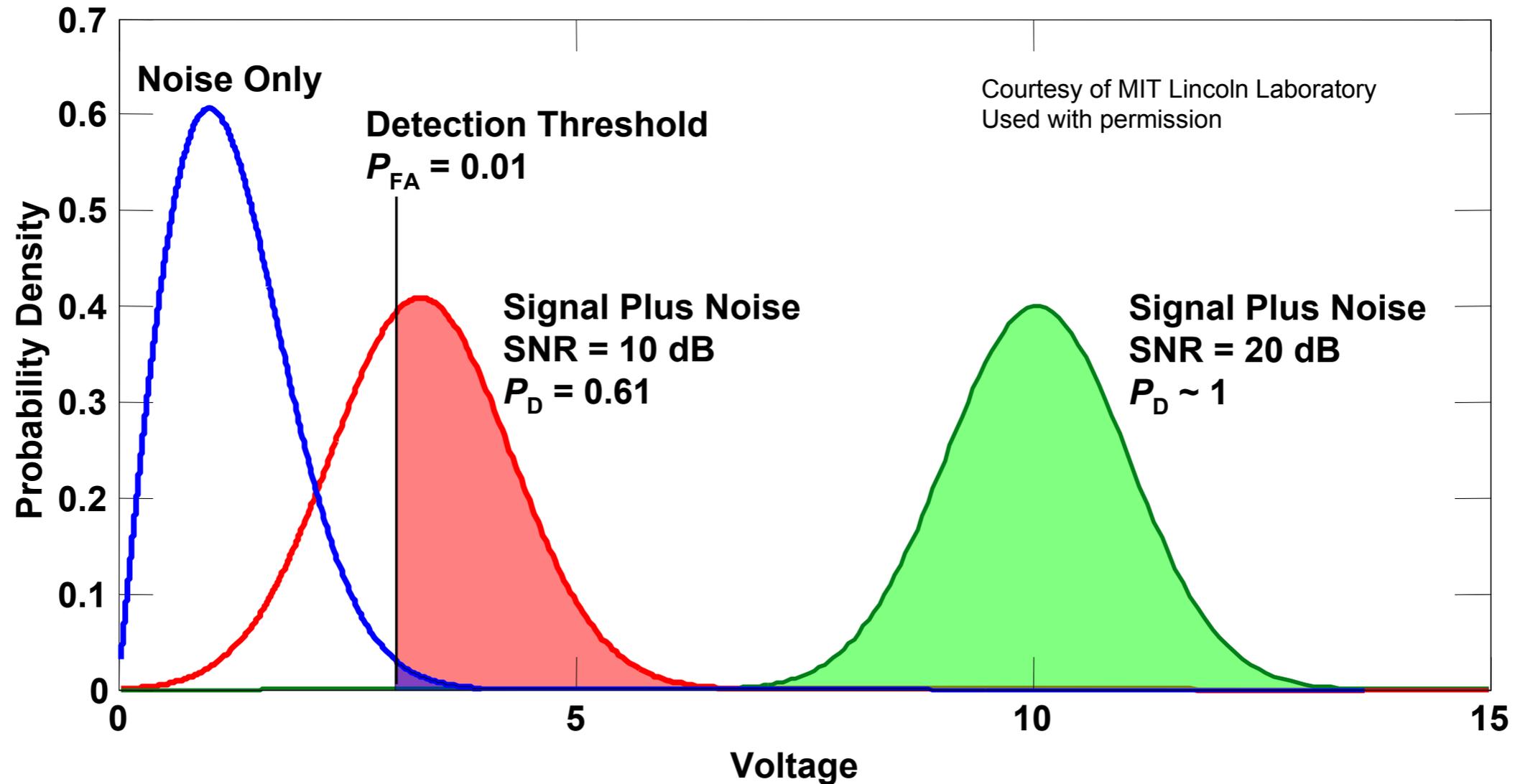
$$P_{fa} = \mathbb{P}(\Lambda(\mathbf{z}) > \lambda/H_0),$$

$$P_d = \mathbb{P}(\Lambda(\mathbf{z}) > \lambda/H_1).$$



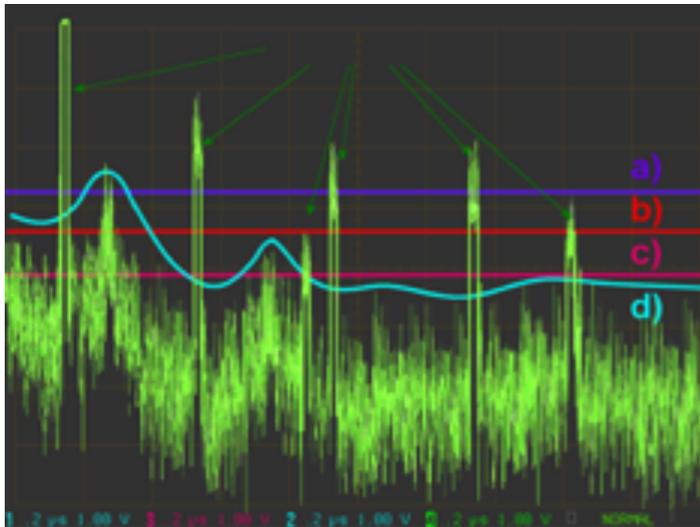
# Pd/Pfa





- $P_D$  increases with target SNR for a fixed threshold ( $P_{FA}$ )
- Raising threshold reduces false alarm rate and increases SNR required for a specified Probability of Detection

# IMPORTANCE OF FALSE ALARM REGULATION



- a. threshold is set too high: Probability of Detection = 20%
- b. threshold is set optimal: Probability of Detection = 80%  
But one false alarm arises!  
False alarm rate =  $1 / 666 = 1,5 \cdot 10^{-3}$
- c. threshold is set too low: a large number of false alarms arises!
- d. threshold is set variable: constant false-alarm rate

## CFAR Property

A detector is said Constant False Alarm Rate (CFAR property) if the PDF of the test is independent on the noise parameter (mean, covariance, variance, statistic) under  $H_0$  hypothesis.

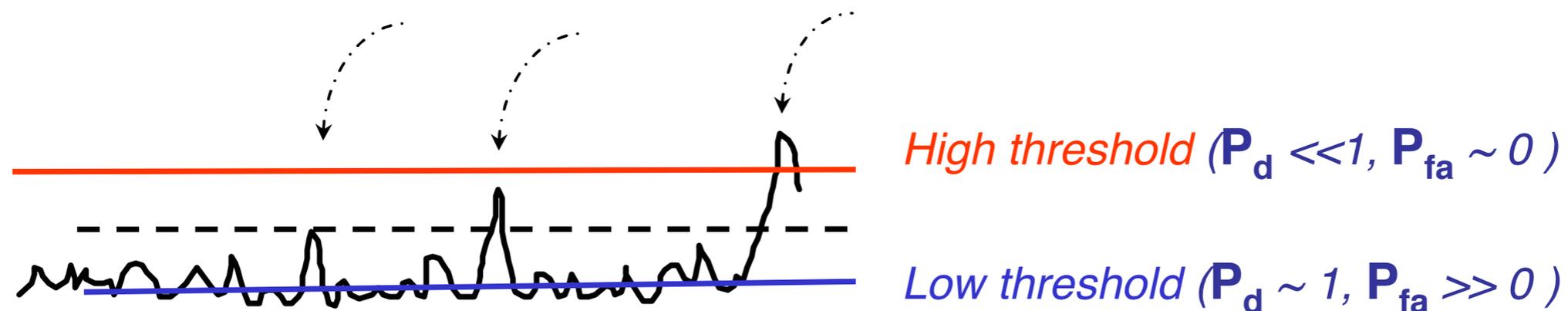
# FALSE ALARM AND PROBABILITY OF DETECTION

**DETECTION = Magnitude of radar signal is threshold**

lower the threshold, higher false alarm, better detection

higher the threshold, lower false alarm, lower detection

$P_{fa}$  = false alarm probability       $P_d$  = detection probability



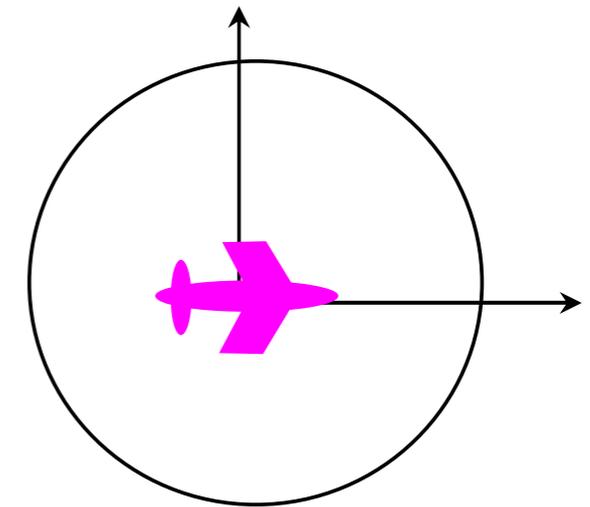
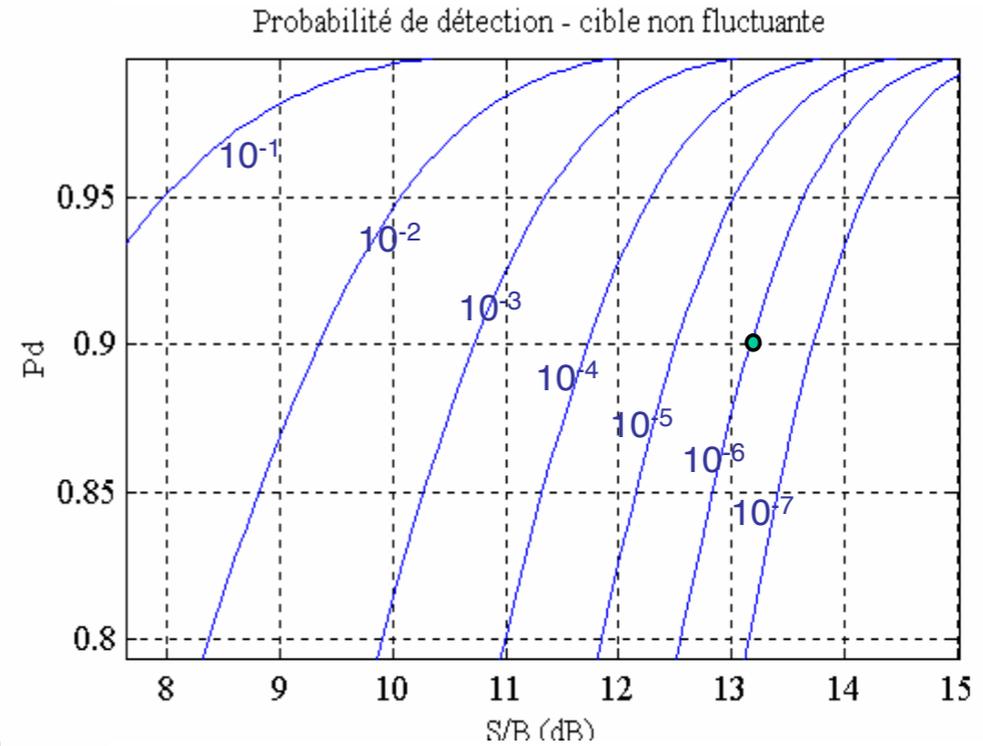
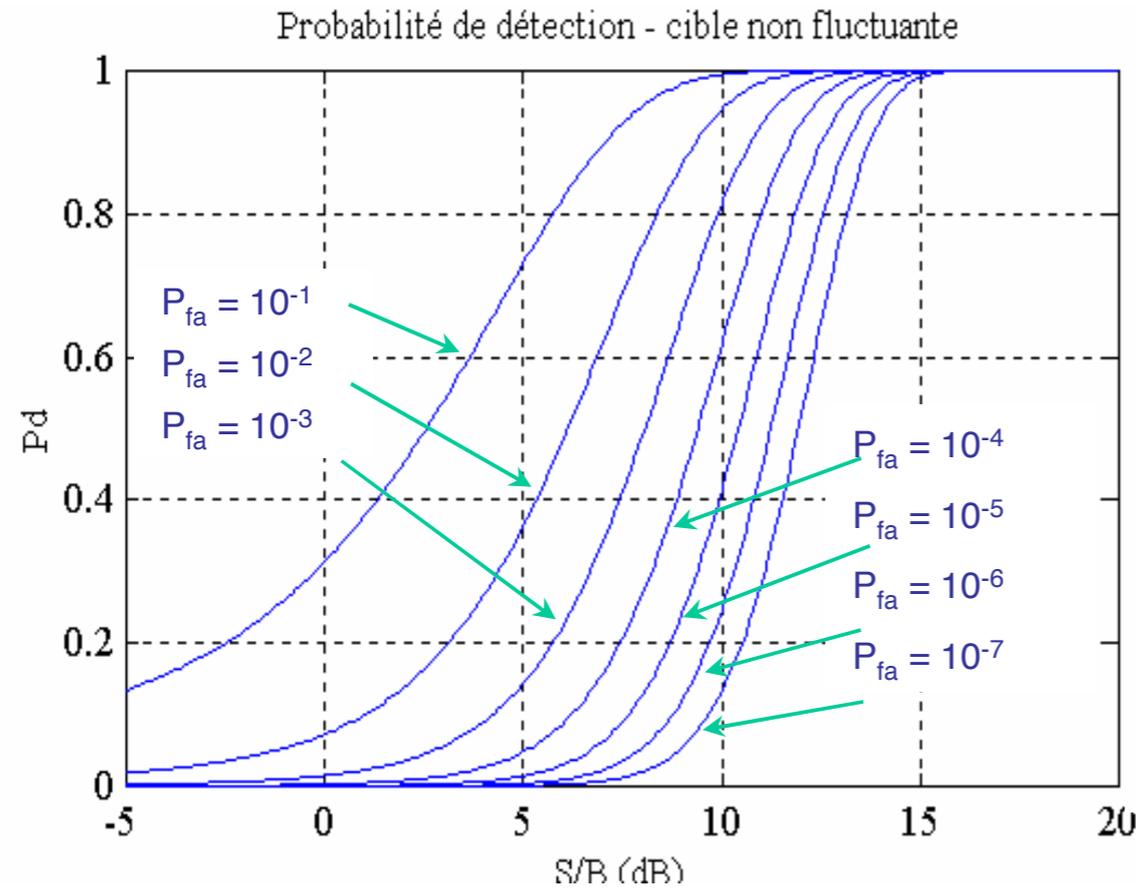
**High SNR (=contrast) = easy compromise  $P_d$  /,  $P_{fa}$**

non fluctuating target :  $S/B \sim 13$  dB pour  $P_{fa} = 10^{-6}$  et  $P_d = 0.9$

fluctuating target :  $S/B \sim 21$  dB pour  $P_{fa} = 10^{-6}$  et  $P_d = 0.9$

# TARGET DETECTION PERFORMANCE

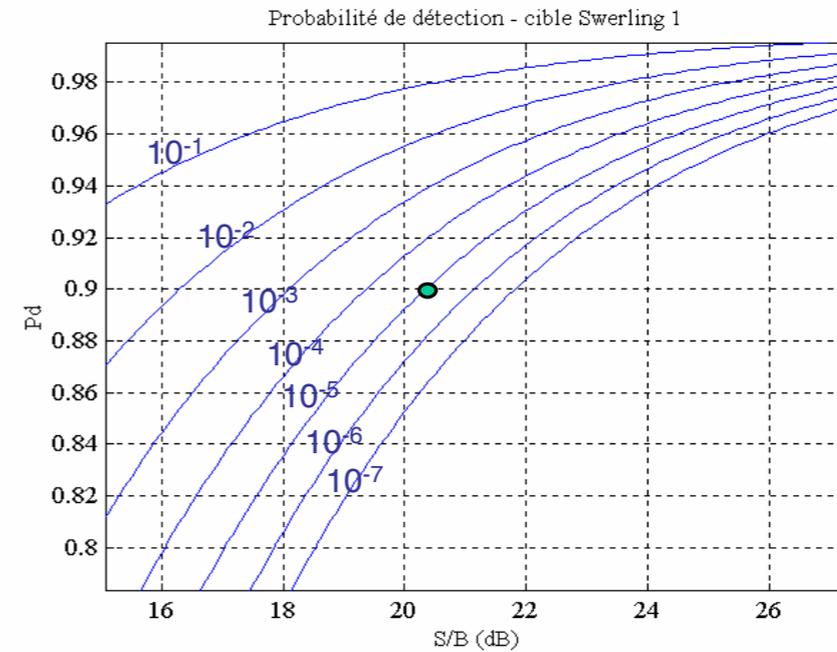
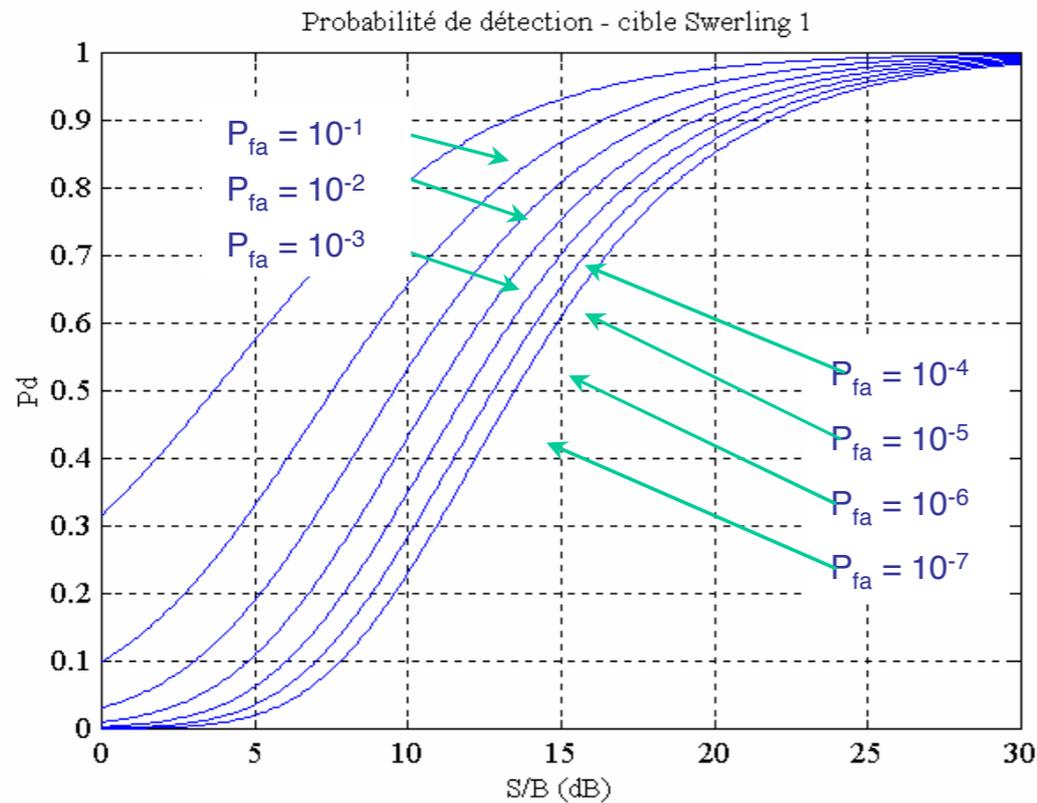
## Non fluctuating target (Swerling-0)



$$h = -2 \ln[2P_{fa}] \quad a = \sqrt{2 S/B} \quad \Rightarrow \quad P_d = \frac{1}{\sqrt{2\pi}} \int_{h-a}^{\infty} e^{-\frac{y^2}{2}} dy$$

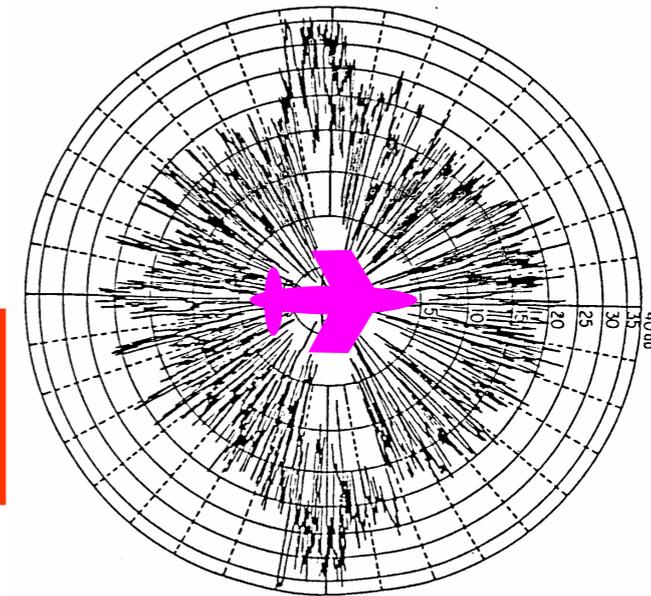
# TARGET DETECTION PERFORMANCE

## Fluctuating target (Swerling-1)



$$P_{fa} = e^{-\frac{h^2}{2}} \quad \text{et} \quad P_d = \frac{h^2}{2(1+\frac{S}{B})}$$

$$S/B = \frac{\log P_{fa}}{\log P_d} - 1 \quad \text{ou} \quad [S/B]_{dB} = 10 \log_{10} \left[ \frac{\log P_{fa}}{\log P_d} - 1 \right]$$



# AIRBORNE RADAR MISSIONS

## Different kinds of radar

Fighter radar

Early warning systems(EAW,  
AWACS)

Missile seeker

Weather radar

## Various functions

Air target detection

Ground Imaging, earth mapping

Ground target detection and tracking

Terrain following

Turbulence and air detection

# FIGHTER CONTROL RADAR

## Multifunctional / Multimode Radar

Air Surveillance, volume search

Tracking of air targets

Cueing

Identification

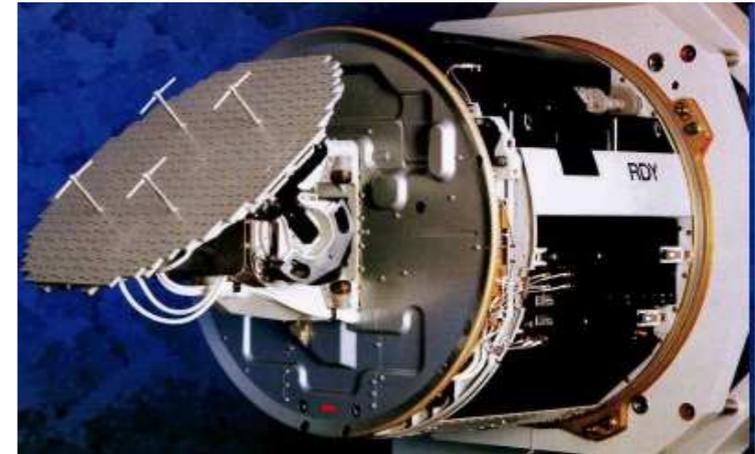
Ground target surveillance

SAR / imaging mode

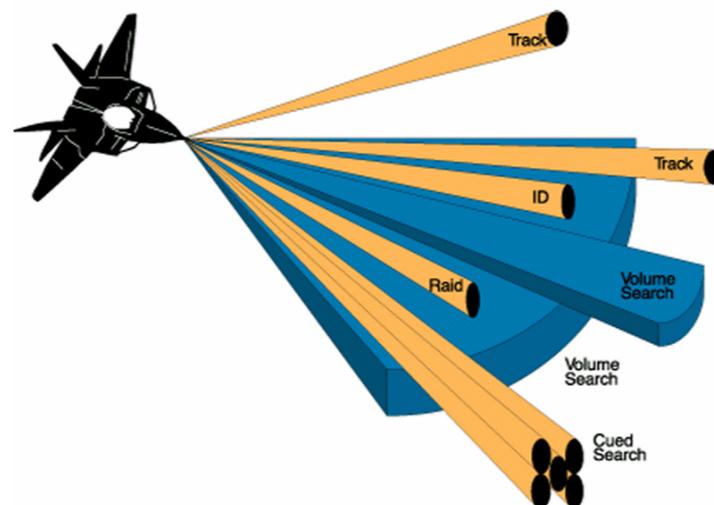
ESM, jammer tracking

Terrain following

**Usually operates at X-band**



RDY (Thales) M2000 Radar



AN/APG-77 (Northrop Grumman) F-22 Radar



RBE2-AA (Thales)  
Rafale Radar

# AIRBORNE EARLY WARNING SURVEILLANCE

## Airborne Early Warning and control

Defensive and offensive air operations

To direct fighters to their target locations

Defensively to counter attacks.

Surveillance, to support C2BM (command and control, battle management) functions

Detection of low altitude targets

Usually operates from UHF to S band

(depending on the coverage, aircraft and mission)



AWACS E-3 Sentry (US)  
S-band



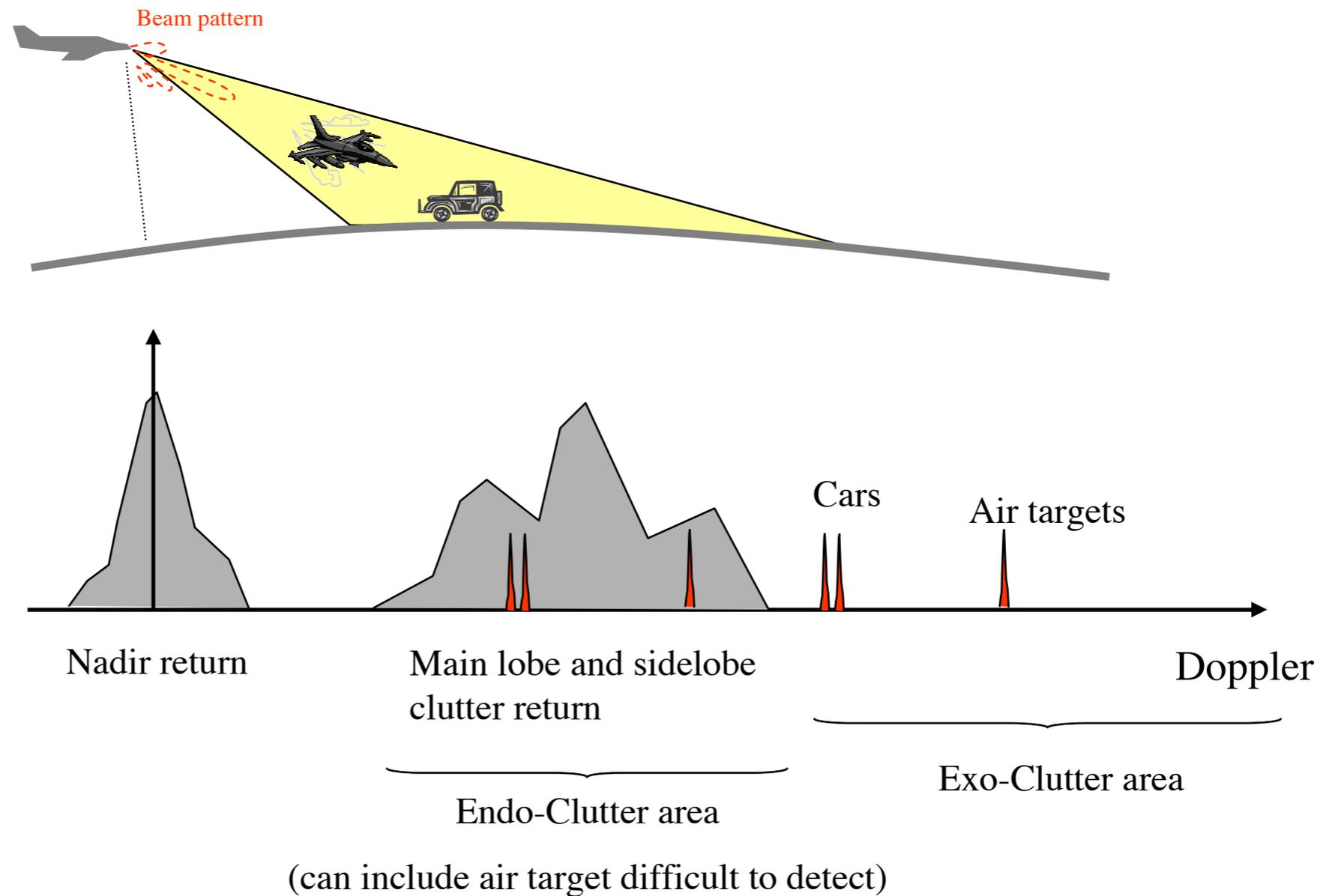
EMB-145 Erieye Airborne Early  
Warning and Control Aircraft,  
Brazil (L-band)



E-2C Hawkeye (Northrop  
Grumman) – UHF band

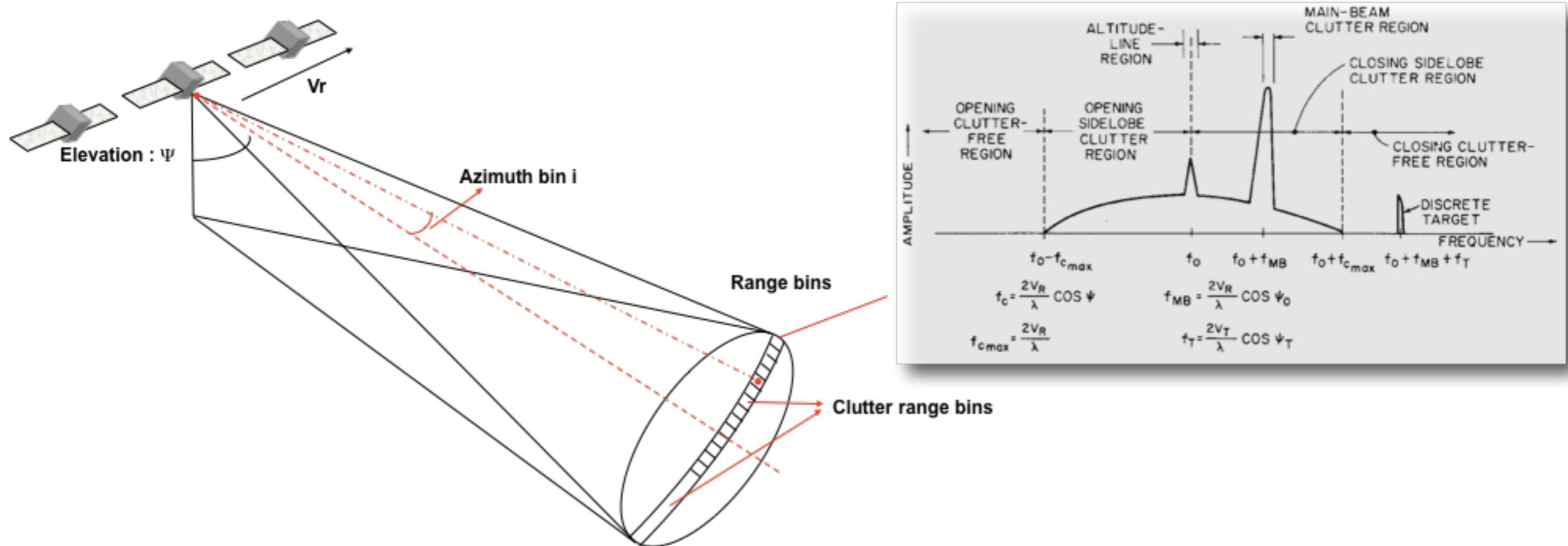
# COMPLEXITY OF AIRBORNE RADAR

## A complex environment



**New processing schemes are considered to mitigate clutter contamination, both for air and ground targets : STAP (Space Time Adaptive Processing)**

# COMPLEXITY OF AIRBORNE RADAR



The illuminated area is wide:

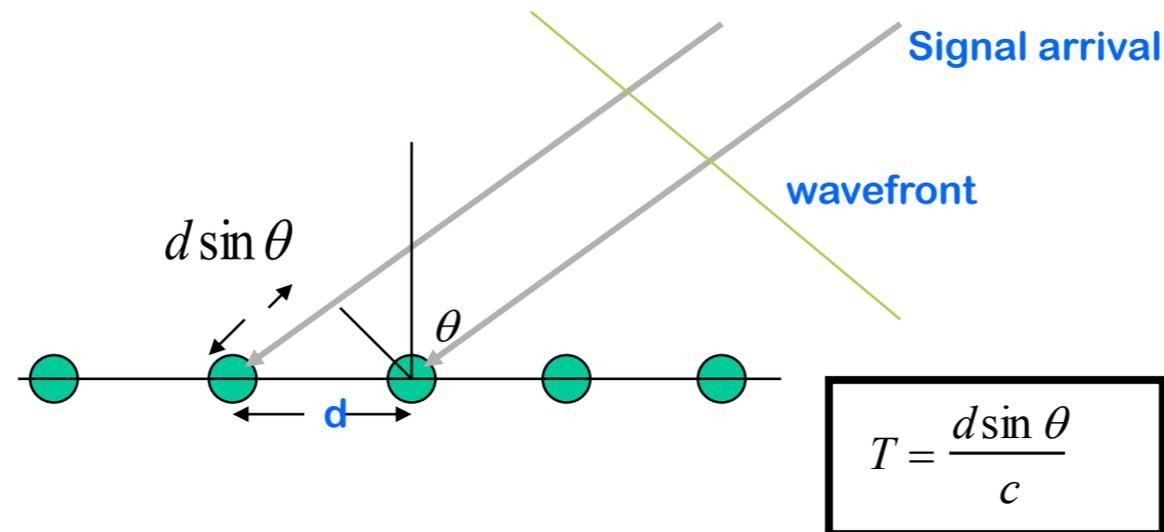
- the radar collects strong ground clutter echos in the same angular domain as targets to detect.
- the Doppler spread can be important

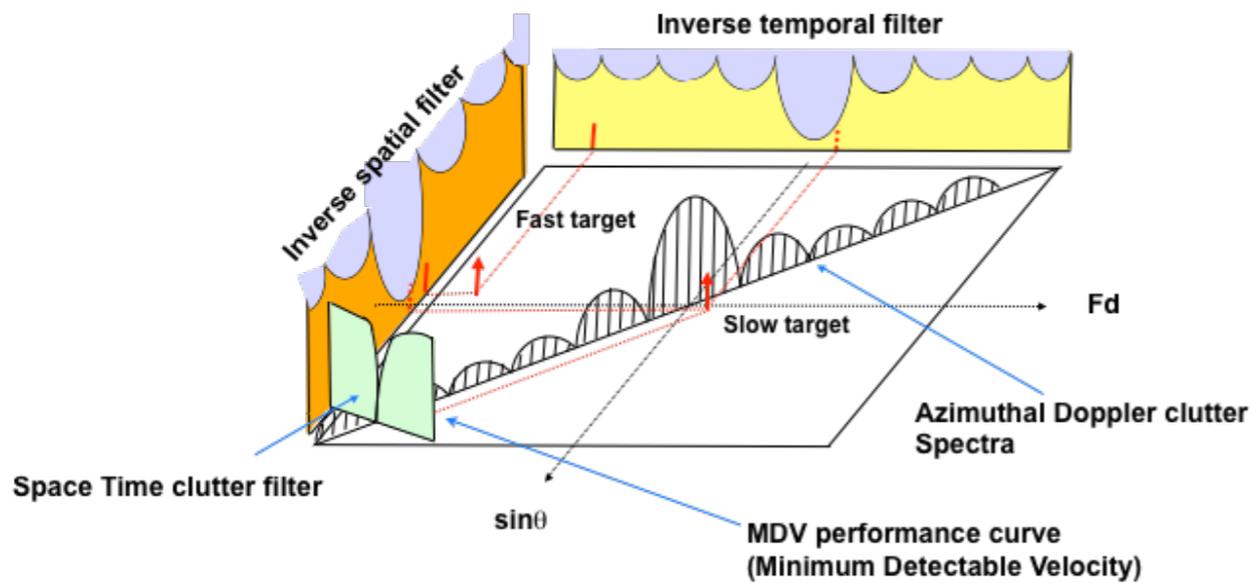
# ARRAY PROCESSING - STAP

## Source locating in azimuth $\theta$ , at Doppler $\nu$ and in range bin $c\tau/2$

If the radar receives signal on antenna array, each antenna is collecting  $s_r(t)$  delayed by the time shift  $T = nd \sin \theta / c$  depending on its spatial position  $nd$  ( $n \in [0, N_s]$ ) on the array. Supposing that the array is non-dispersive ( $N_s d \sin \theta \ll c/B$ ), the concatenated  $N_s \times m$ -observation vector  $\mathbf{y}$  collected by the radar on the antenna array for a given range bin  $c\tau/2$  and Doppler  $\nu$  is then:

$$\mathbf{y} = \mathbf{A} \mathbf{p} \otimes \left( 1, e^{2i\pi f_0 d \sin \theta / c}, \dots, e^{2i\pi f_0 (N_s - 1) d \sin \theta / c} \right)^T + \mathbf{b}(t).$$





- Spatial clutter filtering
- Temporal clutter filtering
- Space-Time clutter filtering

## Spatial Filter

- Band stop in the azimuthal antenna main lobe
- Cancellation of the target return
- Adaptive process which makes the radar blind

## Temporal Filter

- Band stop in the spectral clutter spread in the main beam of the antenna
- Used in situations where the clutter has no more spectral spread
- Fast targets will be detected in the main lobe of the antenna will be detected in secondary temporal lobes. Slow targets are canceled.

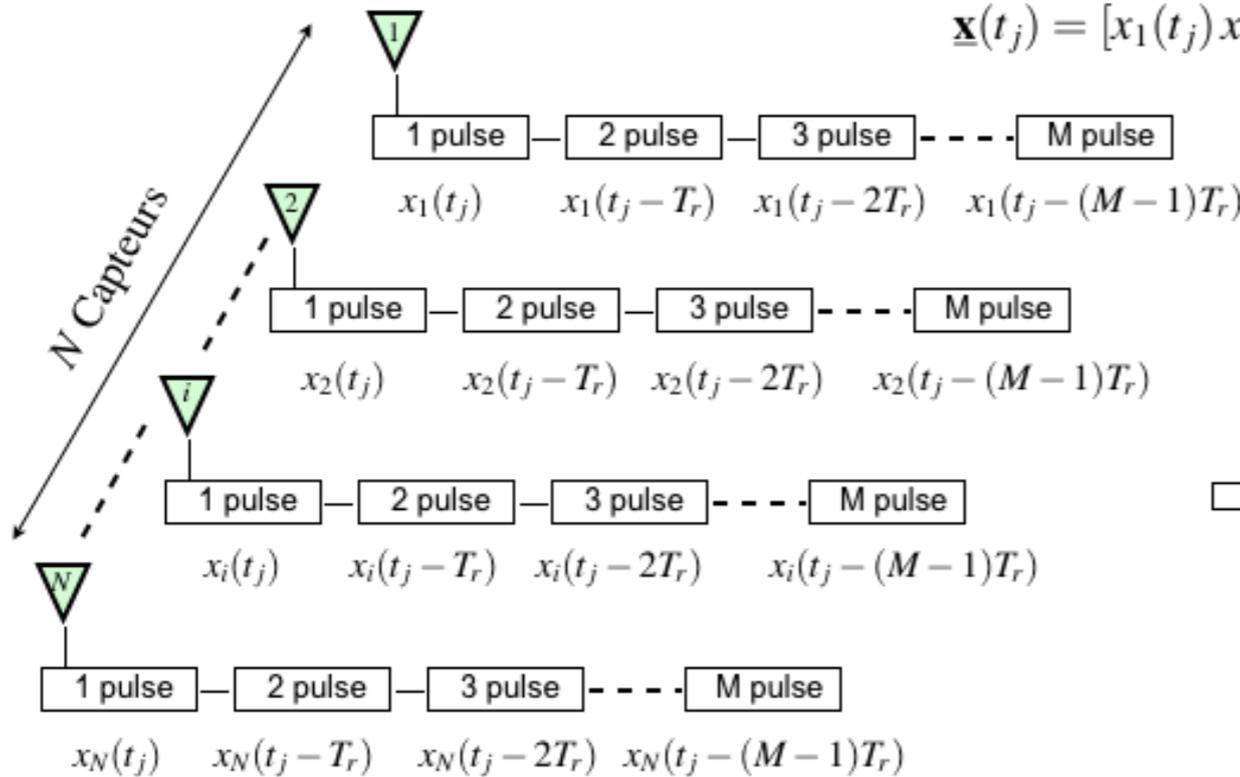
## Joint Spatio-Temporal filter: Space Time Adaptive Processing

# DATA COLLECTED IN THE ARRAY

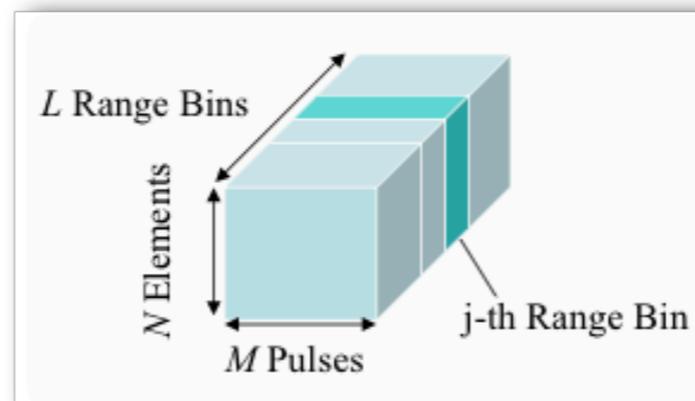
Antennas  $\nabla 1 \quad \nabla 2 \quad \dots \quad \nabla i \quad \dots \quad \nabla N$   
 Output  $x_1(t_j) \quad x_2(t_j) \quad \dots \quad x_i(t_j) \quad \dots \quad x_N(t_j)$

$$\underline{\mathbf{x}}(t_j) = [x_1(t_j) \ x_2(t_j) \ \dots \ x_i(t_j) \ \dots \ x_N(t_j)]^T$$

data collected in  $MN \times 1$  data vector with period  $T_r$  in the range bin  $j$



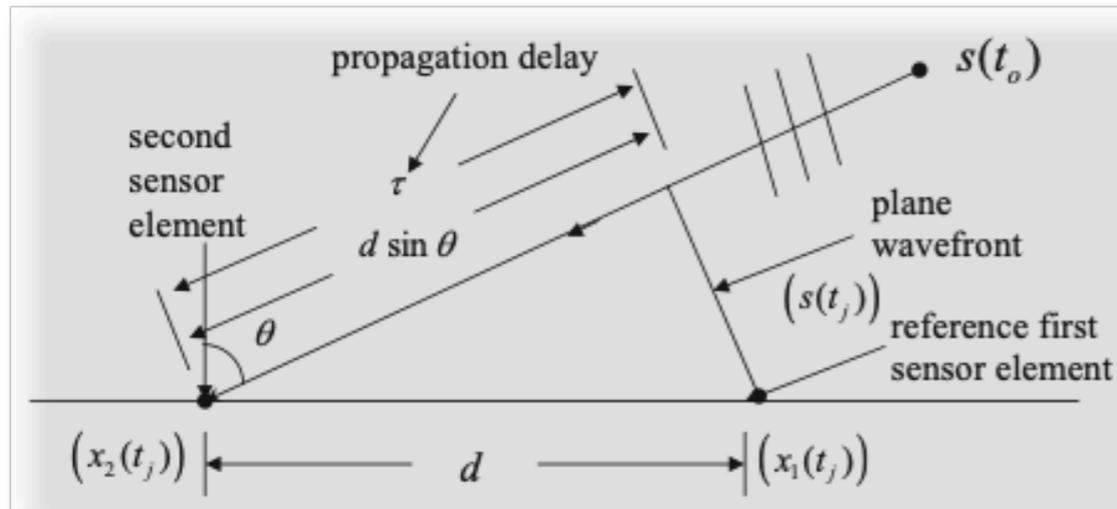
$$\underline{\mathbf{X}}_j = \begin{pmatrix} \underline{\mathbf{x}}(t_j) \\ \underline{\mathbf{x}}(t_j - T_r) \\ \vdots \\ \underline{\mathbf{x}}(t_j - kT_r) \\ \vdots \\ \underline{\mathbf{x}}(t_j - (M-1)T_r) \end{pmatrix}$$



Data collection on  $L$  range bins

# JOINT USE OF THE TEMPORAL AND SPATIAL DIMENSION

Use of the difference march for a source localized in the direction  $\theta$



$$\underline{\mathbf{x}}(t_j) = \begin{pmatrix} x_1(t_j) \\ x_2(t_j) \\ \vdots \\ x_k(t_j) \\ \vdots \\ x_N(t_j) \end{pmatrix} = s(t_j) \begin{pmatrix} 1 \\ e^{-2i\pi \frac{d}{\lambda} \sin \theta} \\ \vdots \\ e^{-2i\pi(k-1) \frac{d}{\lambda} \sin \theta} \\ \vdots \\ e^{-2i\pi(N-1) \frac{d}{\lambda} \sin \theta} \end{pmatrix} = s(t_j) \underline{\mathbf{a}}_N(\theta)$$

Use of the relative Doppler  $f_d = \frac{2v}{\lambda} \sin \theta$  between the sensors and the target for all the period of repetition  $T_r$

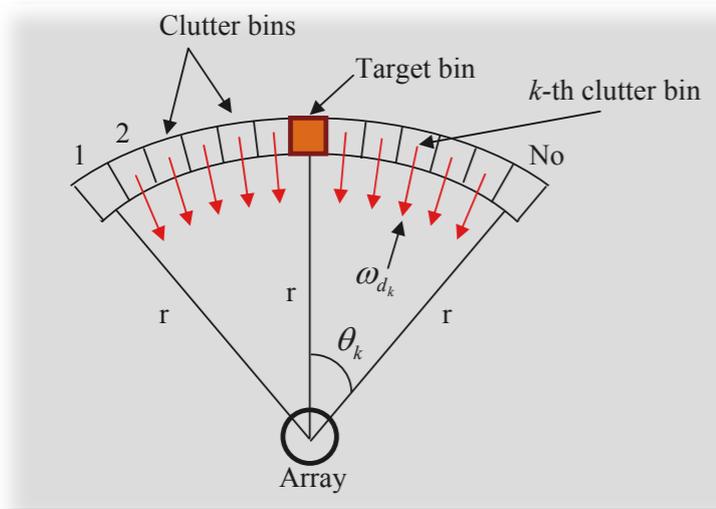
$$\underline{\mathbf{x}}(t_j - kT_r) = \underline{\mathbf{x}}(t_j) e^{-2i\pi(k-1)f_d T_r} = s(t_j) \underline{\mathbf{a}}_N(\theta) e^{-2i\pi(k-1)f_d T_r}$$

$$\underline{\mathbf{X}}_j = \begin{pmatrix} \underline{\mathbf{x}}(t_j) \\ \underline{\mathbf{x}}(t_j - T_r) \\ \vdots \\ \underline{\mathbf{x}}(t_j - kT_r) \\ \vdots \\ \underline{\mathbf{x}}(t_j - (M-1)T_r) \end{pmatrix} = s(t_j) \begin{pmatrix} \underline{\mathbf{a}}_N(\theta) \\ \underline{\mathbf{a}}_N(\theta) e^{-2i\pi f_d T_r} \\ \vdots \\ \underline{\mathbf{a}}_N(\theta) e^{-2i\pi(k-1)f_d T_r} \\ \vdots \\ \underline{\mathbf{a}}_N(\theta) e^{-2i\pi(M-1)f_d T_r} \end{pmatrix} \downarrow = s(t_j) \begin{pmatrix} 1 \\ e^{-2i\pi f_d T_r} \\ \vdots \\ e^{-2i\pi(k-1)f_d T_r} \\ \vdots \\ e^{-2i\pi(M-1)f_d T_r} \end{pmatrix} \otimes \underline{\mathbf{a}}_N(\theta) = s(t_j) \underline{\mathbf{b}}_M(f_d) \otimes \underline{\mathbf{a}}_N(\theta)$$

$$\underline{\mathbf{X}}_j = s(t_j) \underline{\mathbf{b}}_M(f_d) \otimes \underline{\mathbf{a}}_N(\theta) = s(t_j) \underline{\mathbf{a}}(\theta, f_d)$$

# STAP OPTIMAL DETECTION

Detection Scheme in the  $j$ -th range bin:  $\underline{\mathbf{X}}_j = \begin{cases} \alpha_0 \underline{\mathbf{a}}(\theta_0, f_{d,0}) + \underline{\mathbf{X}}_c, & \text{under } H_0 \text{ hypothesis} \\ \underline{\mathbf{X}}_c, & \text{under } H_1 \text{ hypothesis} \end{cases}$



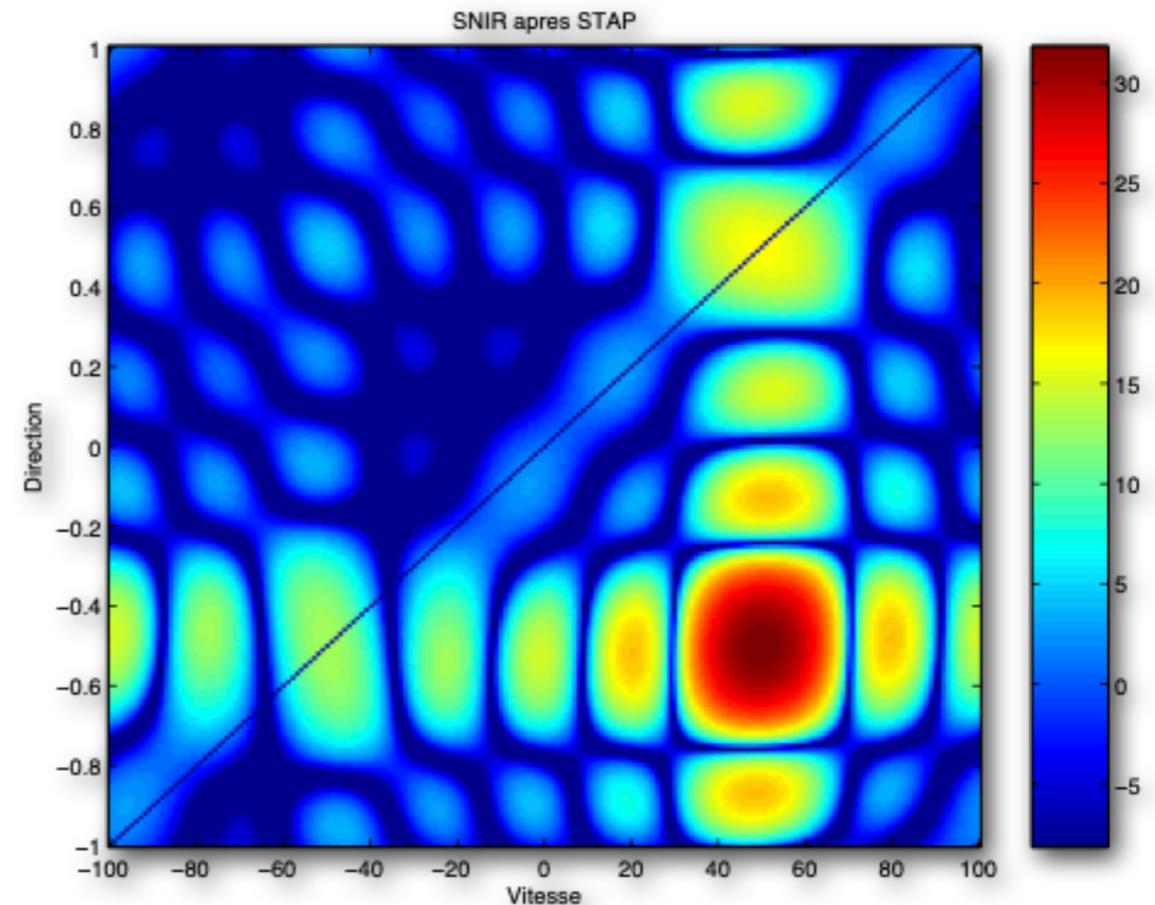
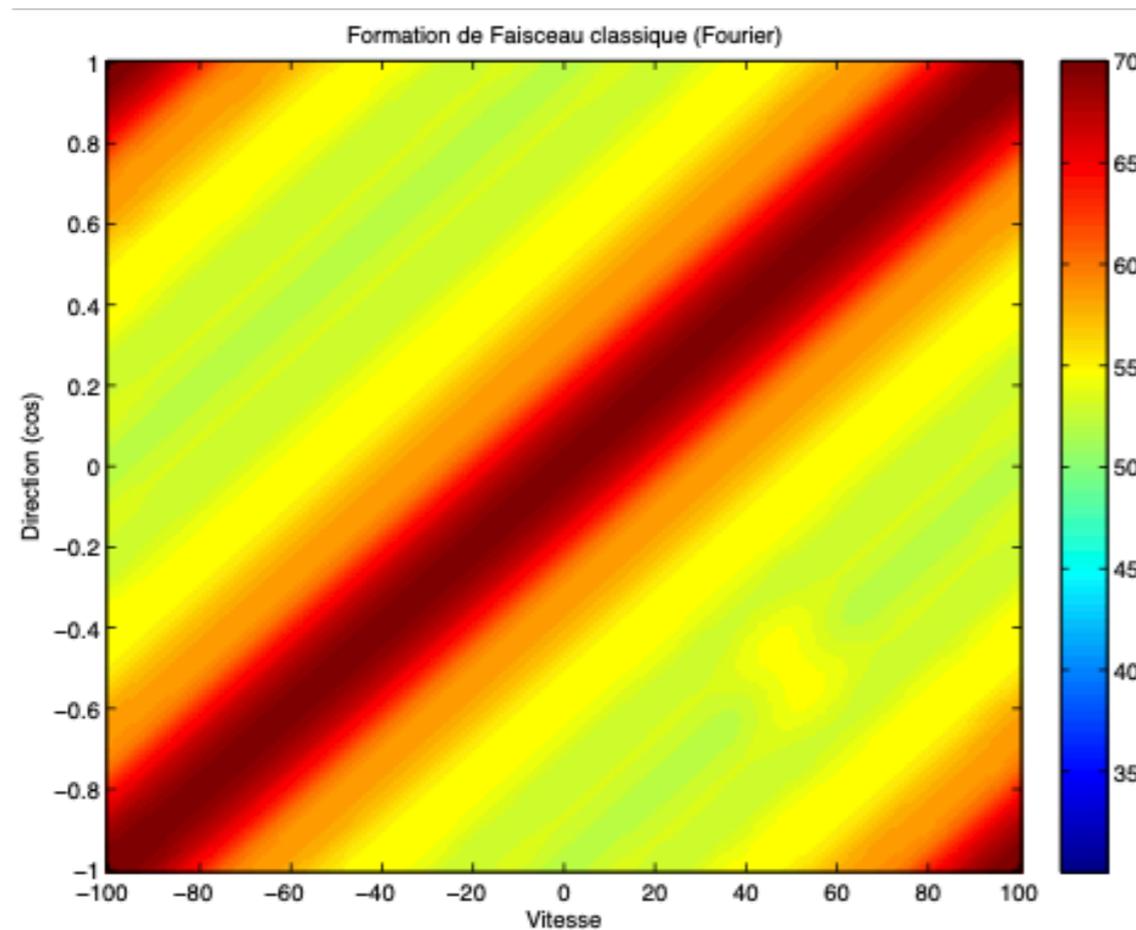
- $\underline{\mathbf{X}}_c = \sum_{k=1}^{N_0} c_k(f_{d,k}) \underline{\mathbf{a}}(\theta_k, f_{d,k}) + \underline{\mathbf{n}}$ ,
- $f(d, k) = \frac{2v T_r}{d} \frac{2d \sin \theta_k}{\lambda} = \beta \frac{2d \sin \theta_k}{\lambda}$ ,
- $\underline{\mathbf{n}}$  is the thermal noise,
- $\{c_k\}_{k=1, N_0}$  the clutter amplitudes in direction  $\theta_k$ ,
- $\alpha_0, \theta_0, f_{d,0}$  are the unknown target parameters.

