Altimétrie spatiale

L'altimétrie radar : de la physique à l'instrumentation

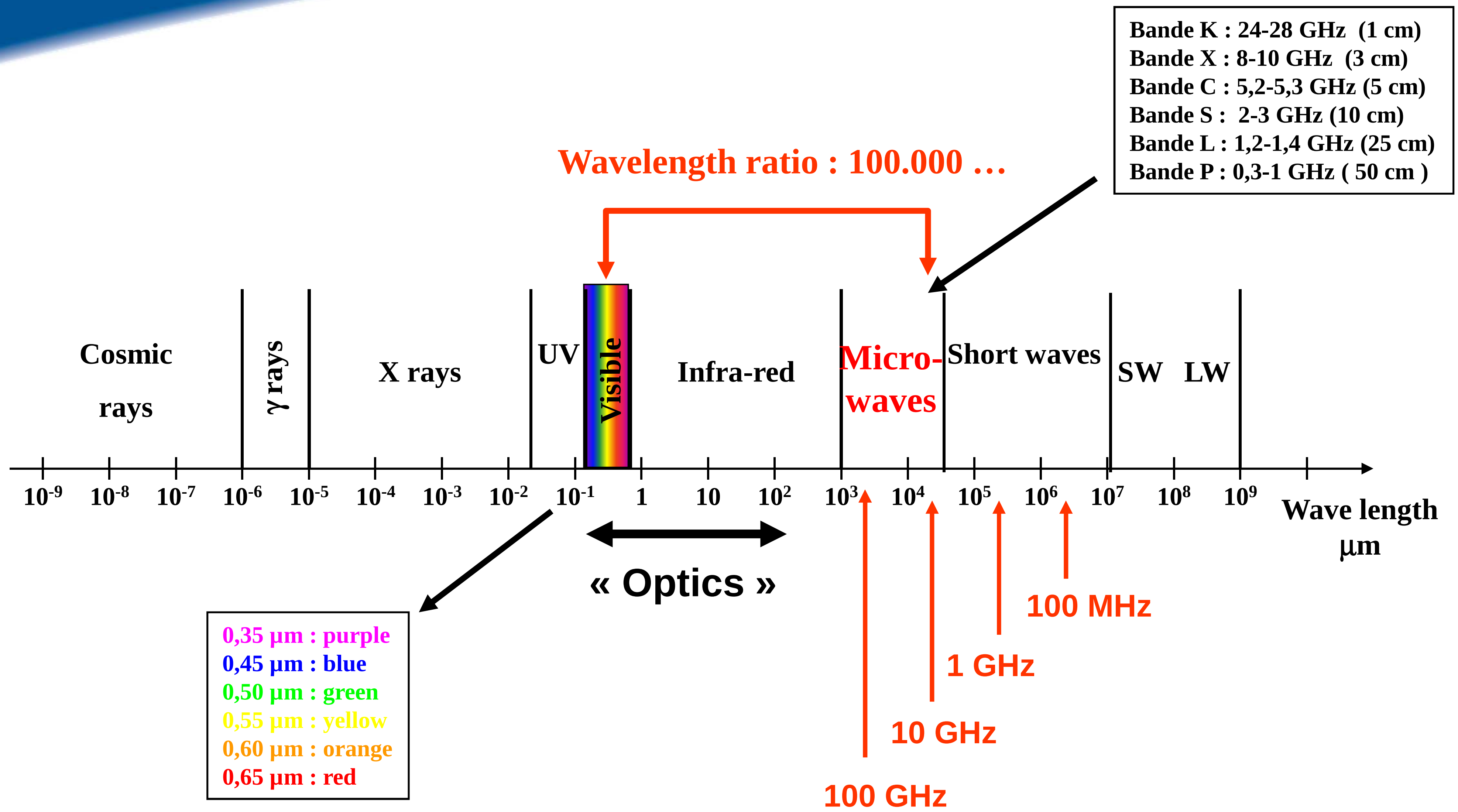
Jean-Claude SOUYRIS

Service Altimétrie et Radar

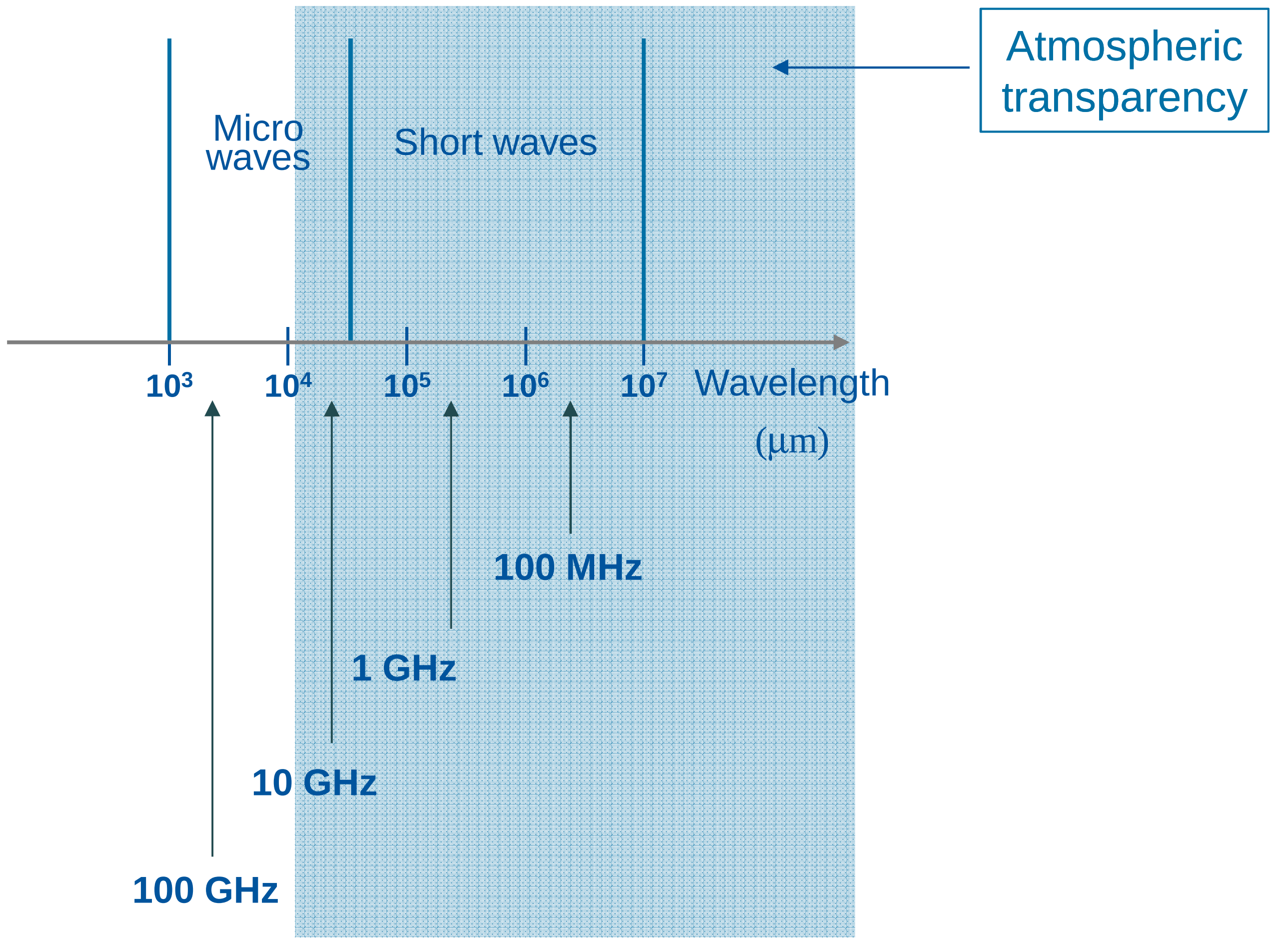
Centre National d'Etudes Spatiales (CNES)

- **Principes physiques de la mesure micro-ondes (propagation, structure de l'onde radar, rétrodiffusion, polarisation)**
- **Fondamentaux de la mesure radar**
- **Géométrie Nadir vs. Géométrie Off-Nadir**
- **Altimétrie Nadir, formes d'ondes et speckle**
- **Architecture de la charge utile Nadir**
- **Synthèse d'ouverture (analyse Doppler) des échos nadir**