The detection test in the range bin  $j$ , in the azimuth  $\theta$  and for Doppler  $f_d$  becomes:

$$\Lambda(\underline{\mathbf{X}}_j, \theta, f_d) = \frac{p(\underline{\mathbf{X}}_j / H_1)}{p(\underline{\mathbf{X}}_j / H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda.$$

where  $p(\cdot)$  is the Probability Density Function of the cell under test  $\underline{\mathbf{X}}_j$ .

# IDEAL STAP PROCESSING



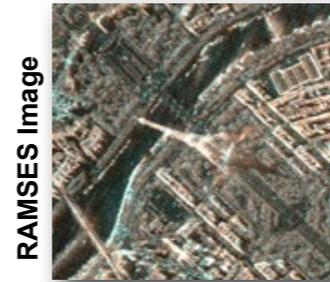
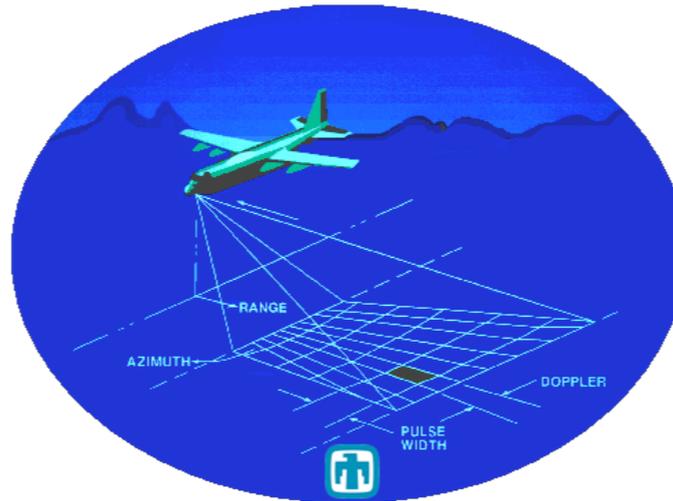
$$\Lambda(\underline{\mathbf{X}}_j, \theta, f_d) = \frac{|\underline{\mathbf{a}}^H(\theta, f_d) \mathbf{M}^{-1} \underline{\mathbf{X}}_j|^2}{\underline{\mathbf{a}}^H(\theta, f_d) \mathbf{M}^{-1} \underline{\mathbf{a}}(\theta, f_d)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda,$$

where  $\mathbf{M} = E[\underline{\mathbf{X}}_c \underline{\mathbf{X}}_c^H]$  if the true covariance matrix of the clutter.

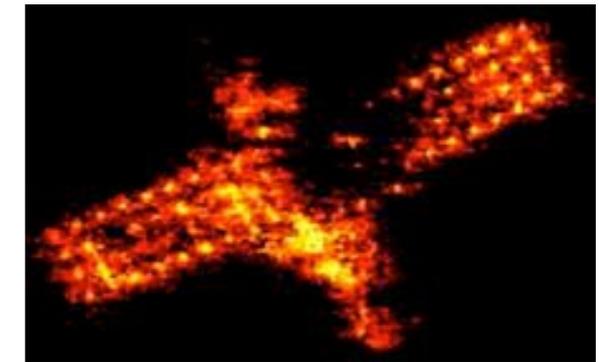
# SYNTHETIC APERTURE RADAR



ONERA RAMSES Image



RAMSES Image



ONERA ISAR Image



ONERA RAMSES Image

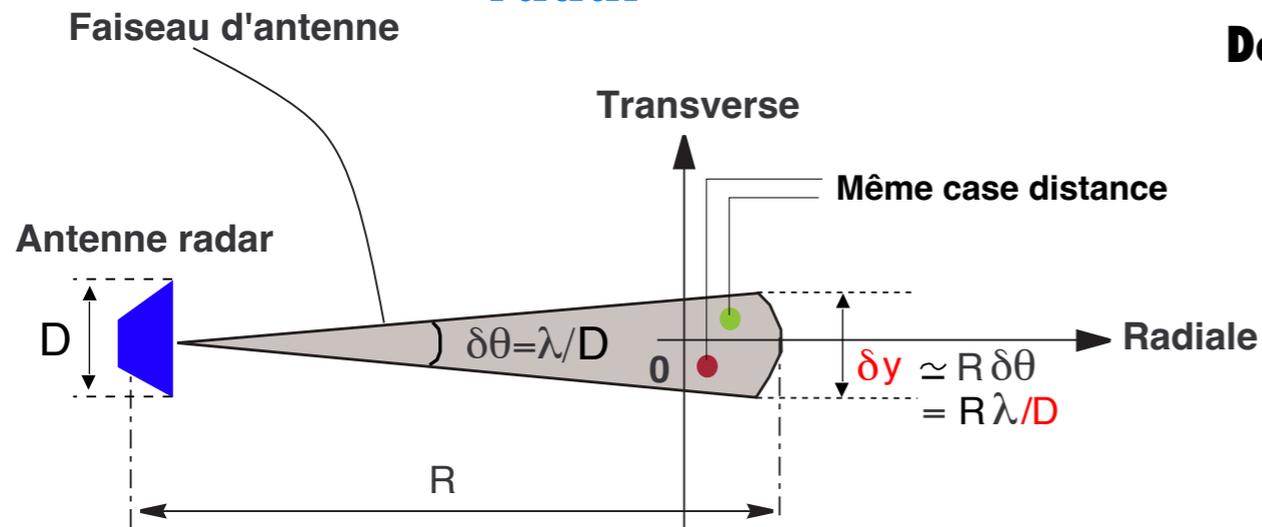
Radar Imaging [Mensa, 1981, Soumekh, 1994, Soumekh, 1999] allows to build more and more precise images:

- Current use of **very high spectral bandwidth** and **very high angular bandwidth** leading to very high spatial resolution,
- Application to monitoring (detection, change detection), classification, 3D reconstruction, EM analysis, etc.

These applications require some physical diversity to reach good performances.

# Formation d'image à haute résolution

## Résolution transverse en radar



## Radar RAMSES\* à l'ONERA



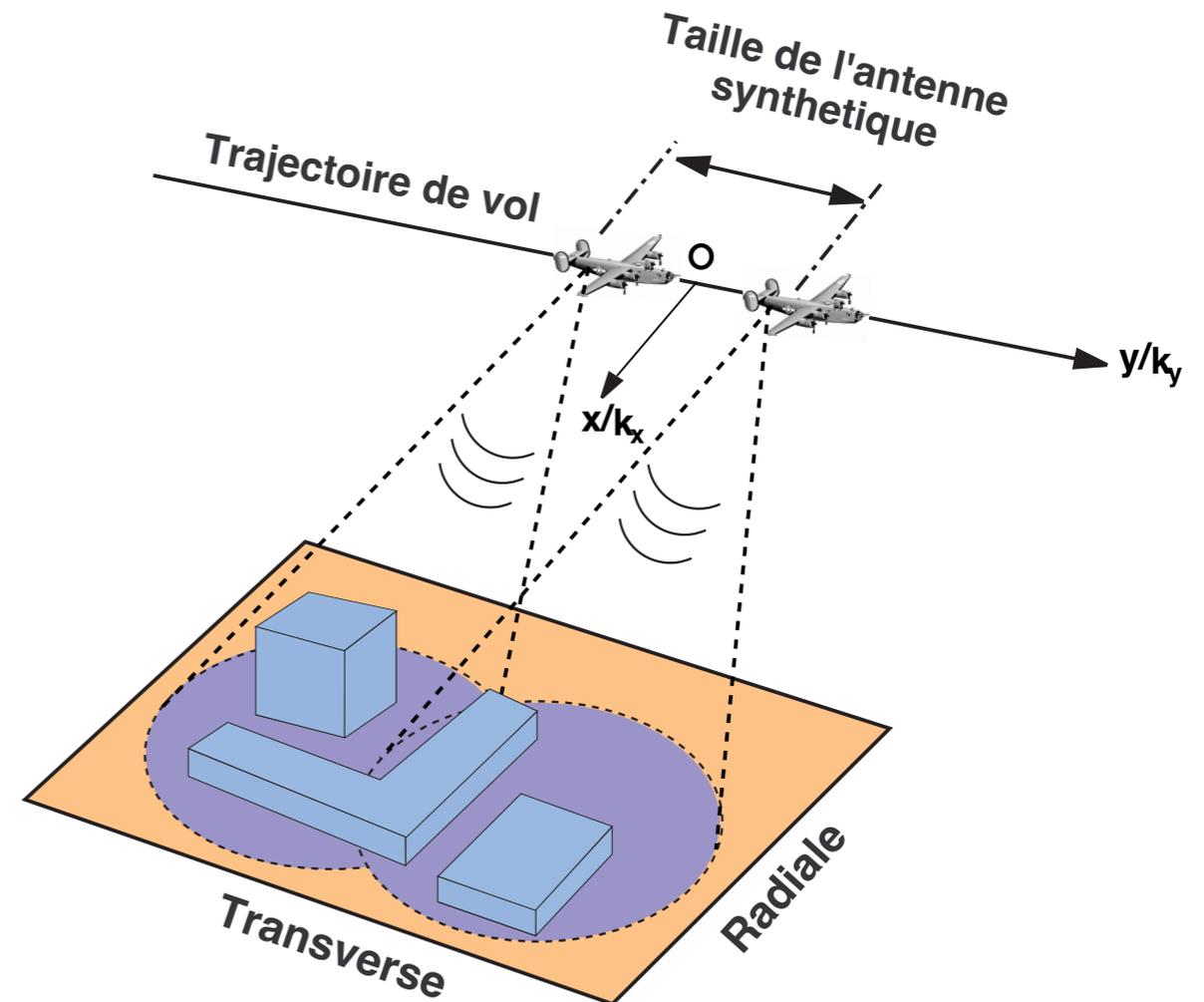
\* **RAMSES** : Radar d'Analyse MultiSpectrale et d'Etudes de Signatures

## Principe de l'imagerie SAR

Déplacement de l'antenne =  
**antenne virtuelle de grande dimension**



**Meilleure résolution transverse**

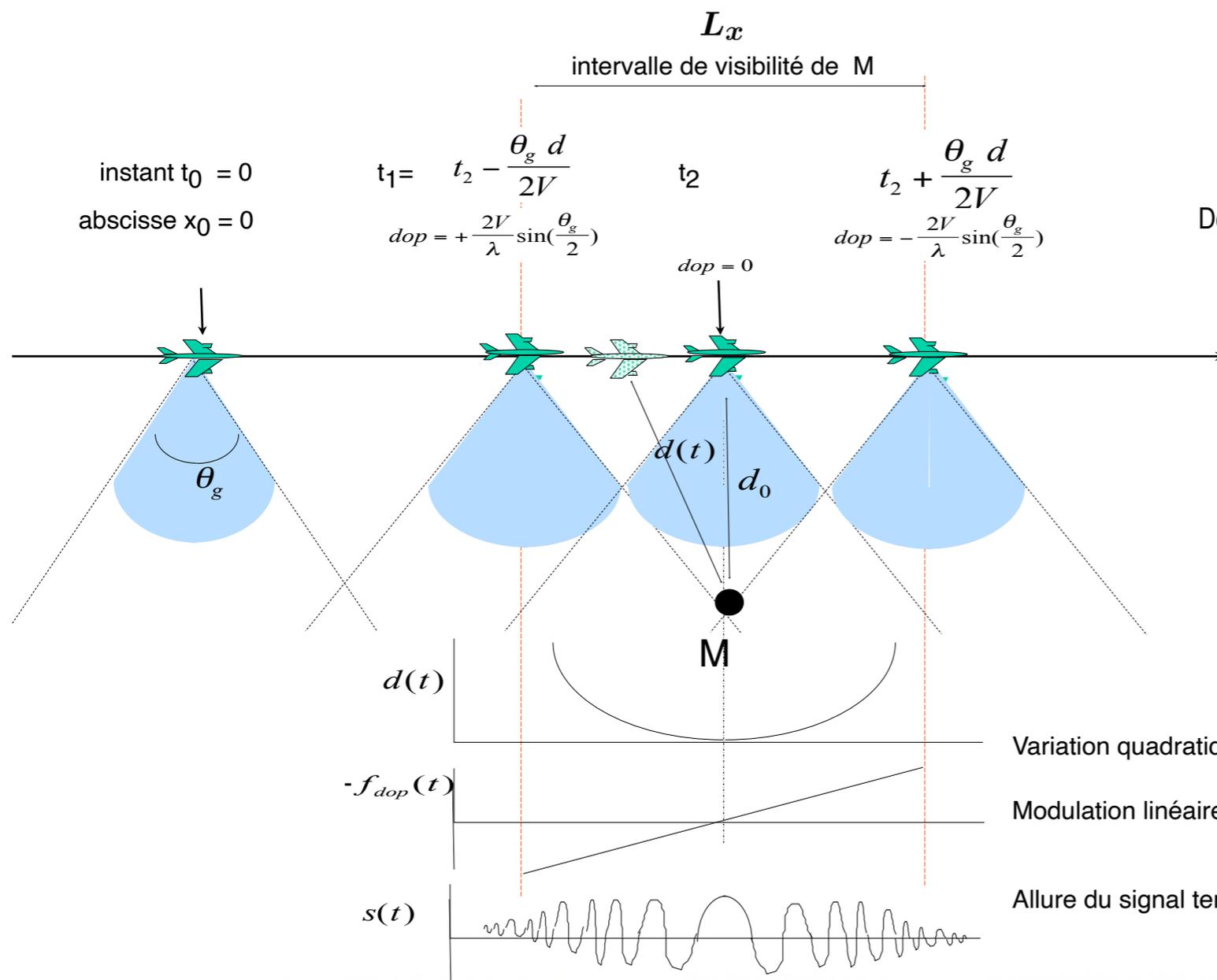
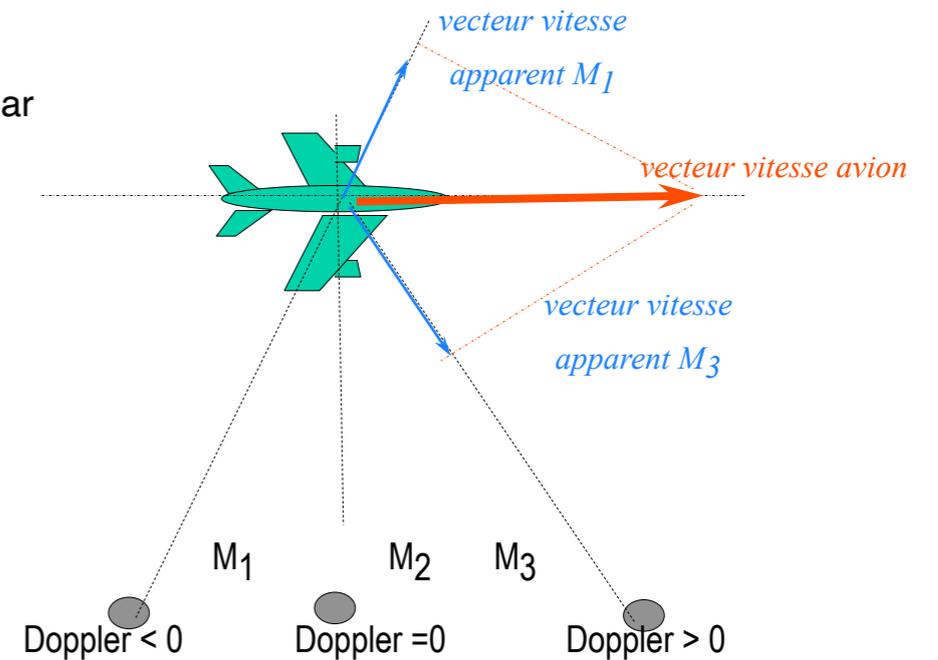


# LE RADAR A OUVERTURE SYNTHETIQUE (SAR)

Exploitation de l'effet Doppler

La fréquence Doppler dépend de la position transversale du rétrodiffuseur (point brillant) par rapport au radar

La fréquence Doppler apparente d'un rétrodiffuseur varie dans le temps d'observation d'un radar



$$L_x = v (t_2 - t_1)$$

# Généralités

## Applications civiles et militaires

- Cartographie (IGN...) ; 2D & 3D
- Navigation, suivi de terrain
- Recalage de la navigation ; guidage
- Reconnaissance et acquisition d'objectifs
- Contrôle/étude de la végétation (forêts, cultures), écologie
- Océanographie ; glaciologie
- Surveillance / imagerie (véhicules, satellites ...)

...

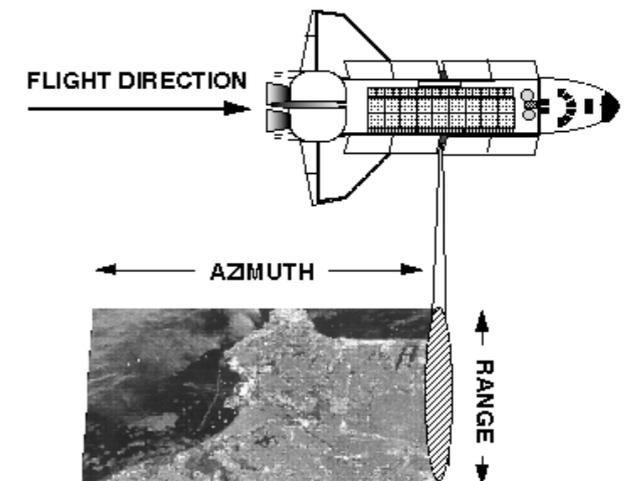
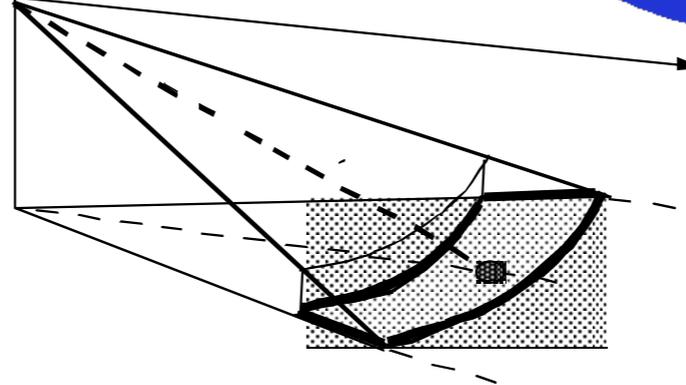
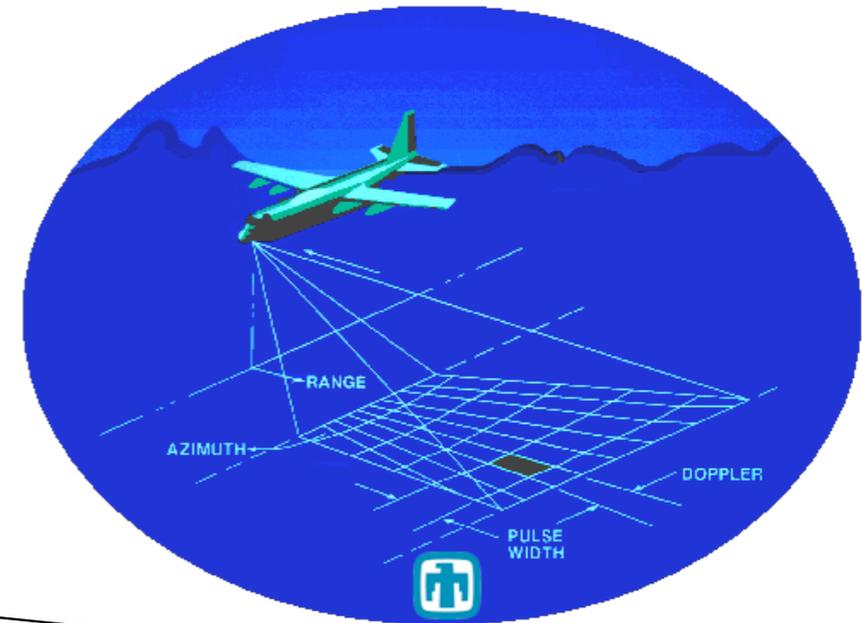
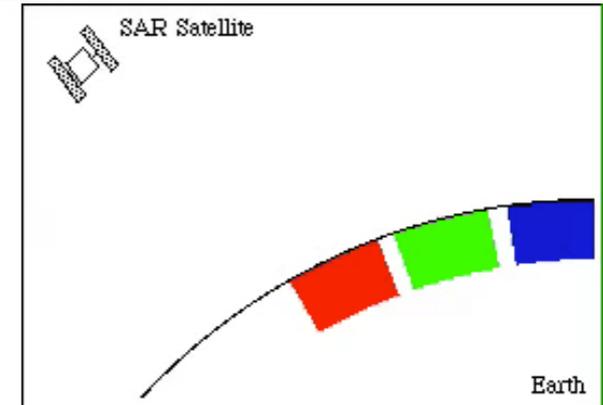
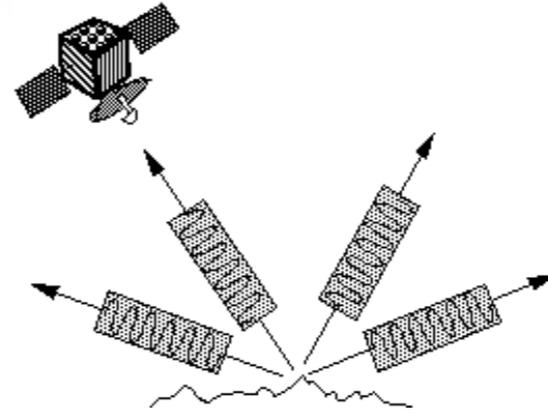
## Plate - forme

### Observation du sol :

- Avion
- Drone (+ missile)
- Satellite
- Navette spatiale

### Observation des objets mobiles :

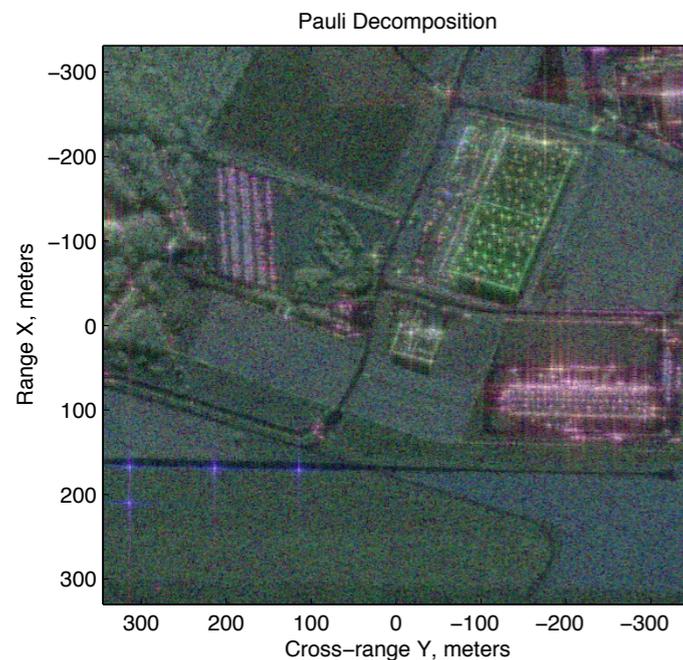
- Radar sol/mer vers avion, satellite ou bateaux
- Avion/satellite vers avion, sol et mer



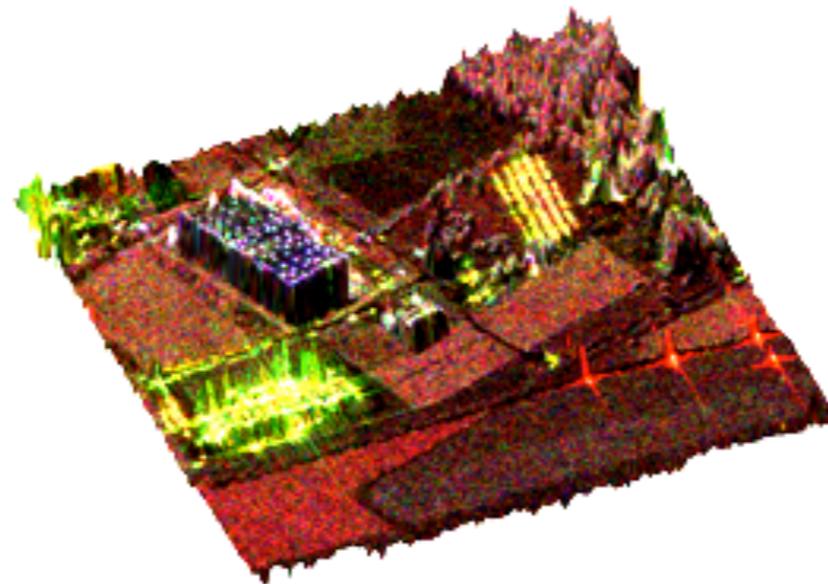
# MULTI-CHANNELS SAR IMAGES

Multi-channel SAR images automatically propose this diversity through:

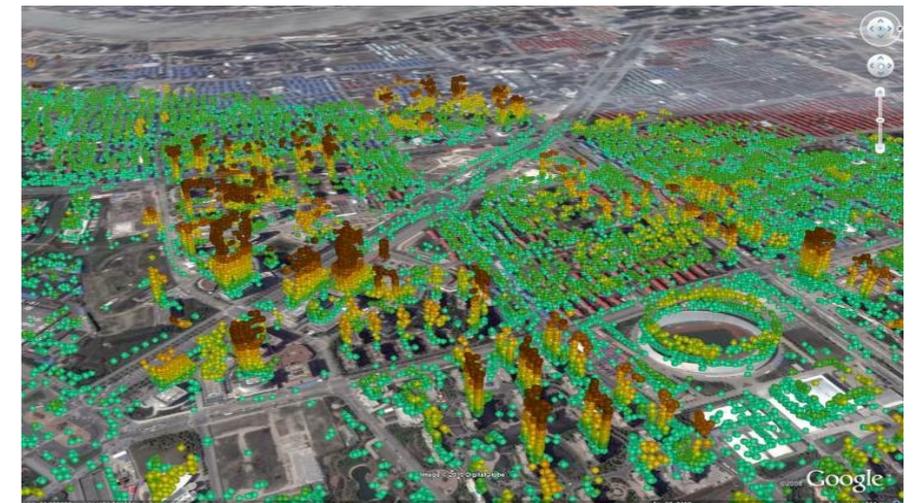
- polarimetric channels (POLSAR), interferometric channels (INSAR), polarimetric and interferometric channels (POLINSAR),
- multi-temporal, multi-passes SAR Image, etc.



EM behavior of the terrain  
in POLSAR images



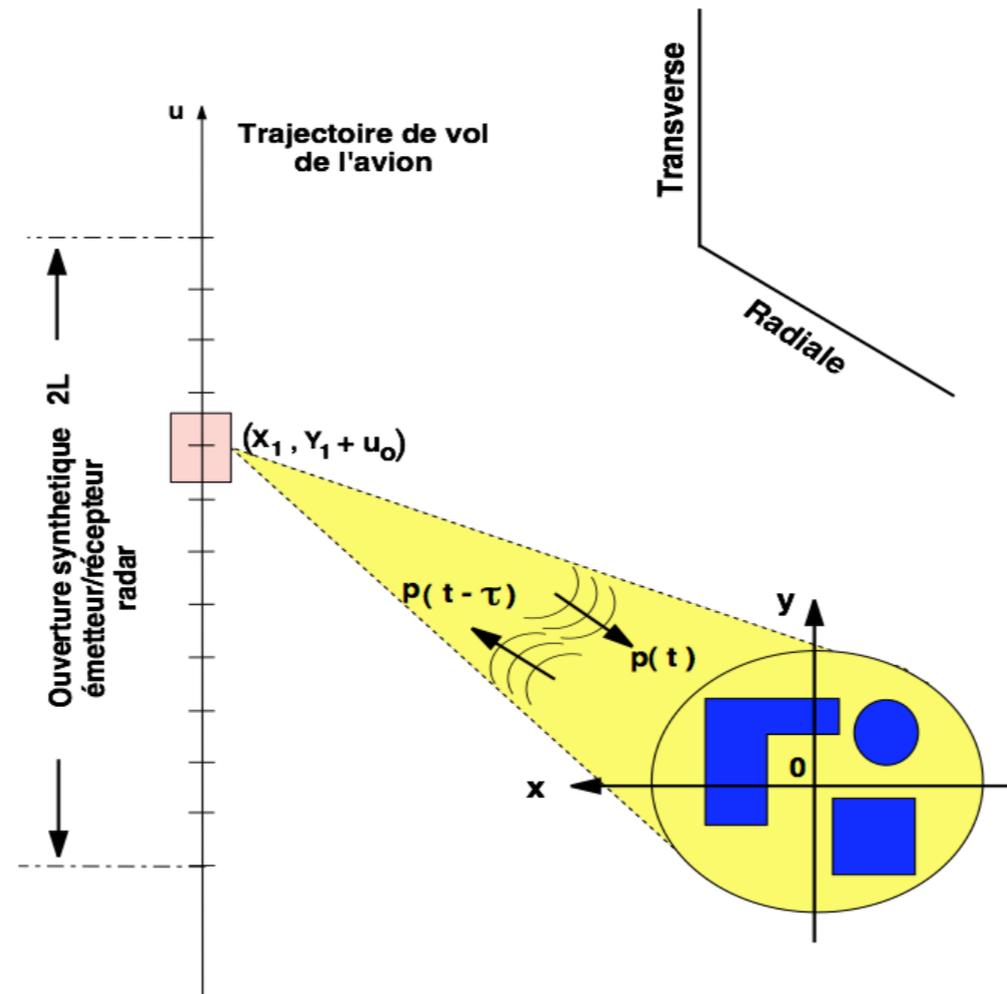
Estimation of the height  
in POLINSAR images



Analysis of the structures displacement in  
Shanghai with multi-temporal SAR images  
(@Telespazio)

**Almost all** the conventional techniques of detection, parameters estimation, speckle filtering techniques, classification in multi-channel SAR images (e.g. polarimetric covariance matrix, interferometric coherency matrix) are based on the **multivariate statistic**.

# SAR PROCESSING



**Goal of SAR Imaging:** Invert the relation:

$$s_r(t, u) = \iint_{\mathbb{R}^2} I(x, y) s_e \left( t - \frac{c}{2} \sqrt{(X - x)^2 + (Y_1 + u - y)^2} \right) dx dy$$

# RANGE MIGRATION (RMA) SAR PROCESSING STEPS

$$s_r(t, u) = \iint_{\mathbb{R}^2} I(x, y) s_e \left( t - \frac{c}{2} \sqrt{(X - x)^2 + (Y_1 + u - y)^2} \right) dx dy,$$

$$\Downarrow \quad t \xrightarrow{\mathcal{F}} k = \frac{2f}{c},$$

$$S_r(k, u) = S_e(k) \iint_{\mathbb{R}^2} I(x, y) \exp \left( -2i\pi k \sqrt{(X_1 - x)^2 + (Y_1 + u - y)^2} \right) dx dy,$$

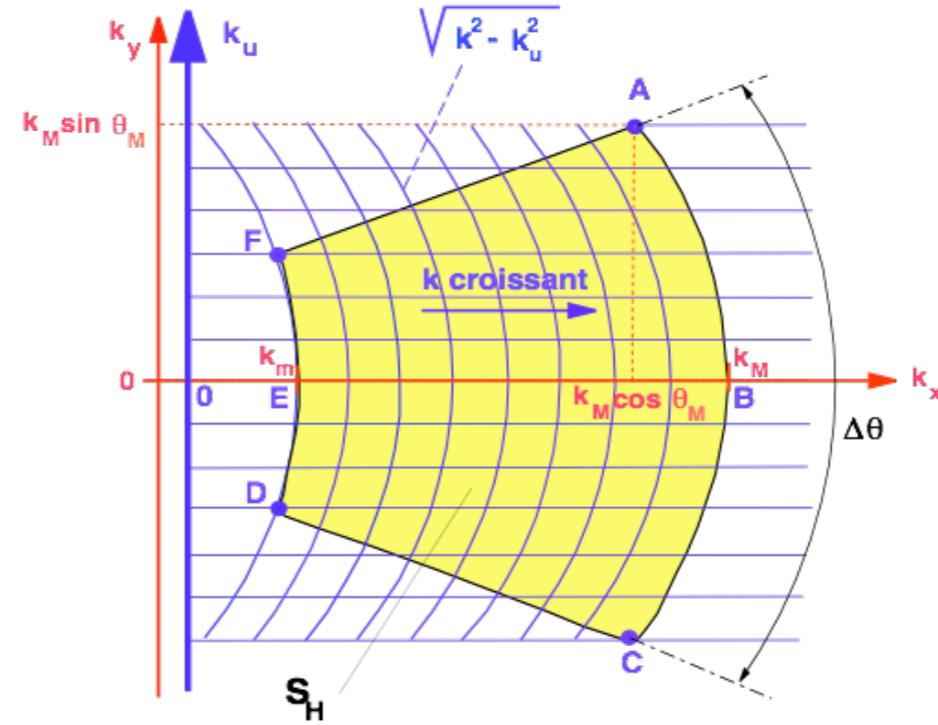
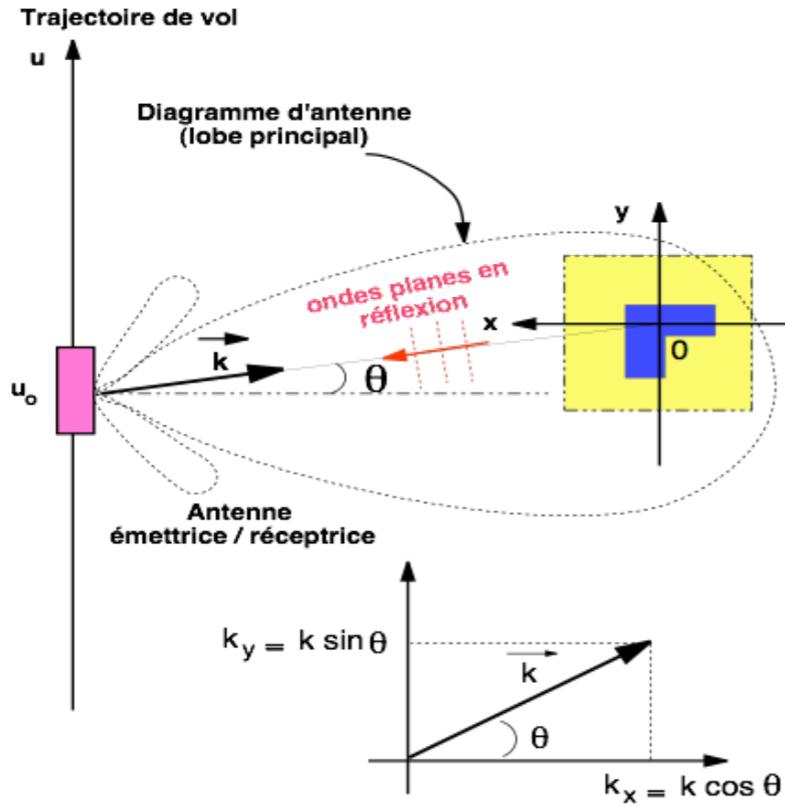
$$\Downarrow \quad u \xrightarrow{\mathcal{F}^{-1}} k_u,$$

$$S_r(k, k_u) = S_e(k) \iint_{\mathbb{R}^2} I(x, y) \exp \left( -2i\pi \left( (X_1 - x) \sqrt{k^2 - k_u^2} + (Y_1 - y) k_u \right) \right) dx dy,$$

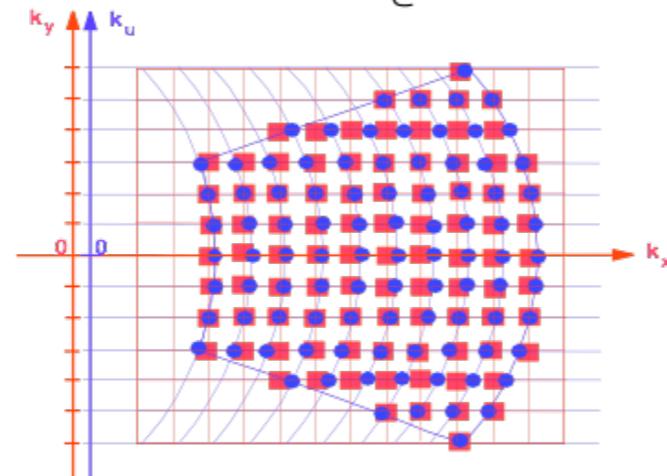
$$\Downarrow \quad \begin{cases} k_x = \sqrt{k^2 - k_u^2} \\ k_y = k_u \end{cases}$$

$$S_r(k_x, k_y) = S_e(k) \exp(-2i\pi k_x X_1 + k_y Y_1) \iint_{\mathbb{R}^2} I(x, y) \exp(2i\pi(k_x x + k_y y)) dx dy$$

# RANGE MIGRATION ALGORITHM PRINCIPLES



Interpolation de Stolt

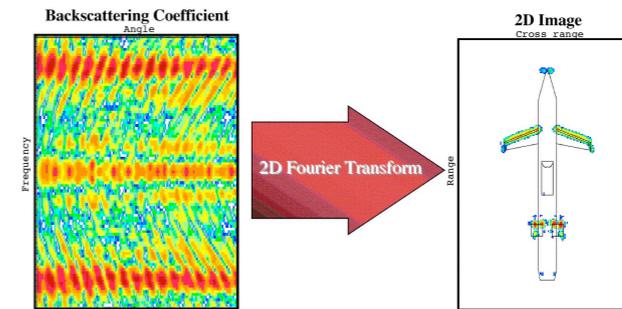
$$\begin{cases} \sqrt{k^2 - k_u^2} \longrightarrow k_x \\ k_u \longrightarrow k_y \end{cases}$$


- Echantillons de données en domaine  $(\sqrt{k^2 - k_u^2}, k_u)$
- Echantillons interpolés sur la grille régulière  $(k_x, k_y)$

# CONVENTIONAL PRINCIPLE OF RADAR/SAR IMAGING

Conventional Fourier Imaging (laboratory, SAR, ISAR):

- Assumptions of white and isotropic bright points
- It does not exploit the potential non-stationarities or diversities of the scatterers



- Hypothesis of bright points modeling: all the scatterers localized in  $\mathbf{x}$  and characterized by the complex spatial amplitude distribution  $I(\mathbf{x})$  have **the same behavior** for any wave vector  $\mathbf{k} = \frac{2f}{c} (\cos \theta, \sin \theta)^T$ . After some processing, the backscattering coefficient  $H(\mathbf{k})$  acquired by the radar is simply related to the SAR image  $I(\mathbf{x})$  through:

$$H(\mathbf{k}) = \int_{\mathcal{D}_{\mathbf{x}}} I(\mathbf{x}) \exp(-2i\pi \mathbf{k}^T \mathbf{x}) d\mathbf{x}.$$

- The SAR image  $I(\mathbf{x})$  is then obtained through the Inverse Fourier Transform:

$$I(\mathbf{x}) = \int_{\mathcal{D}_{\mathbf{k}}} H(\mathbf{k}) \exp(2i\pi \mathbf{k}^T \mathbf{x}) d\mathbf{k}.$$

With this model, all information relative to frequency  $f$  and angle  $\theta$  are lost. Hence, spectral and angular diversities are lost [Bertrand et al., 1994].

# PERFORMANCES DU SAR

## Nature du signal

Existe pendant la durée d'illumination du diffuseur par le lobe d'antenne

Effet Doppler qui dépend de la position transversale du diffuseur

Evolution Doppler assimilable à une rampe linéaire de fréquence

## Performances

durée d'intégration maximale :

$$T_i = \frac{\theta_g d}{v} = \frac{L_x}{v}$$

bande Doppler totale de la modulation:

$$B_{dop} = \frac{4v}{\lambda} \sin \frac{\theta_g}{2} = \frac{2v}{\lambda} \theta_g$$

Nombre de cases de résolution Doppler :

$$N = B_{dop} T_i = \frac{2v}{\lambda} \theta_g \frac{L_x}{v} = 2 \theta_g \frac{L_x}{\lambda}$$

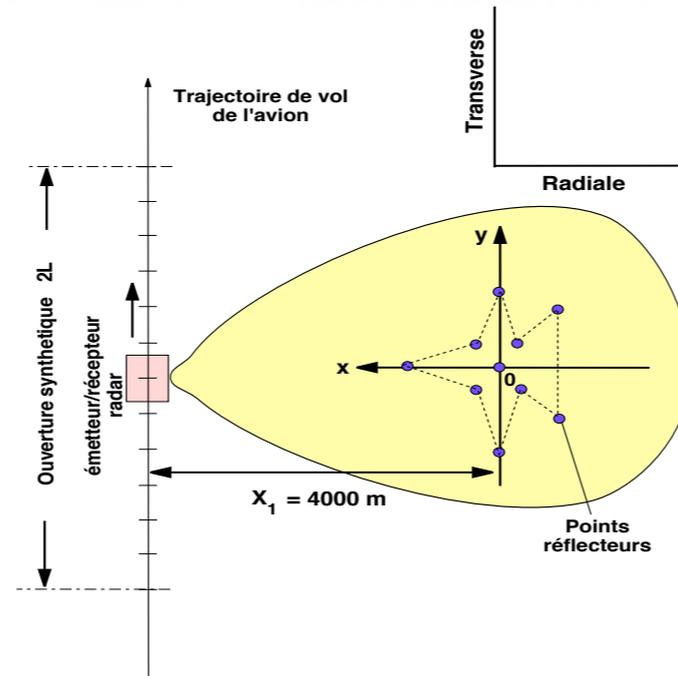
Après traitement, la bande de longueur  $L_x$  parcourue par l'avion est découpée en  $N$  pixels de largeur  $L_x/N$  :

$$\delta_x = \frac{\lambda}{2 \theta_g}$$

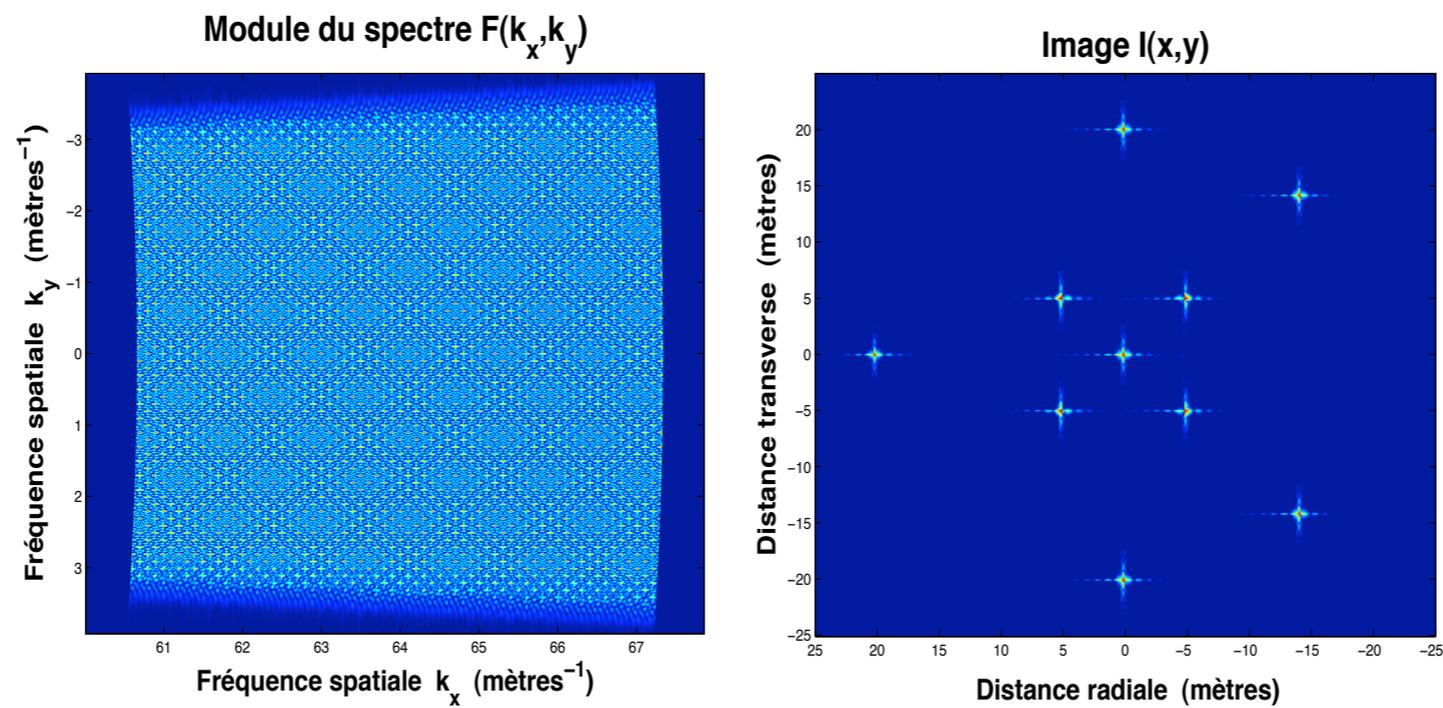
Résolutions azimuthale et radiale

$$\delta_x = \frac{\lambda}{2 \theta_g} = \frac{L}{2} \quad \delta_y = \frac{c}{2 B \cos \theta_s}$$

# TRAITEMENT SAR



(a) Scénario stripmap d'acquisition des données simulées en mode non squint.

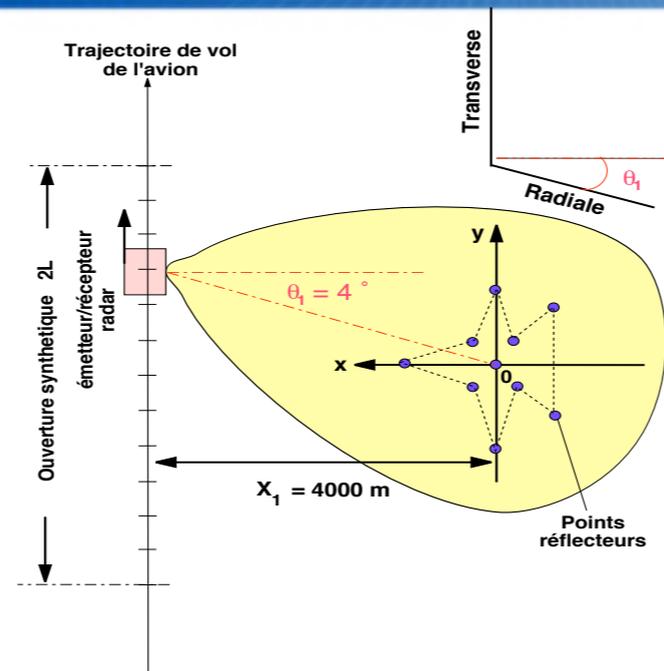


(b) Module du Spectre  $F(k_x, k_y)$ .

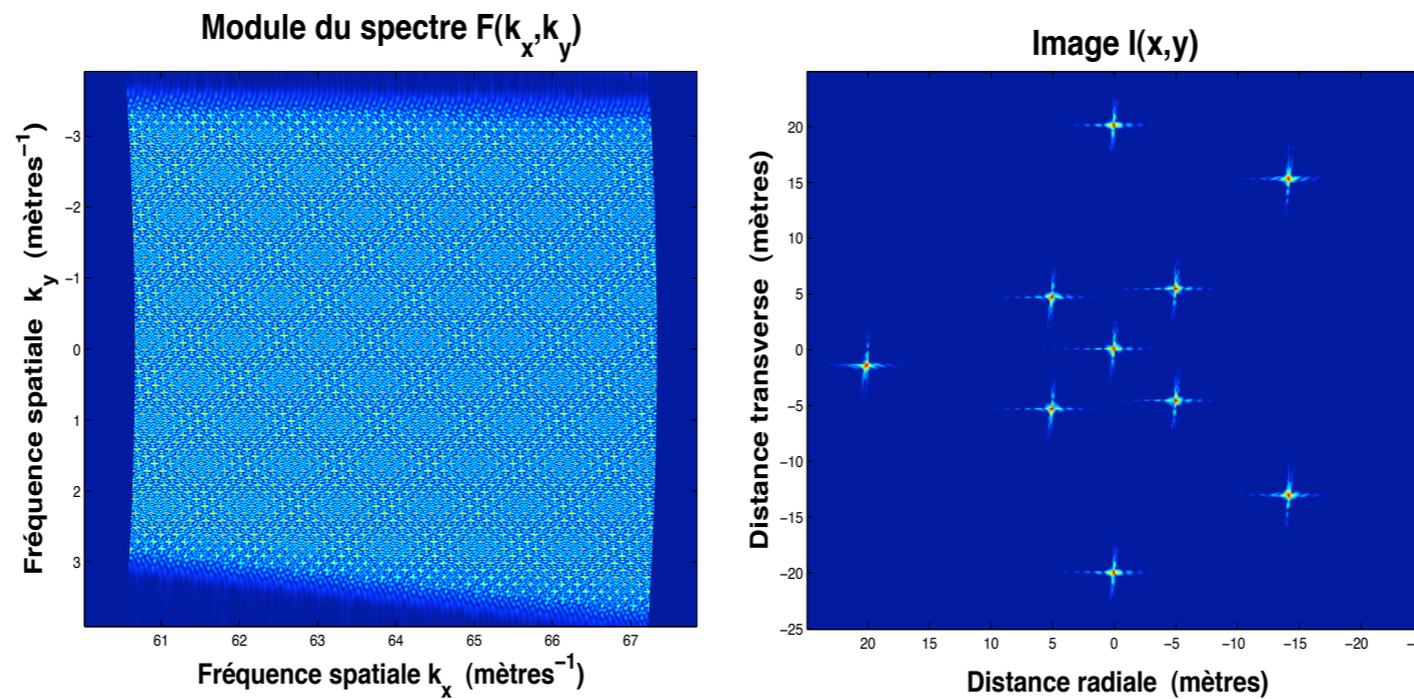
(c) Module de la fonction cible  $f(x, y)$ .

FIG. 1.26 – Spectre et image en mode non-squint.

# TRAITEMENT SAR



(a) Scénario stripmap d'acquisition des données simulées en mode squint.



(b) Module du Spectre  $F(k_x, k_y)$ .

(c) Module de la fonction cible  $f(x, y)$ .

FIG. 1.27 – Spectre et image en mode squint.

# OPTIC/SAR ?

**optics**



**radar**



*Try to observe and identify the differences*

# Applications Très Haute Résolution (THR)

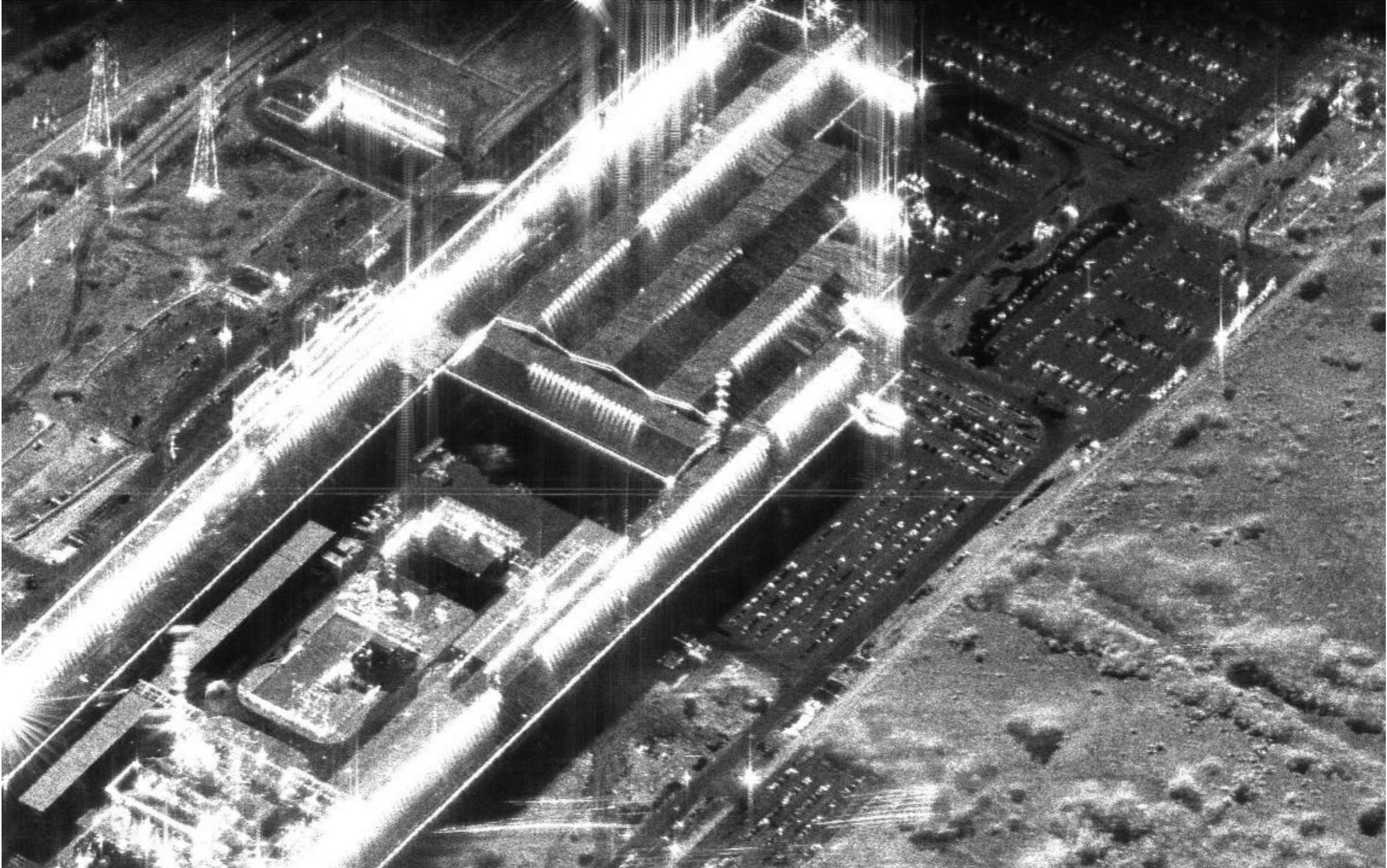
Fos Sur Mer



 DEMIR



 ONERA



# SAR aéroporté :



RAMSES (ONERA) : [Dunkerque 0.7x0.7m 4looks](#)

# Très Haute Résolution large fauchée

(Premiers résultats, résolution de l'ordre de 30 cm)

## TOULOUSE



**CNES**

Bande X  
dépression =  $30^\circ$   
Alt = 6600 ft.



**Immeuble  
10-11 étages**



**Prison St Michel**

# Très Haute Résolution large fauchée

(Premiers résultats , résolution de l'ordre de 30 cm)  
TOULOUSE : centre ville



# Très Haute Résolution large fauchée

(Premiers résultats , résolution de l'ordre de 30 cm)  
TOULOUSE : Grand Rond et Cathédrale St Etienne



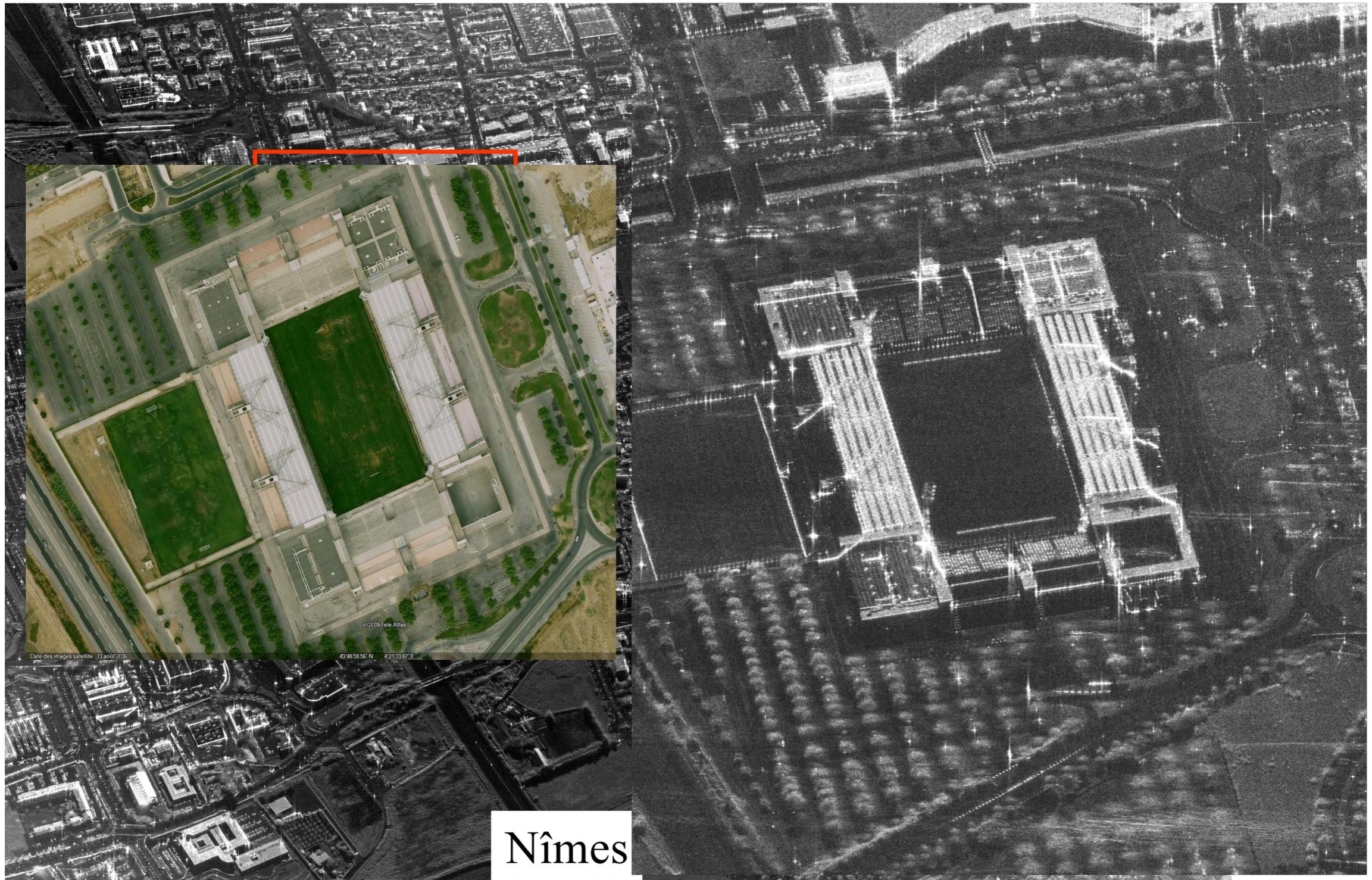
# Très Haute Résolution large fauchée

(résolution de l'ordre de 30 cm)

**TOULOUSE** : Places Wilson et du Capitole, Basilique Saint Sernin



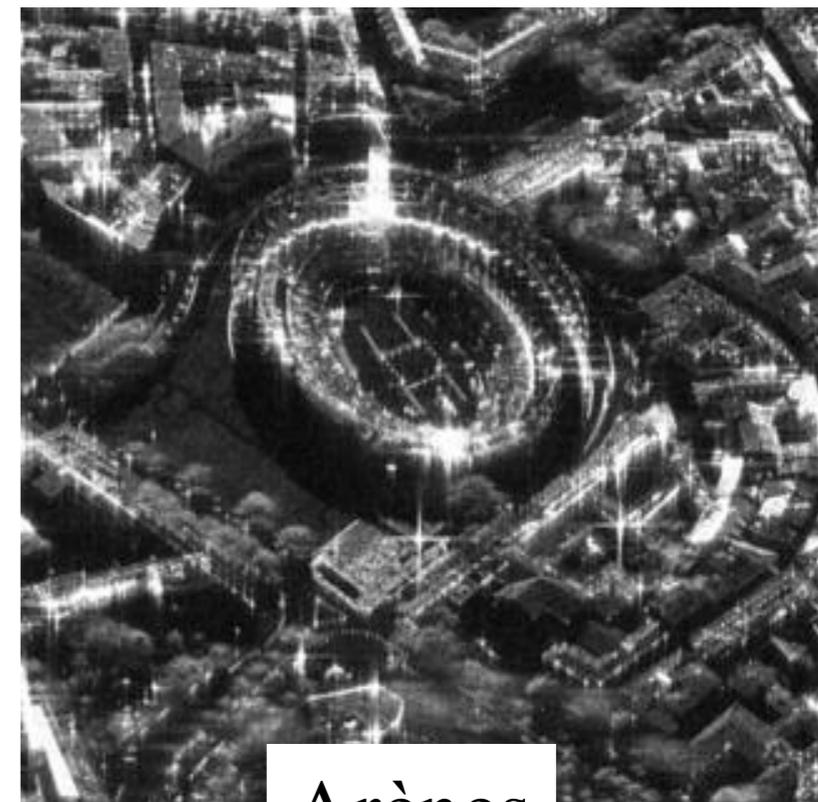
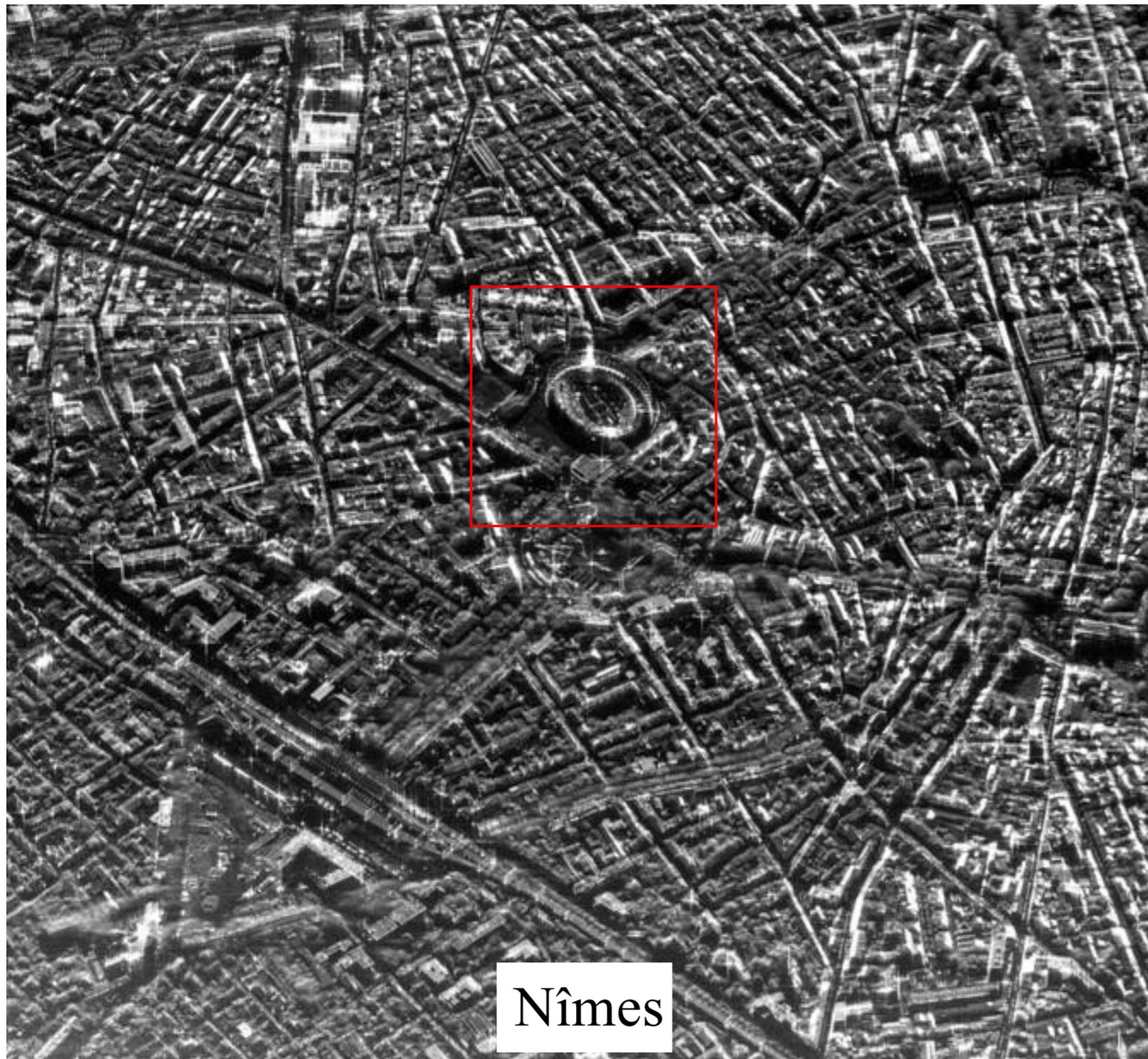
# TRES HAUTE RESOLUTION



Nîmes

Stade de Nîmes Costières

# TRES HAUTE RESOLUTION



# TRES HAUTE RESOLUTION

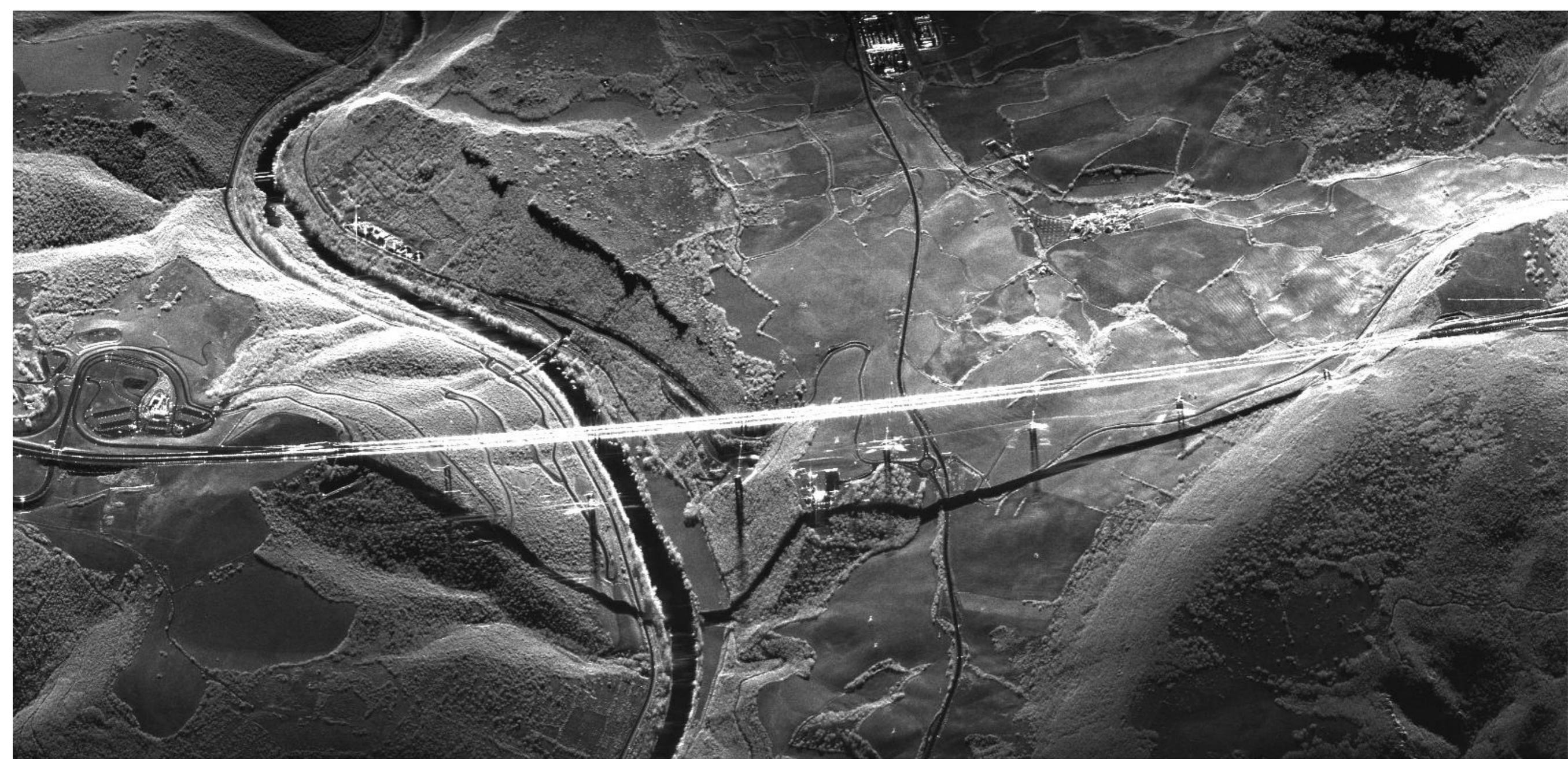


# TRES HAUTE RESOLUTION



Banlieue de Nîmes

# TRES HAUTE RESOLUTION

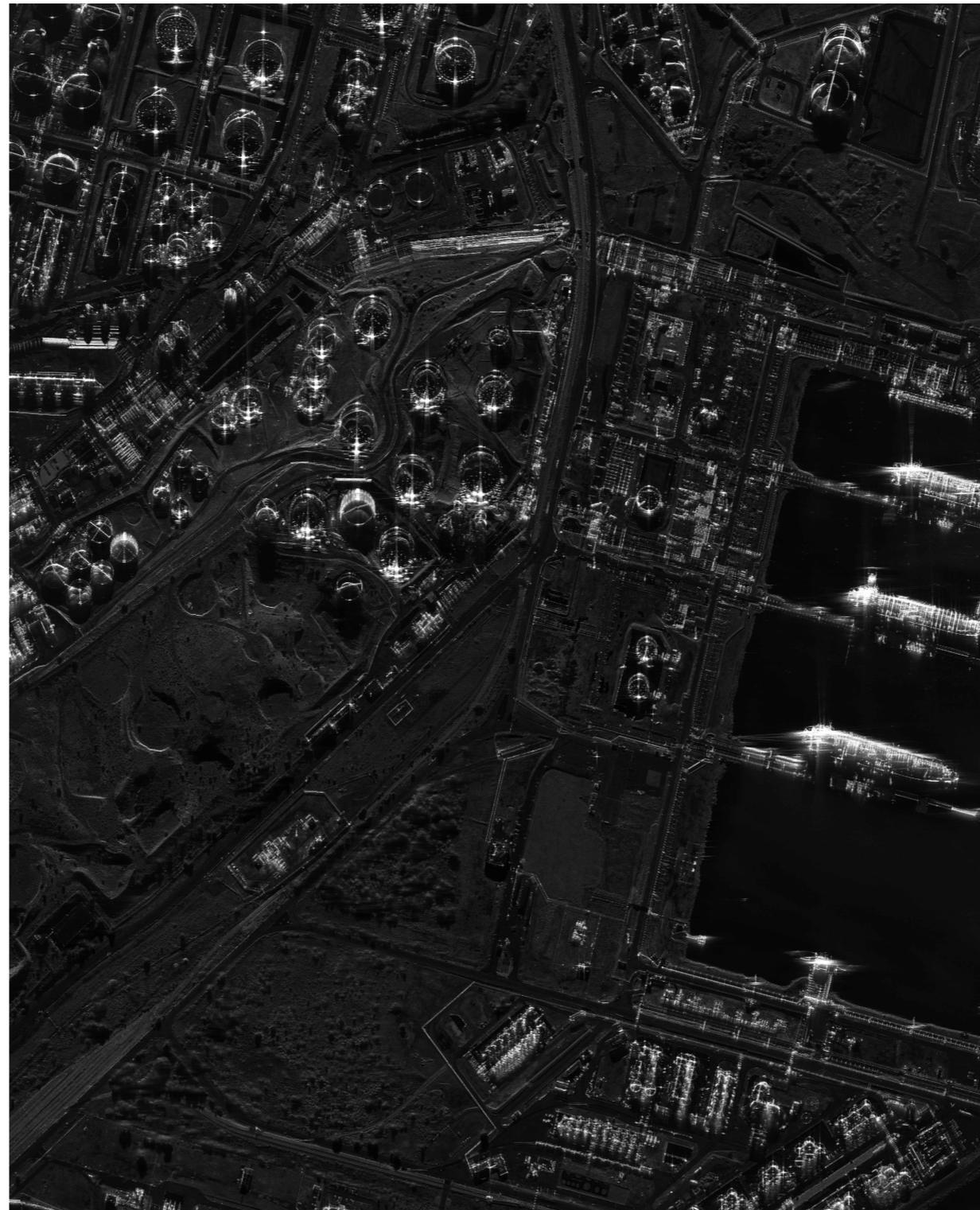


Viaduc de Millau

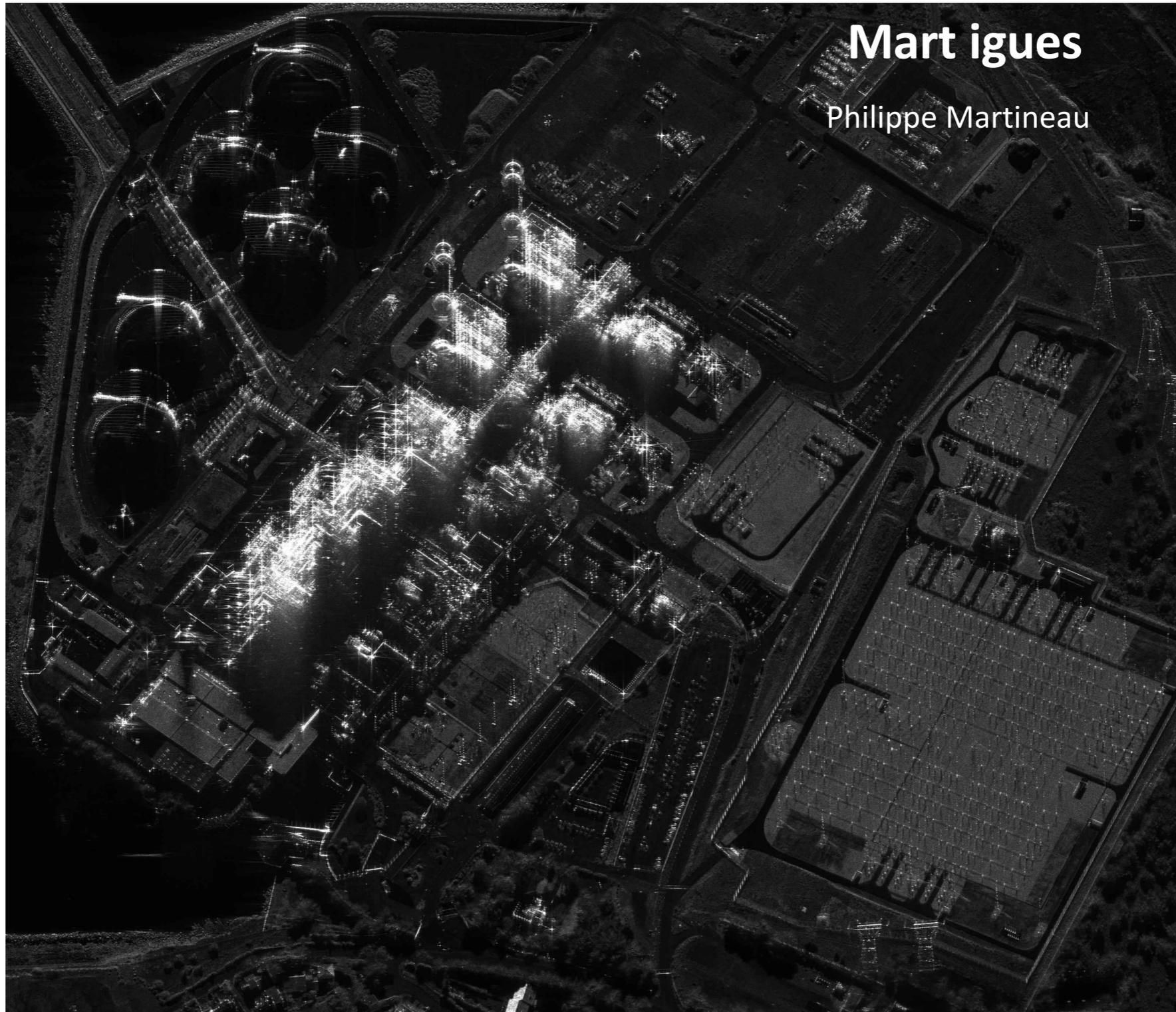
# TRES HAUTE RESOLUTION

## Fos sur Mer

Philippe Martineau



# TRES HAUTE RESOLUTION



**Mart igues**

Philippe Martineau

# TRES HAUTE RESOLUTION

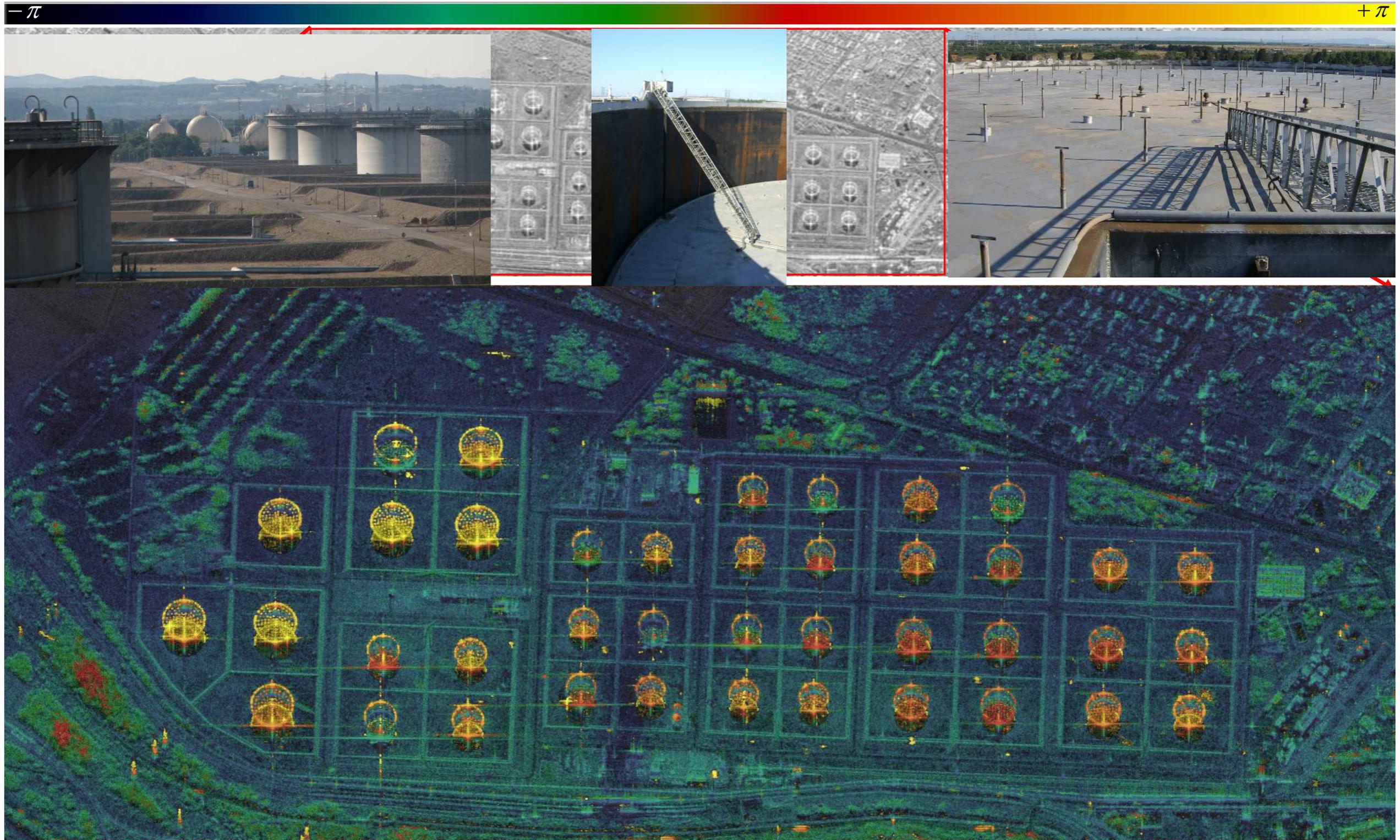


Image SAR avec altitude codée en couleur

# TRES HAUTE RESOLUTION

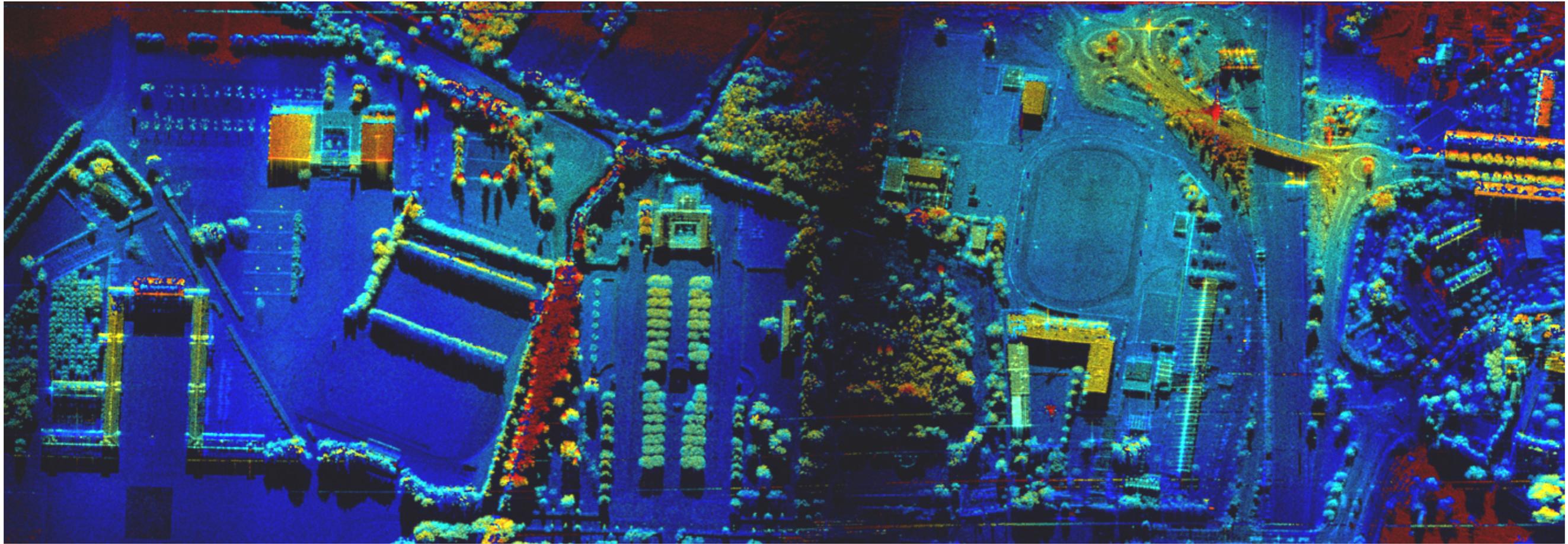


Image SAR avec altitude codée en couleur

# TRES HAUTE RESOLUTION

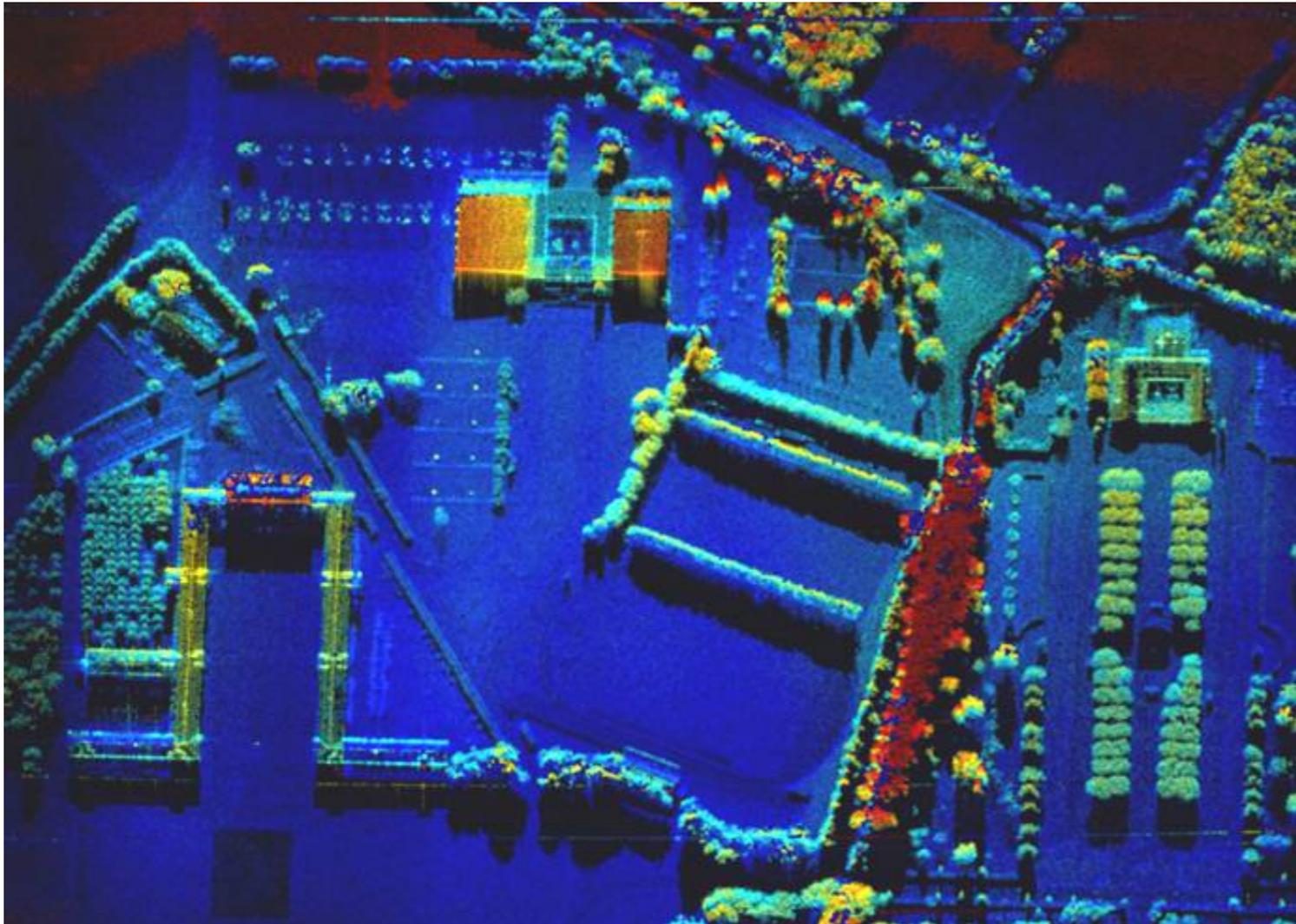
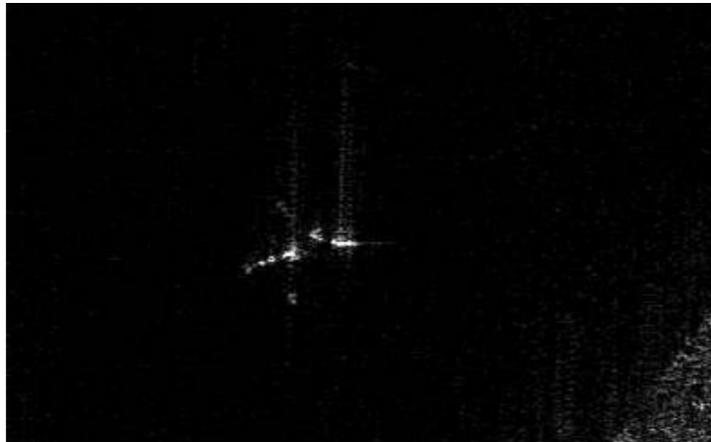


Image SAR avec altitude codée en couleur

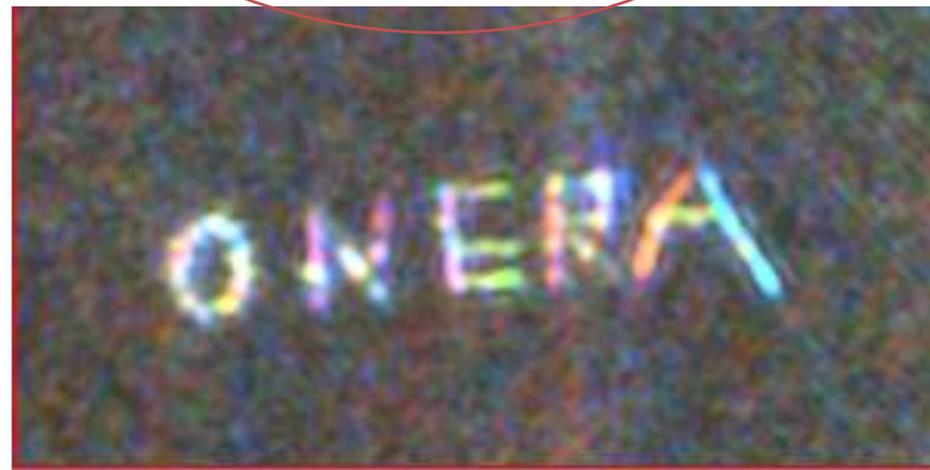
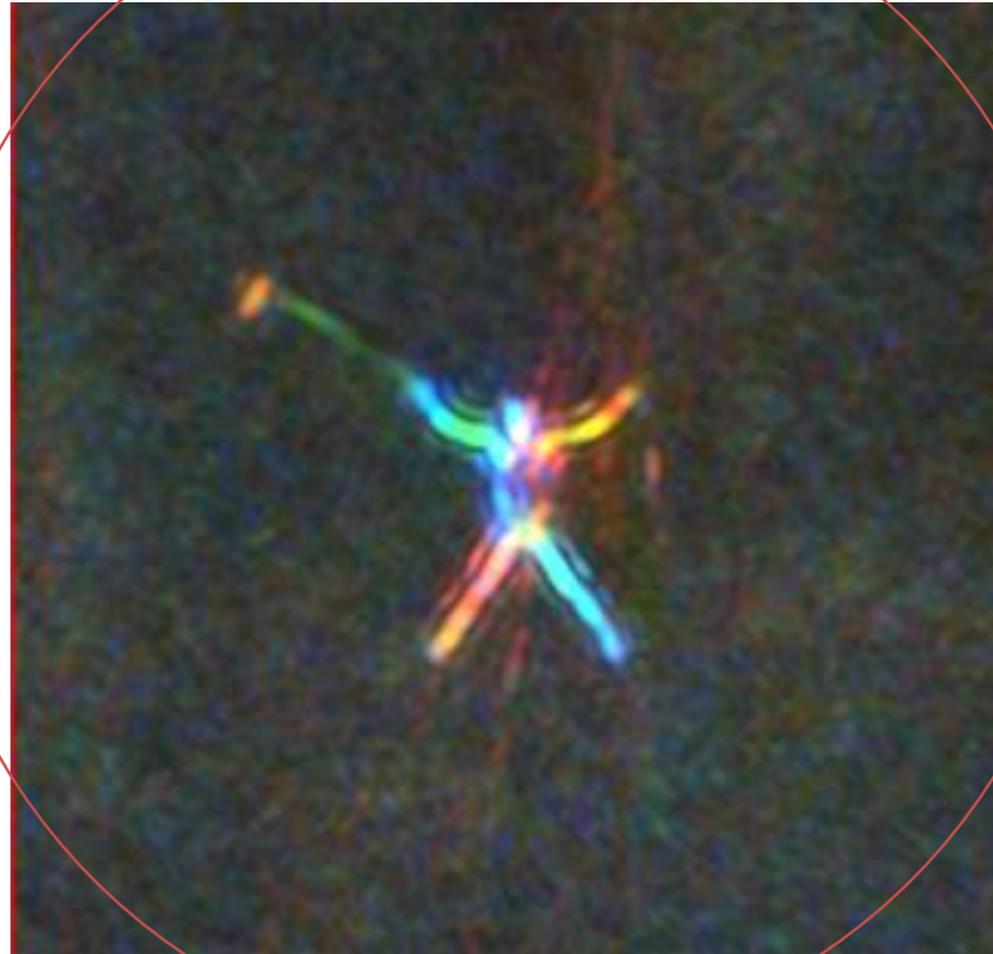
Interférométrie Ka – Busard  
image d'altitude sur la base de Salon de Provence

# TRES HAUTE RESOLUTION

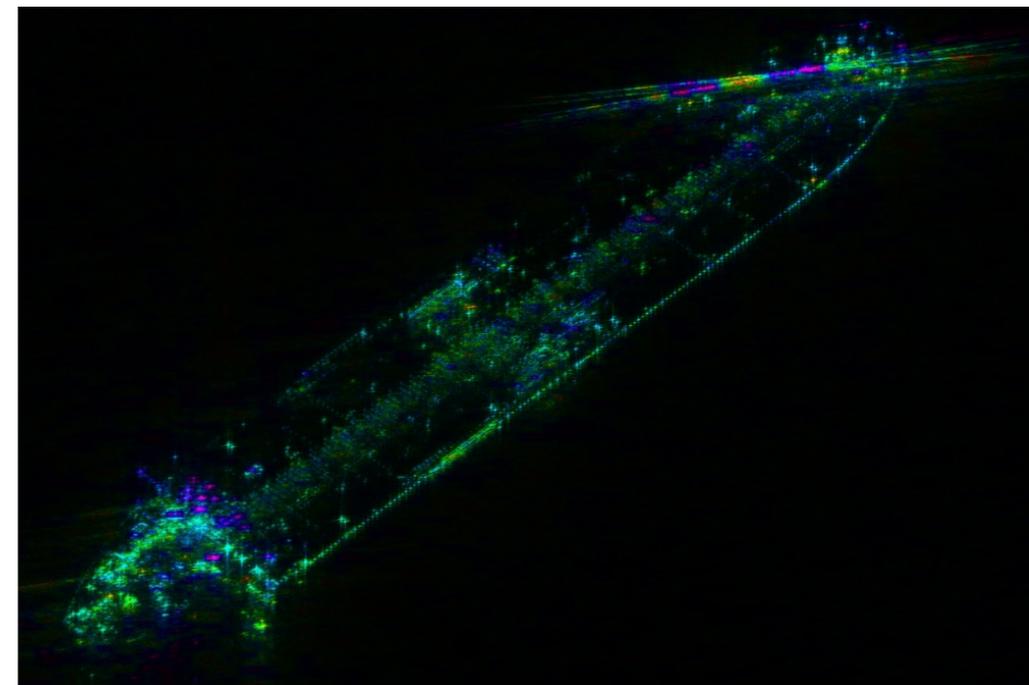
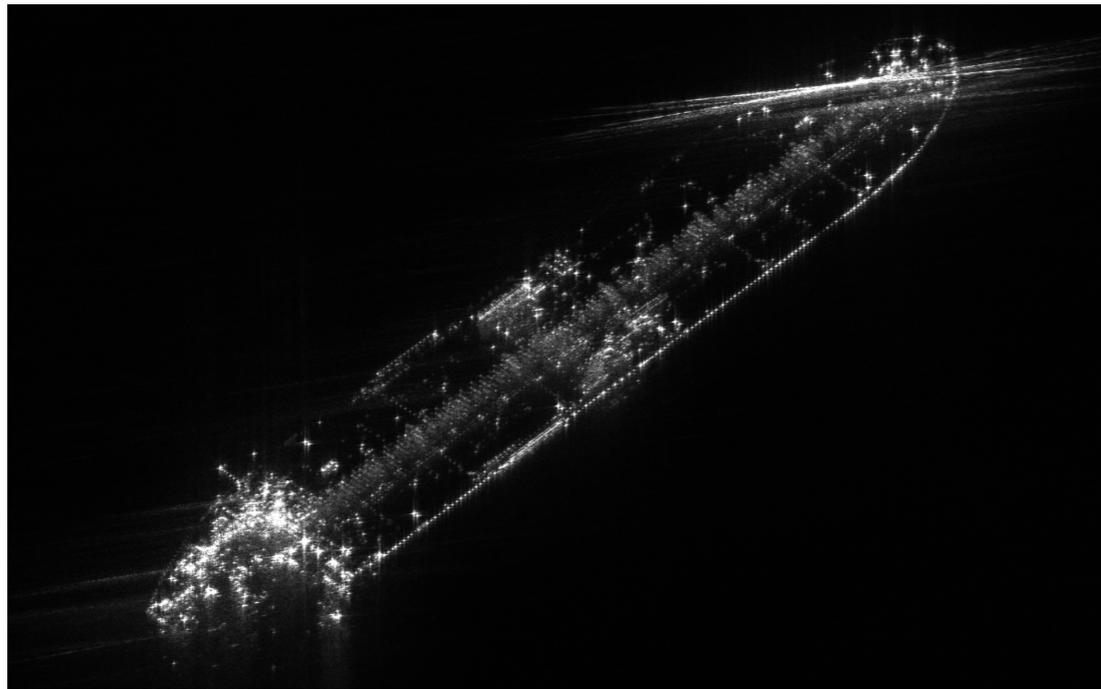
Hubert Cantalloube



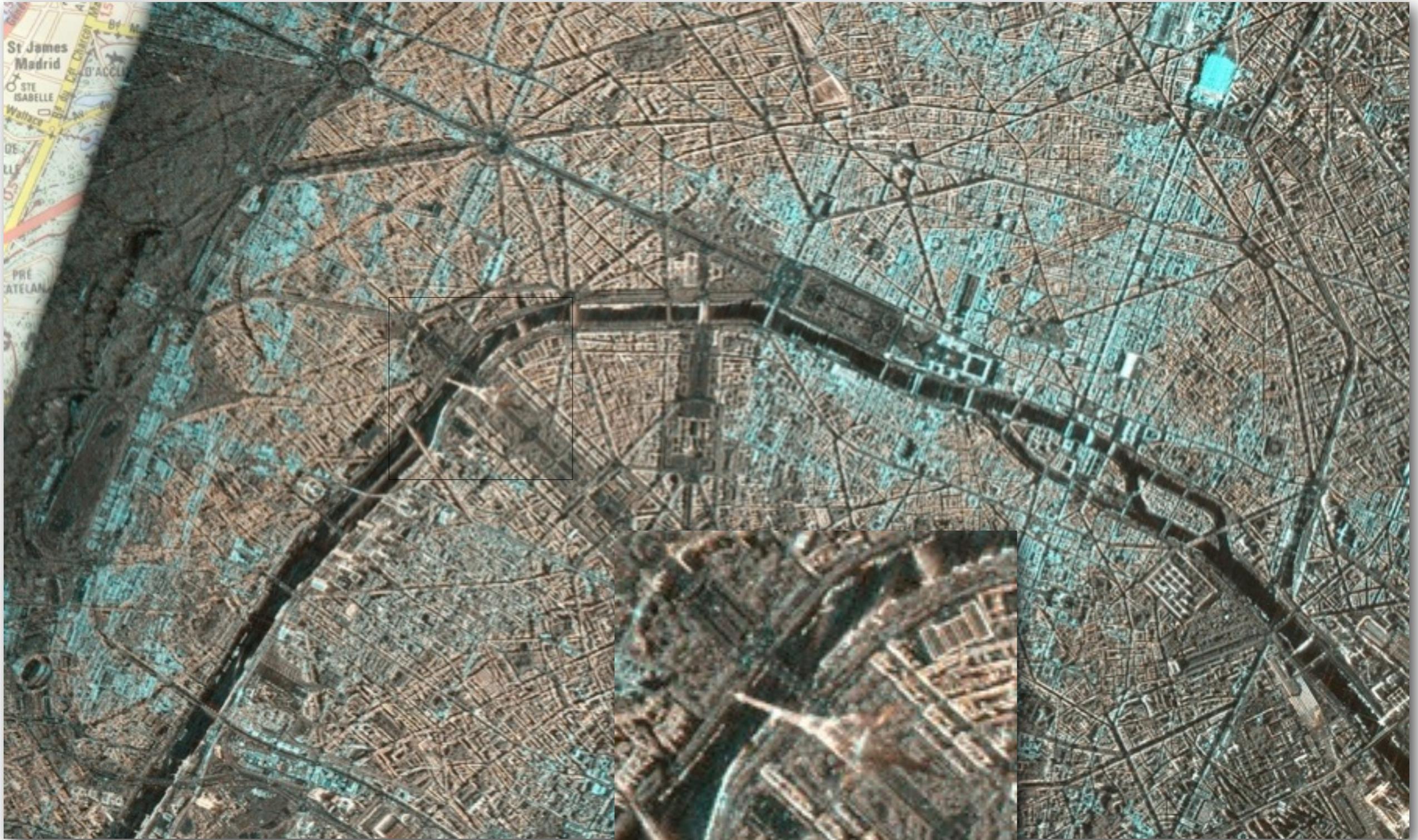
Hubert couché sur le tarmac, face au ciel,  
Imagé par une passe circulaire