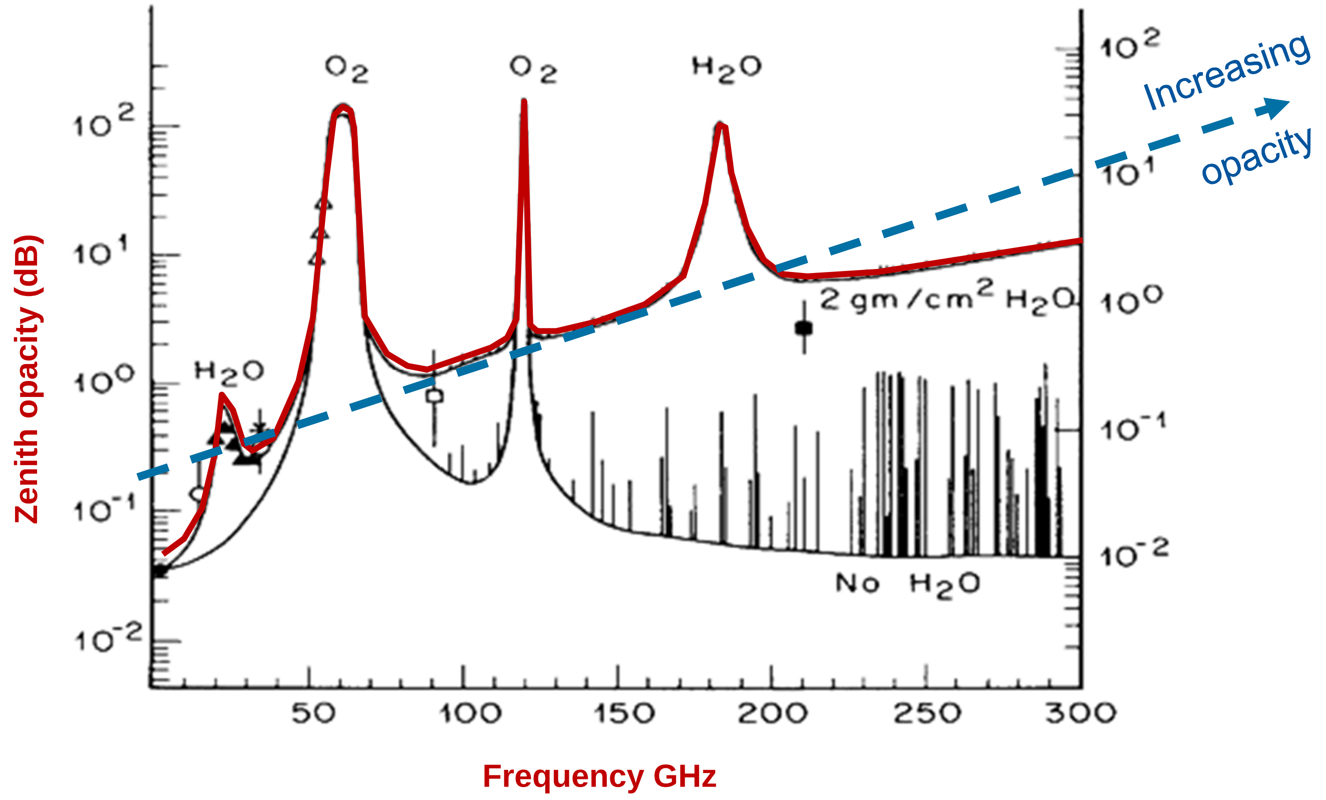
The electromagnetic spectrum



On the atmospheric transparency



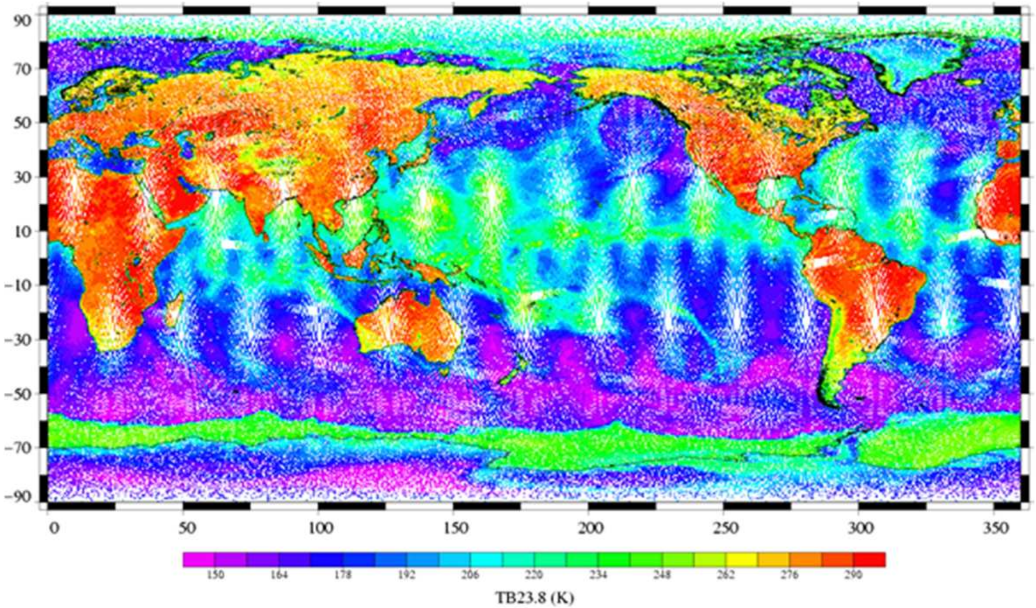
Atmospheric absorbtion rays



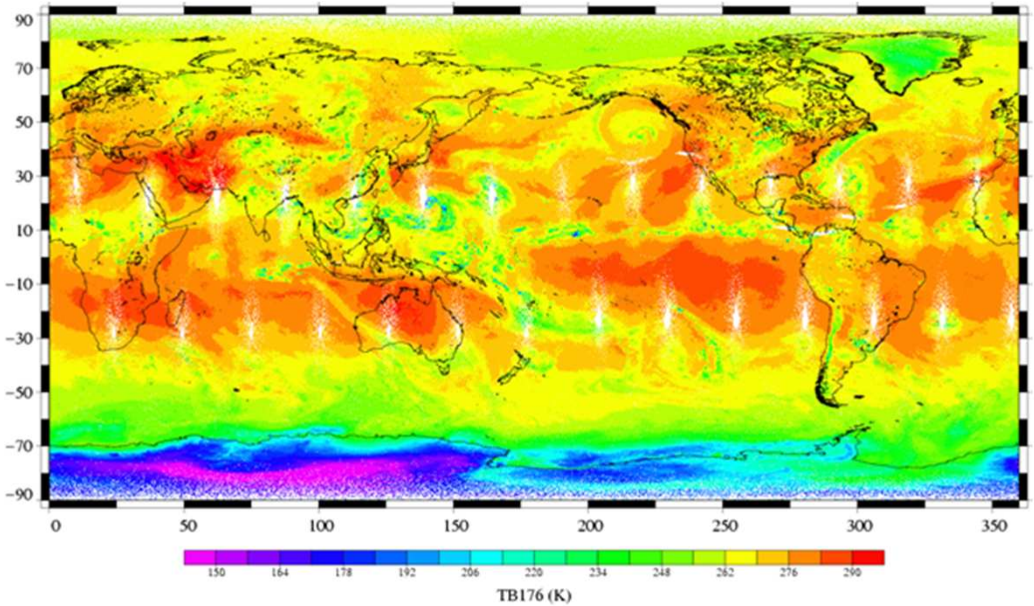
E.M. transparency

Optics

Atmosphere:
limits of the transparency



Nb of data	:	202678	St. Dev	:	43.476142	Skewness	:	0.426003	Minimum	:	131.700000
Mean	:	212.069296	Rms	:	216.479933	Kurtosis	:	−1.044244	Maximum	:	313.180000