# TRES HAUTE RESOLUTION

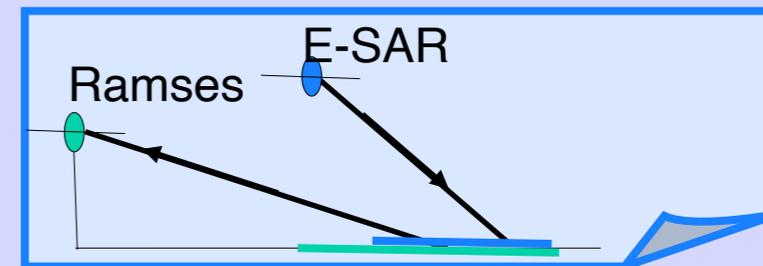


Bateau au mouillage

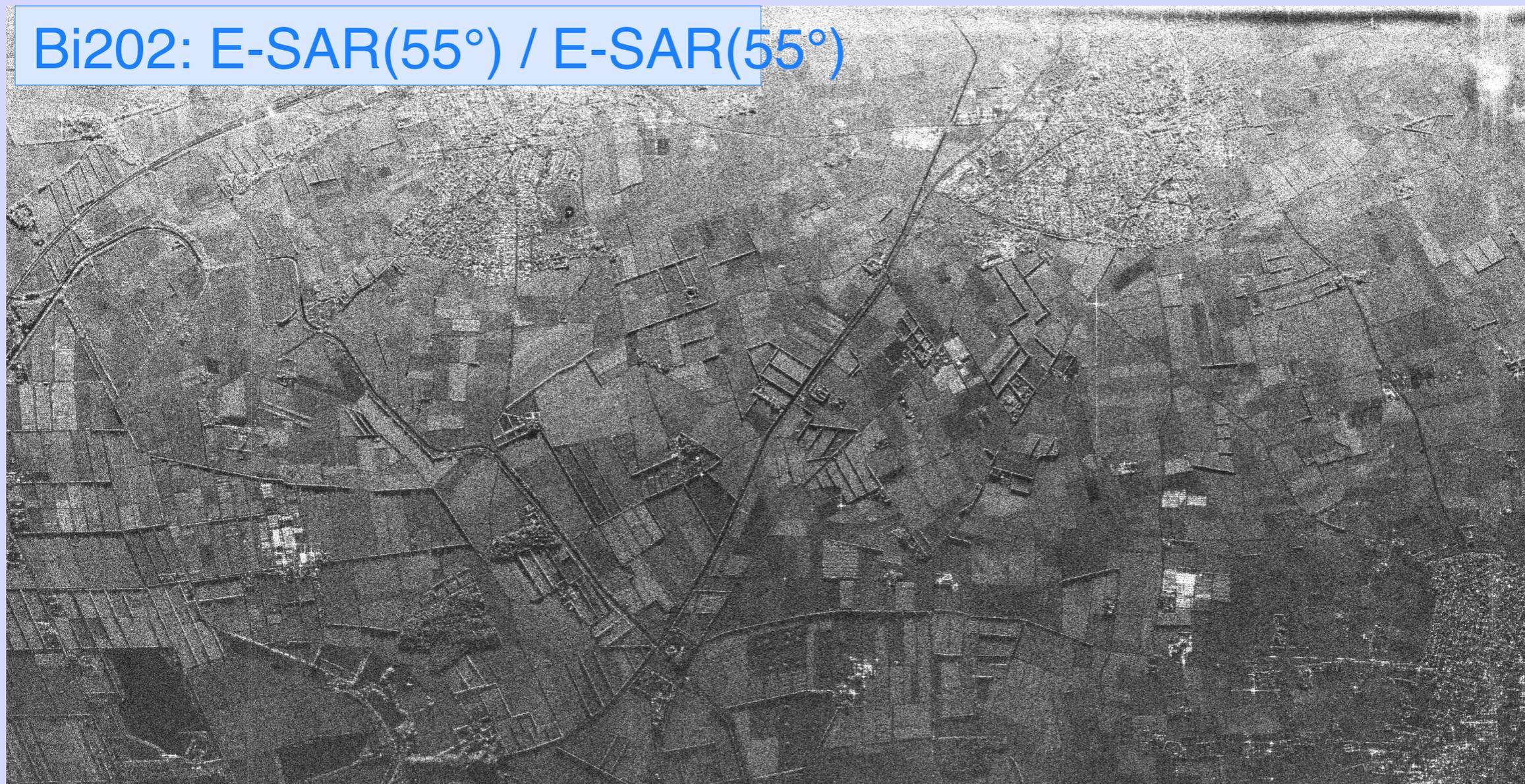


# Campagne bi-statique DLR-ONERA

Résultat: mode mono-statique ESAR (émission et réception ESAR (DLR))

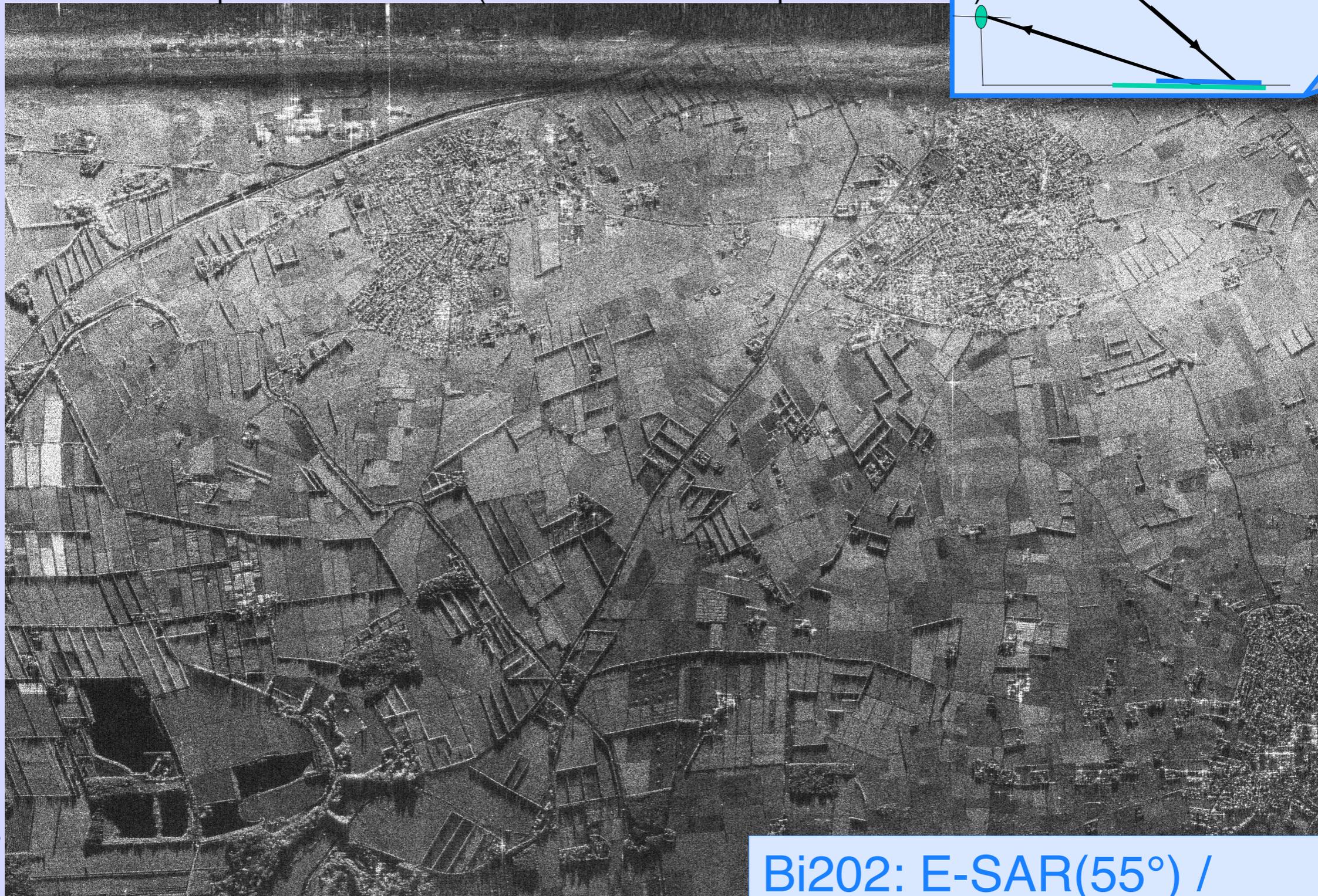
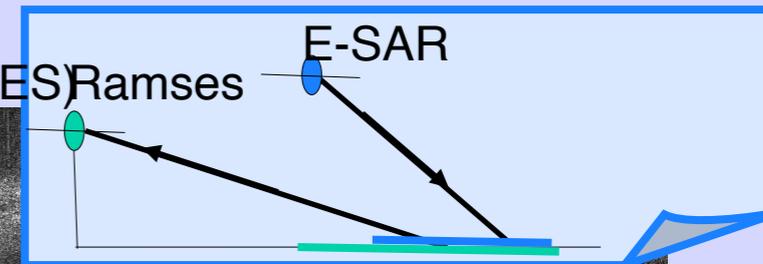


Bi202: E-SAR(55°) / E-SAR(55°)



# Campagne bi-statique DLR-ONERA

Résultat: mode bi-statique ESAR-RAMSES (émission ESAR et réception RAMSES)

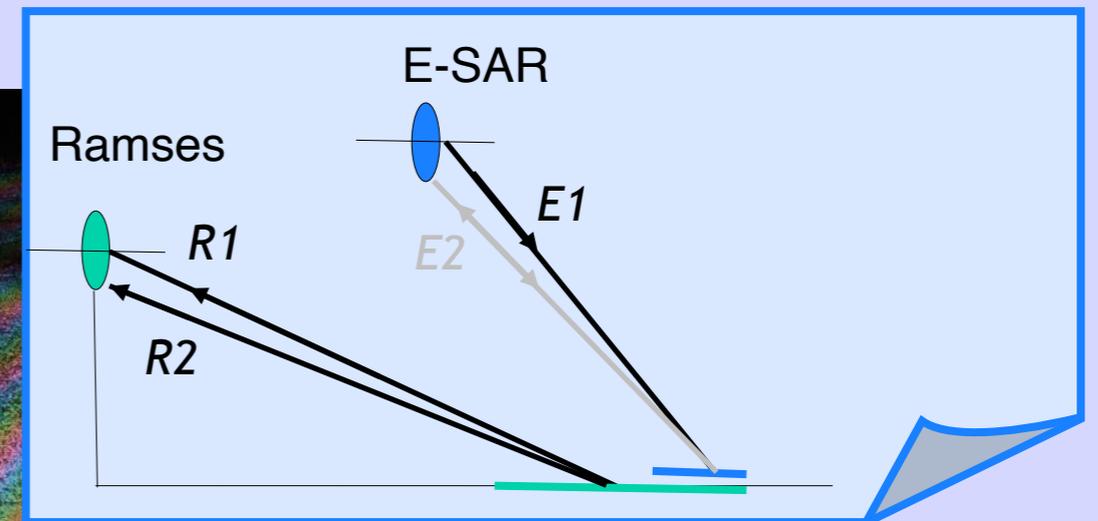


Bi202: E-SAR(55°) /  
Ramses(75°)

# Campagne bi-statique DLR-ONERA

Résultat: mode bi-statique et interférométrique ESAR-RAMSES (émission ESAR et réception RAMSES sur deux antennes)

Bi202: E-SAR(55°) / Ramses(75°)



ONERA

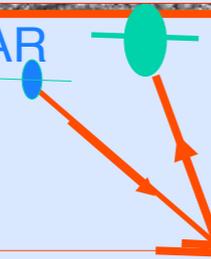
# Campagne bi-statique DLR- ONERA



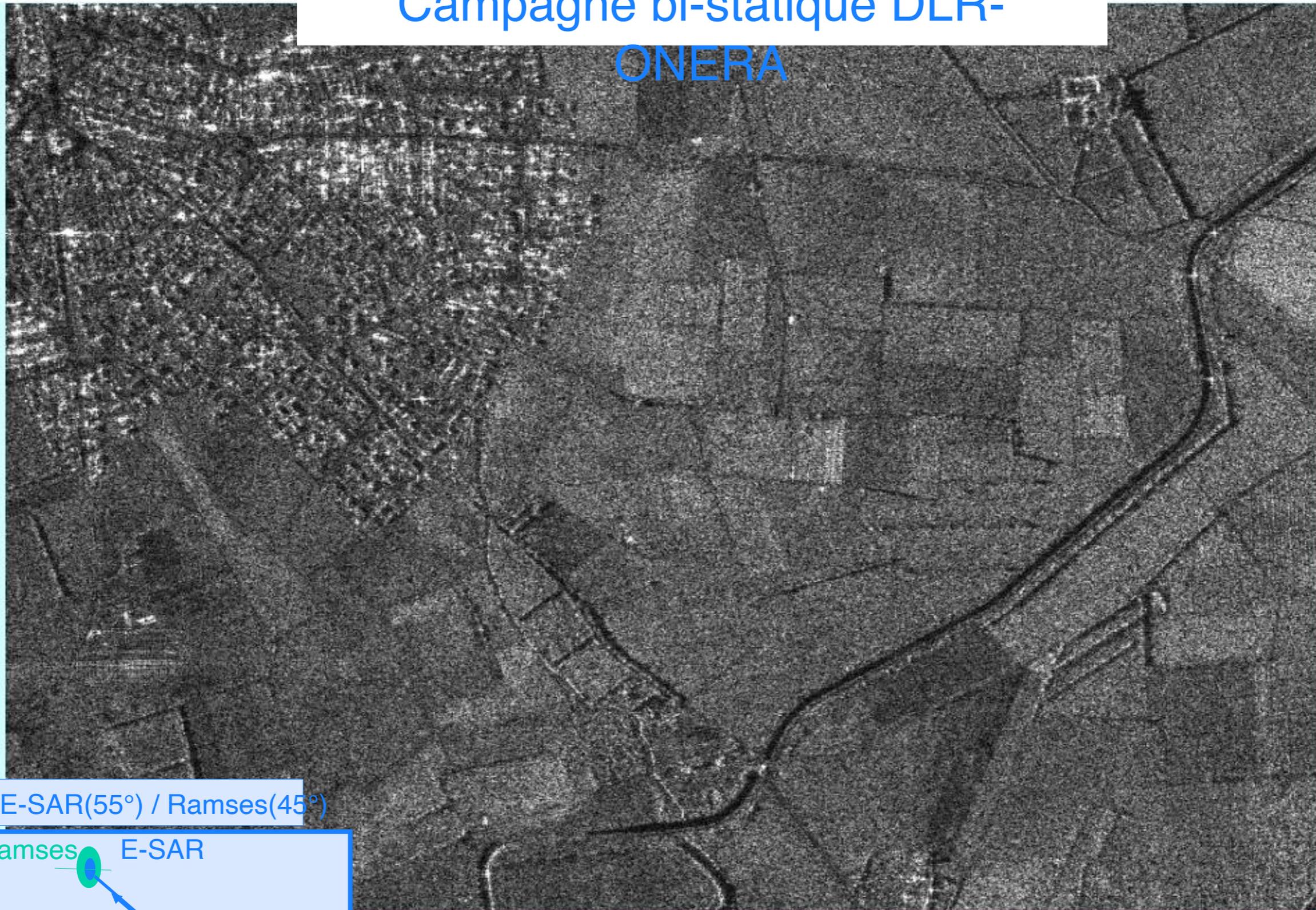
E-SAR(55°) / Ramses(30°)

E-SAR

Ramses



# Campagne bi-statique DLR- ONERA



E-SAR(55°) / Ramses(45°)

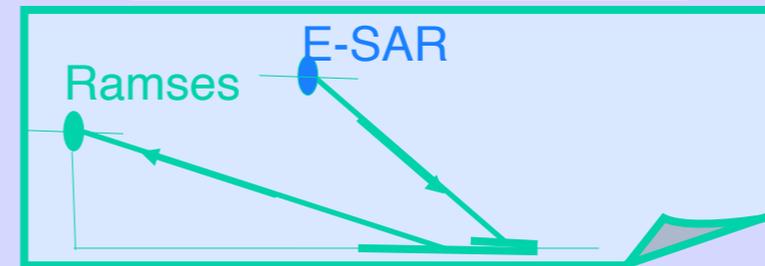


# Campagne bi-statique DLR-ONERA

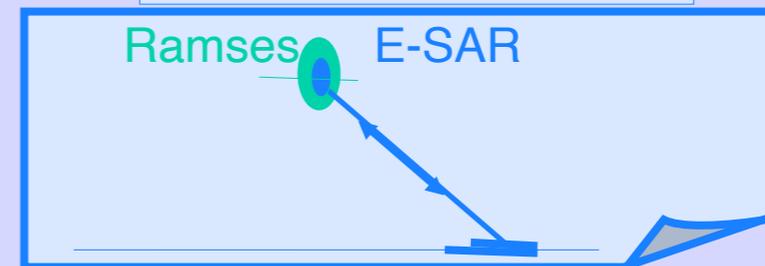
Résultat: mode bi-statique Emission ESAR, réception RAMSES (3 configurations bi-statiques)



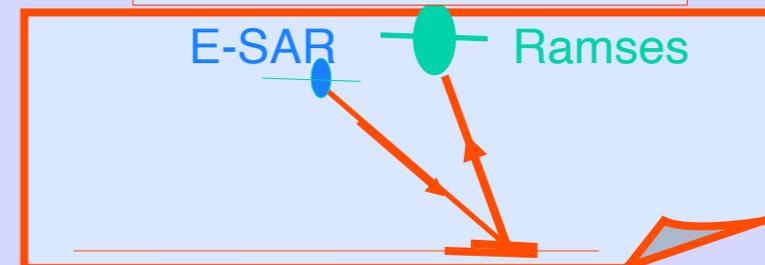
E-SAR(55°) / Ramses(75°)



E-SAR(55°) / Ramses(45°)



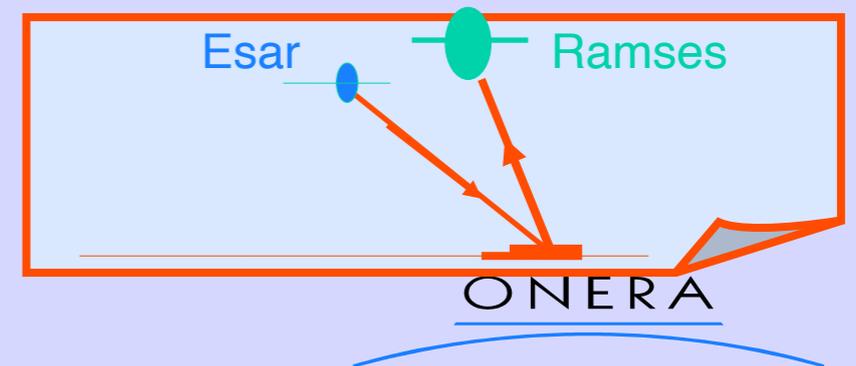
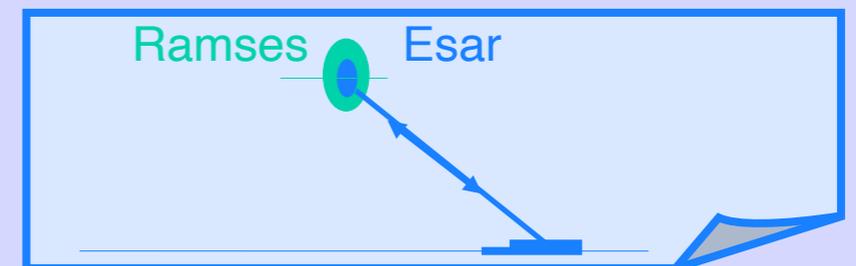
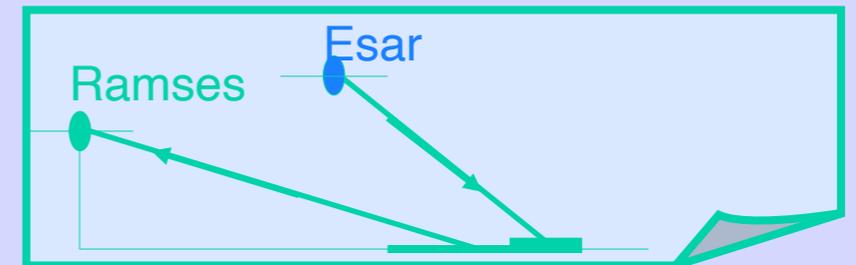
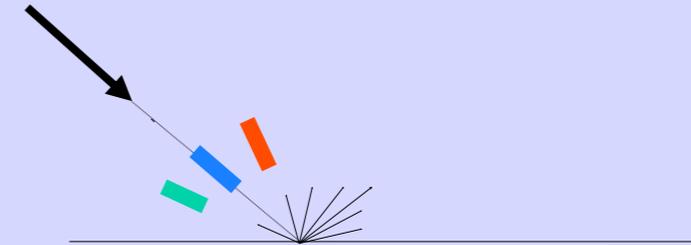
E-SAR(55°) / Ramses(30°)

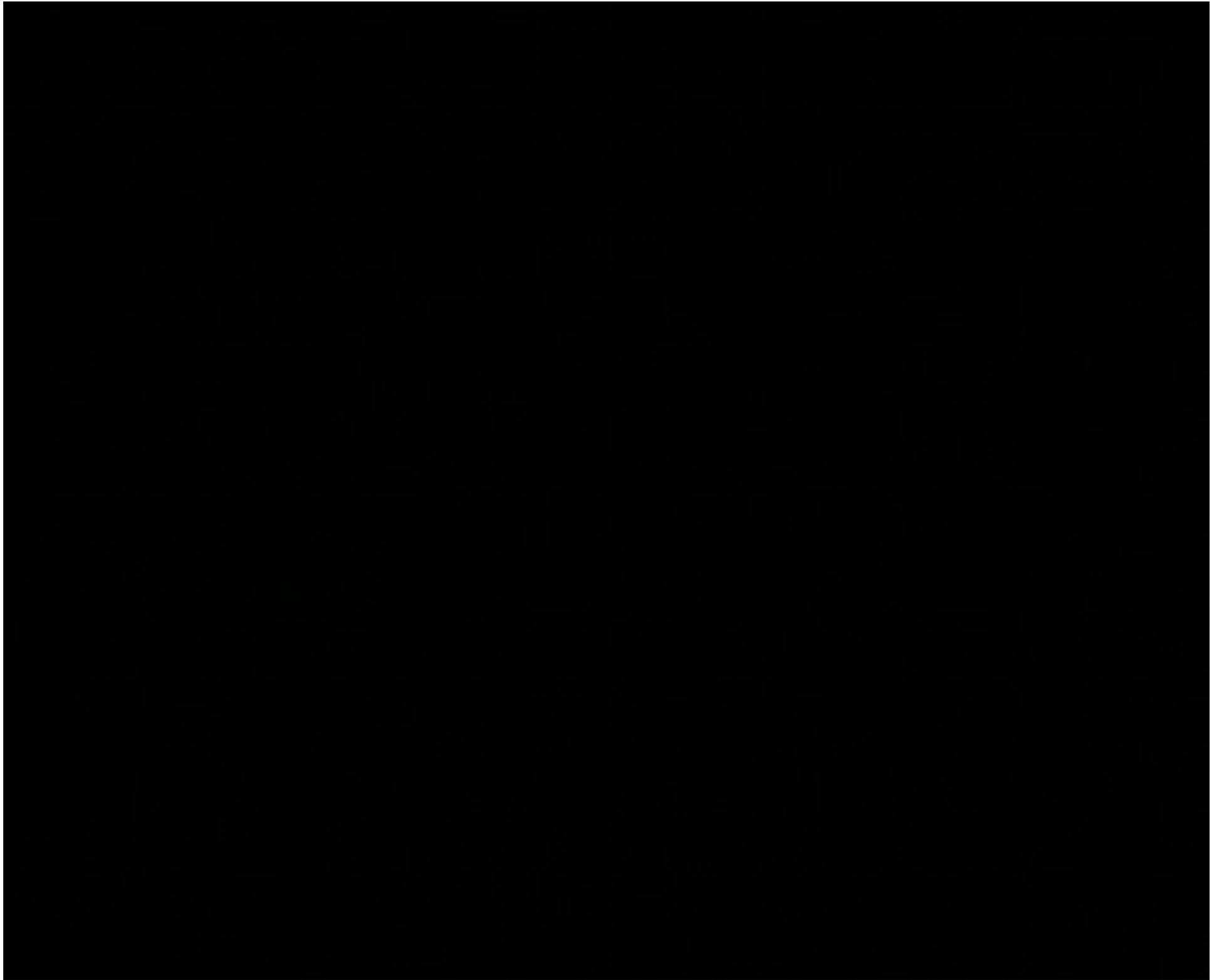


# Campagne bi-statique DLR-ONERA

## Résultats

Combinaison colorée  
Angle de bistatisme

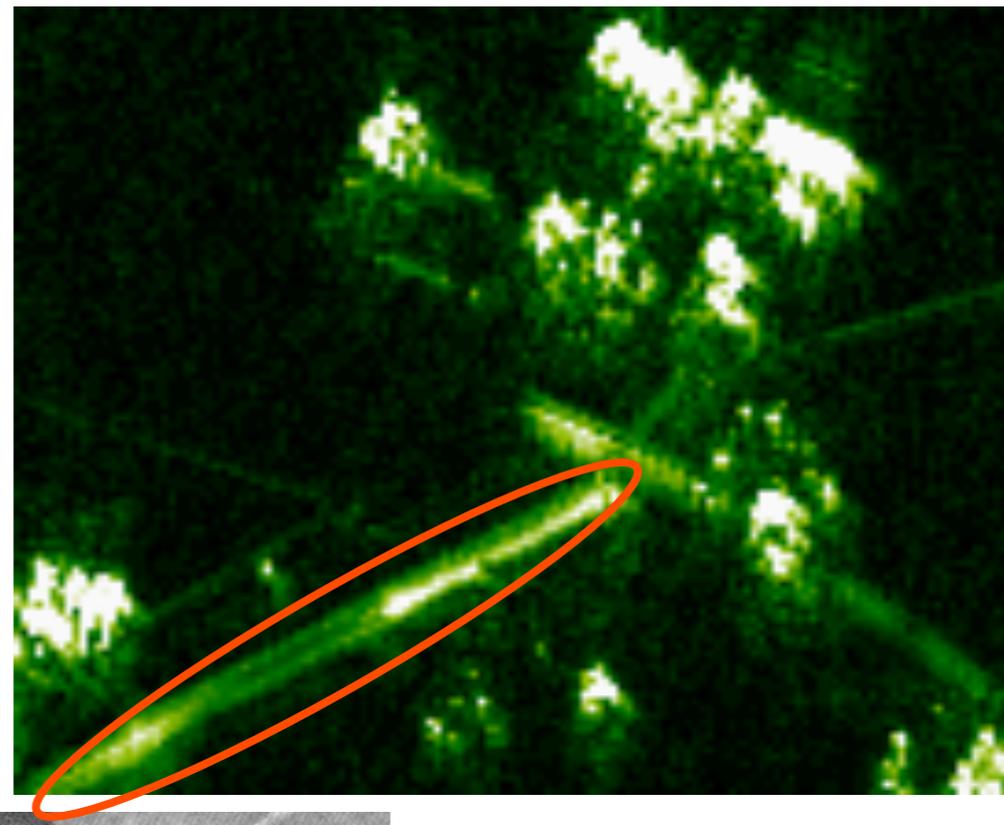




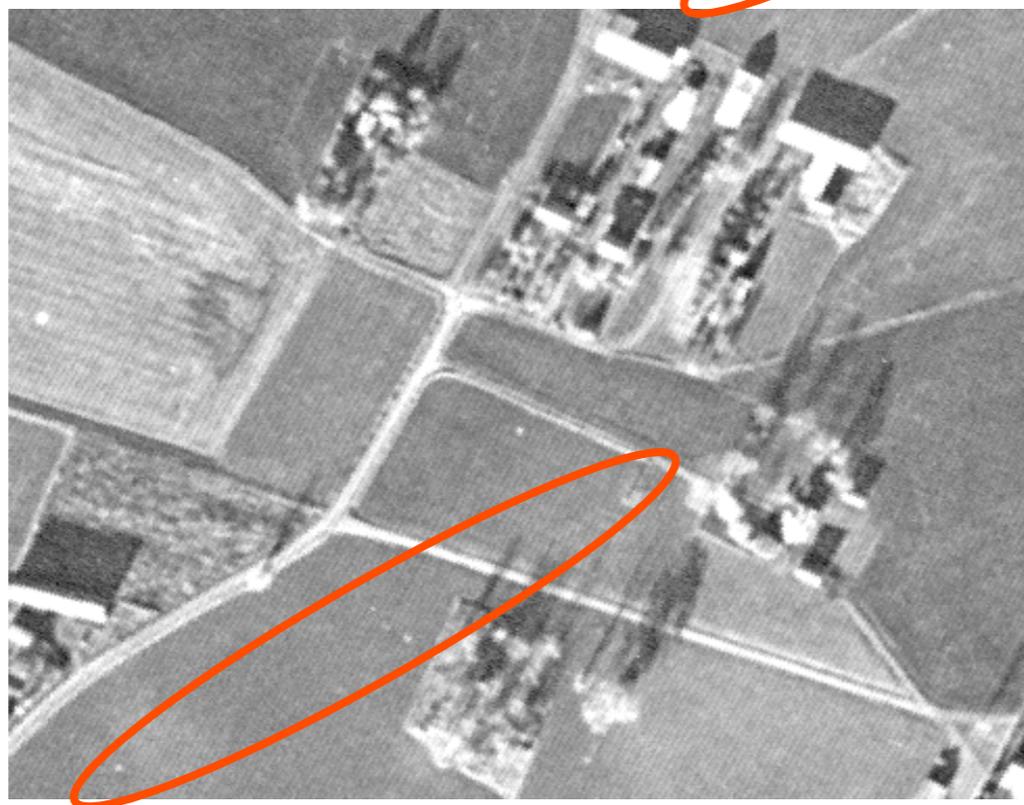
## SAR bande basse (4)



**LORA SAR (Suède) UHF :**  
**219-420 MHz HH-pol**  
**Resolution = 0.7 x 0.7 m<sup>2</sup>**



**CARABAS (Suède) VHF:**  
**22-82 MHz HH-pol**  
**Resolution = 2.5 x 2.5 m<sup>2</sup>**



**Photo aérienne**

Lignes électriques

# EXAMPLES OF AIRBORNE SAR SYSTEMS



## AIRSAR (NASA/JPL)

Fully Pol. mode at P-, L- C-bands  
Interferometric mode in L- and C-  
band simultaneously.



## RAMSES / Transall (ONERA)

X-, C-, S-, L- and P-bands  
POL-INSAR full- pol in X band.  
Operated up to 2008



**PAMIR/ Transall (FGAN) – Ge**  
X-band, High resolution SAR with  
Scan MTI mode (STAP)



## SAR580 / Convair 580 (Canada)

C/X-SAR for remote Sensing  
Interferometric and polarimetric  
modes in C-band radar.



## SETHI / RAMSES NG / Falcon (ONERA)

X-, L- and P-bands  
POL-INSAR full- pol in X band.  
Operated since to 2008



## E-SAR / Dornier 228 (DLR)- Ge

X-, C-, S-, L- and P-bands  
selectable polarisation  
Interferometry & Polari. modes.



## Pi-SAR - Japan

L/ X- bands, X-band  
interferometric for  
topographic mapping



## SRI FolPen III / -----

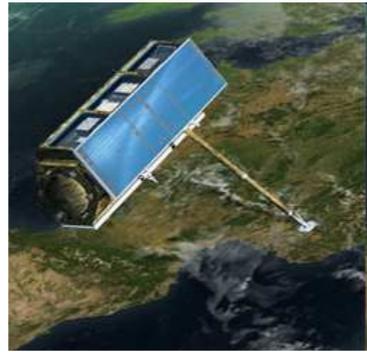
100-300MHz, 200-400MHz, 300-500MHz  
HH,VV or HV, resolution 50cm



## CARABAS (FOI, SAAB),Sueden

VHF 20-90MHz  
FoPen SAR, horizontal polarisation

# EXAMPLES OF SPACEBORNE SAR SYSTEMS



**TerraSAR-X  
(Germany)**



**COSMO-SkyMed  
(Italy)**

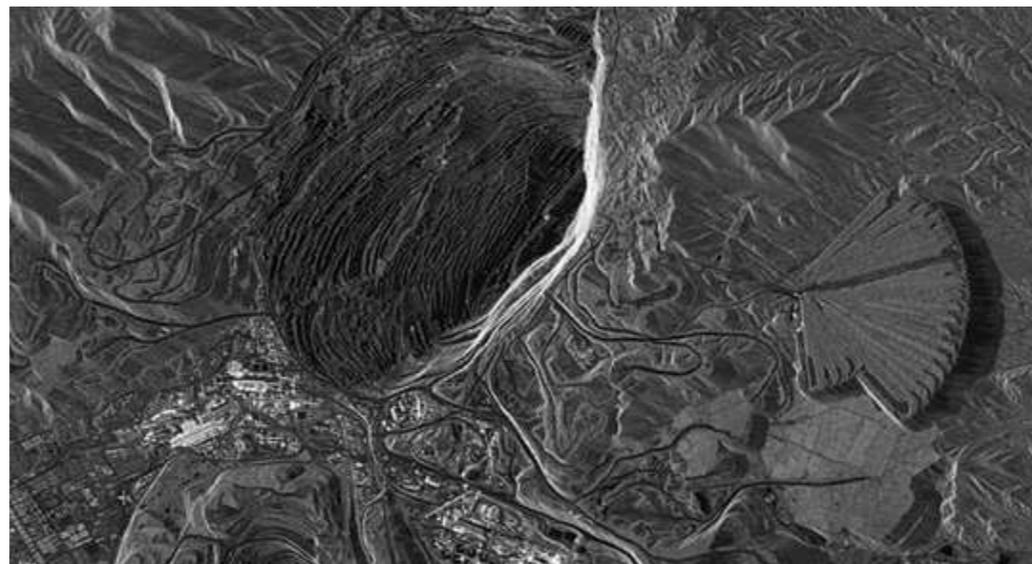


**RADARSAT-2  
(Canada)**



**PALSAR – ALOS  
(Japan)**

Center Frequency (GHz)	9.65 (X-band)	5.405 (C-band)	9.60 (X-band)	1.270 (L-band)
Antenna length	4.78m	15m	5.70m	
Resolution (best)	1m	1m	7m	7m
Launch date	15/06/2007	14/12/2007	7/6/2007	24/01/2006
	1 satellite	1 satellite	4 satellites	1 satellite

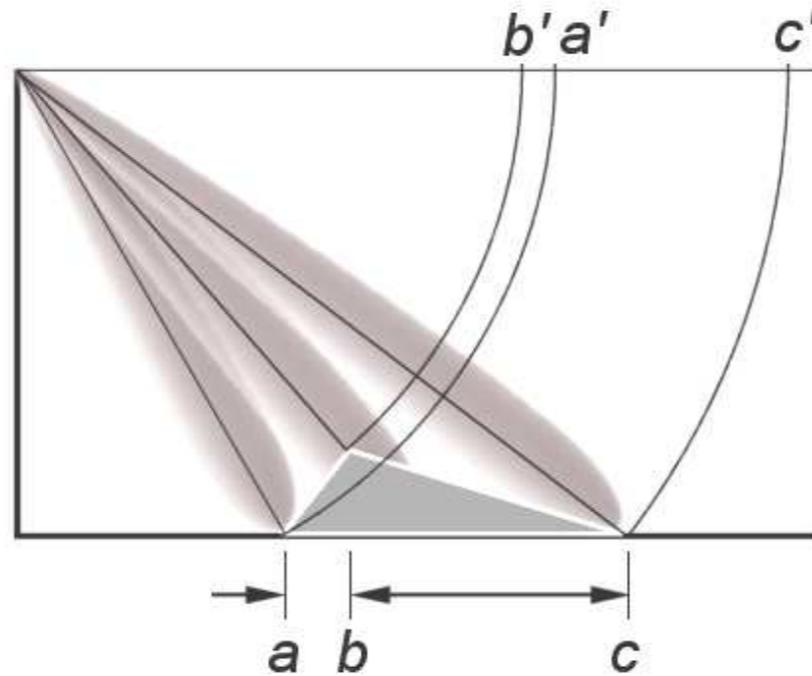


Atacama Desert observed by  
TerraSAR-X

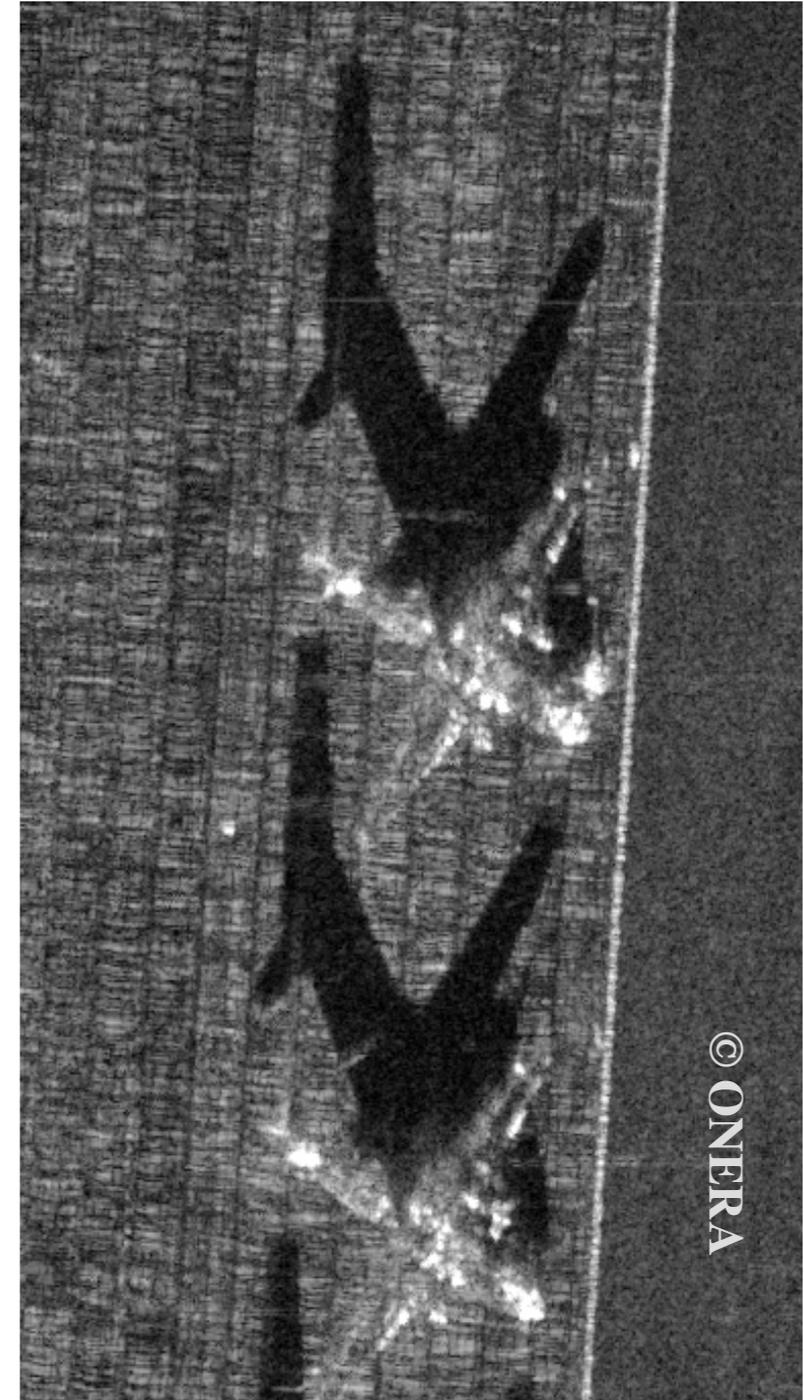
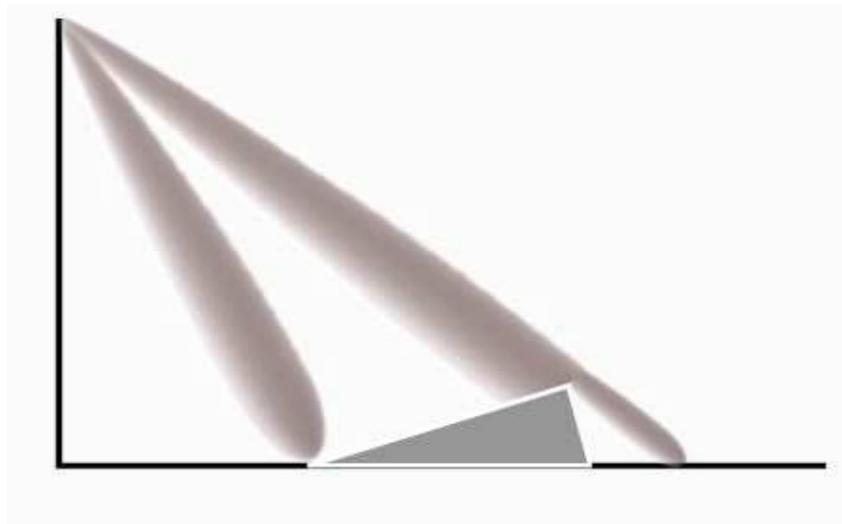
From  
[http://www.imagingnotes.com/go/article\\_free.php?mp\\_id=144](http://www.imagingnotes.com/go/article_free.php?mp_id=144)

# SAR SPECIFIC EFFECTS

Layover

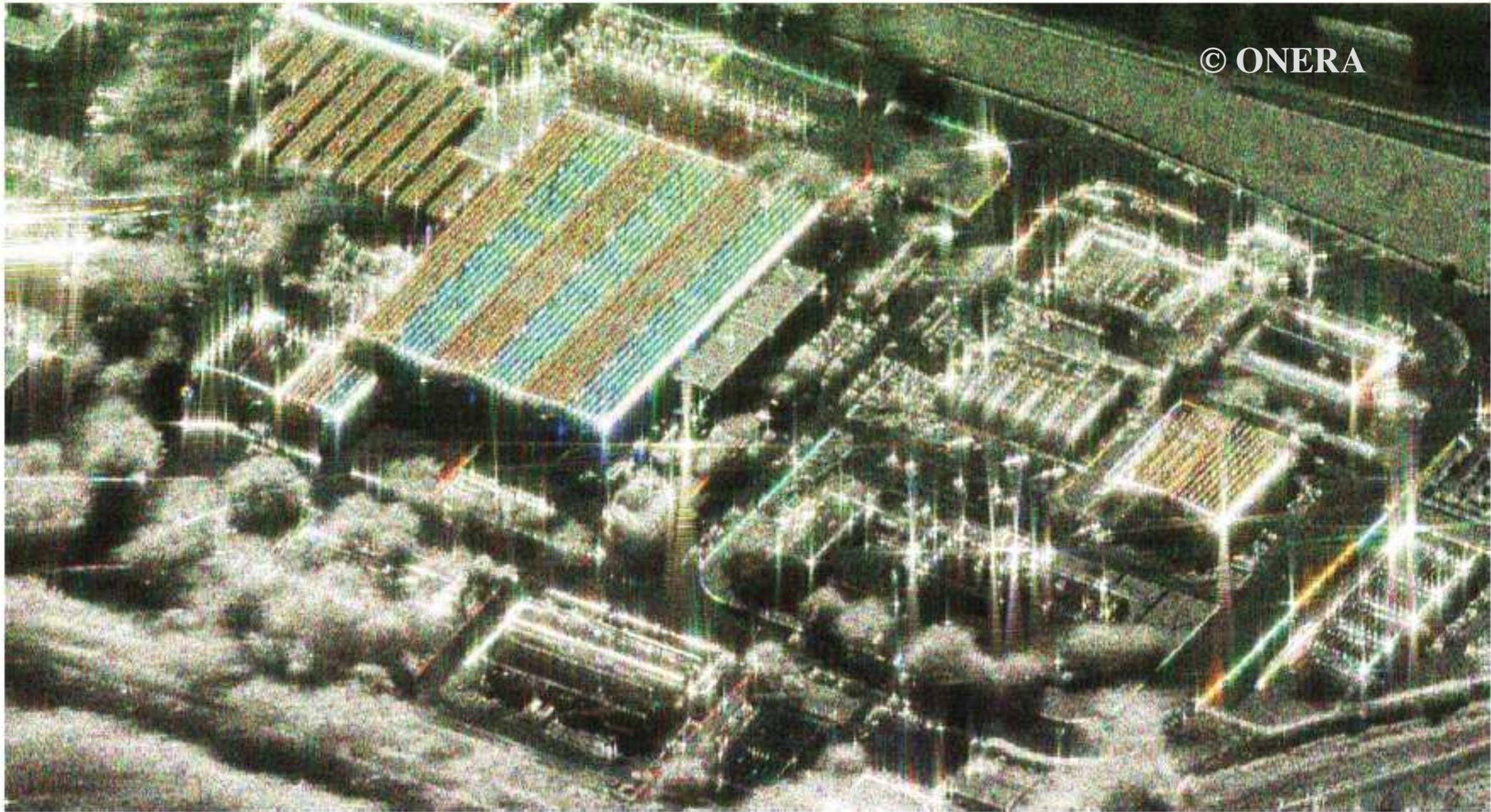


Shadow



# SAR SPECIFIC EFFECTS

## Scatterers frequency dependency



**Frequency RGB colour coding of a SAR image**

$$f_c = 8.82 \text{ Ghz}$$

$$f_c = 9.37 \text{ Ghz}$$

$$f_c = 10 \text{ Ghz}$$

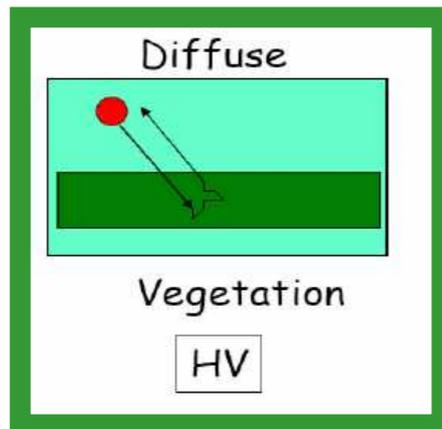
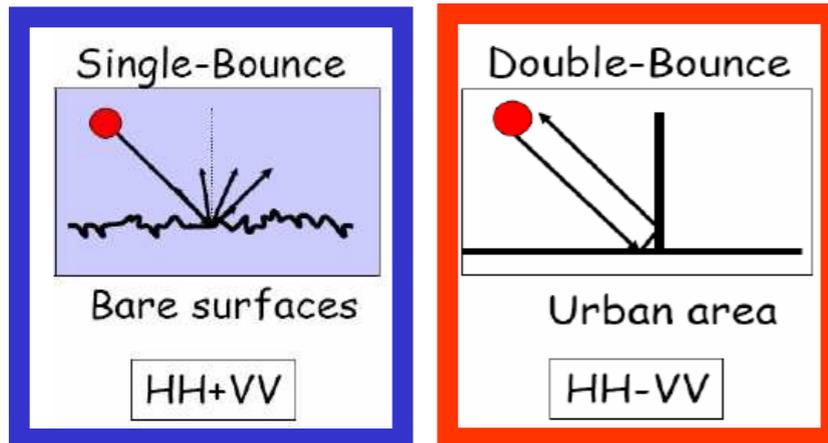
# SAR POLARIMETRY

Acquisition of the Polarimetric Scattering matrix

Transmit  $H$  then  $V$ , Receive  $H$  and  $V$

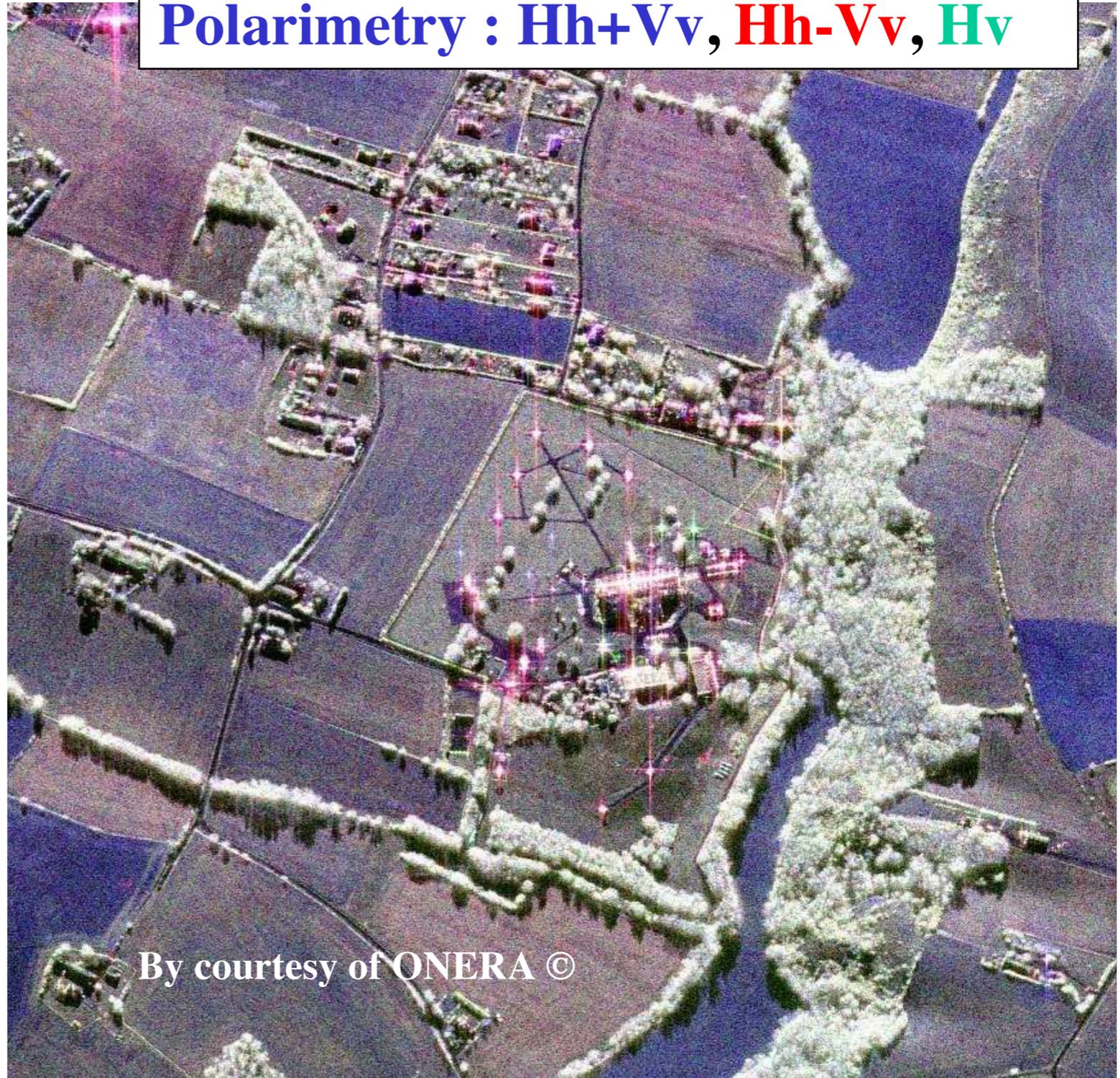
$$\begin{matrix} \text{transmit} \\ \text{receive} \end{matrix} \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix}$$

## Different mechanisms



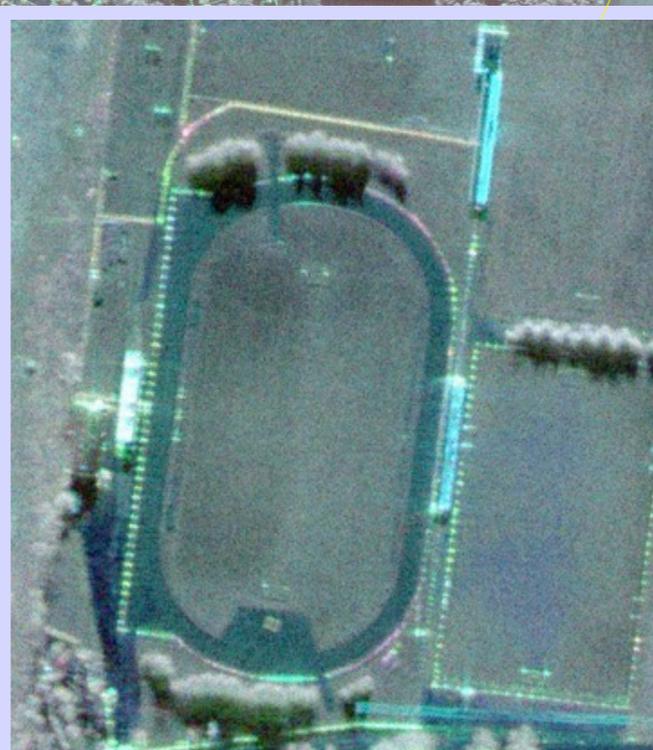
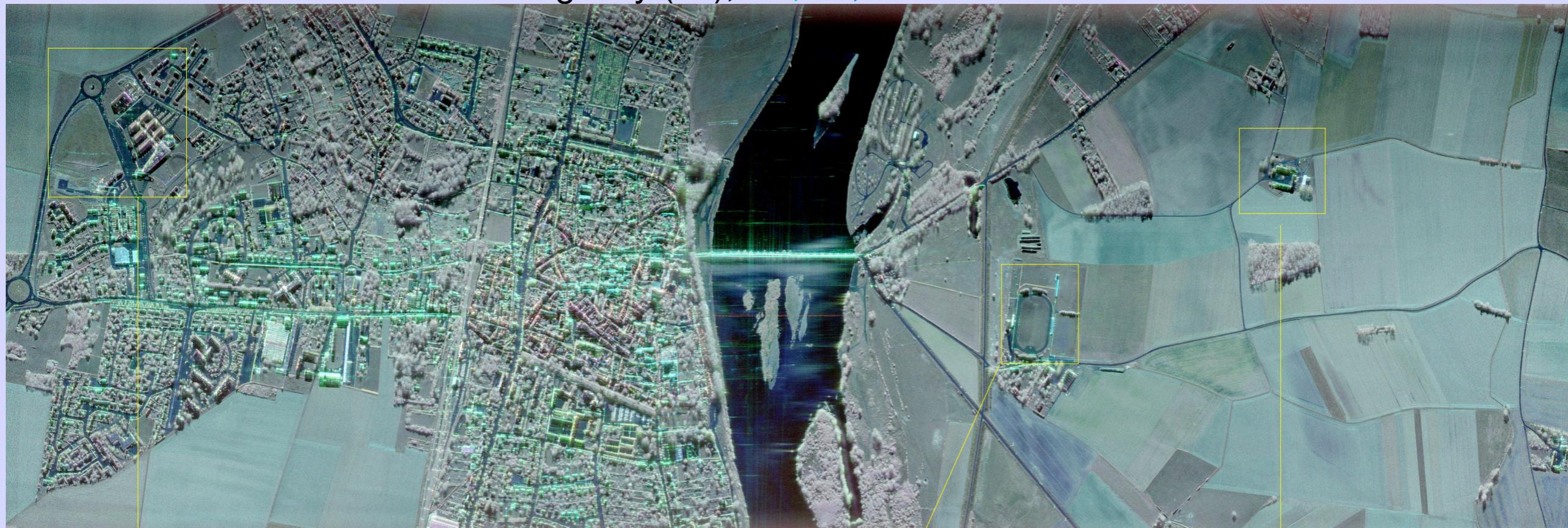
*Polarimetry will be detailed in Chapt. 3*

**Polarimetry :  $Hh+Vv$ ,  $Hh-Vv$ ,  $Hv$**



# Image RAMSES: Polarimétrie et Haute Résolution

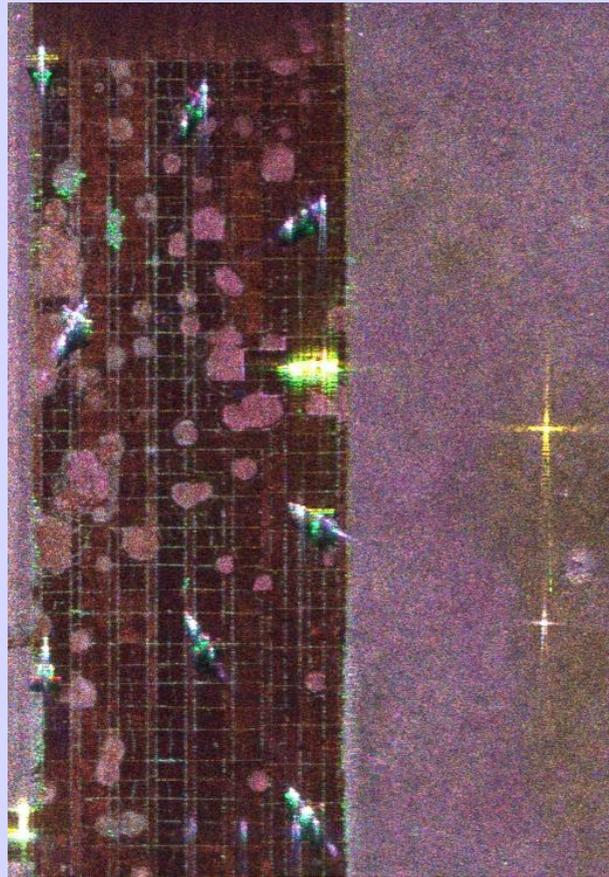
Beaugency (45), Hh, Vv, Hv



# Image RAMSES: Polarimétrie et Haute Résolution

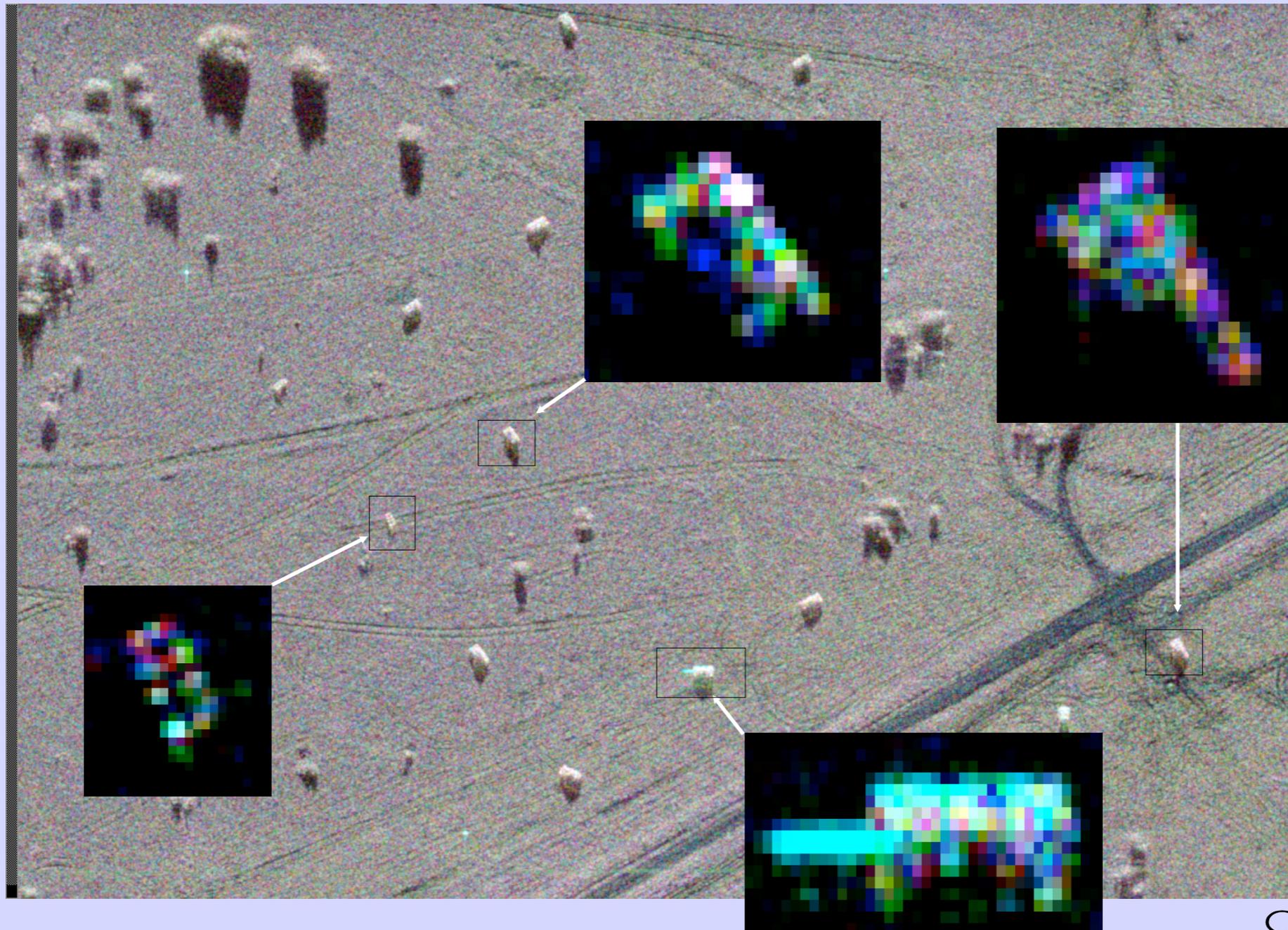
Bande X, dépression : 30

Hh, Vv, Hv



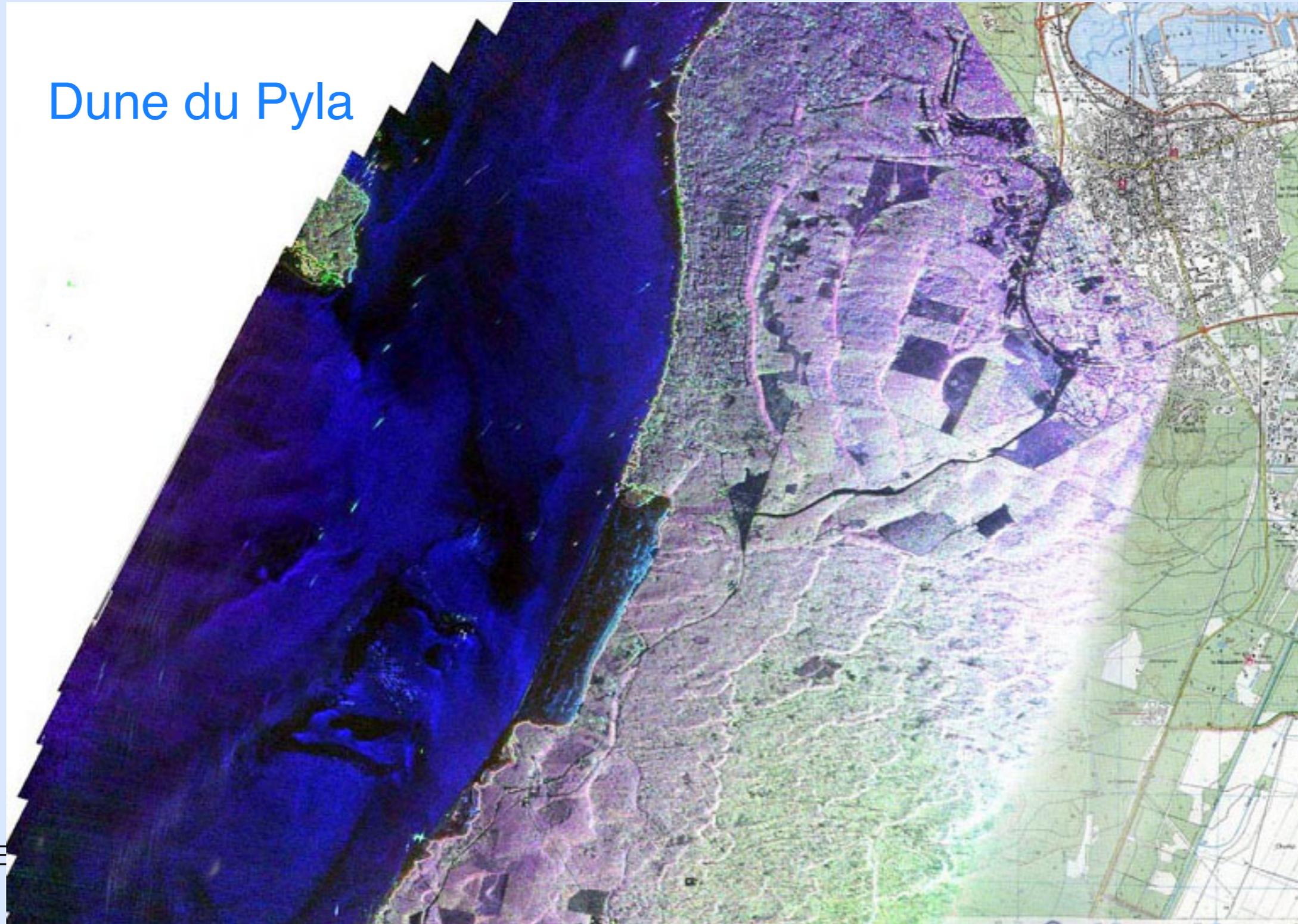
# Image RAMSES: Polarimétrie et Haute Résolution

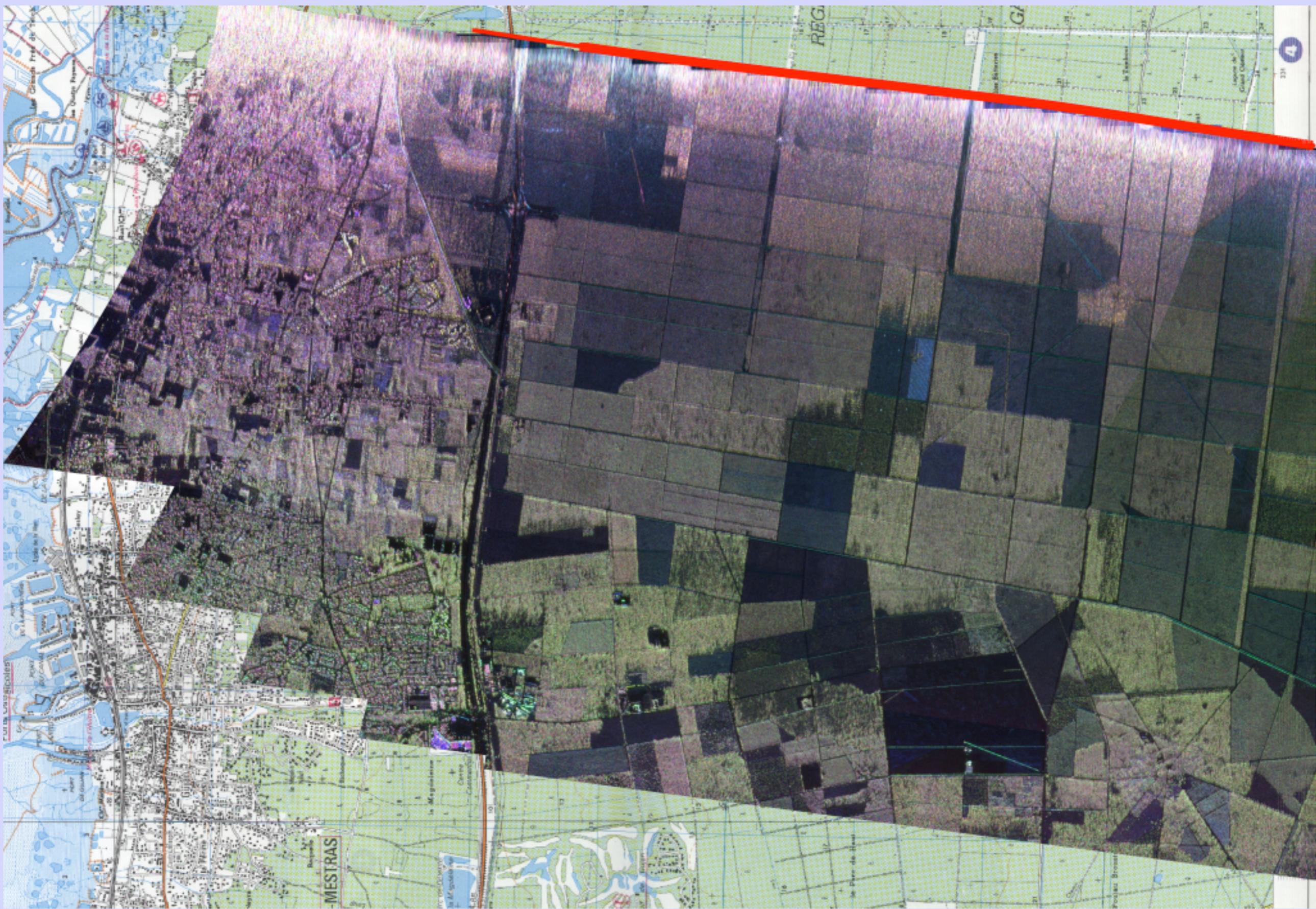
Bande X, dépression : 30 , Hh, Vv, Hv

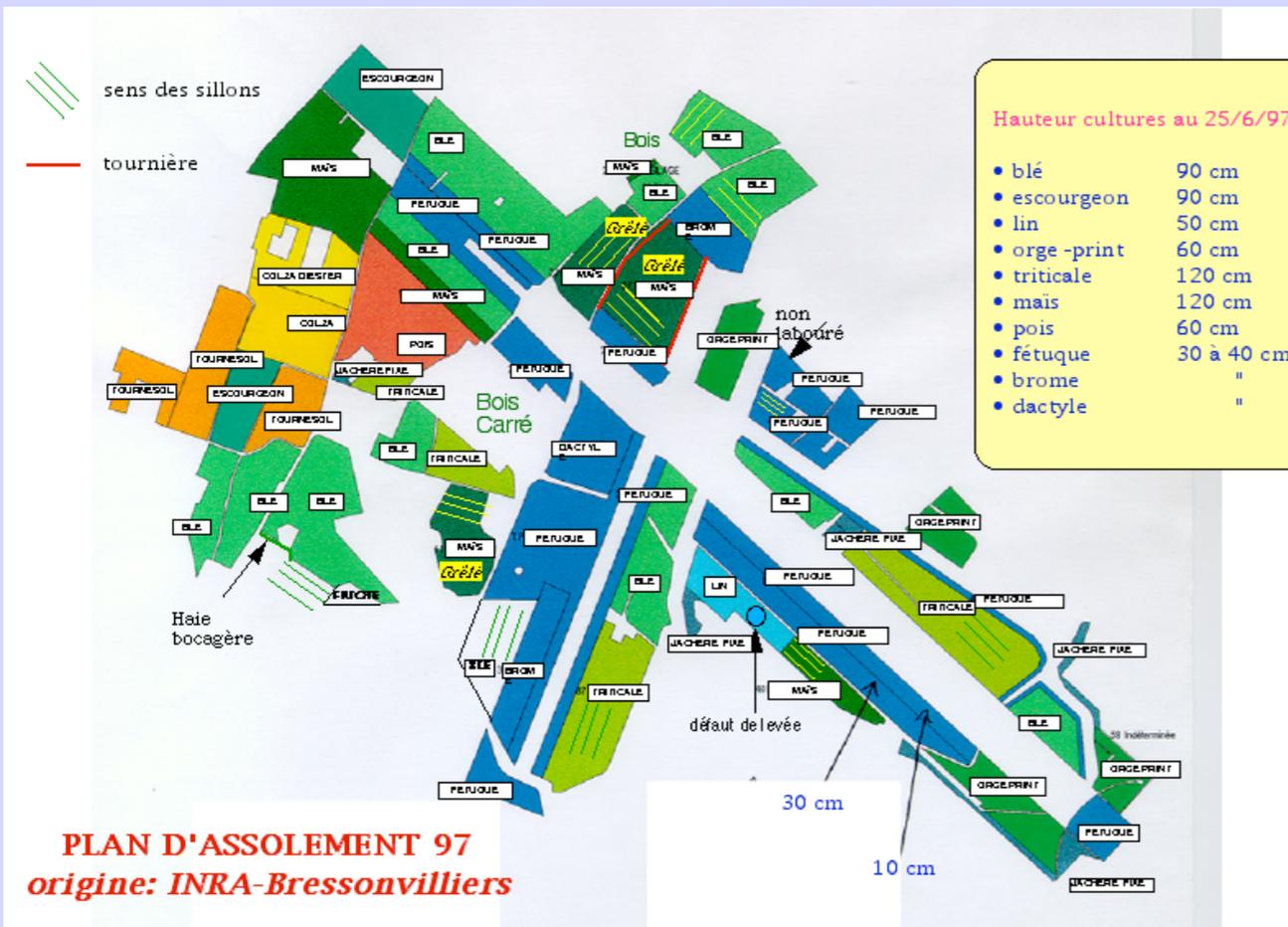


# Image RAMSES: Radar en bande basse (bande P, polarimétrique)

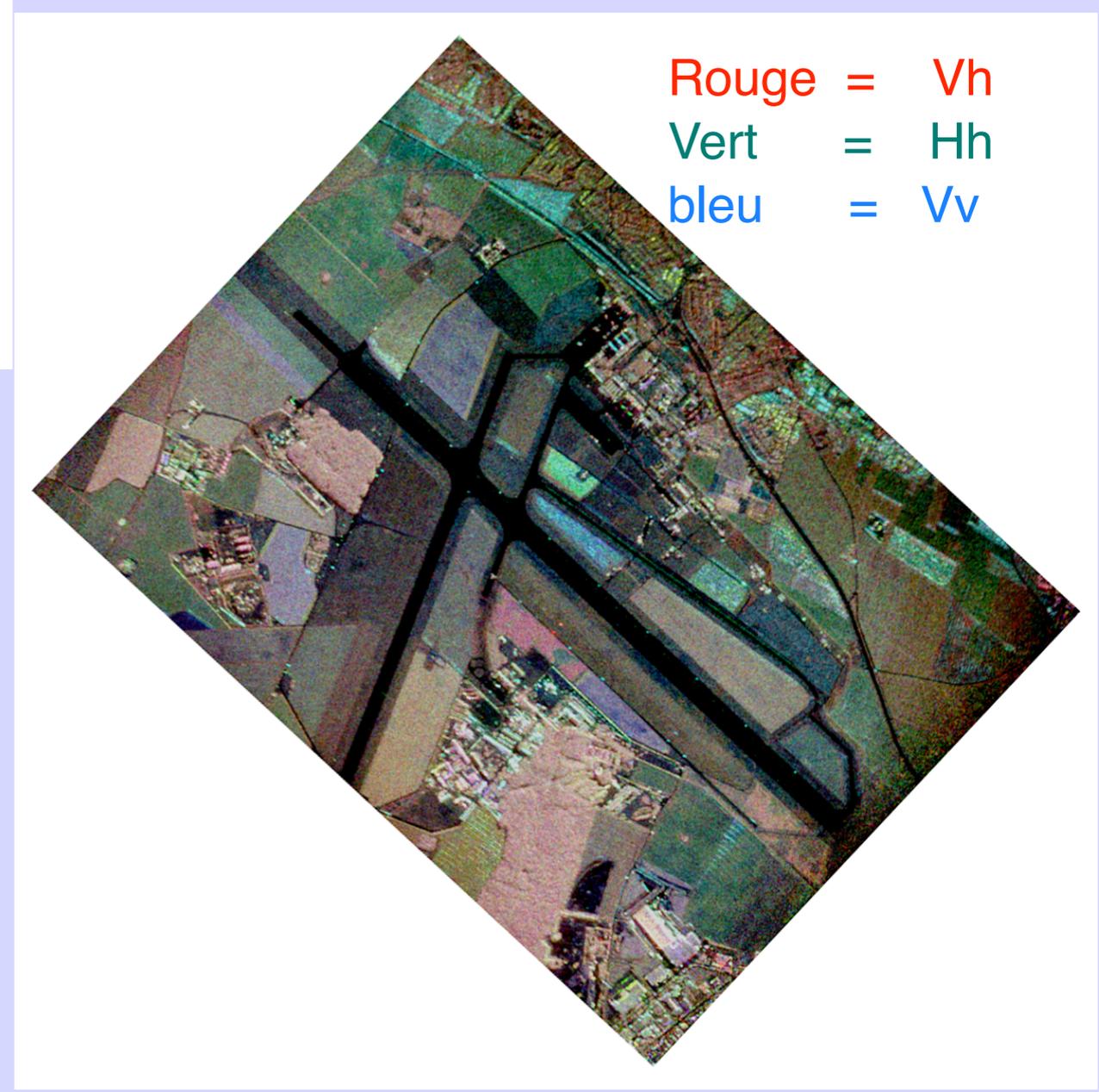
Dune du Pyla





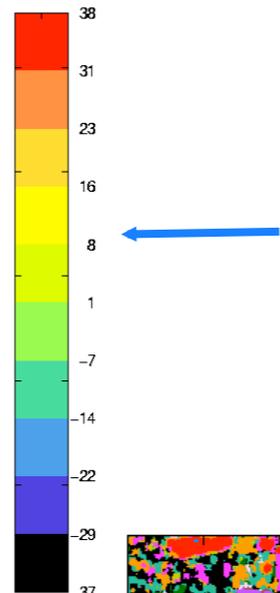
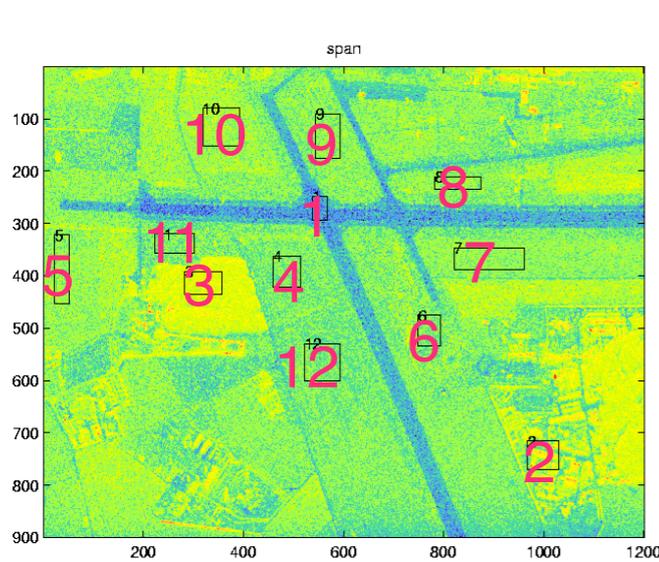


- Configuration polarimétrique complète bande L
- aérodrome de Brétigny
- site expérimental de l'INRA (manip d'opportunité)



# SAR polarimétrique

Capteur Ramses - Bande L zone agricole de Bressonvilliers



Mémoire de référence:  
Choix de 12 parcelles de référence

Image SAR classée  
pixel par pixel



- 12: «Fétuque para»
- prairie
- 11: «Fétuque» prairie
- 10: Blé 2
- 9 : Lin
- 8 : Orge
- 7: «Fétuque crash» prairie
- 6 : Maïs (juste semé)
- 5 : Blé1
- 4 : «Dactyle»prairie
- 3 : Forêt
- 2 : Zone urbaine
- 1 : Piste

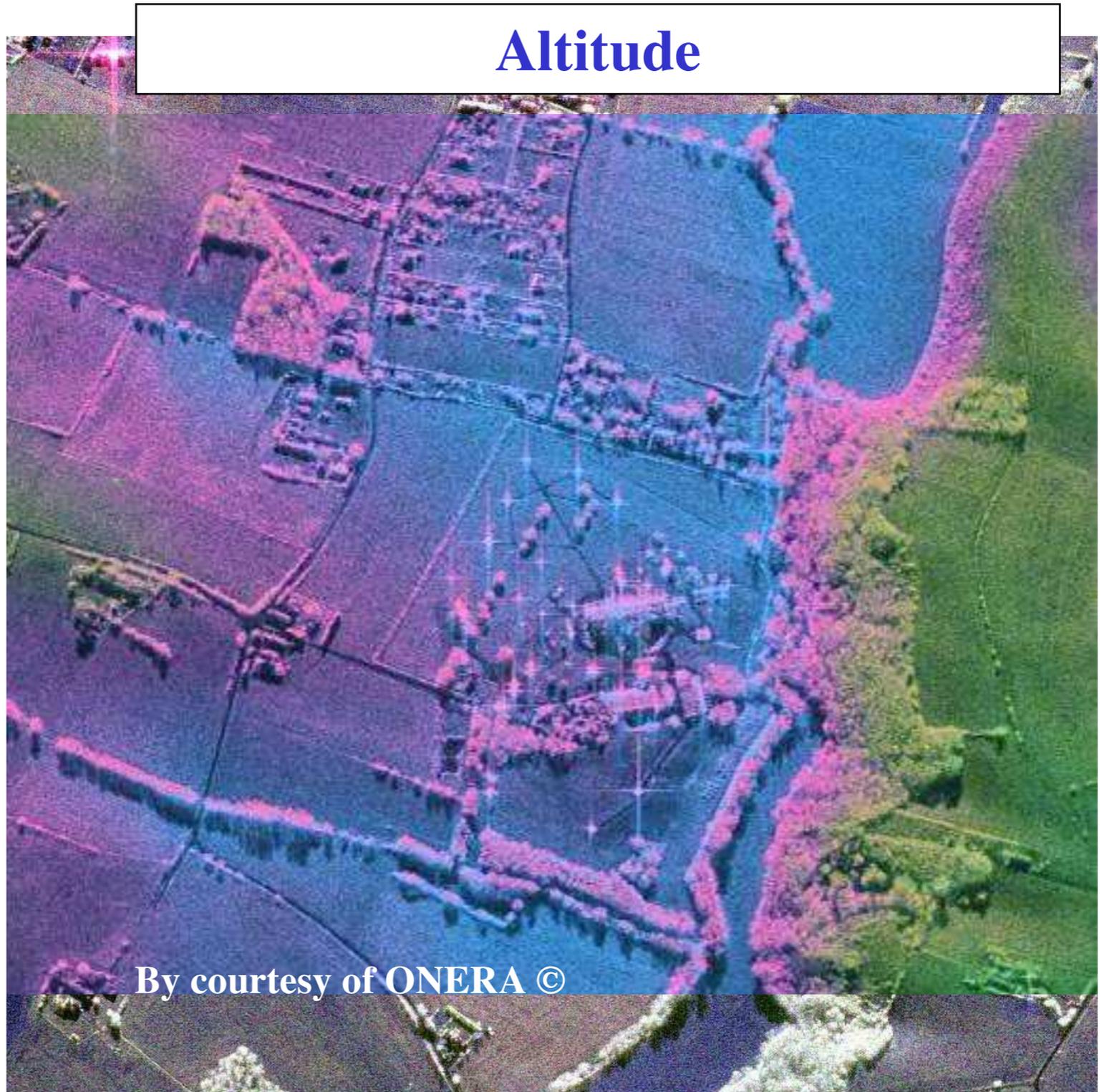
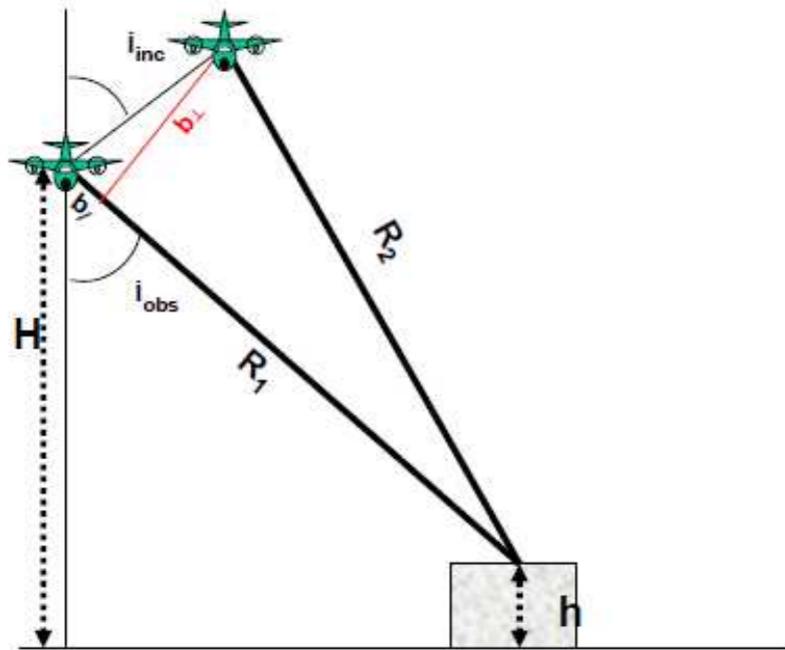
Classification des zones agricoles par utilisation de la polarimétrie

# SAR INTERFEROMETRY

## Interferometry

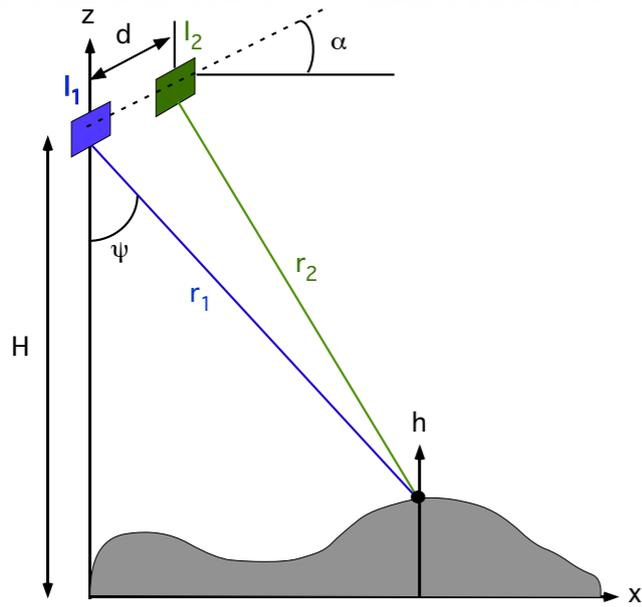
Combination of two SAR images of the same area of the ground, from slightly different angles

The phase difference is related to  $(R_1 - R_2)$  and to the altitude  $h$

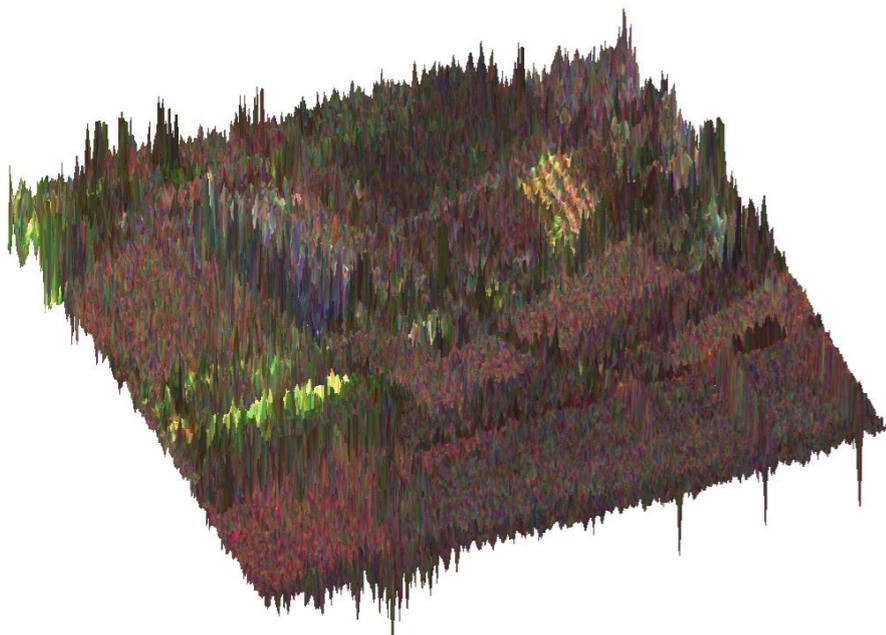


*Interferometry will be detailed in Chapt. 3*

# Principe et objectif de l'interférométrie



Deux antennes faiblement délocalisées spatialement



Interférogramme

Cohérence  
interférométrique

$$\gamma(x, y) = \frac{\langle S_1(x, y) S_2^*(x, y) \rangle}{\sqrt{\langle S_1(x, y) S_1^*(x, y) \rangle} \sqrt{\langle S_2(x, y) S_2^*(x, y) \rangle}}$$

Argument

Module

$$\Phi(x, y) = \arg[\gamma(x, y)]$$

$$|\gamma(x, y)|$$

Estimation de  
hauteur

$$h(x, y) = \frac{\Phi(x, y)}{2\pi} h_a$$

Fiabilité de l'estimation

$h_a$

: hauteur  
d'ambiguïté

# Image RAMSES: Interférométrie



Modèle numérique de terrain

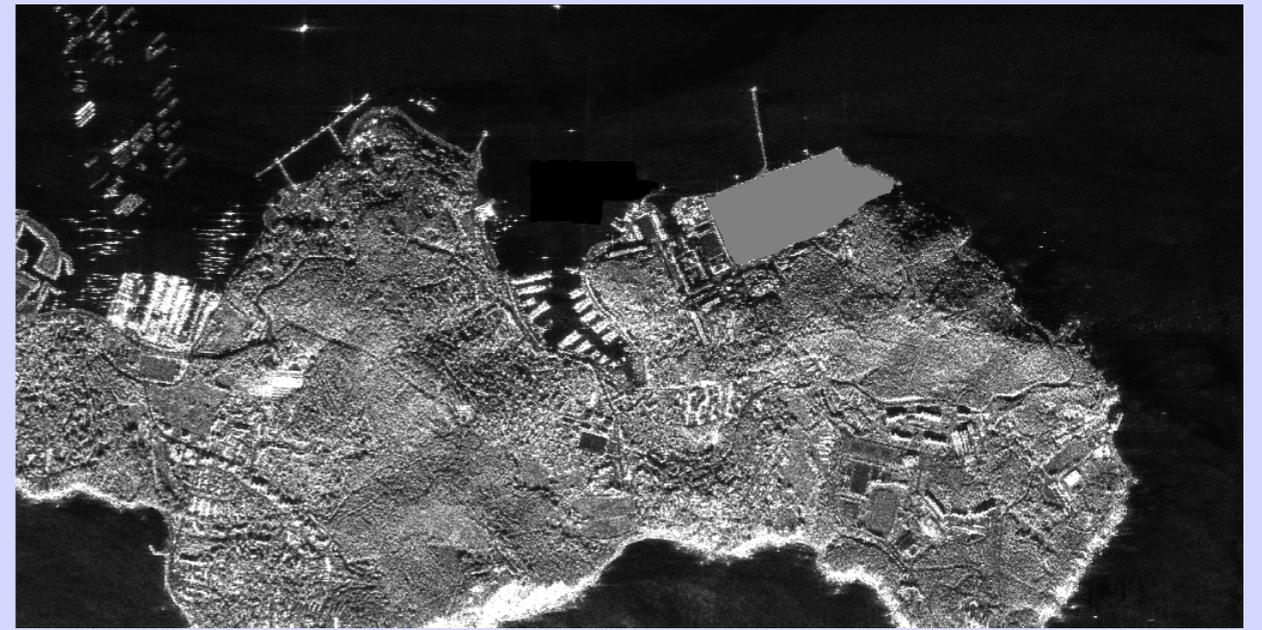
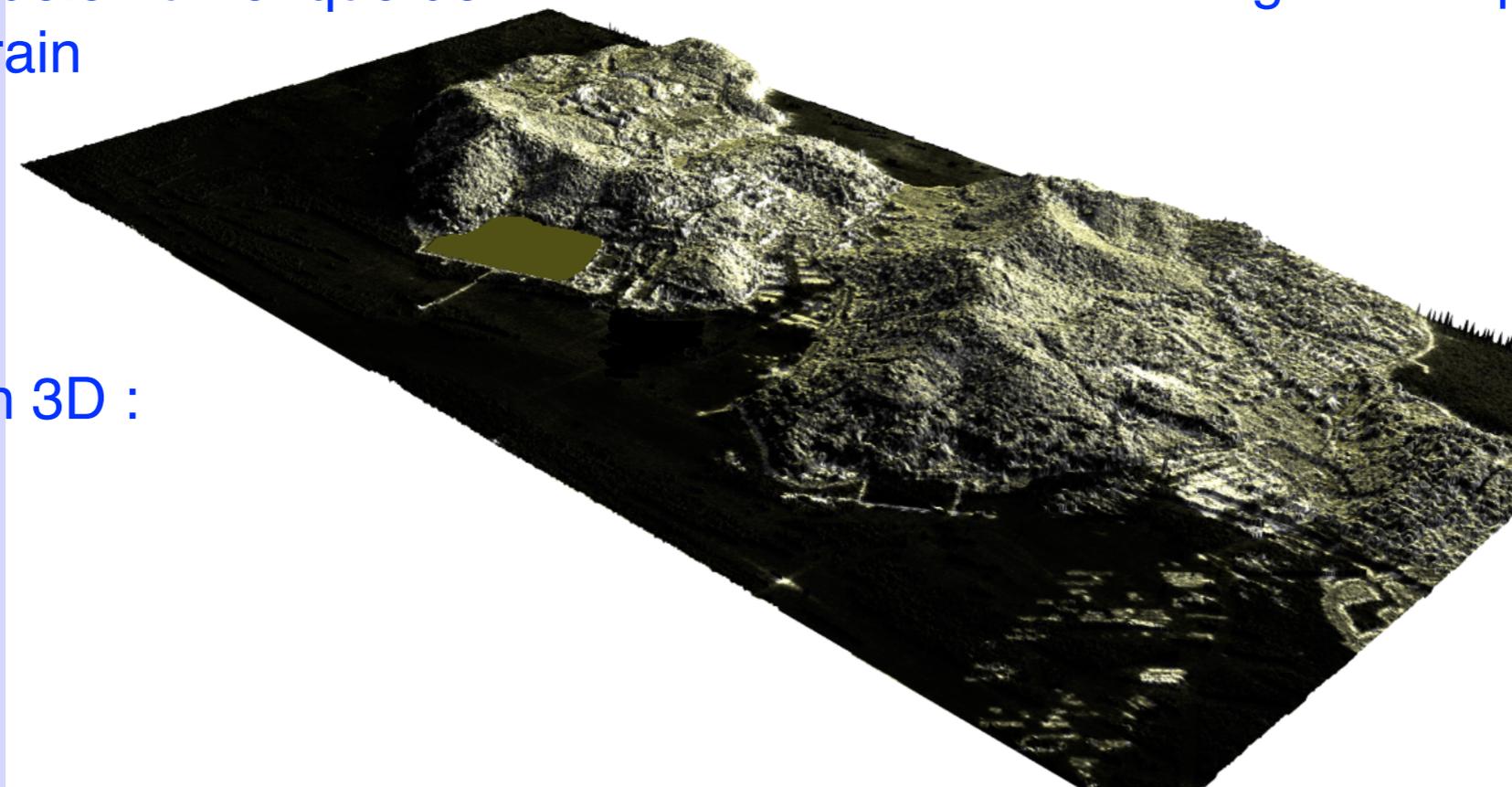


Image en amplitude

Visualisation 3D :

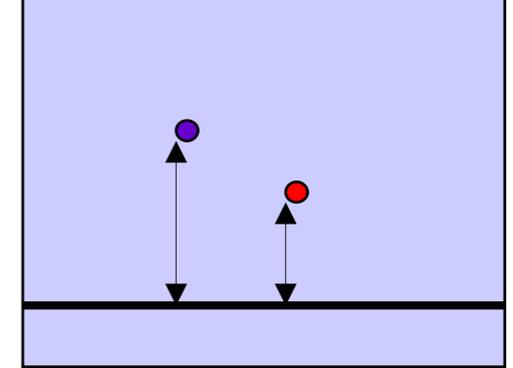
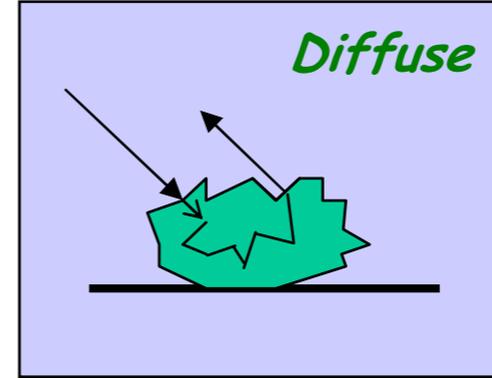
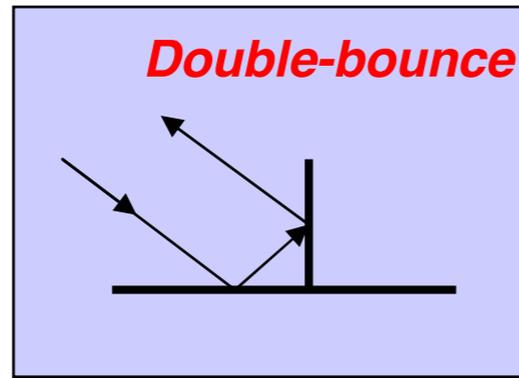
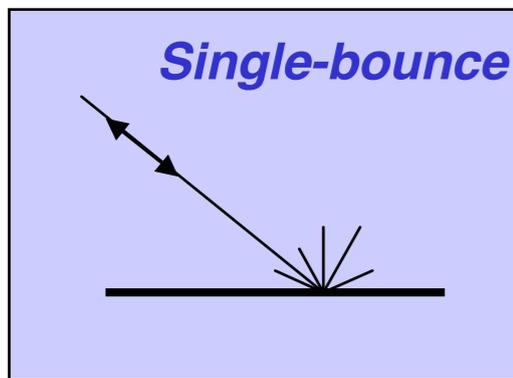


# POLARIMETRIC AND INTERFEROMETRIC SAR

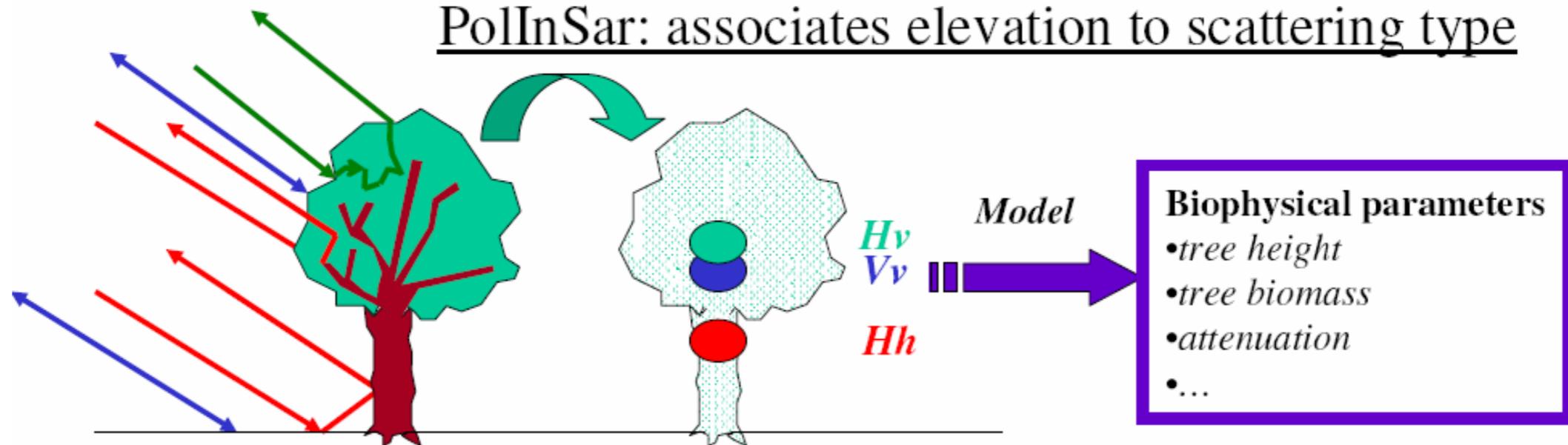
## Why Interferometry can complement polarimetry in FoPen /LF SAR

Polarimetry: sensitivity to scattering mechanism

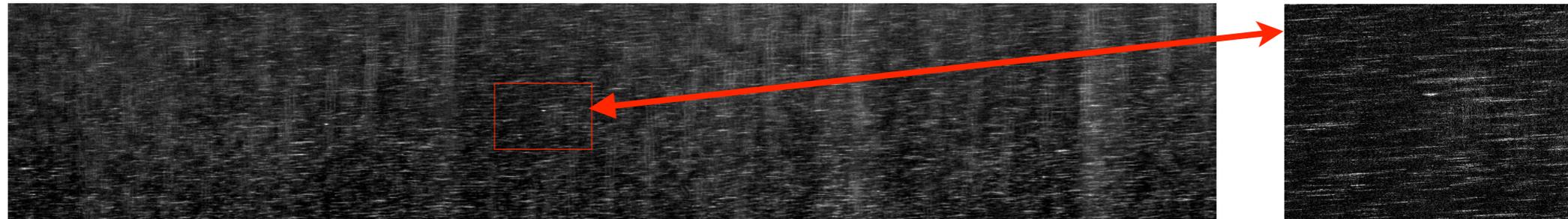
Interferometry: sensitivity in elevation & coherence



PolInSar: associates elevation to scattering type



# DETECTION IN SAR IMAGE



Conventional SAR detection framework on a mono-channel SAR image mainly consists in locally thresholding the complex amplitude of pixel  $x_i$ :

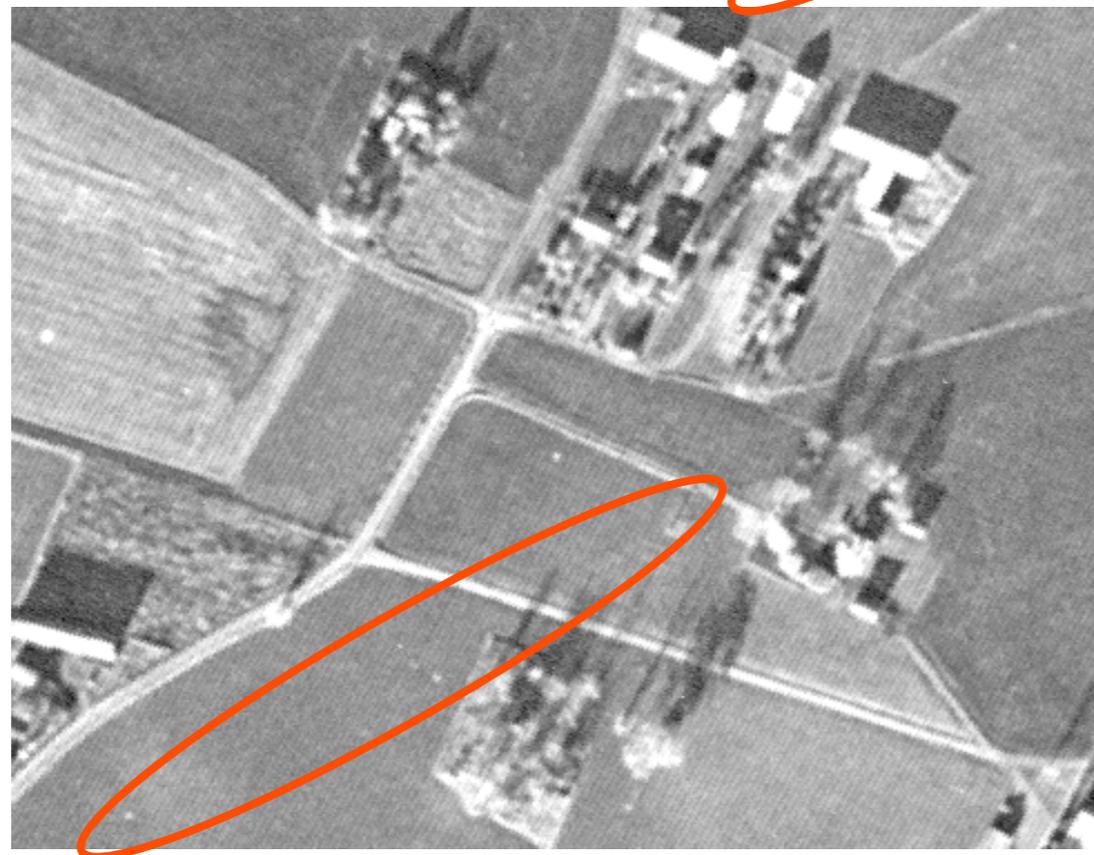
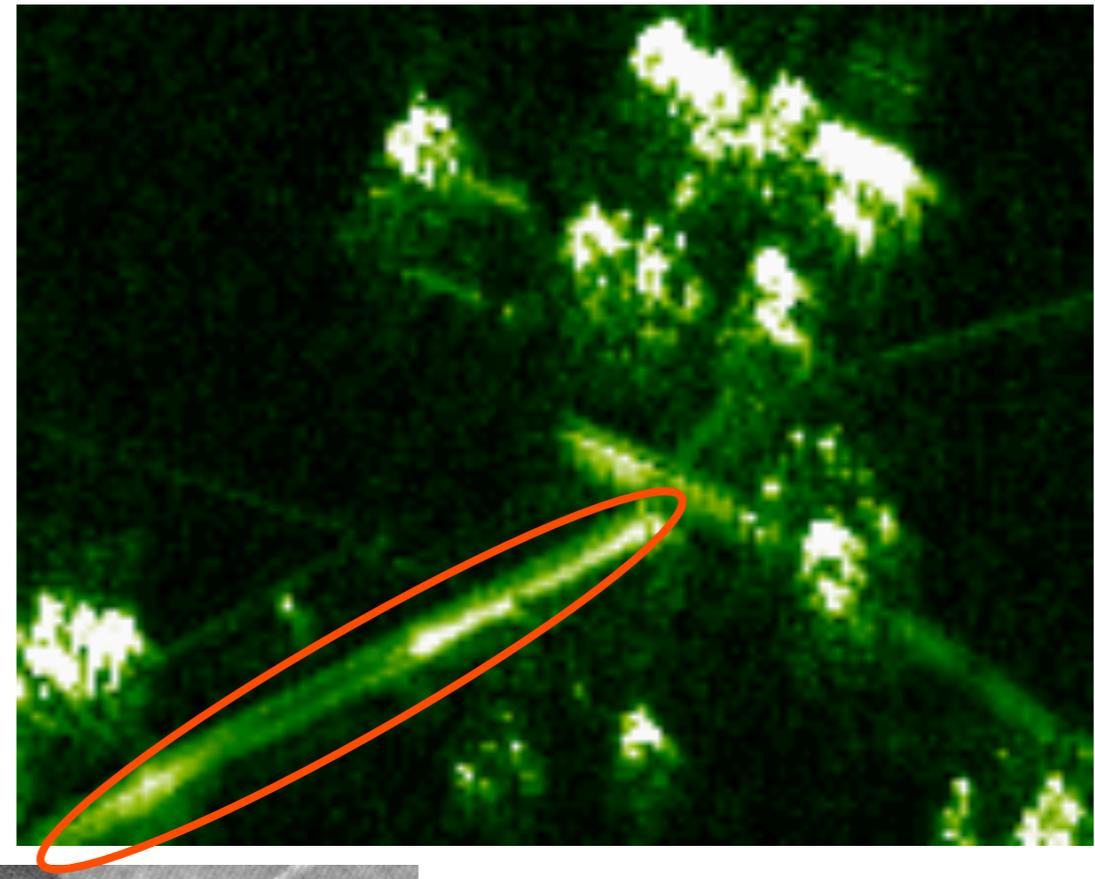
- Global thresholding (Gaussian hypothesis):  $\lambda = -\sigma^2 \log P_{fa}$ ,  $\Lambda(x_i) = |x_i|^2 \underset{H_0}{\overset{H_1}{\geq}} \lambda$ ,
- Adaptive thresholding (Gaussian hypothesis) on  $N$  pixels:

$$\Lambda(x_i) = \frac{|x_i|^2}{\frac{1}{N} \sum_{k \neq i} |x_k|^2} \underset{H_0}{\overset{H_1}{\geq}} \lambda, \quad \lambda = N \left( P_{fa}^{-1/N} - 1 \right),$$

- Statistic-based thresholding (other distributions):  $\lambda = f(P_{fa})$ ,  $\Lambda(x_i) = g(x_i) \underset{H_0}{\overset{H_1}{\geq}} \lambda$ .