Nb of data	:	967258	St. Dev	:	26.31	Skewness	:	−2.38	Minimum	:	123.03
Mean	:	260.12	Rms	:	261.44	Kurtosis	:	5.71	Maximum	:	306.70

TB @ 23.8 GHz

Transparent atmosphere

→ Earth contribution

TB @176.31 GHz

Non transparency →

Atmospheric signal dominant

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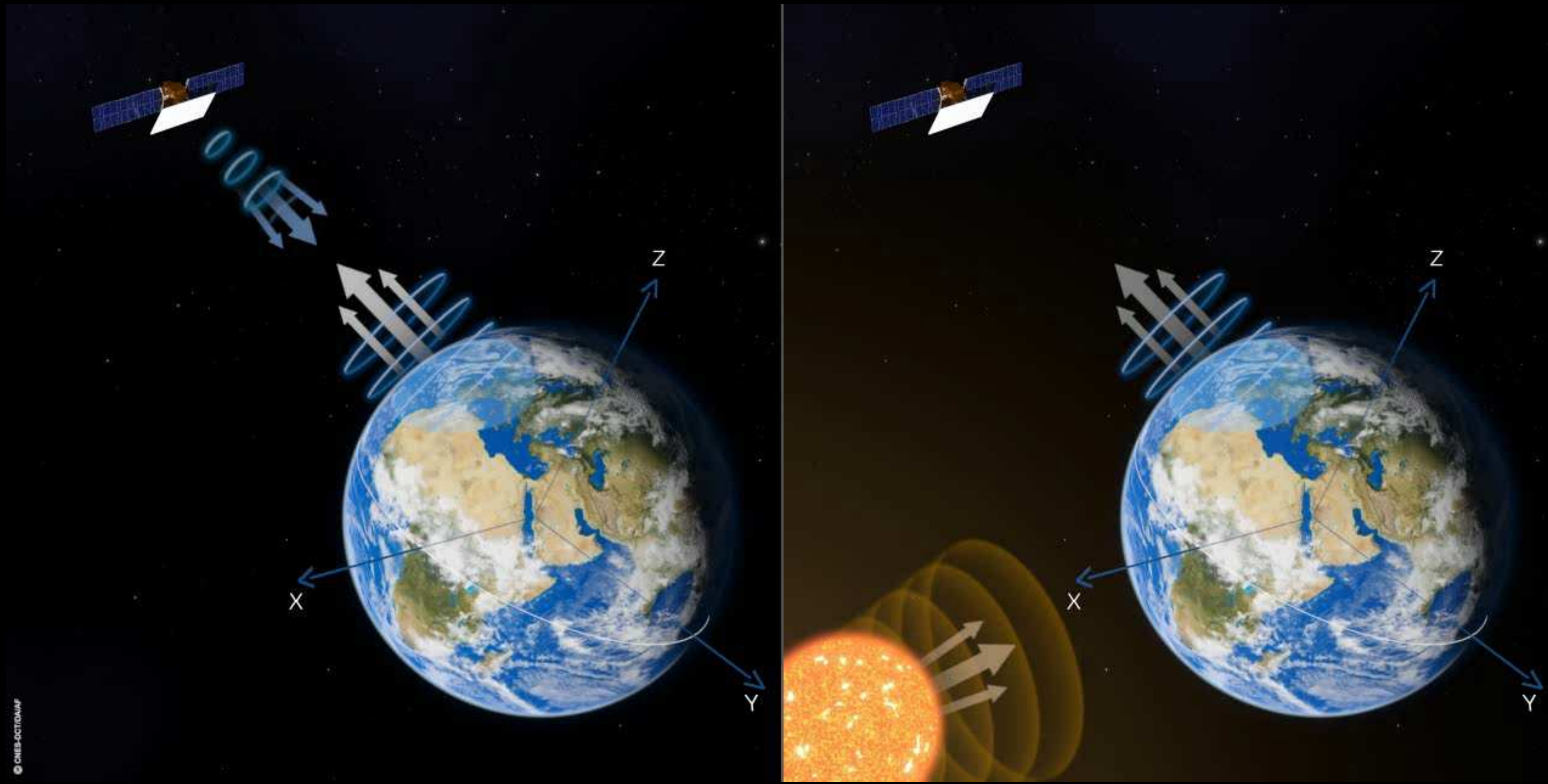
Active sensors – Passive sensors