Adaptive multi-channels SAR detection framework can be extended with diversity contained in the steering vector  $\mathbf{p}$  (polarimetry, interferometry, sub-looks and sub-bands decomposition ([Ovarlez et al., 2017], see Ammar Mian's PhD talk).

# SAR bande basse (4)



**LORA SAR (Suède) UHF :**  
**219-420 MHz HH-pol**  
**Resolution = 0.7 x 0.7 m<sup>2</sup>**

**CARABAS (Suède) VHF:**  
**22-82 MHz HH-pol**  
**Resolution = 2.5 x 2.5 m<sup>2</sup>**

**Photo aérienne**

Lignes électriques

# Campagne Egypte

- Objectif : explorer le potentiel des radars basses fréquence pour:

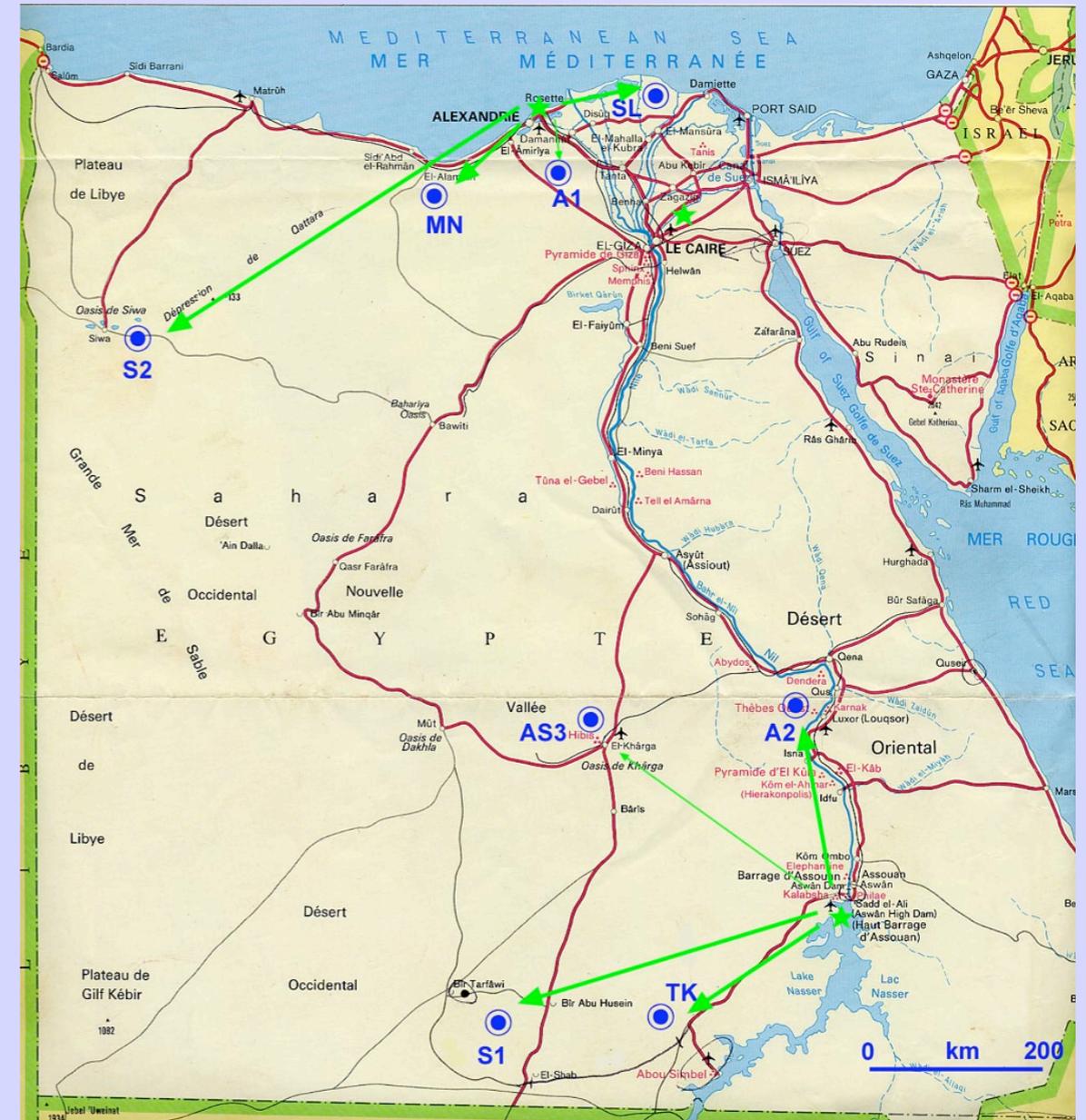
- Détection de mines
- Détection de l'humidité des sols
- Salinité
- Sub-surfacique
- Archéologie

- Date: Janvier-février 2004

- Radars embarqués: Bande L, P

- Zone de mesures:

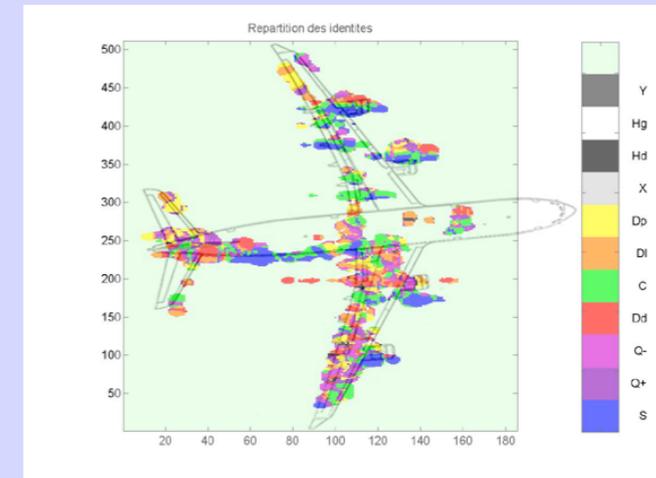
- Campagne Nord Egypte : camp de base Alexandrie
- MN : El Alamein, déminage mines anti-char 2<sup>ème</sup> guerre mondiale.
- S2 : oasis de Siwa, détection de l'humidité des sols.
- SL : delta du Nil, mesure de la salinité des sols.
- A1 : sud d'Alexandrie, site archéologie n° 1.
- Campagne Sud Egypte : camp de base Assouan
- S1 : oasis de Bir Safsaf, paléo-hydrologie.
- TK : départ du canal de Tochka, génie civil.
- AS3 : oasis de El Khârga, géologie du sous-sol.
- A2 : région de Louxor, site archéologie n° 2.



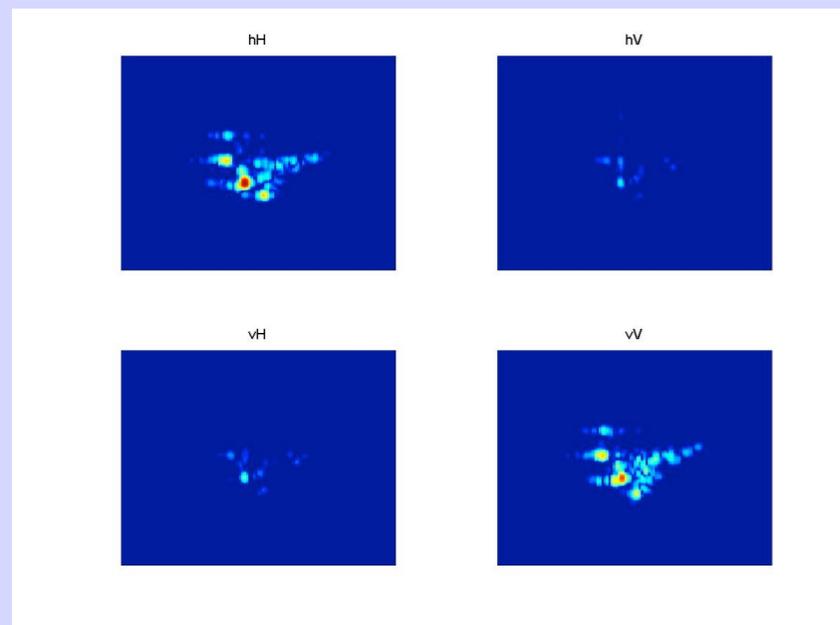
# STATION RADAR MERIC

## MESURES POLARIMETRIQUES HAUTE RESOLUTION (50 cm)

- AVIONS CIVILS (PALAISEAU)
- AVIONS D'ARMES FRANCAIS ET DE L'OTAN (SALON DE PROVENCE)



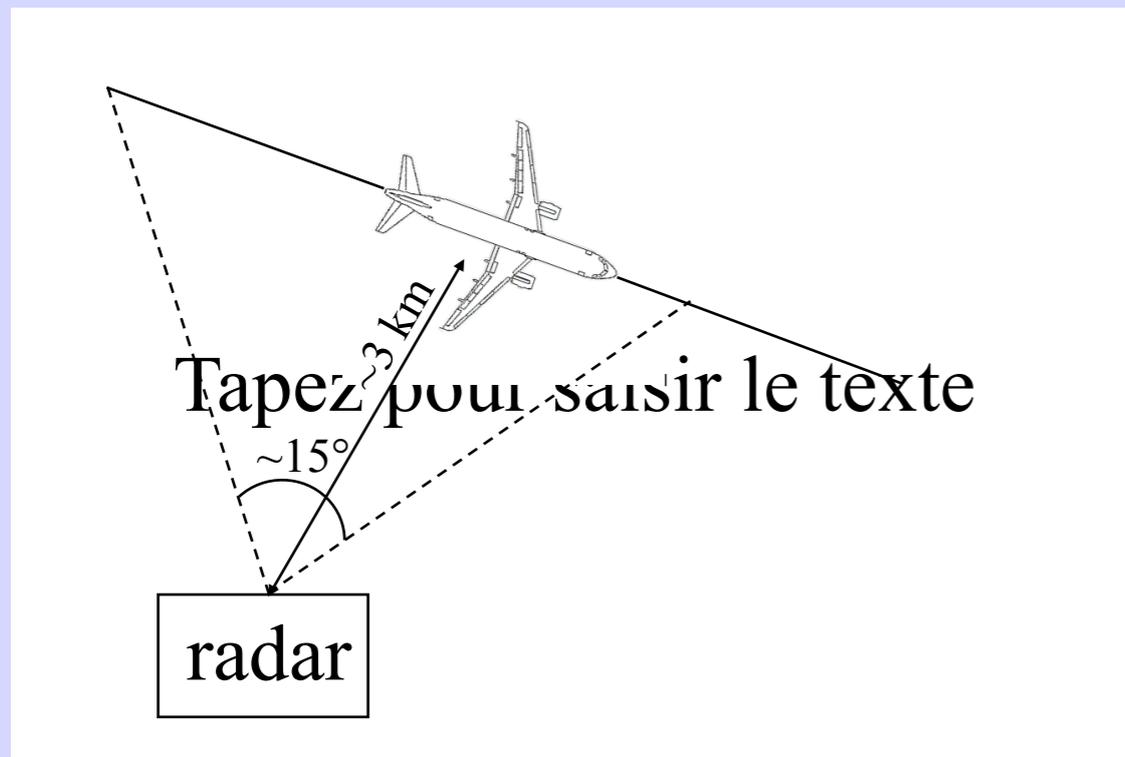
ANALYSE DES POINTS BRILLANTS



IMAGES ISAR



# Implantation de MERIC à Palaiseau



# Mac Donnell Douglas 82

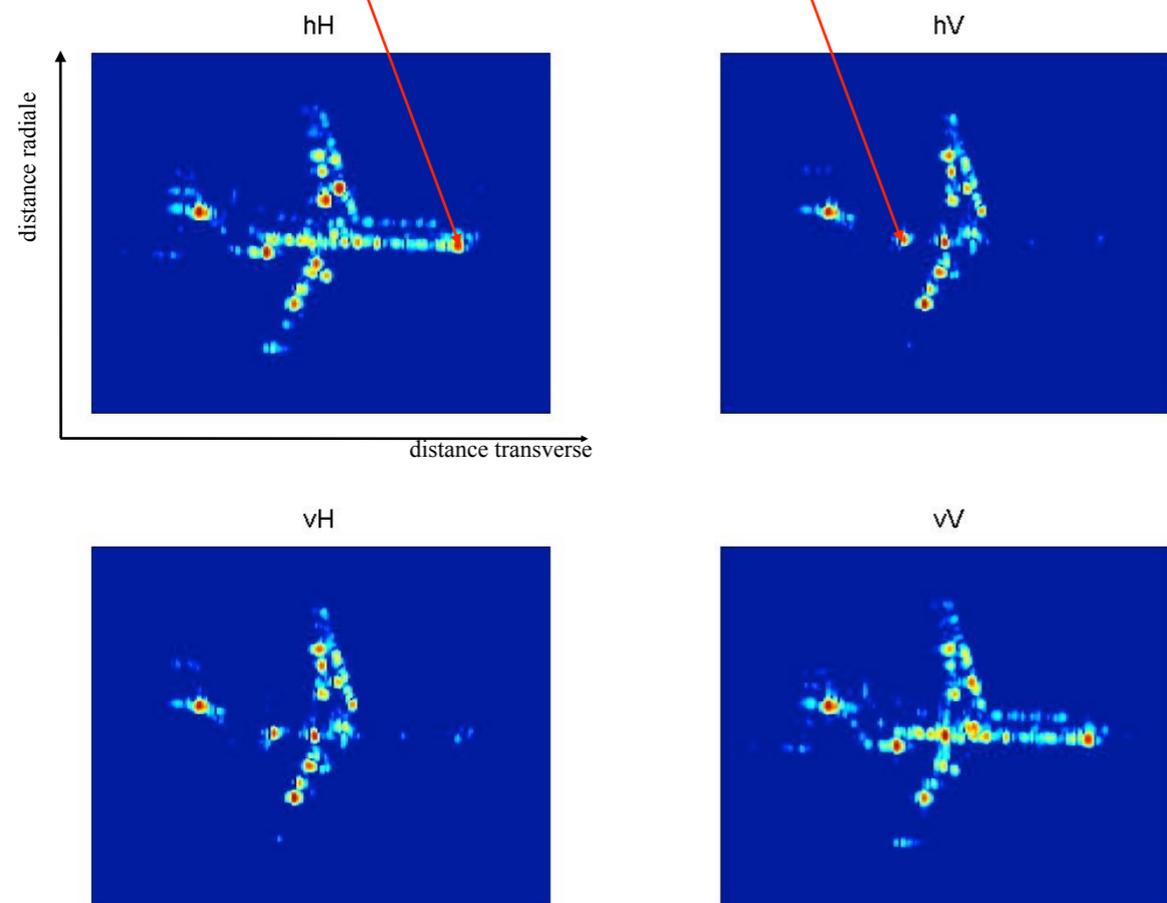


IMAGE VIDEO MERIC

# MD 82 - IMAGE ISAR MULTIPOLARISATION

Point A

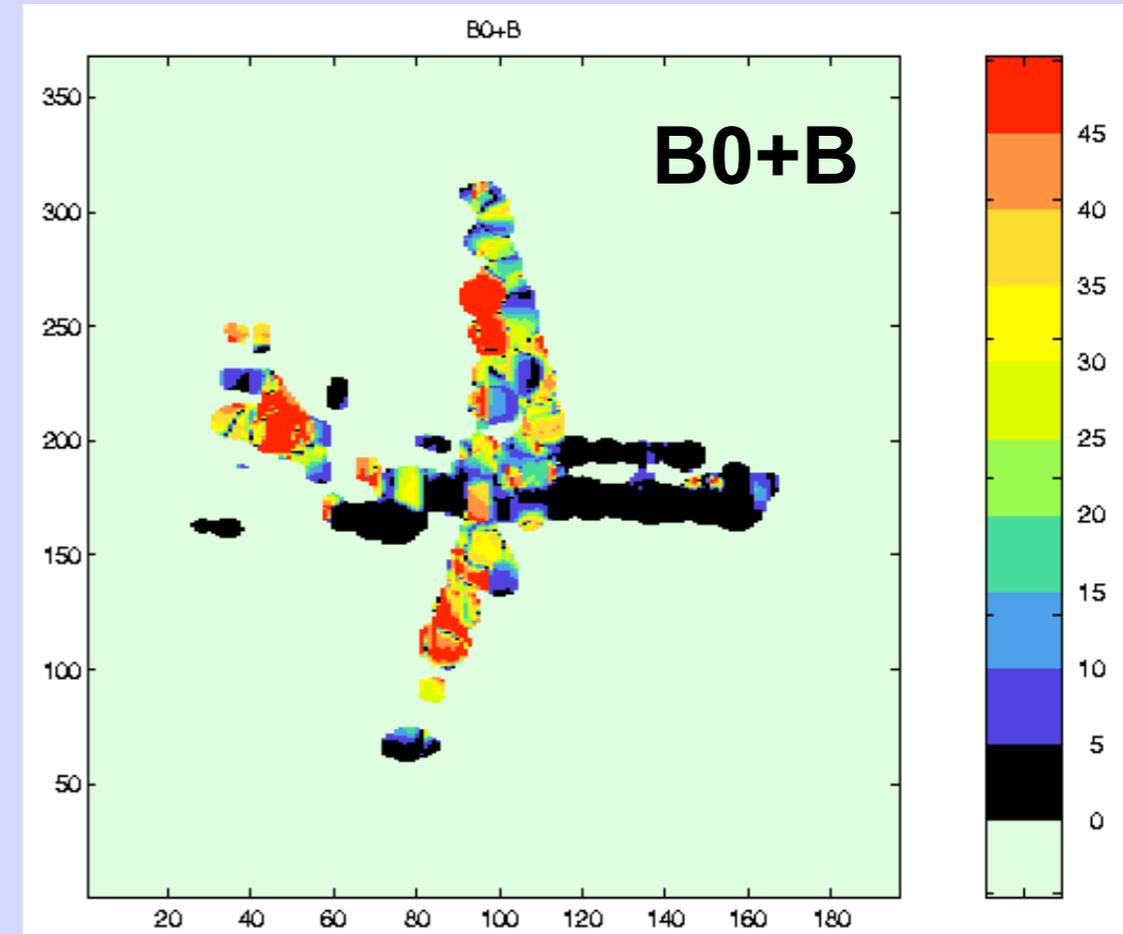
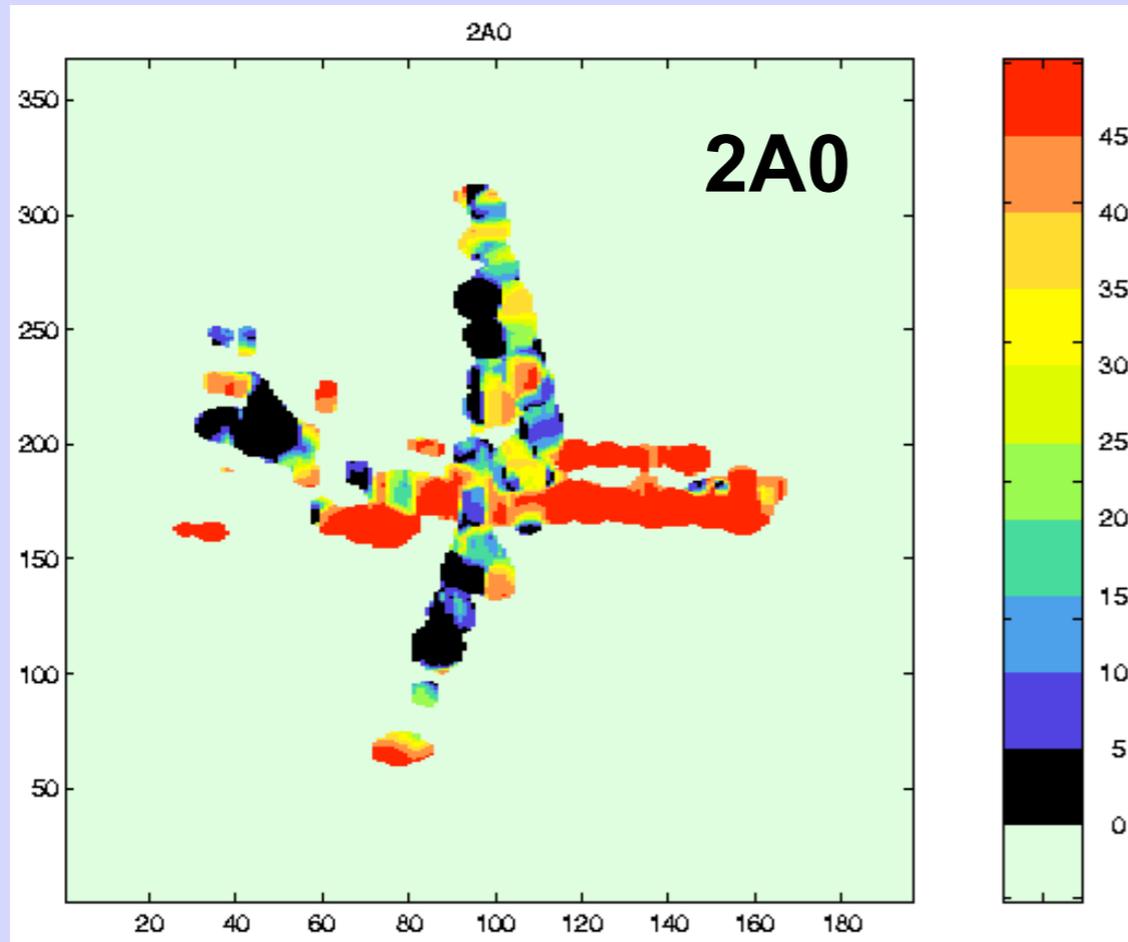
Point B



Un pixel = Une matrice complexe 2 x 2

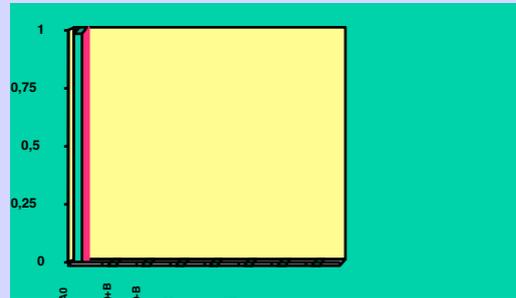
$|\sigma_{i,j}|^2$  : SER en mètres carrés

## Images de 2 paramètres de Huynen



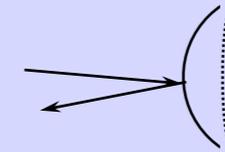
**2A0: indicateur d'interaction de surface**  
**B0+B: indicateur de double rebond (dièdre)**

# QUELQUES MÉCANISMES DE RÉFLEXION

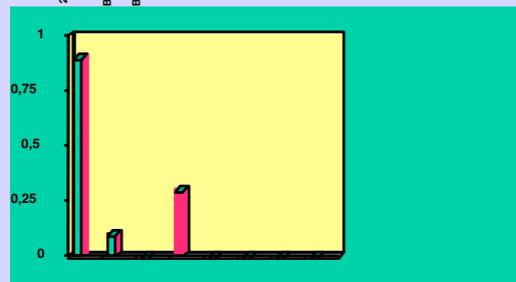


$$2A0 =$$

**SPHÈRE**



Réflexion spéculaire sur une surface localement sphérique

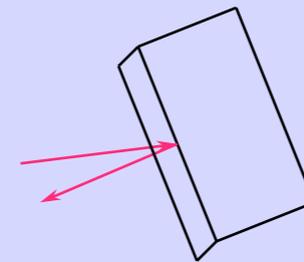


$$2A0 = 0.9$$

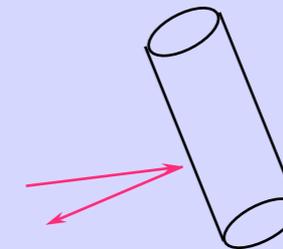
$$B0 + B = 0.1$$

$$C = 0.3$$

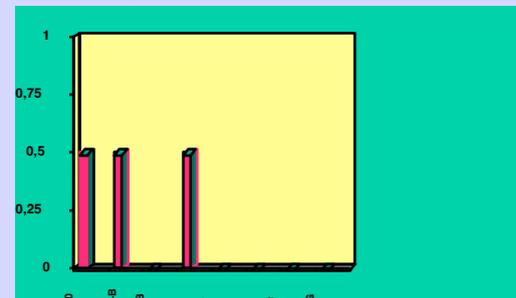
**CYLINDR**



**Bord épais**

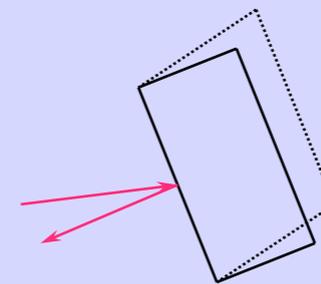


**cylindr**

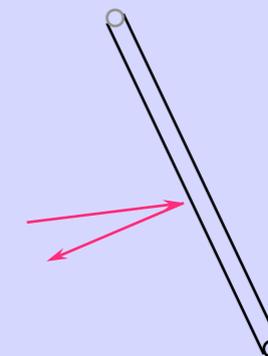


$$2A0 = B0 + B = C = 0.5$$

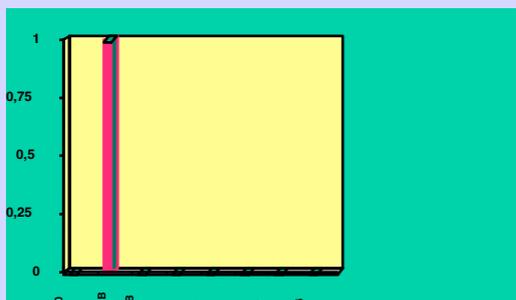
**DIPOL**



**Bord**

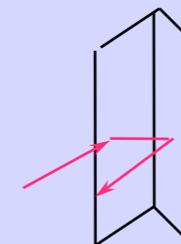


**Fil long et fin**



$$B0 + B =$$

**DIÈDR**

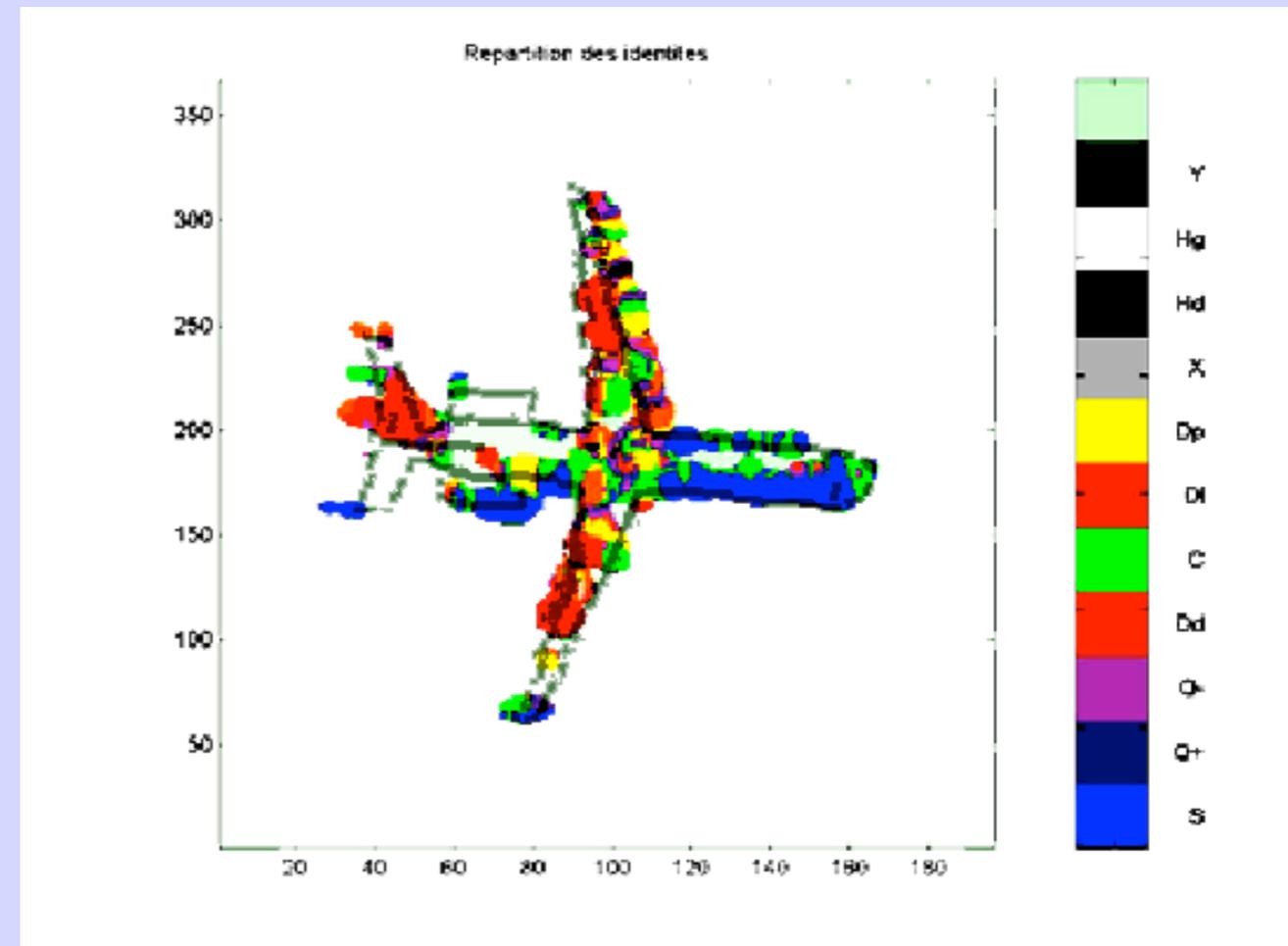


Double rebonds sur deux plaques planes

# Identification de interactions électromagnétiques



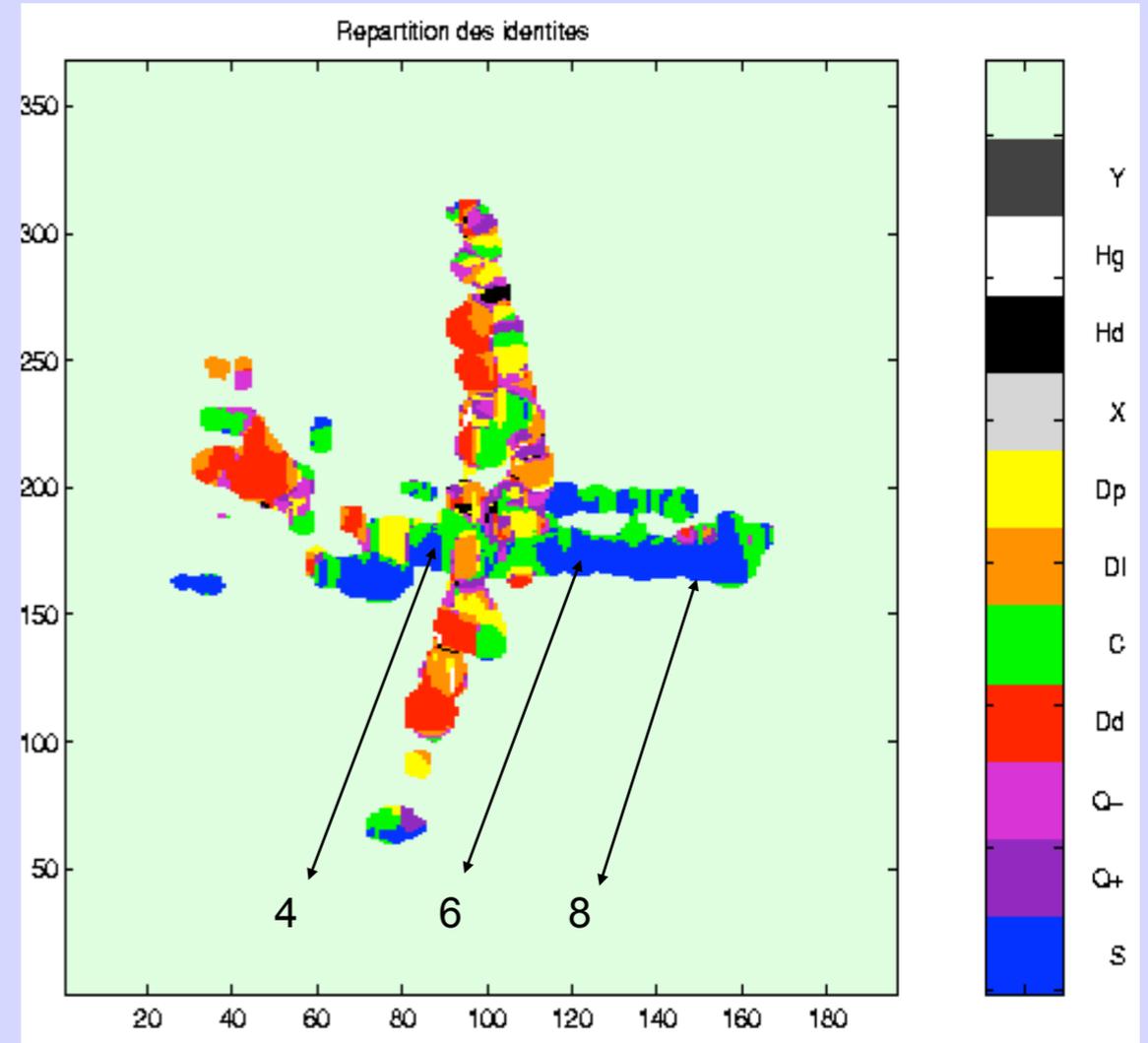
**Photographie**



**Image de l'identité + Silhouette**  
(méthode de Cameron)



**Spéculaire sur le fuselage**

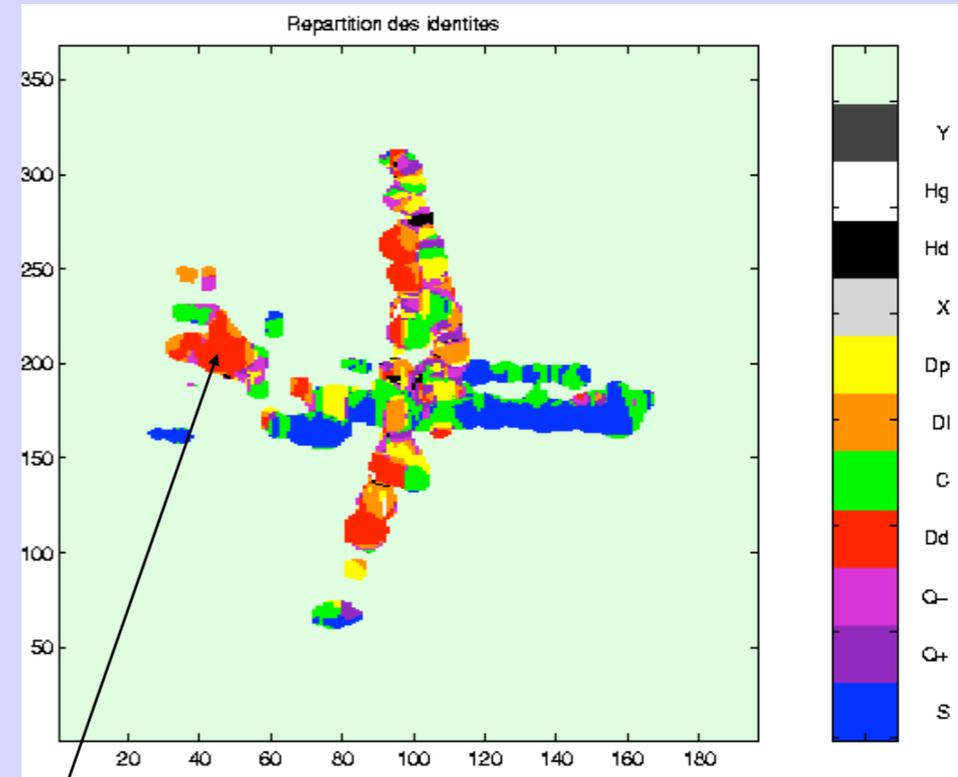


**Identification des interactions électromagnétiques**  
*Interactions de surface*



*1*

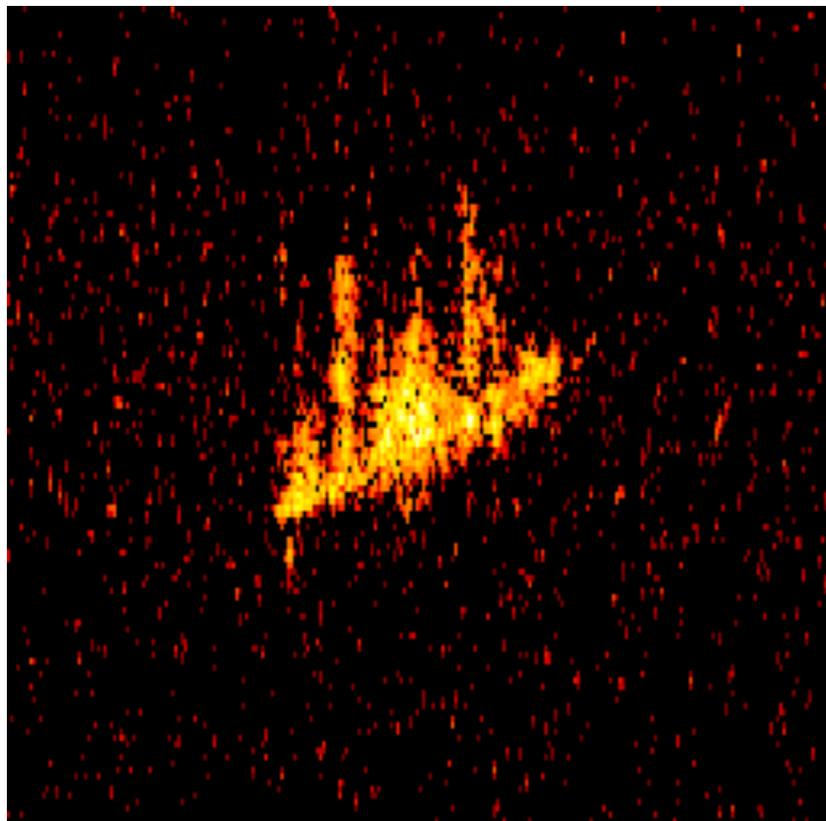
**Dérive / empennage horizontal  
doubles-rebonds**



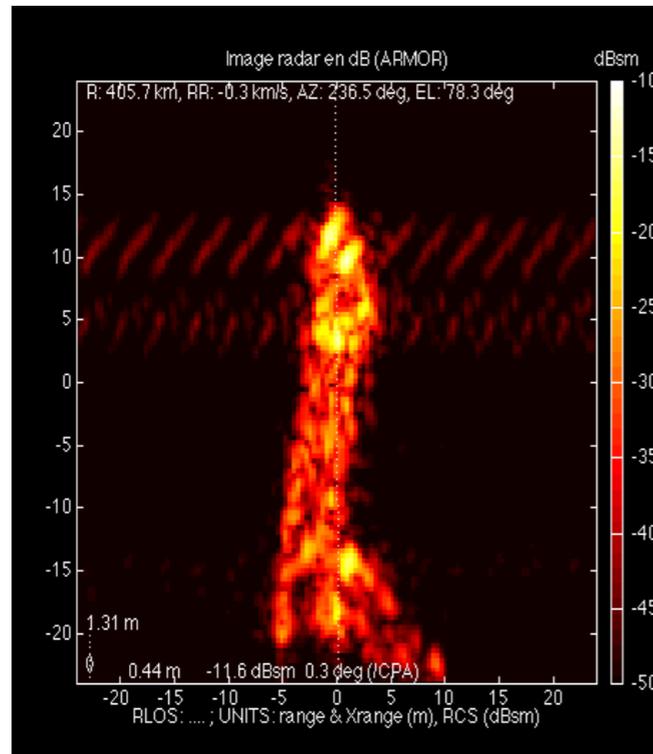
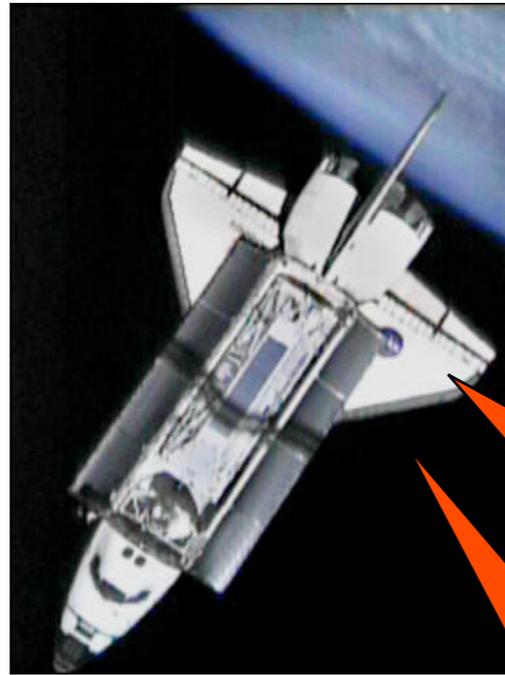
*1*

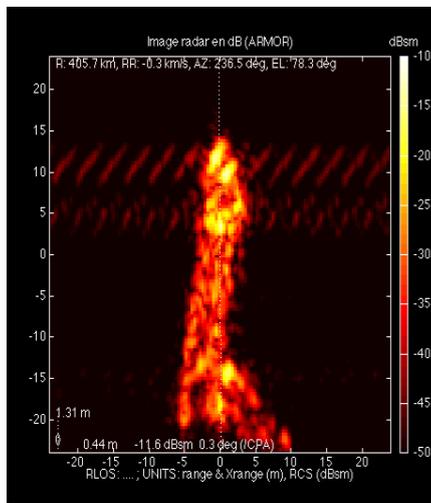
**Identification des interactions électromagnétiques  
doubles-rebonds (~dièdre)**

# L'imagerie ISAR : exemples ...

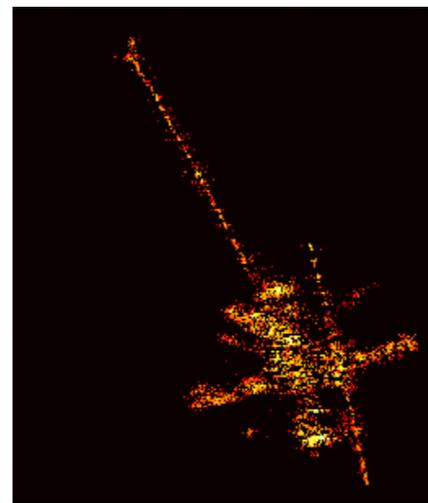


# Exemples ...

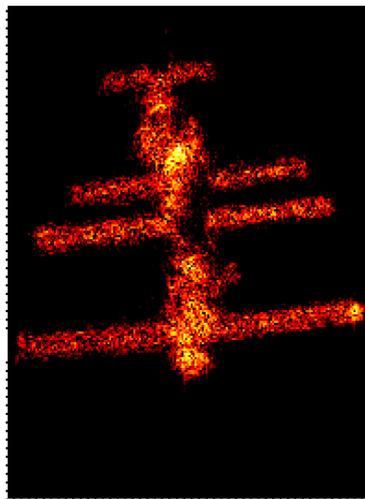
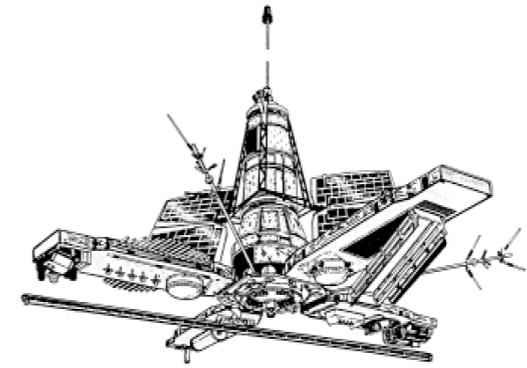




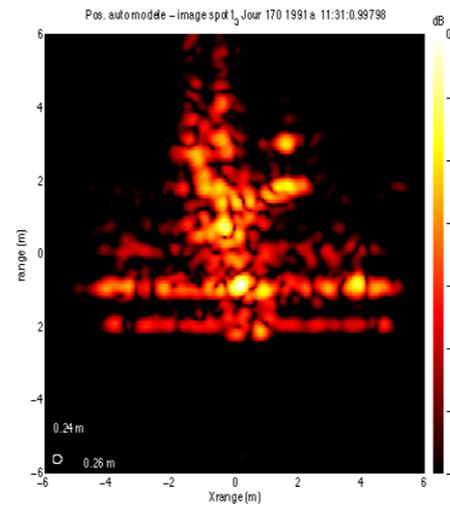
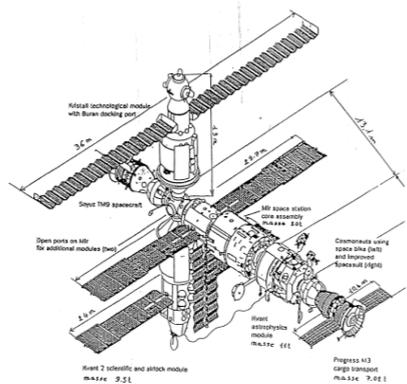
# ATLANTIS