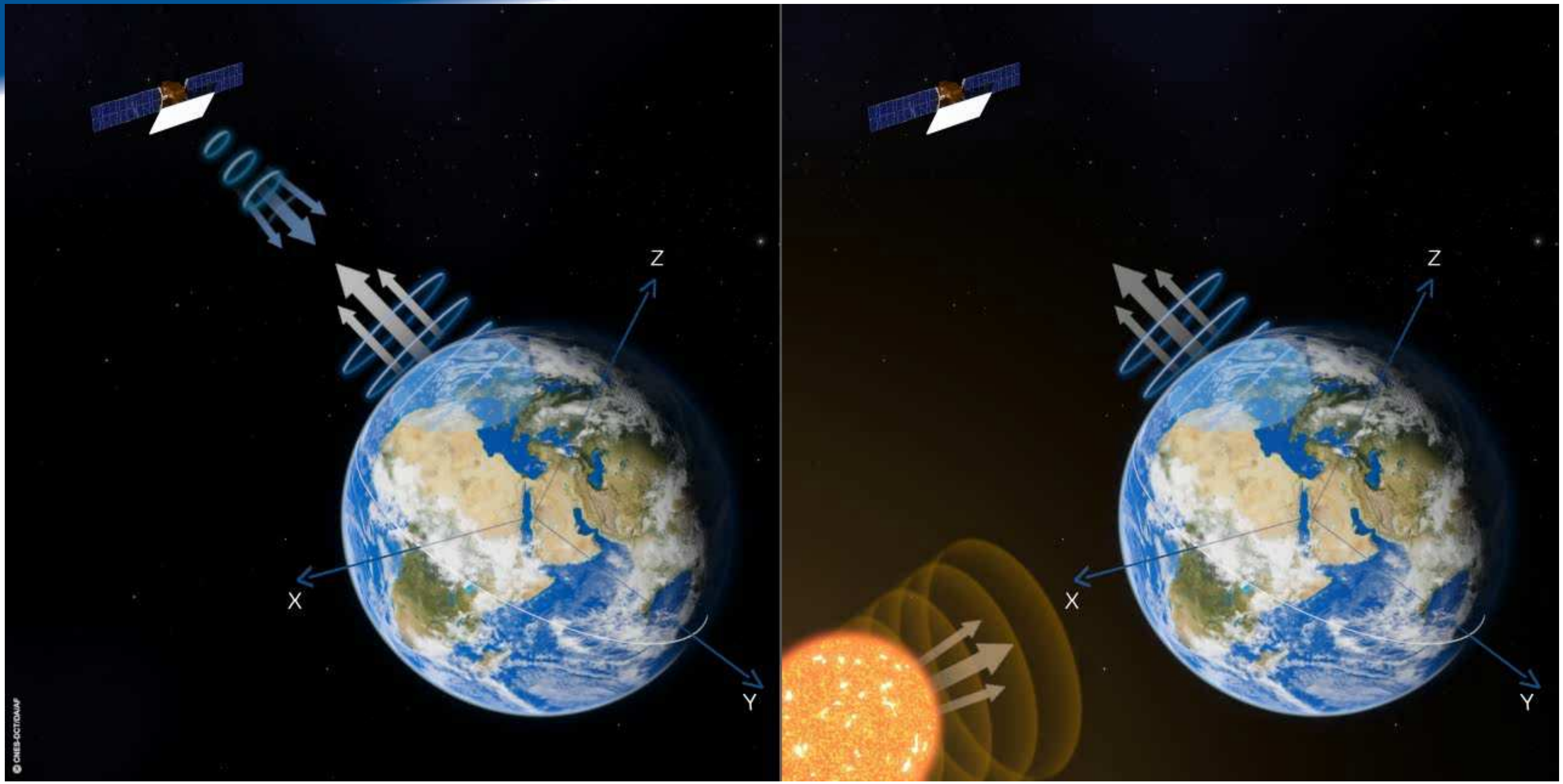


- Oceanography, glaciology,
- continental studies, cartography,
- rain, planetology …