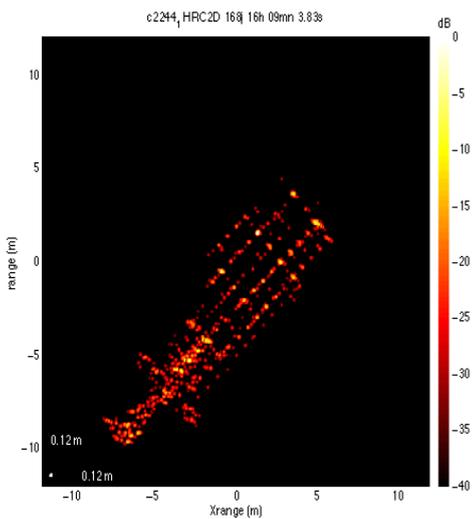
# OKEAN



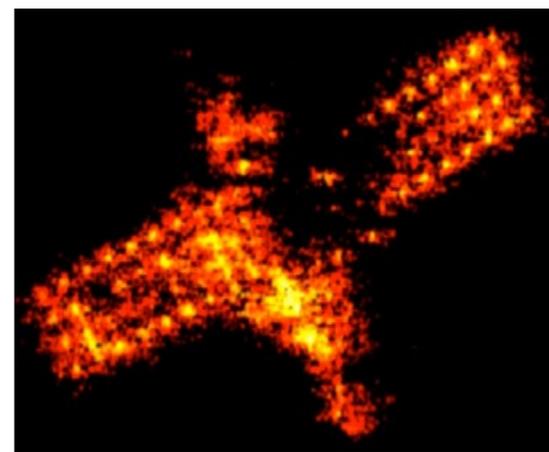
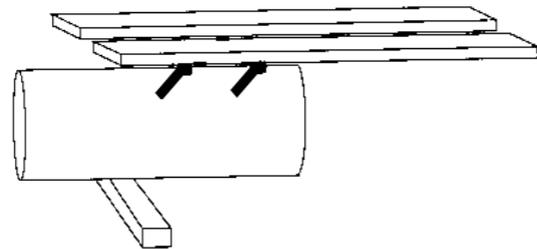
# MIR



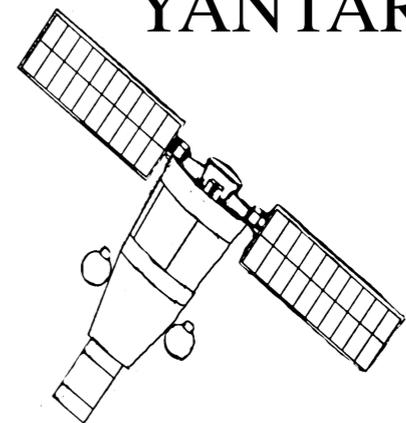
# SPOT



# EORSAT



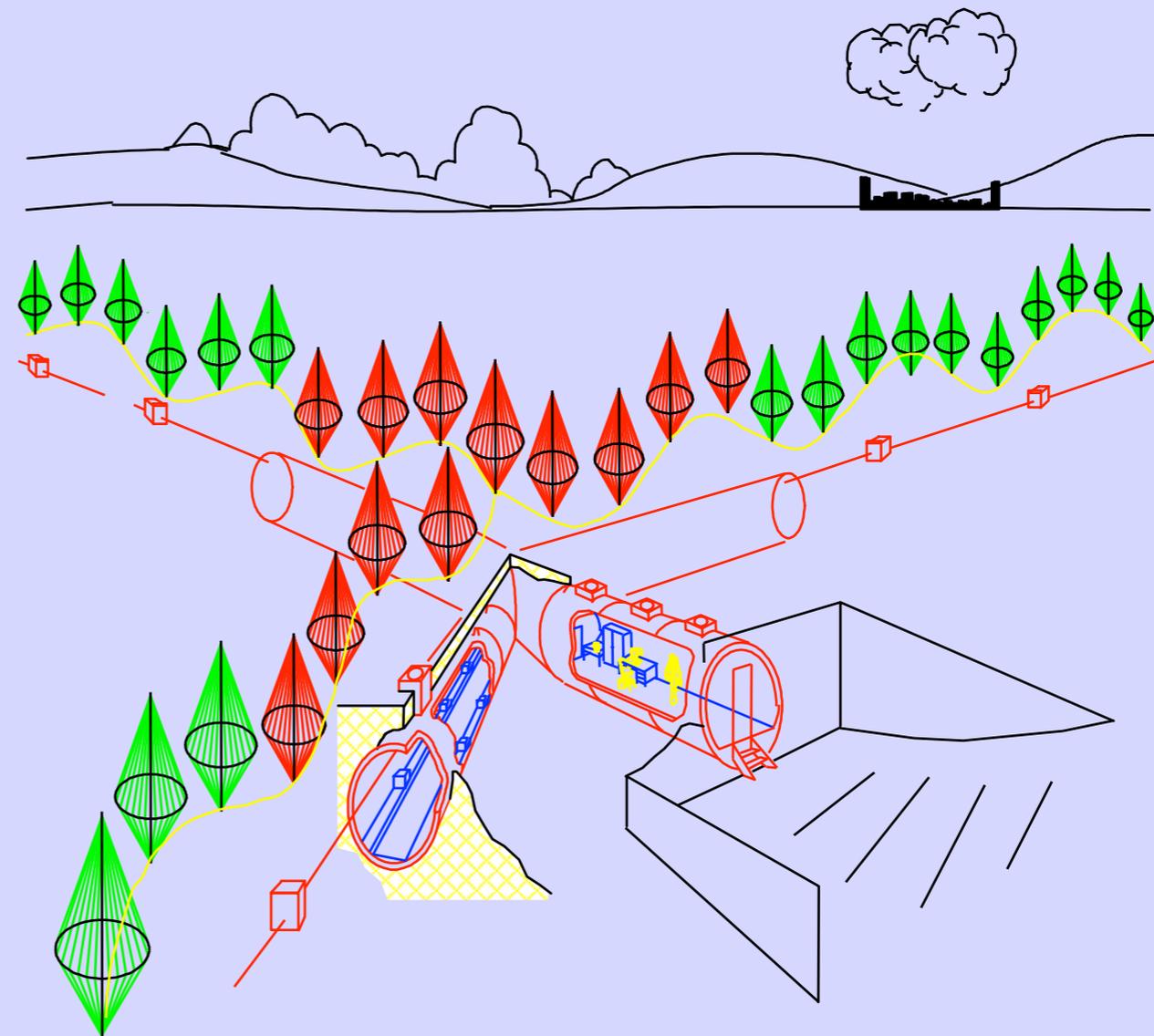
# YANTAR

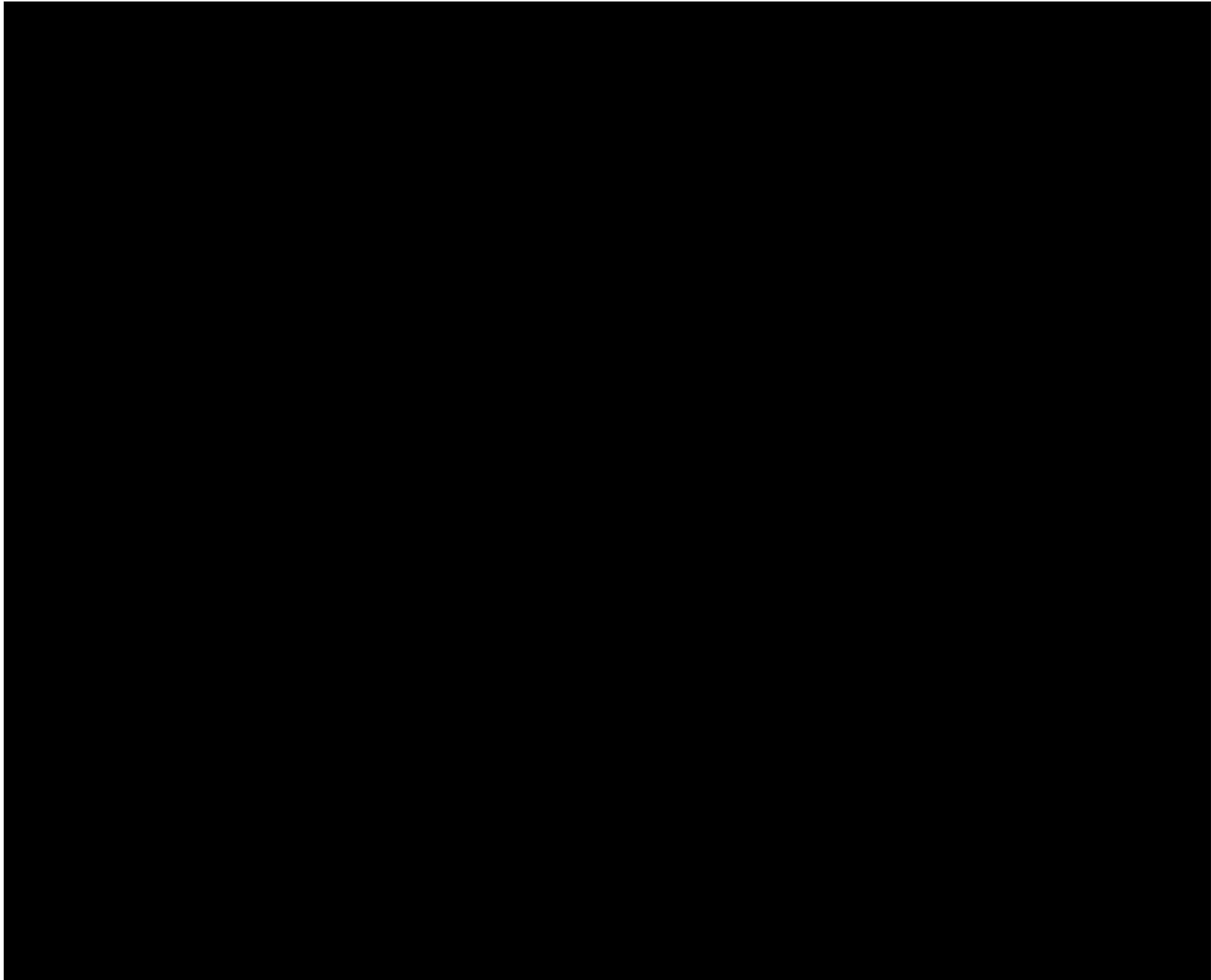


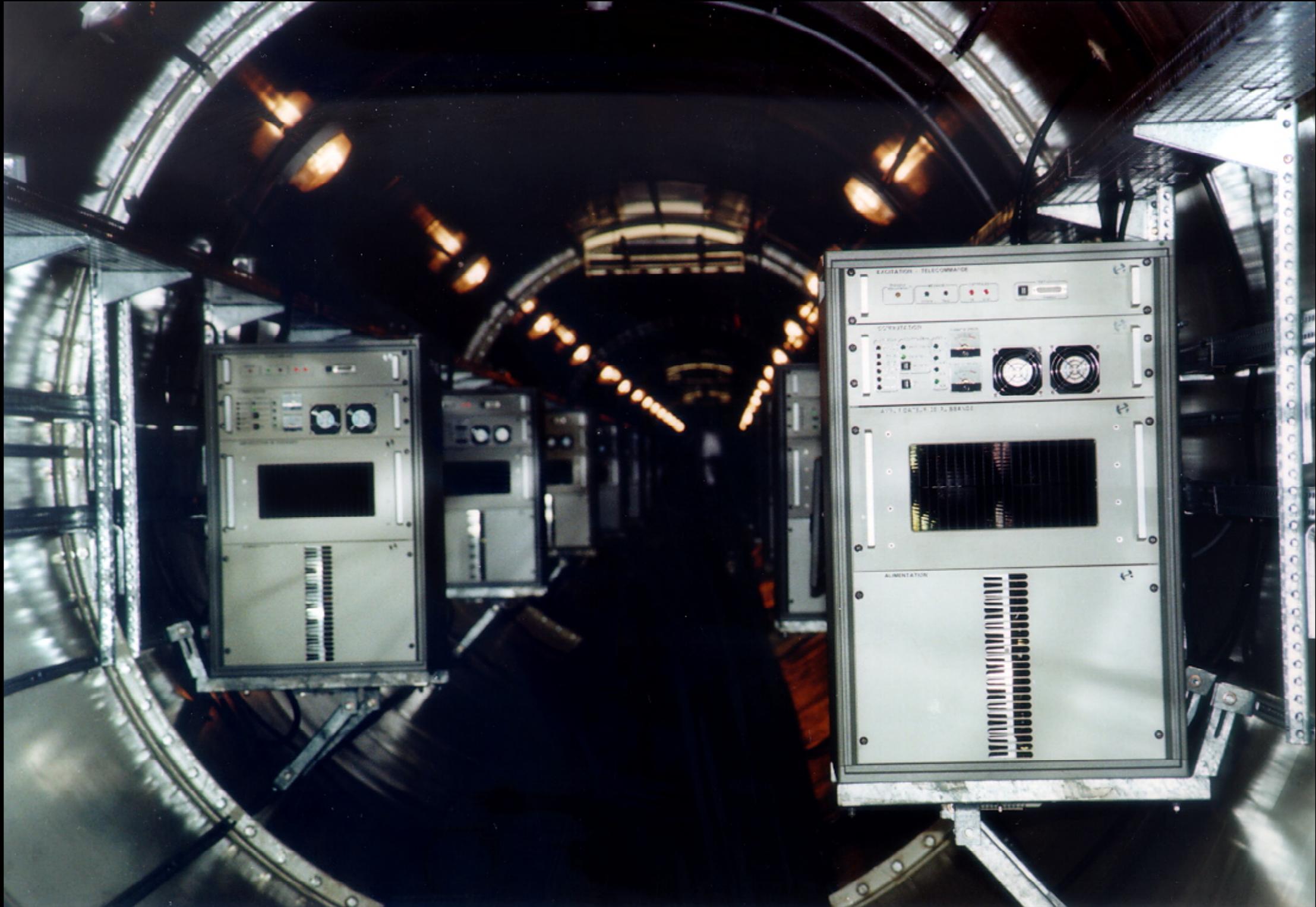
# Le radar Nostradamus

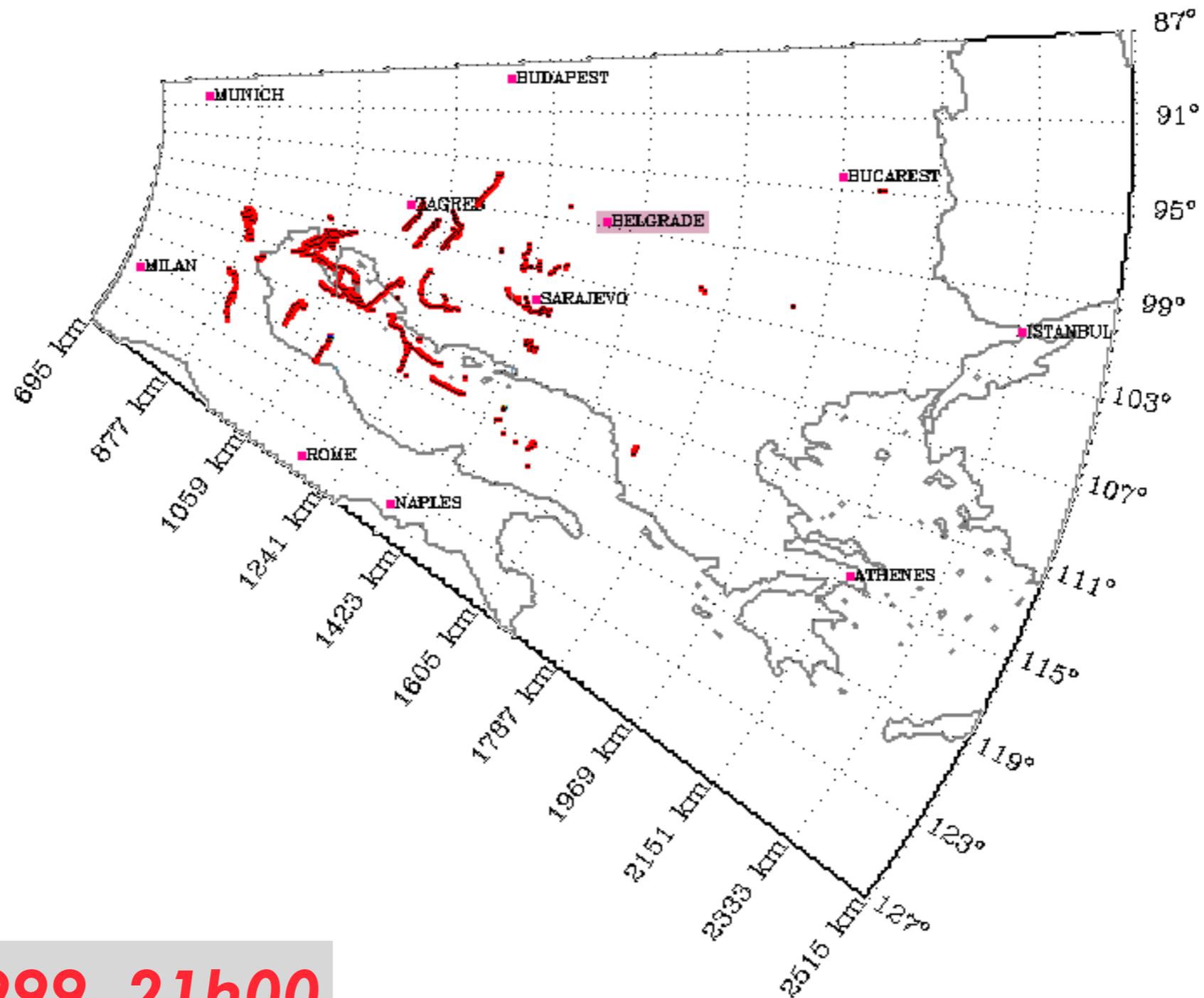
*(particularités..)*

- Monostatique (1 site)
- Réseau surfacique ,
- 360° en azimut,
- Directivité en site,
- Contrôle du site
- Sous réseaux et FFC
- Dimension « raisonnable »





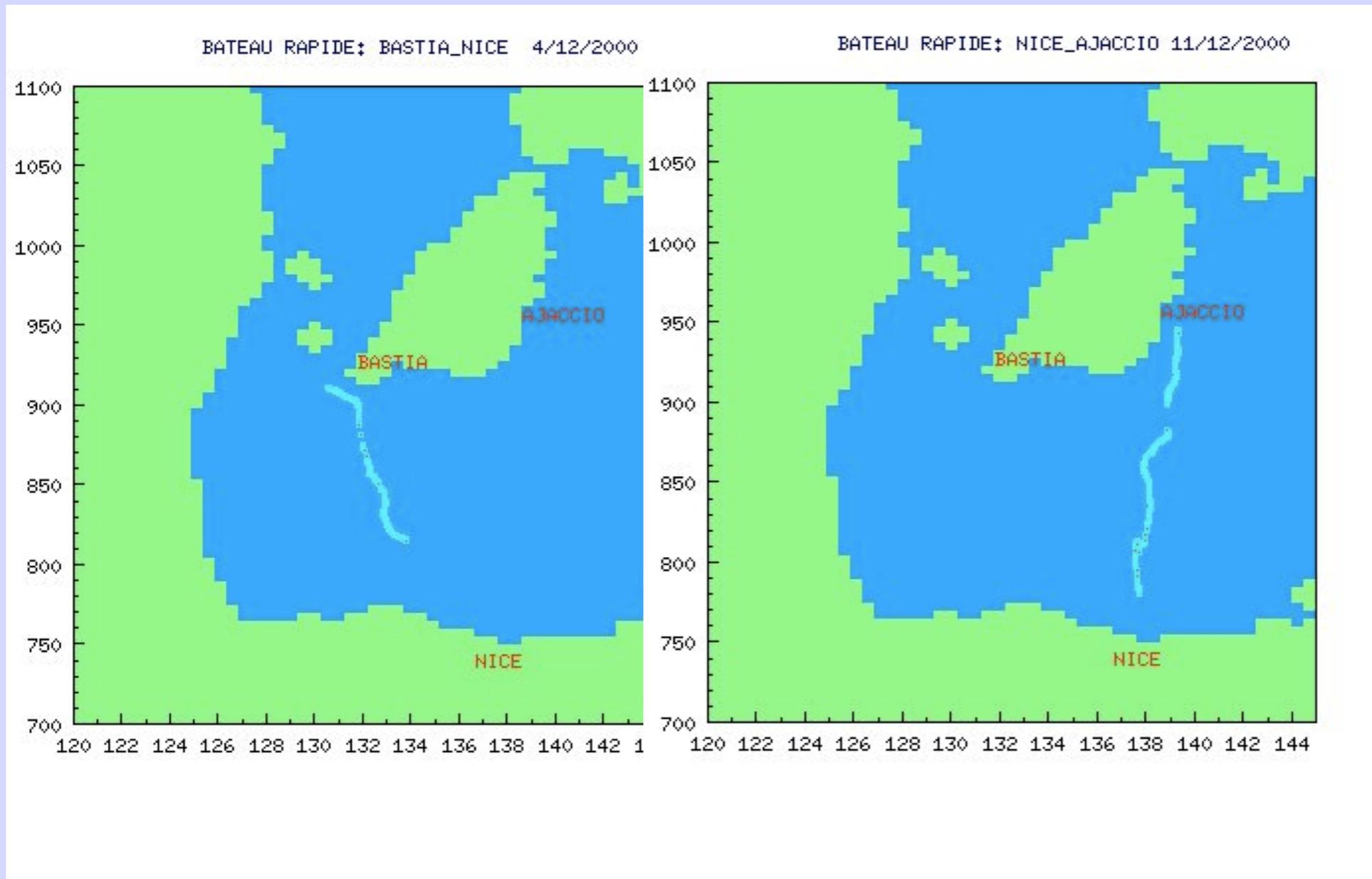




7 avril 1999 21h00

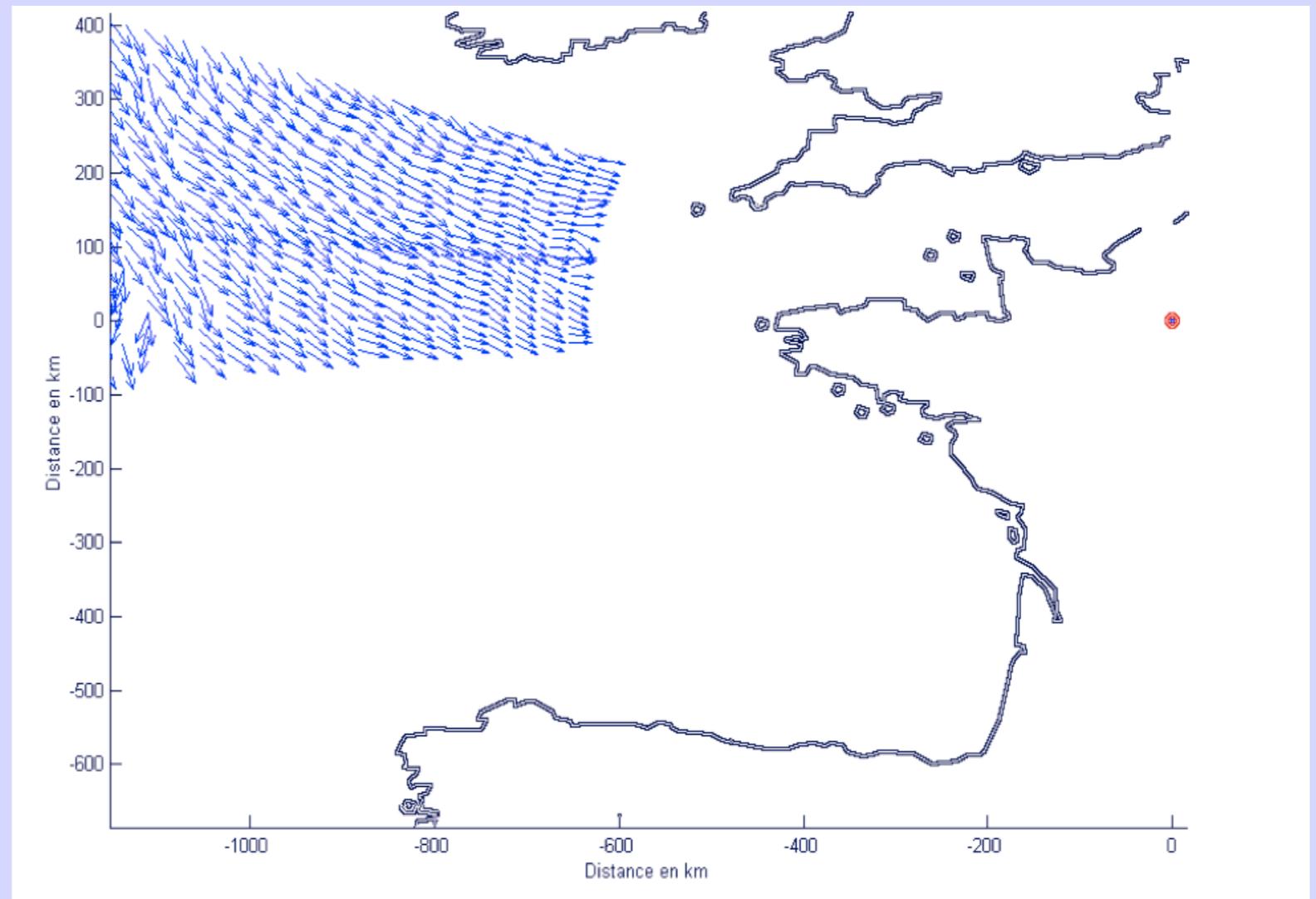
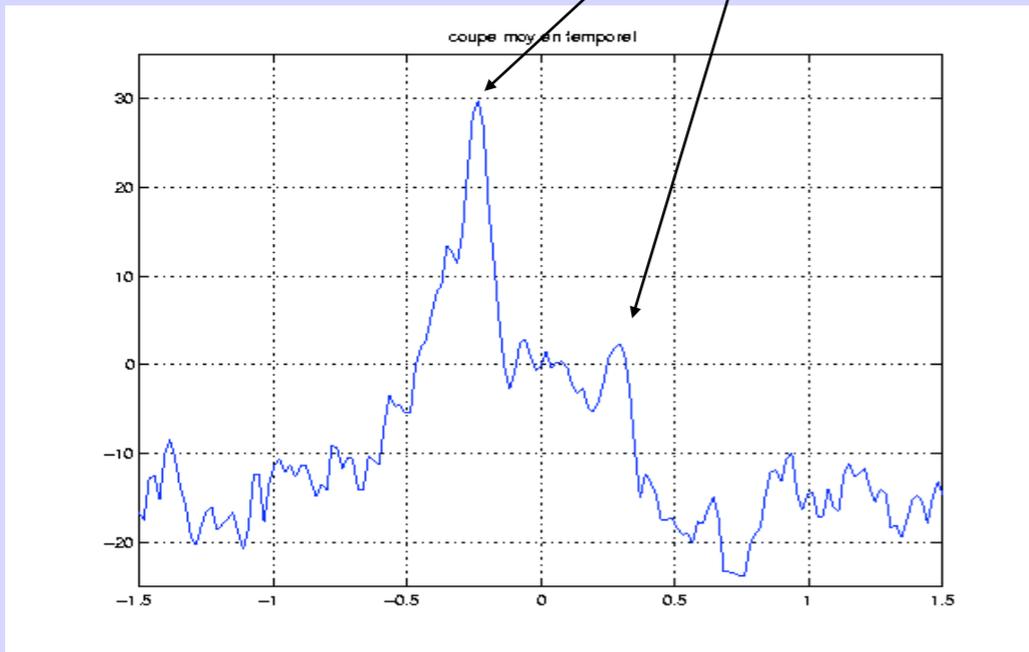
# Détection de bateaux par NOSTRADAMUS

Pistage de bateaux d'opportunité

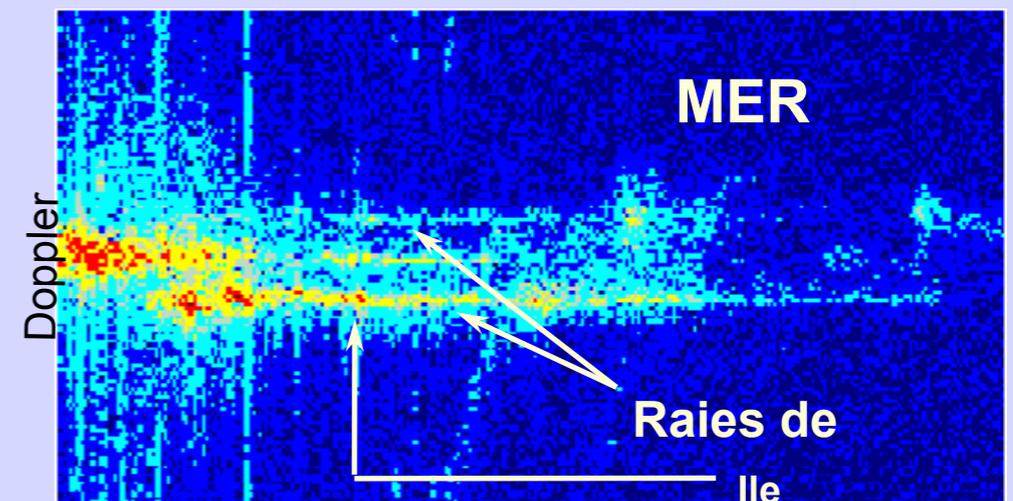
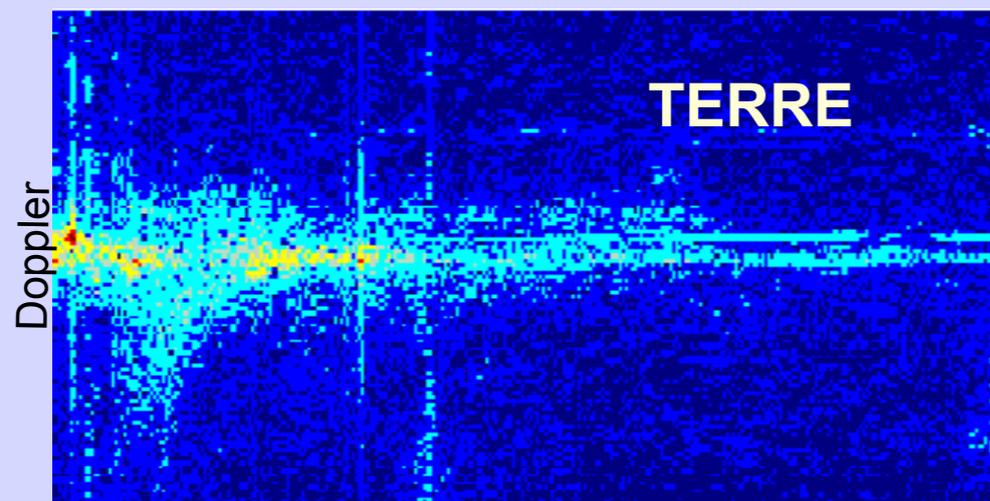
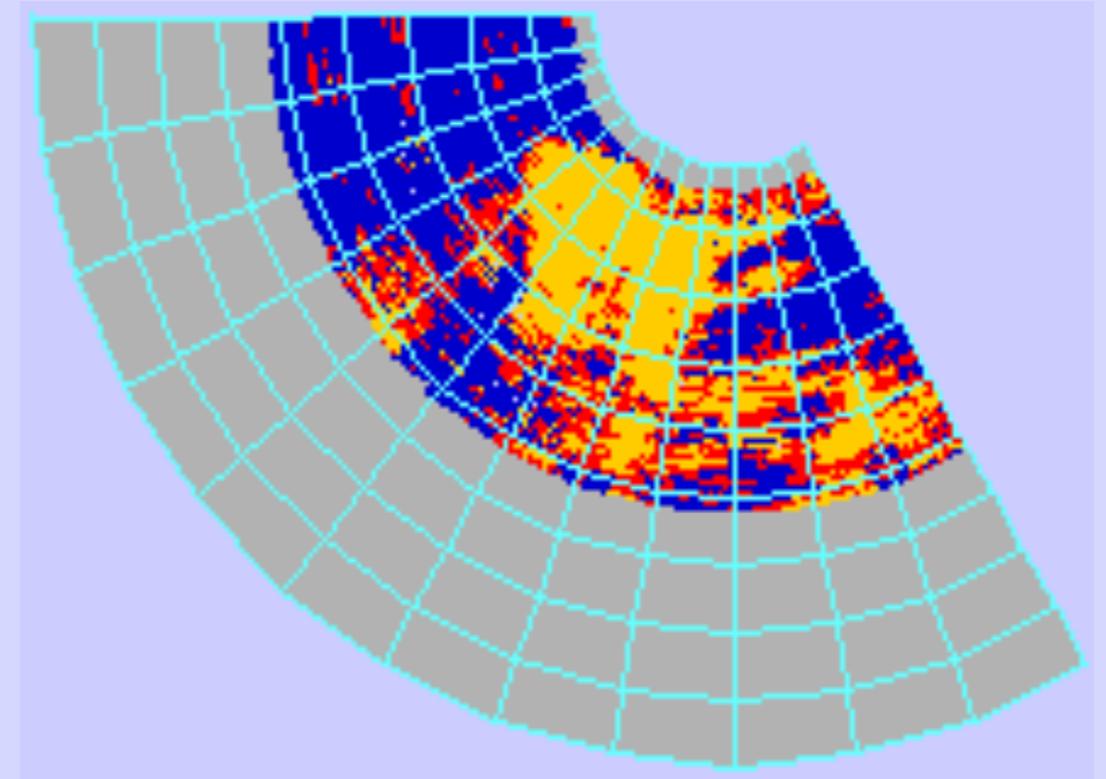
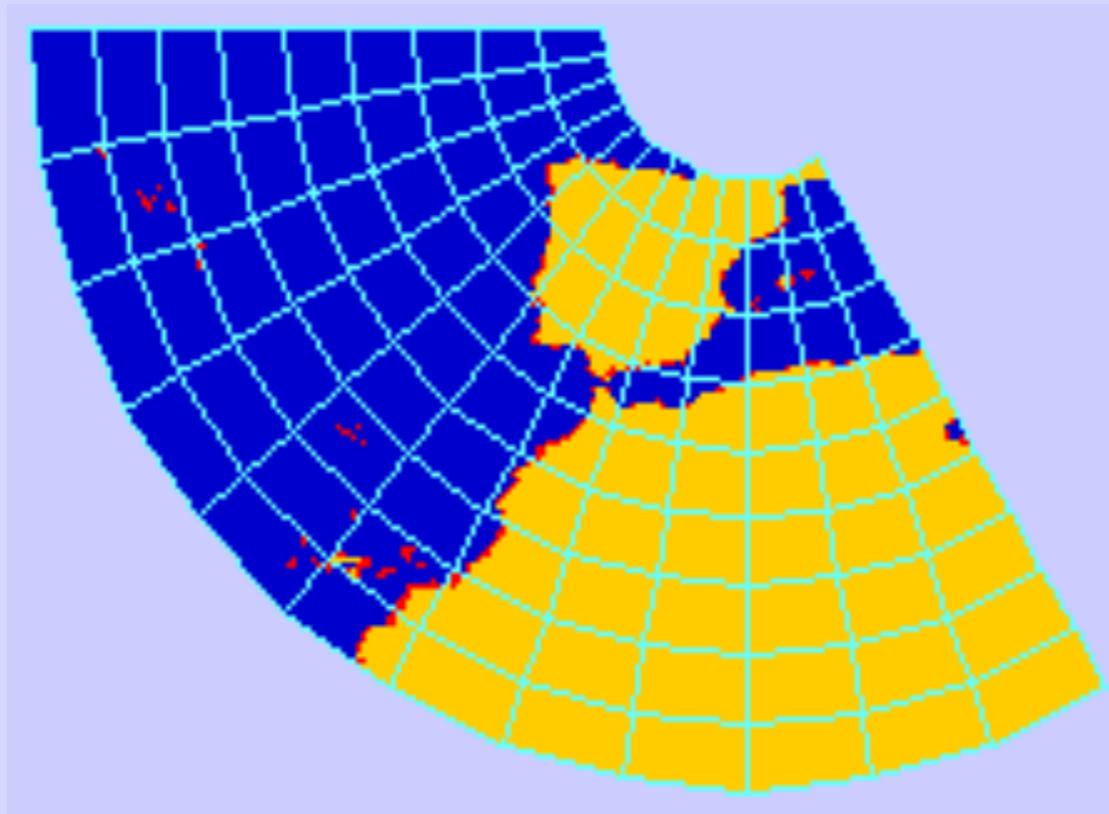


# Mesure de la direction de propagation du vent (RG/D)

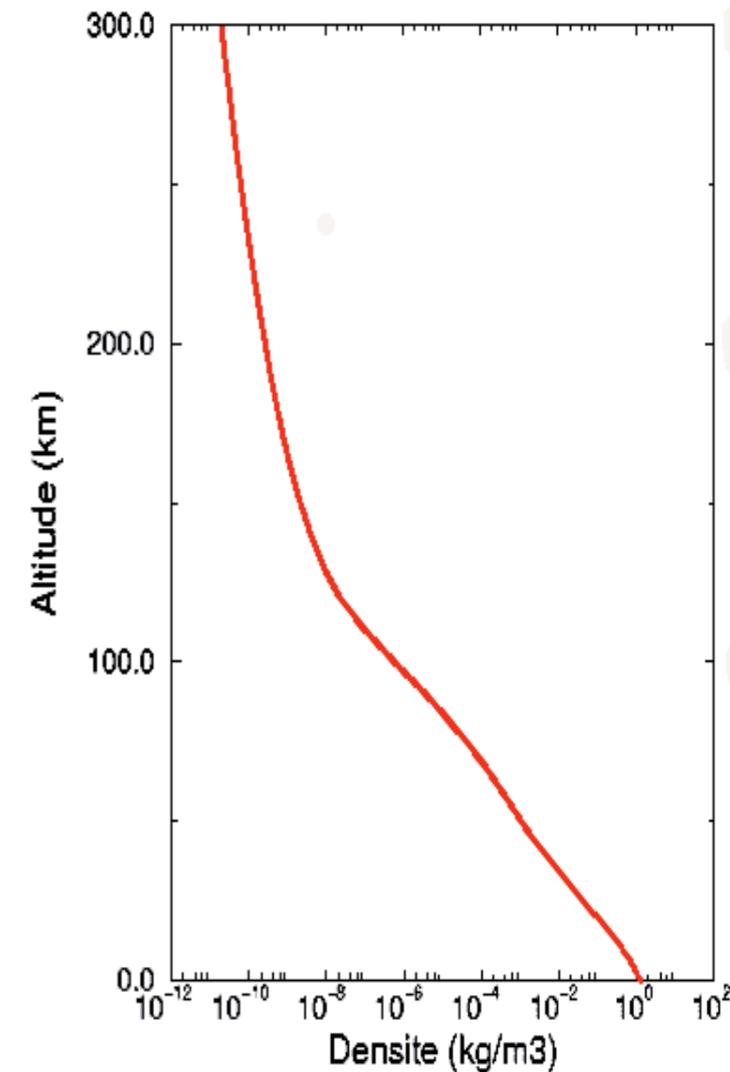
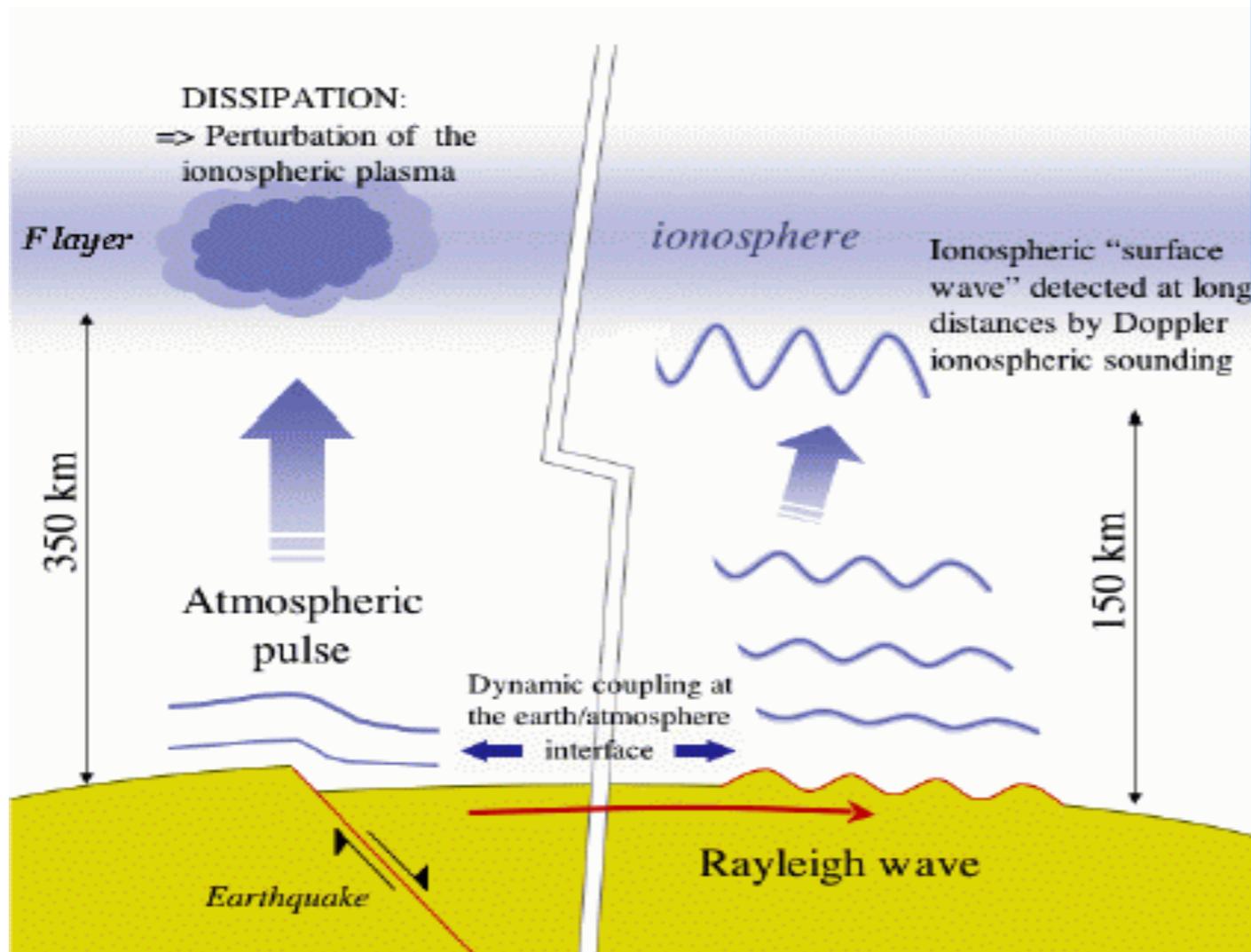
**Raies de Bragg**



# NOSTRADAMUS - Détection des transitions terre - mer

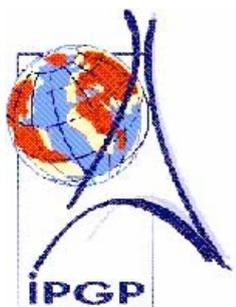


*Les séismes génèrent des ondes acoustiques par couplage dynamique*

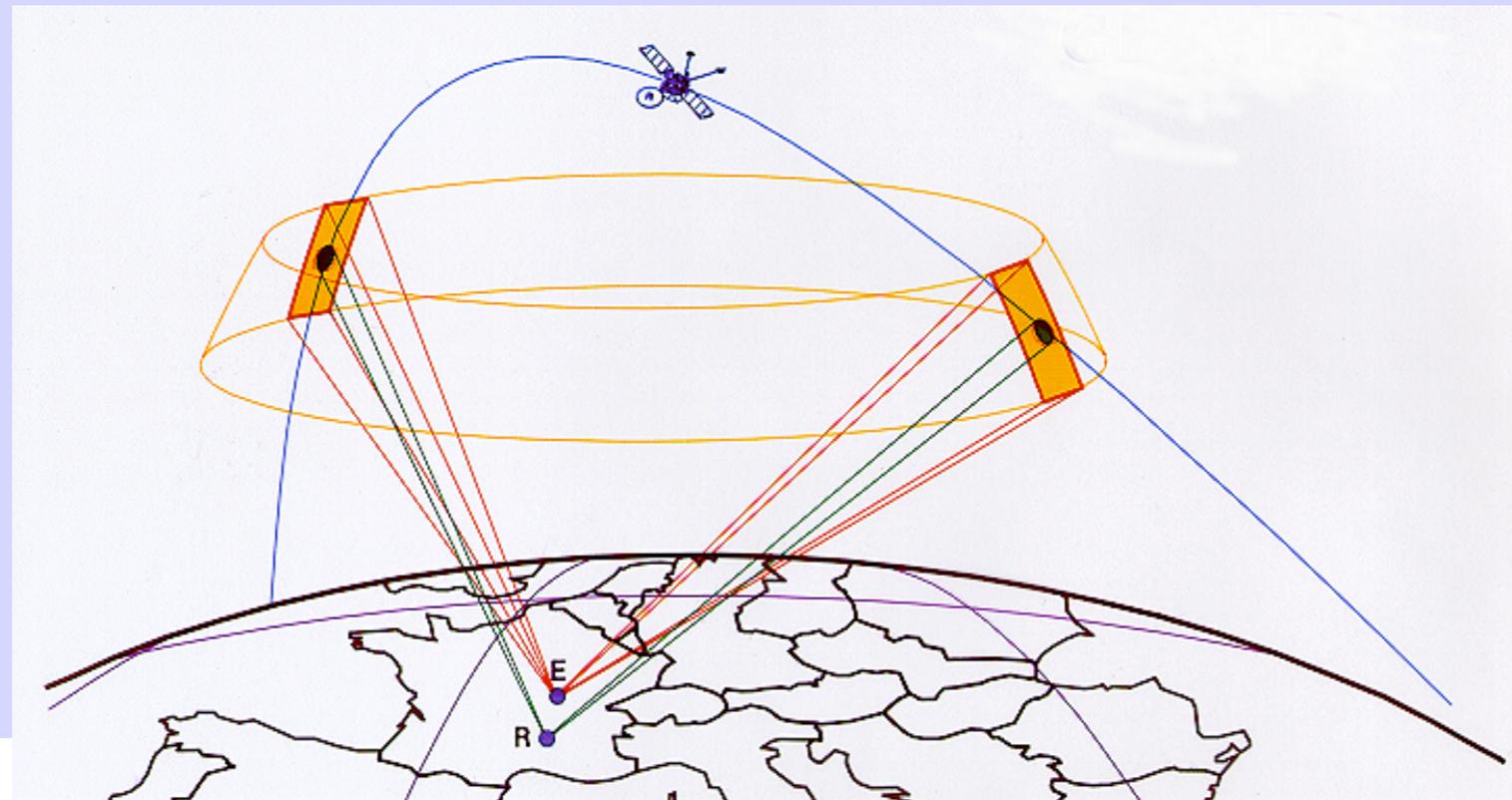


$$\rho v^2 = C \cdot te$$

amplification de  
10.000 et 100.000  
entre  
150 et 250 Km d'altitude



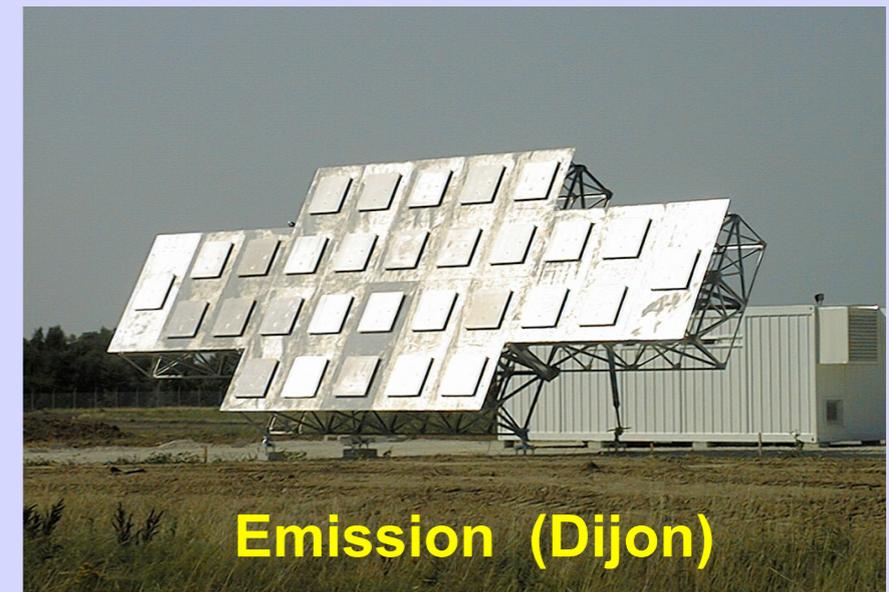
radar bistatique , VHF  
très longue portée  
réception 64 m de rayon  
émission 10 MW (ERP)



*Veille et poursuite de satellites LEO, délai de détection < 24 H*



Réception (Apt)



Emission (Dijon)



$\partial_t \psi + \frac{M}{\epsilon} \int_{\Omega} \frac{|u(x,t)|^2}{2} u \Delta \psi + \int_{\Omega} \nabla p = 0, \quad \nabla \psi \Big|_{\partial \Omega} = 0, \quad \psi(x,0) = \psi_0(x), \quad \psi(x,t) \in e$

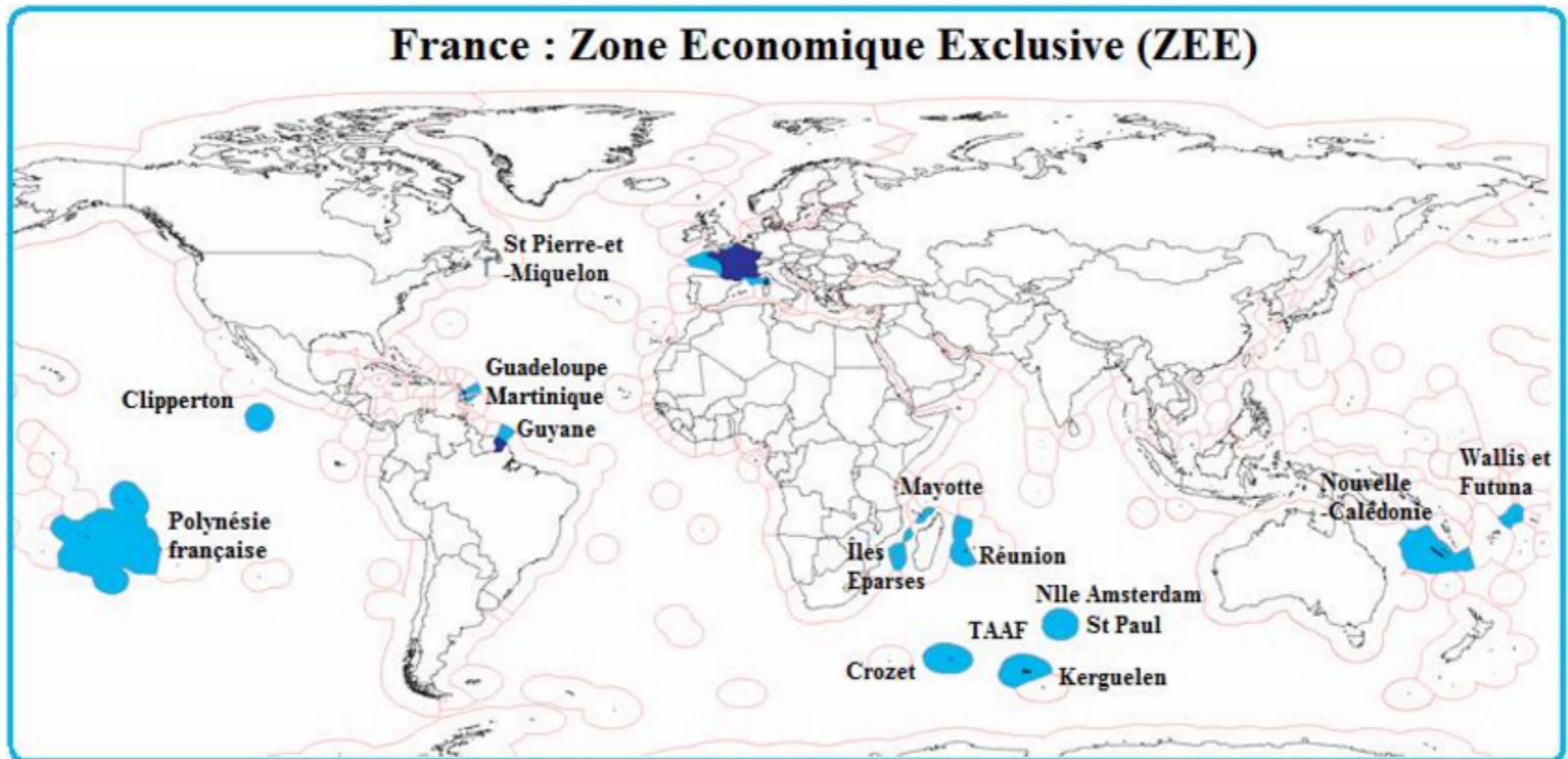
# Radars à onde de surface

ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

La France possède la plus grande Zone Economique Exclusive (200 milles marins) mondiale avec 11 691 000km<sup>2</sup>