- Meteorology, astronomy,
- oceanography, atmospheric studies

TTVS

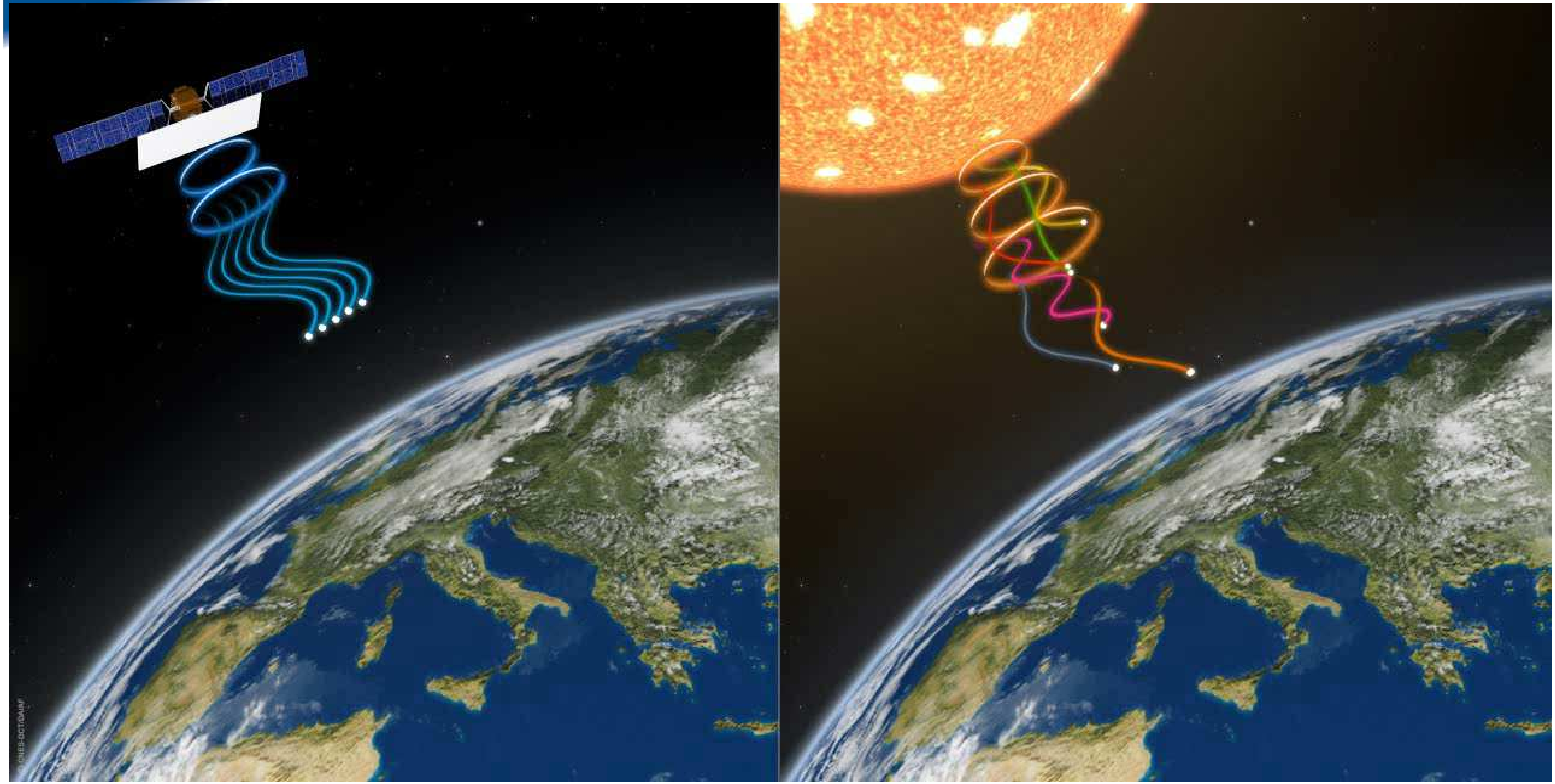
Active sensors (diffusiomètres, altimètres, imageurs) – vs. Passive sensors (radiomètres micro-ondes)



- Oceanography, glaciology,
- continental studies, cartography,
- rain, planetology …