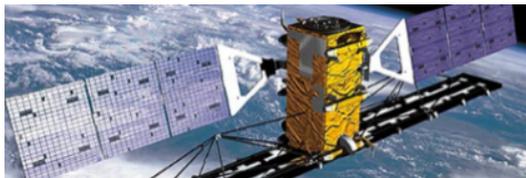
# Surveillance de la ZEE



Navire  
Détection à 40km,  
fonction de l'état  
de mer  
Coût



Avion patrouilleur  
Bateaux de 20m  
Coût, autonomie



Satellite - Bateaux de 25m  
Période de re visite 6heures - Coût

Moyens mobiles

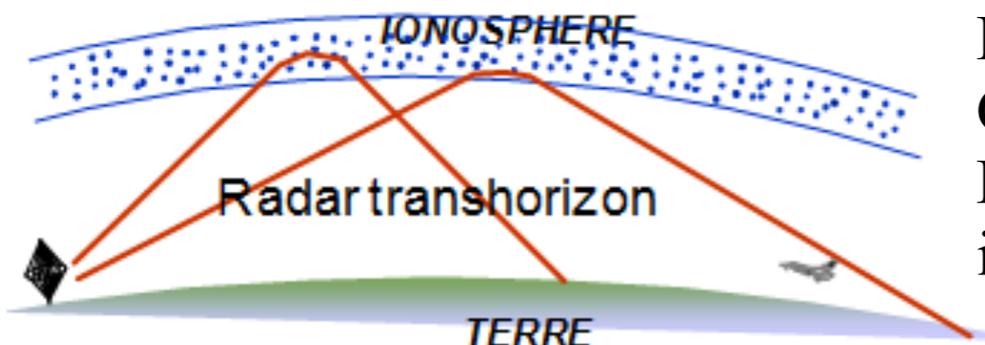


Radar côtier  
Bande S ou X  
Portée typique 50km

Moyens fixes



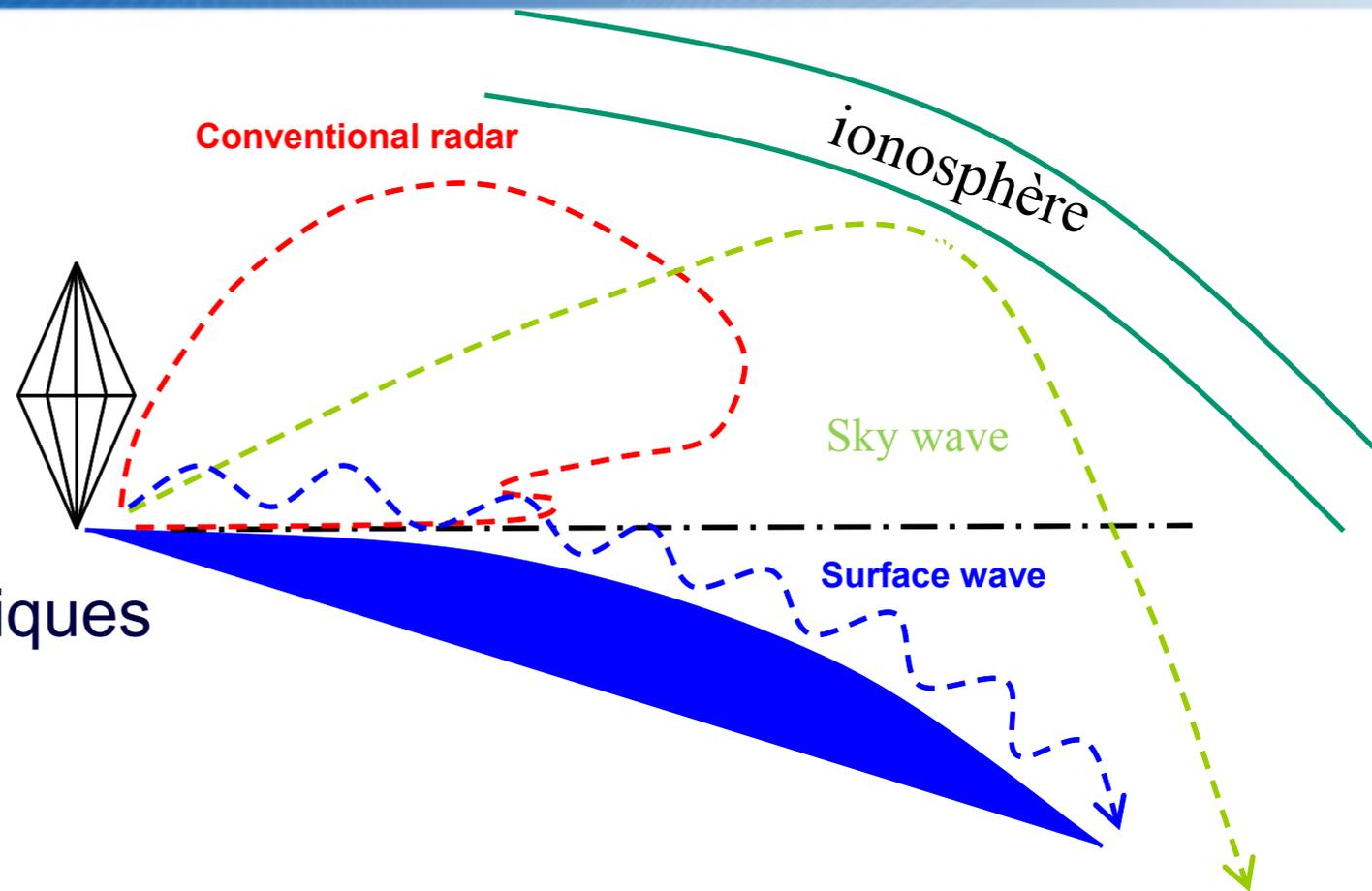
Radar à onde de surface  
Portée ZEE sur navire de  
commerce  
Cible de 15m à 150km



Radar à onde de ciel  
Cible de 30m à 2000km  
Dépend des couches  
ionosphériques

# Radars transhorizon

- Bande HF 3-30MHz
- Les radars transhorizon:
  - Onde de ciel 5-30MHz
    - Grande portée
    - Installation déportée
    - Stabilité des couches ionosphériques
  - Onde de surface 4-10MHz
    - Propagation constante
    - Portée ZEE
    - Fouillis ionosphérique
    - Installation en bord de mer (Natura 2000)



Forte interaction avec le fouillis de mer :

- Possibilité de mesure de l'état de mer (radar océanographique)
- Limite la détection des petits bateaux

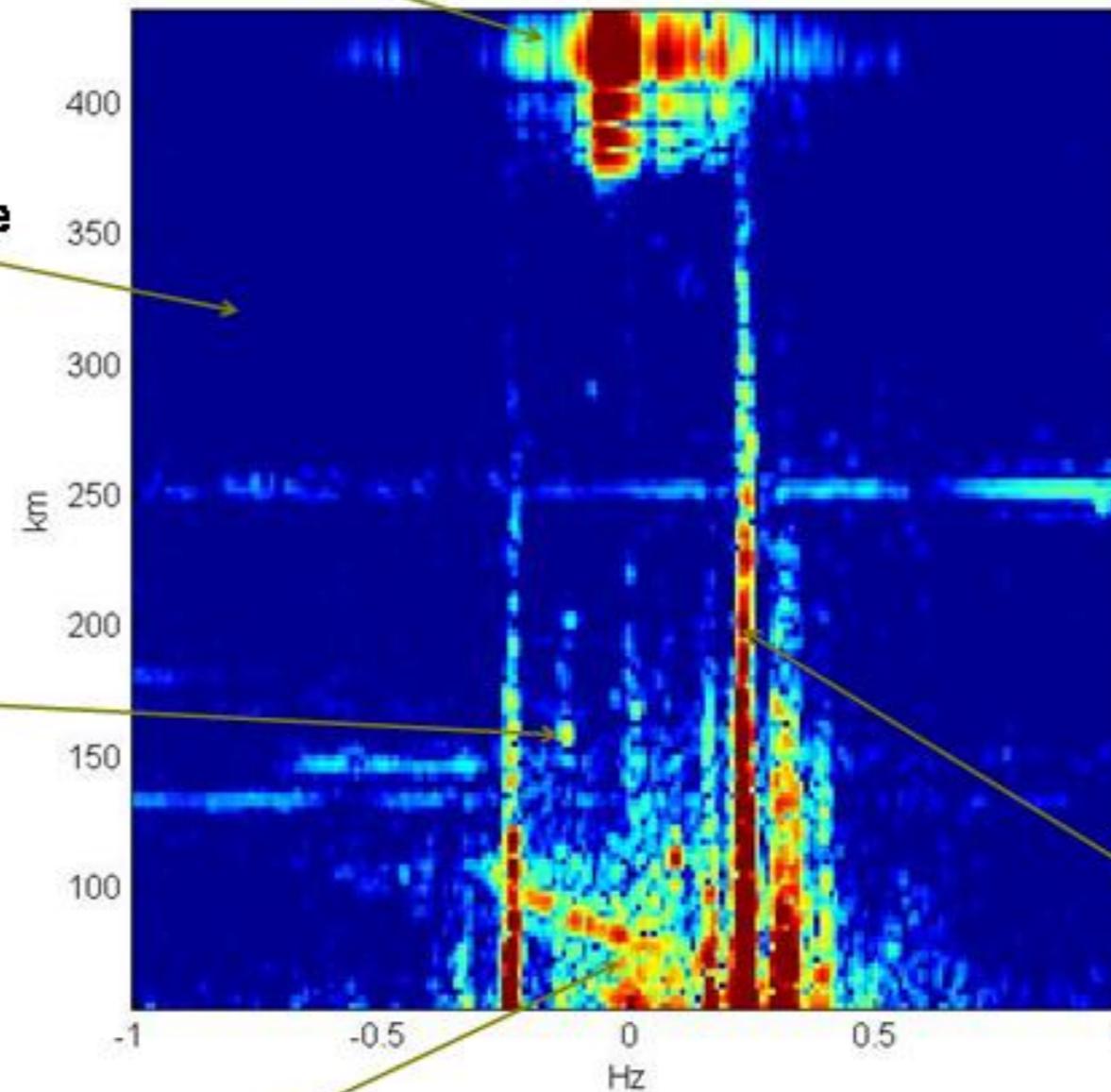
# Image Doppler/distance ROS typique

Ionospheric clutter

External noise

Target

Second order sea clutter



Meteor trail

Bragg line

# Capacités d'un ROS classique

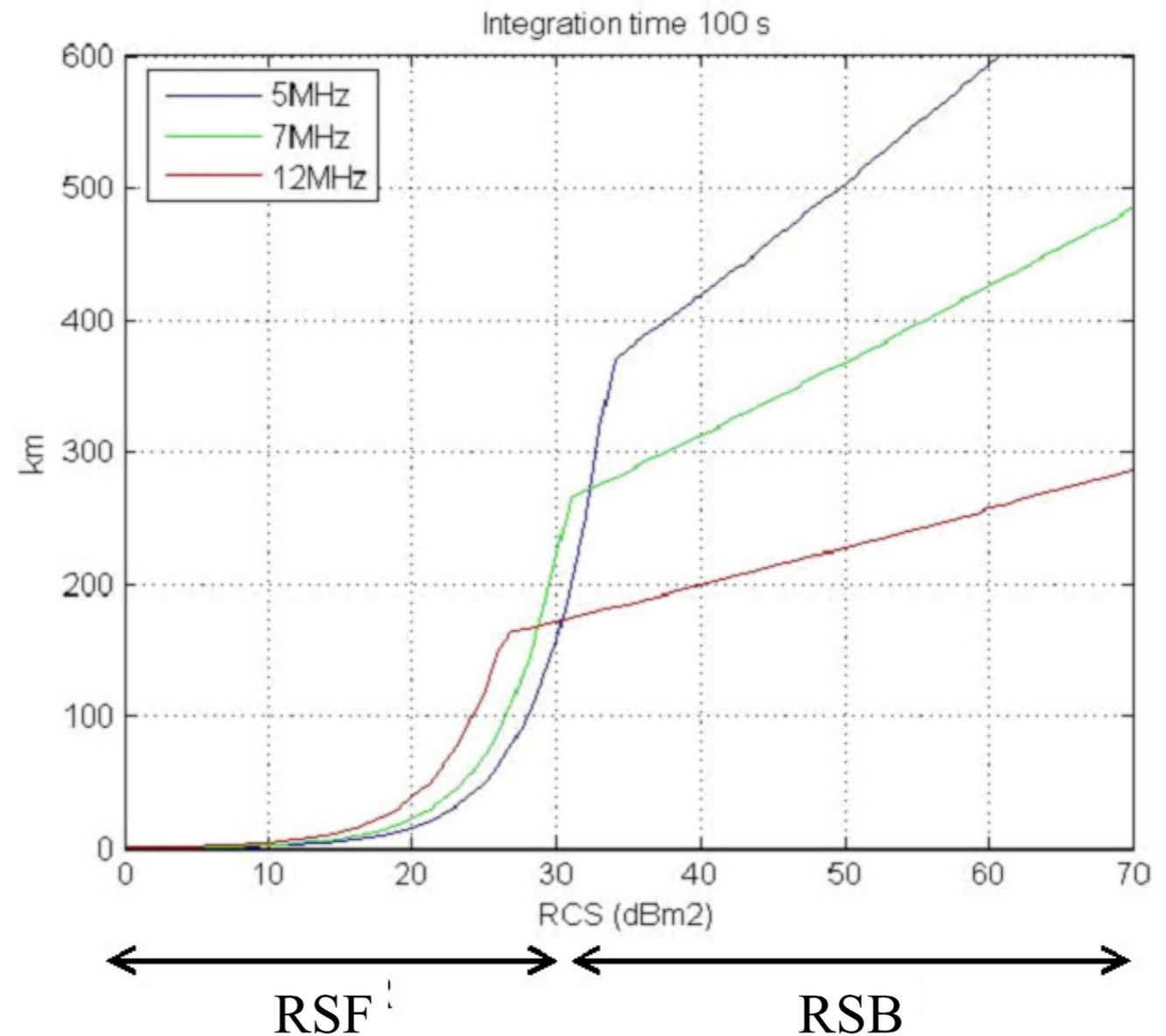
## Distance de détection fonction de la SER

### RSF: rapport signal à fouillis

- La détection des petits bateaux est limitée par le fouillis
- *A taille donnée, les fréquences hautes sont préférables.*

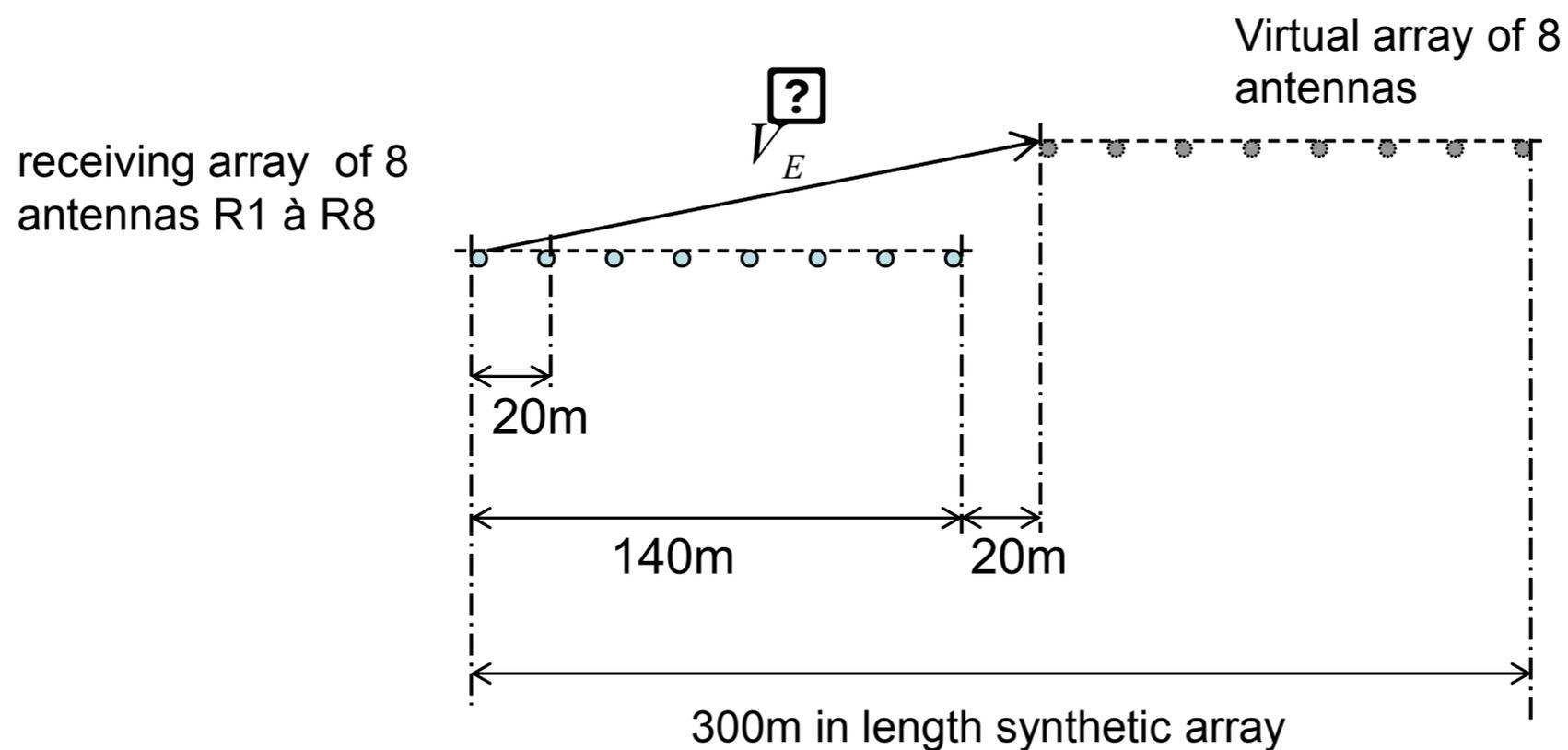
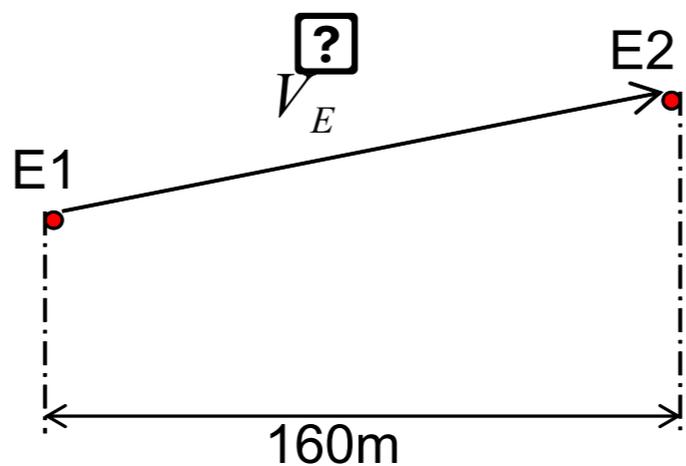
### RSB: rapport signal à bruit

- La détection des gros navires est limitée par le bilan de puissance
- *A taille donnée, les fréquences basses sont préférables*



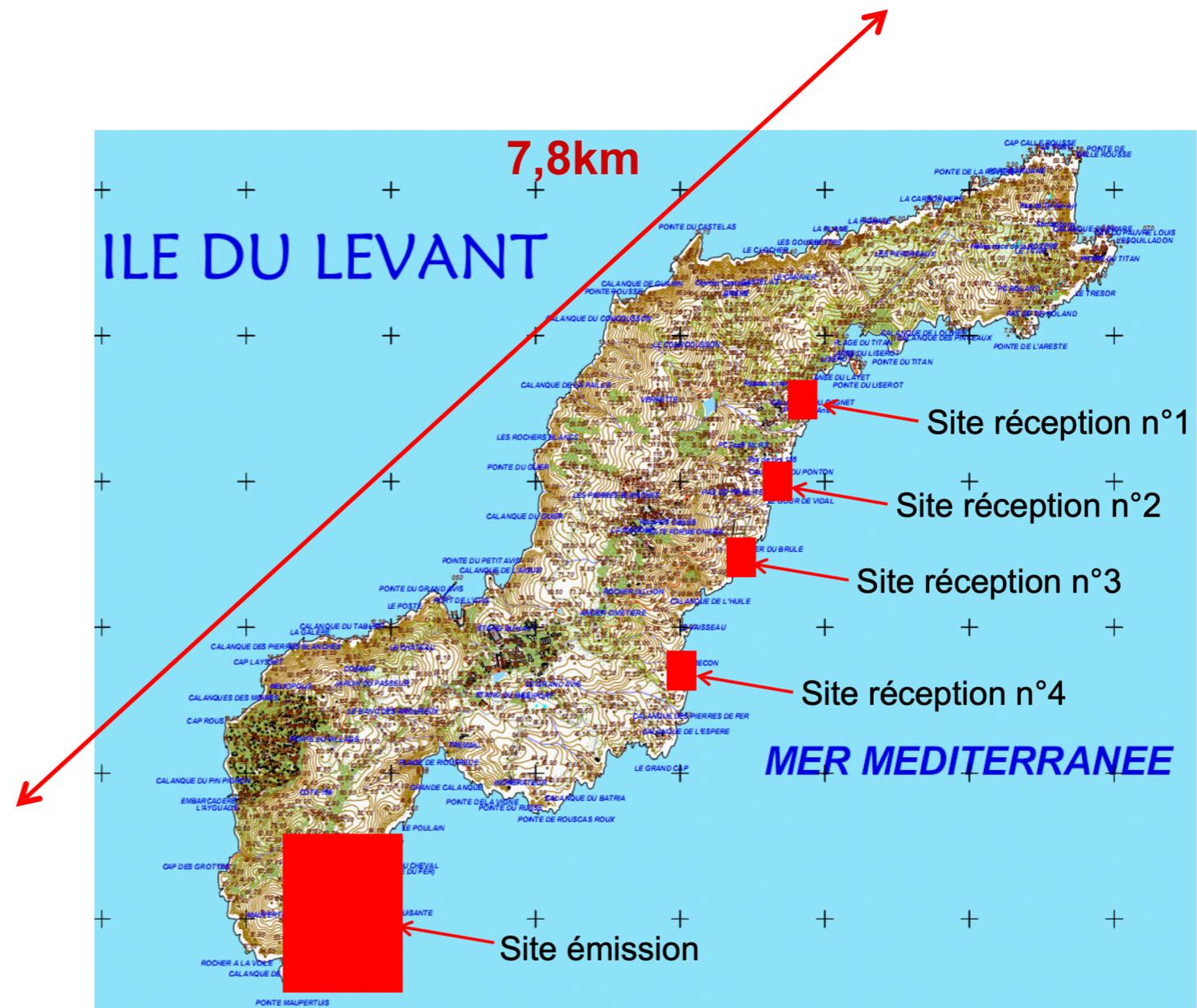
# Principe de l'antenne synthétique

Avec 2 antennes qui émettent des codes orthogonaux et un réseau de 8 antennes de réception, un réseau de réception synthétique de 16 antennes est créé

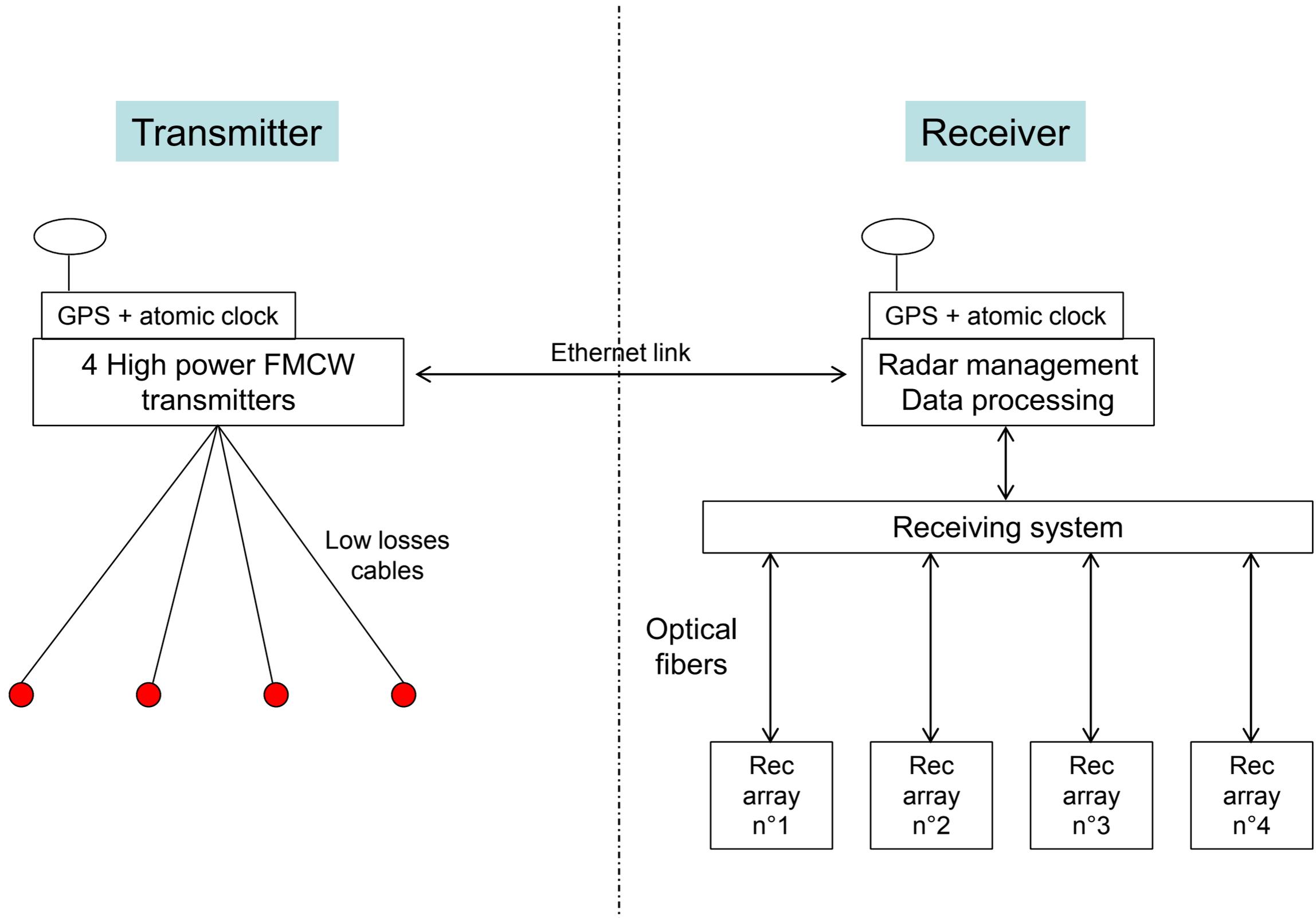


# Radar de l'île du Levant

- Antenne synthétique de 2500m de long
- 1 site d'émission, avec 4 antennes, au sud de l'île
- 4 site de réception de 8 antennes chacun sur la côte est
- Deux fréquences simultanées (5 / 9MHz)



# Architecture générale



# Site d'émission



Plateforme

Intérieur du shelter émission



# Antennes biconiques d'émission



# Sites de réception

Rx 1



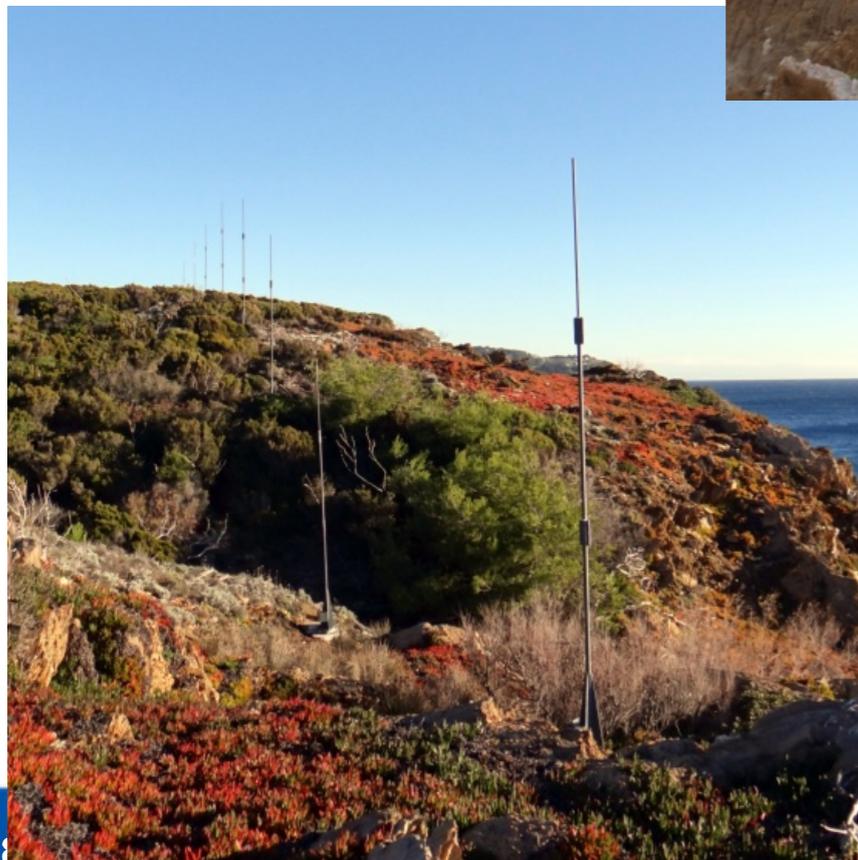
Rx 2



Rx 4

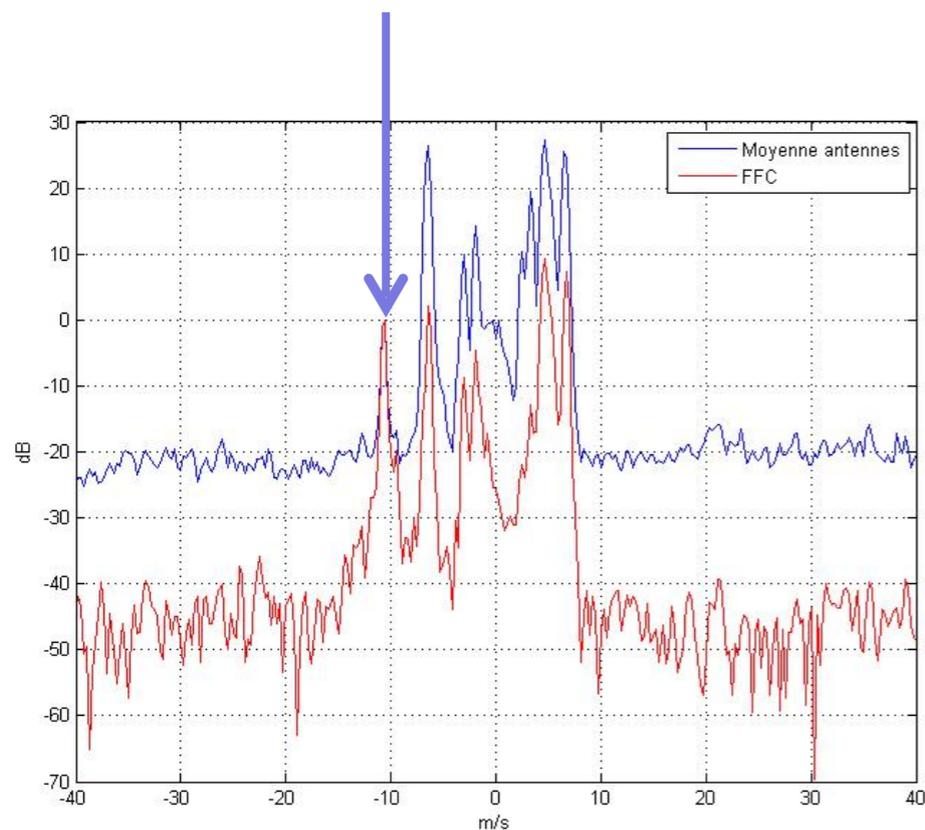


Rx 3

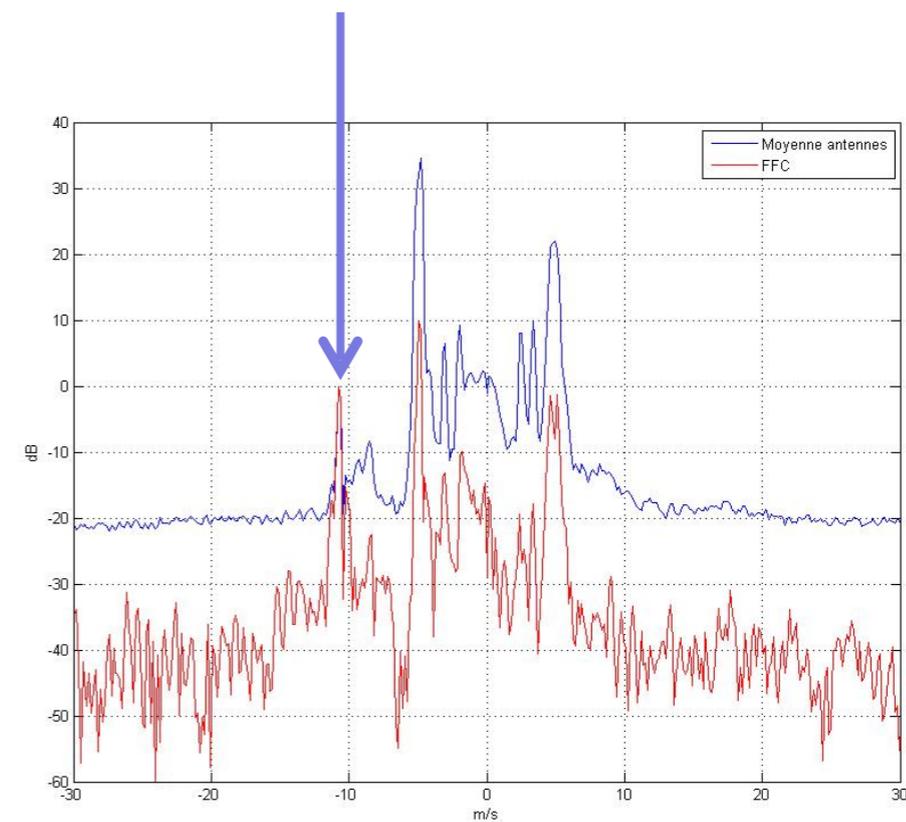


# Validation de l'antenne synthétique

- Vérification du gain sur cible coopérative de 15m de long
- Le rapport entre le signal moyen des 32 antennes de réception et la FFC est de l'ordre de 20dB soit l'équivalent d'un réseau de 128 antennes



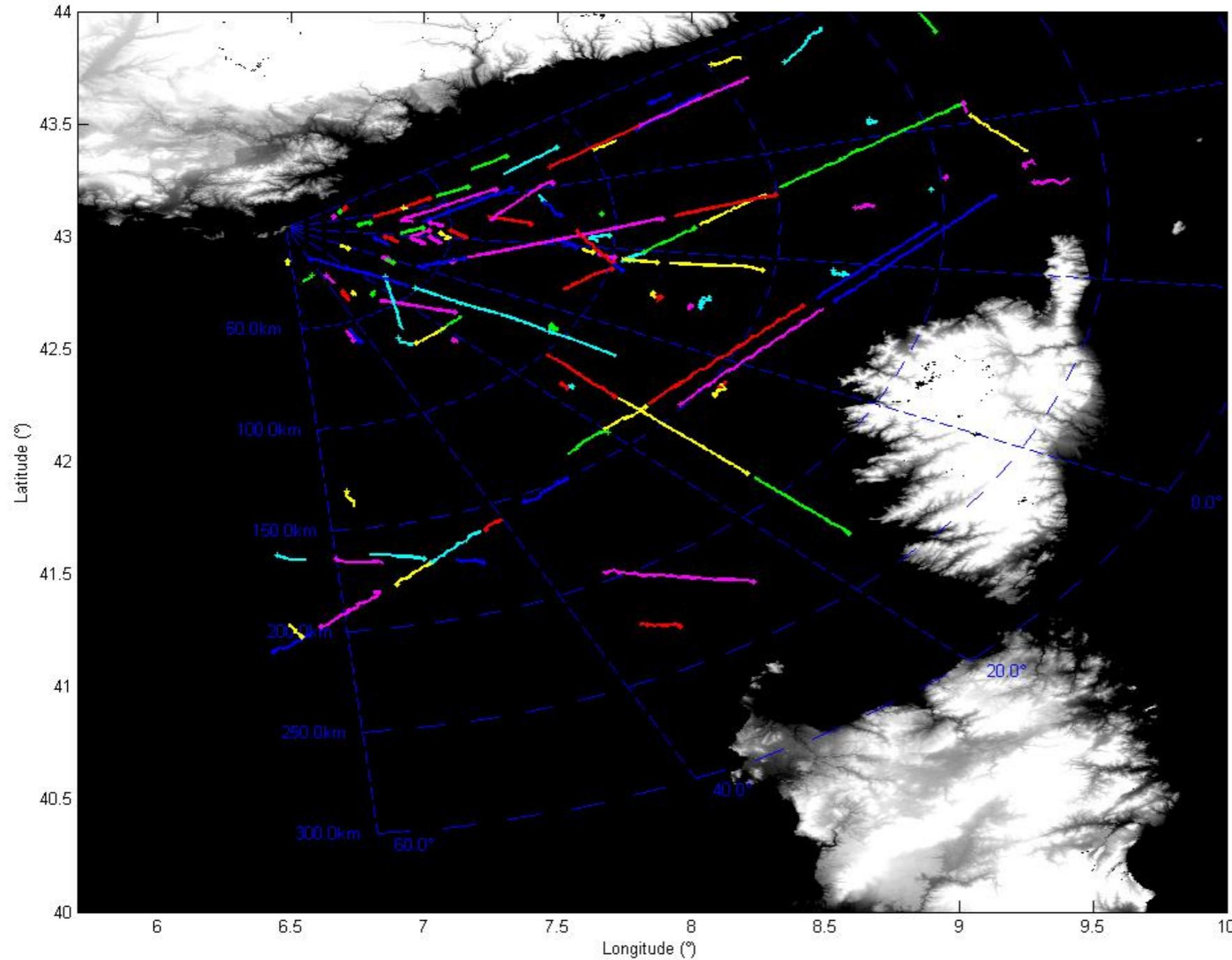
Gain réseau à 5MHz



Gain réseau à 9MHz

# Exemple de pistage(1/2)

05/03/2014 - 15H 52mn TU



-40.0°

-20.0°

0.0°

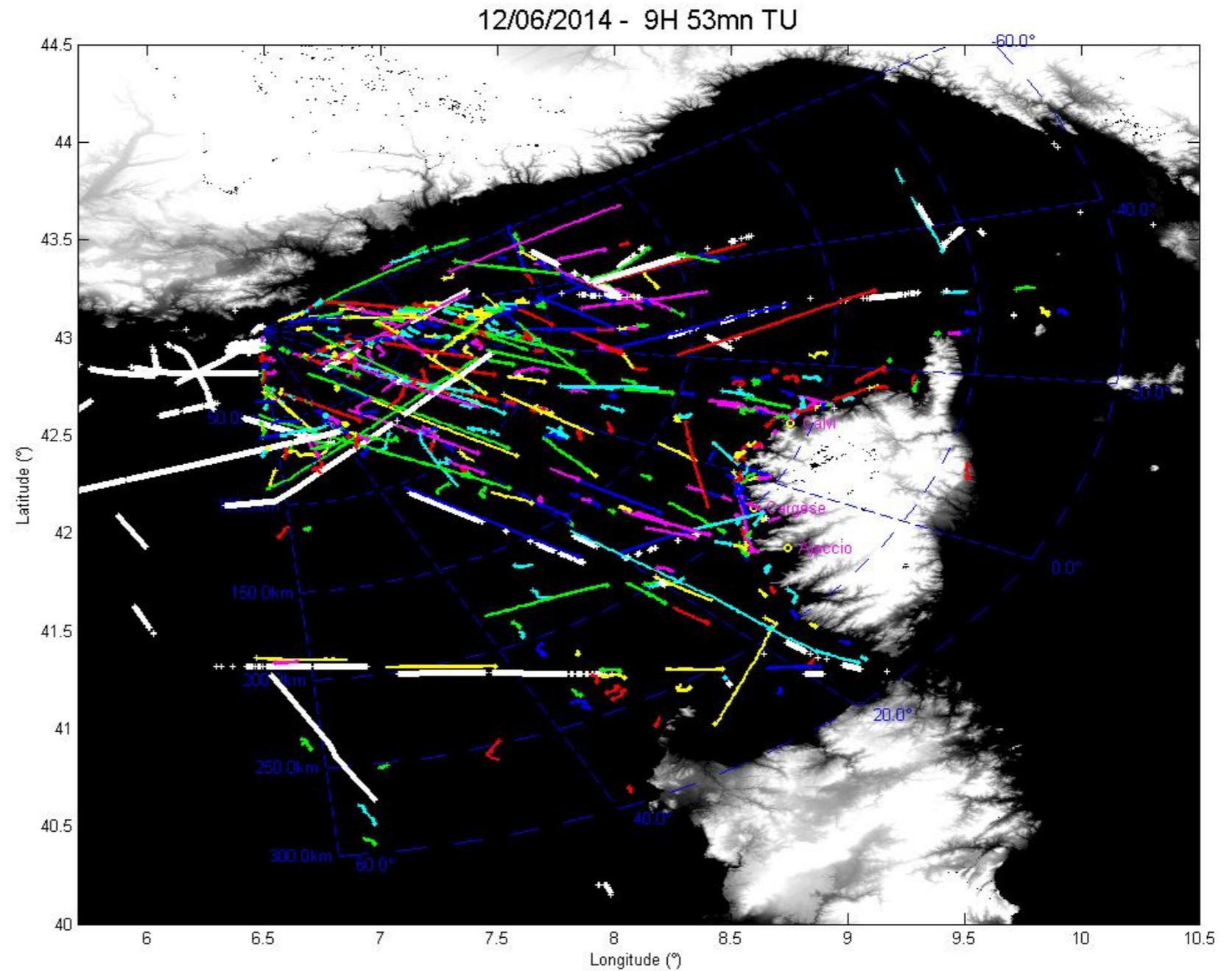
20.0°

40.0°

**Hauteur de vague 2  
m  
Mer 4**

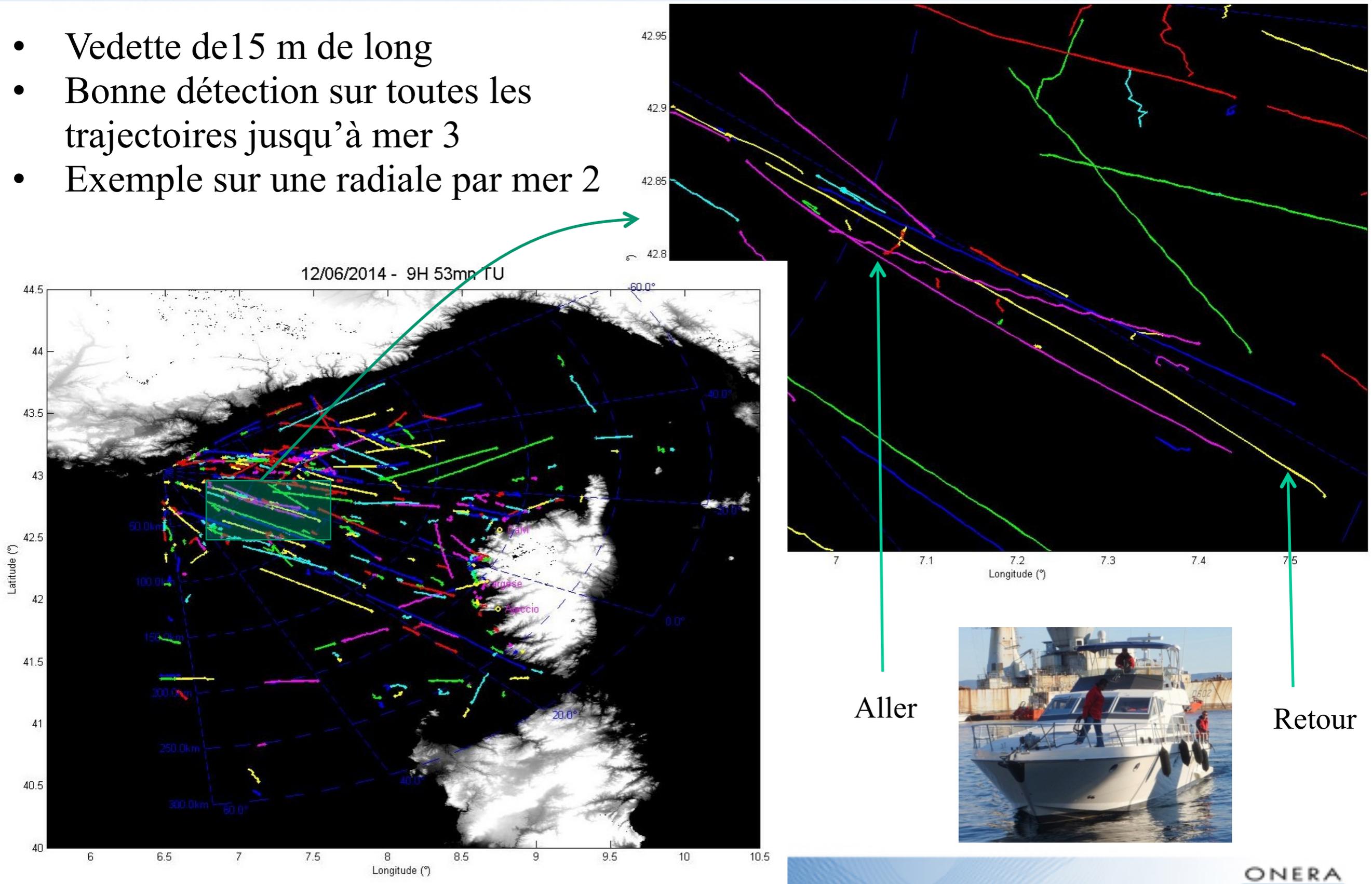
# Exemple de pistage (2/2)

**Hauteur de vague  
0,5 m  
Mer 2**



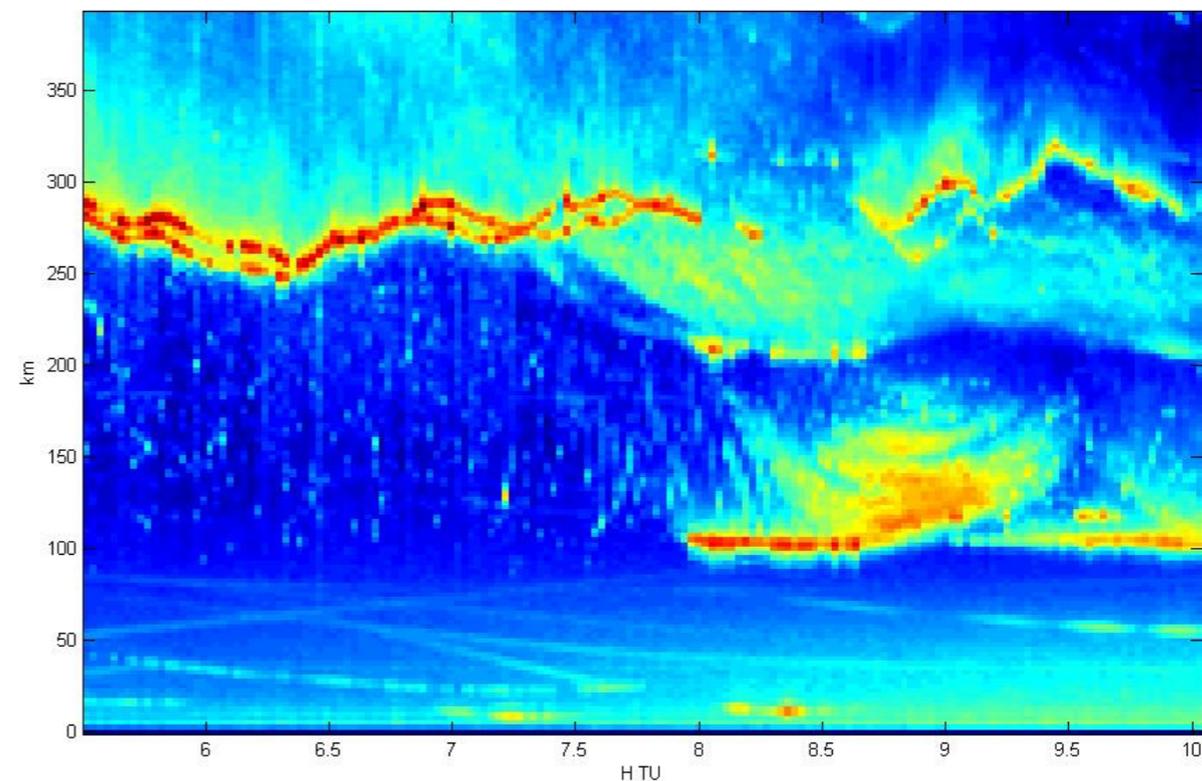
# Essais avec cible coopérative

- Vedette de 15 m de long
- Bonne détection sur toutes les trajectoires jusqu'à mer 3
- Exemple sur une radiale par mer 2



## Fouillis ionosphérique

- Apparition fréquente de fouillis ionosphérique de mai à septembre
- Antenne d'émission à méta matériau
- Réseau à 2 dimensions
- Antenne bi polarisation
- Traitement ondelettes
- Multi fréquence



## Bruit extérieur et brouilleurs

- Remontée de 15 à 20dB du bruit la nuit, apparition de nombreux brouilleurs
- Doubler les antennes (F/B)
- Amélioration du bilan
- Mode passif?