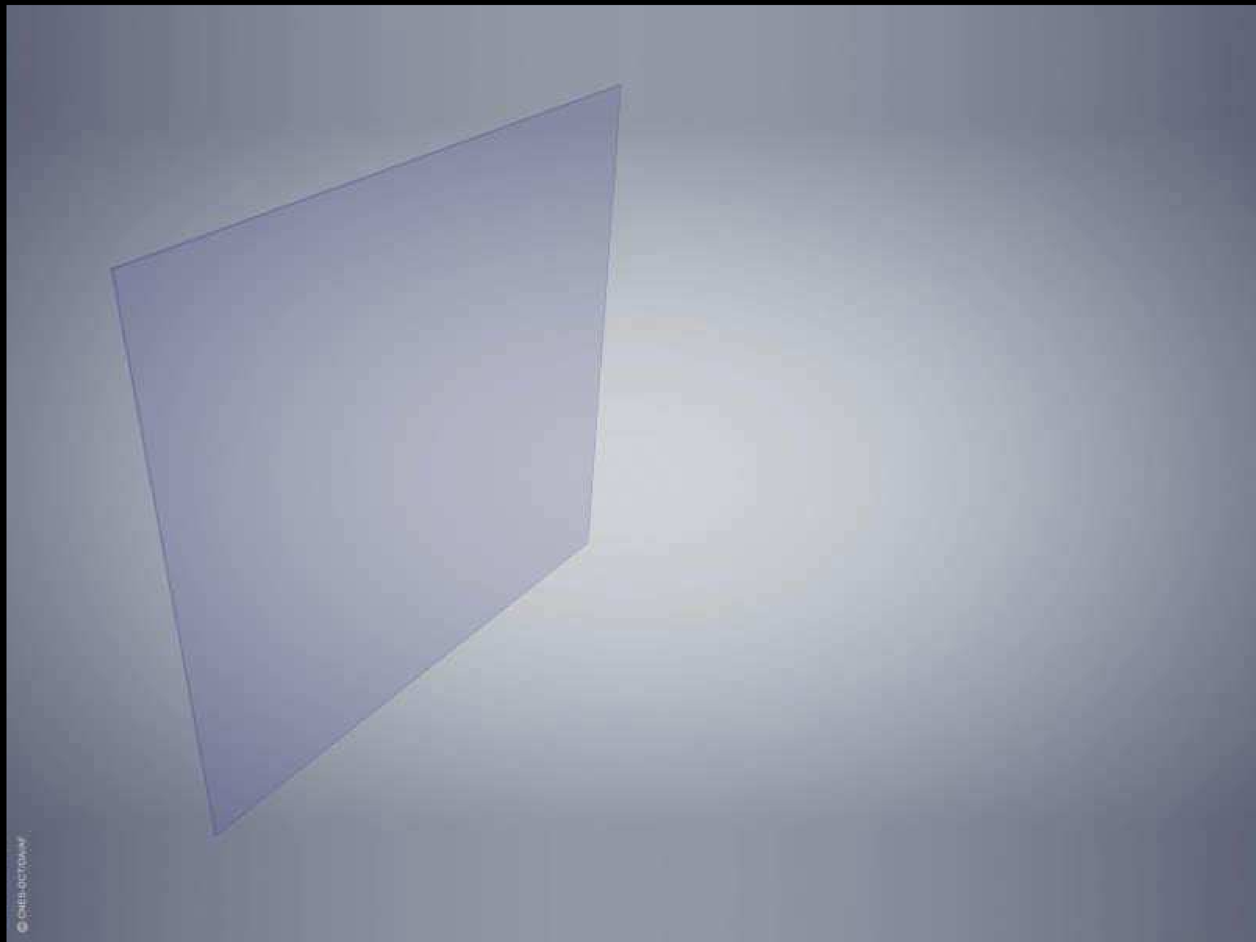
- Meteorology, astronomy,
- oceanography, atmospheric studies

Coherent / uncoherent illumination



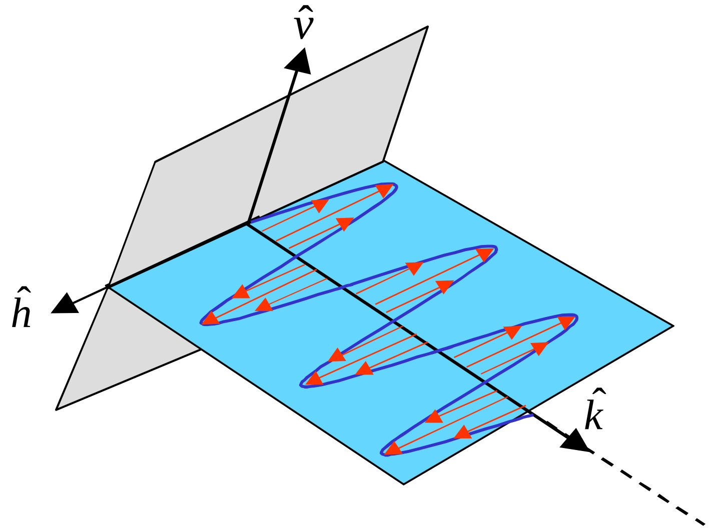
Electro-Magnetic Wave Propagation

Linear polarization

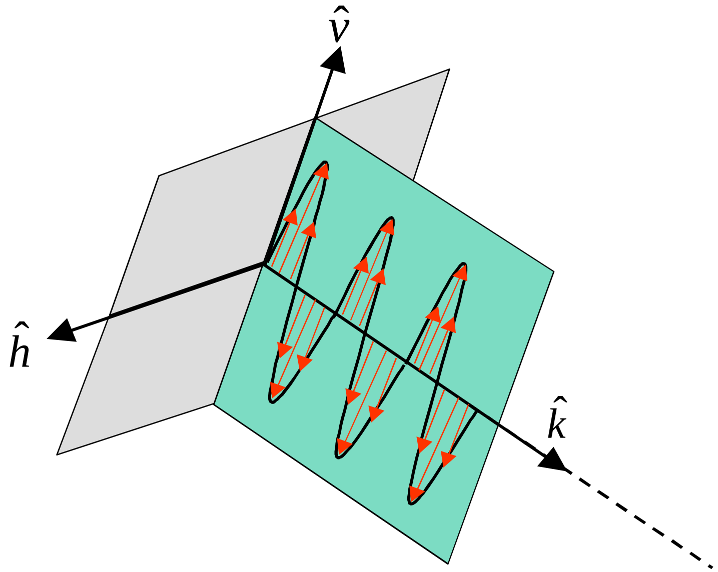


TTVS

Polarization diversity

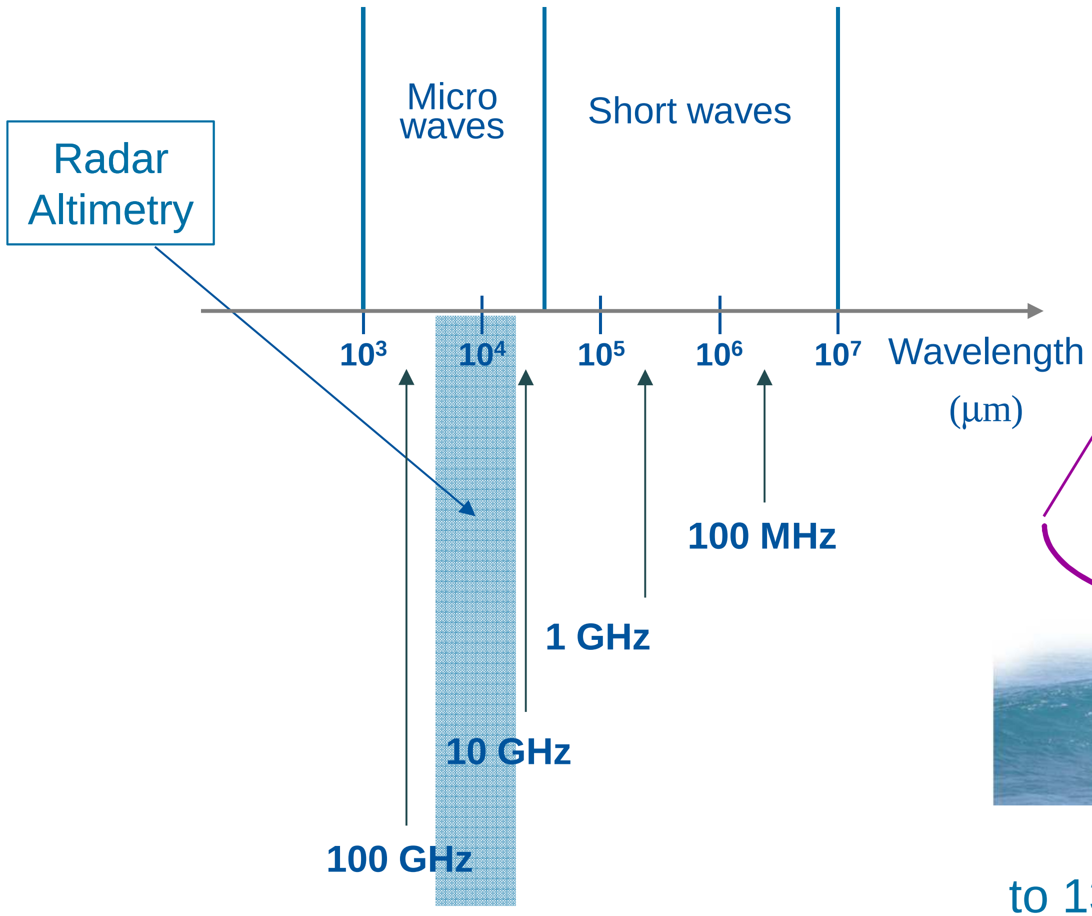


Horizontal polarization

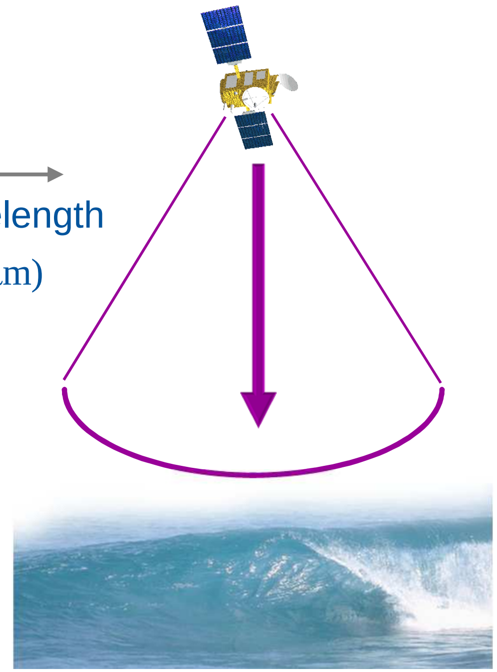


Vertical polarization

Radar altimetry
active observation



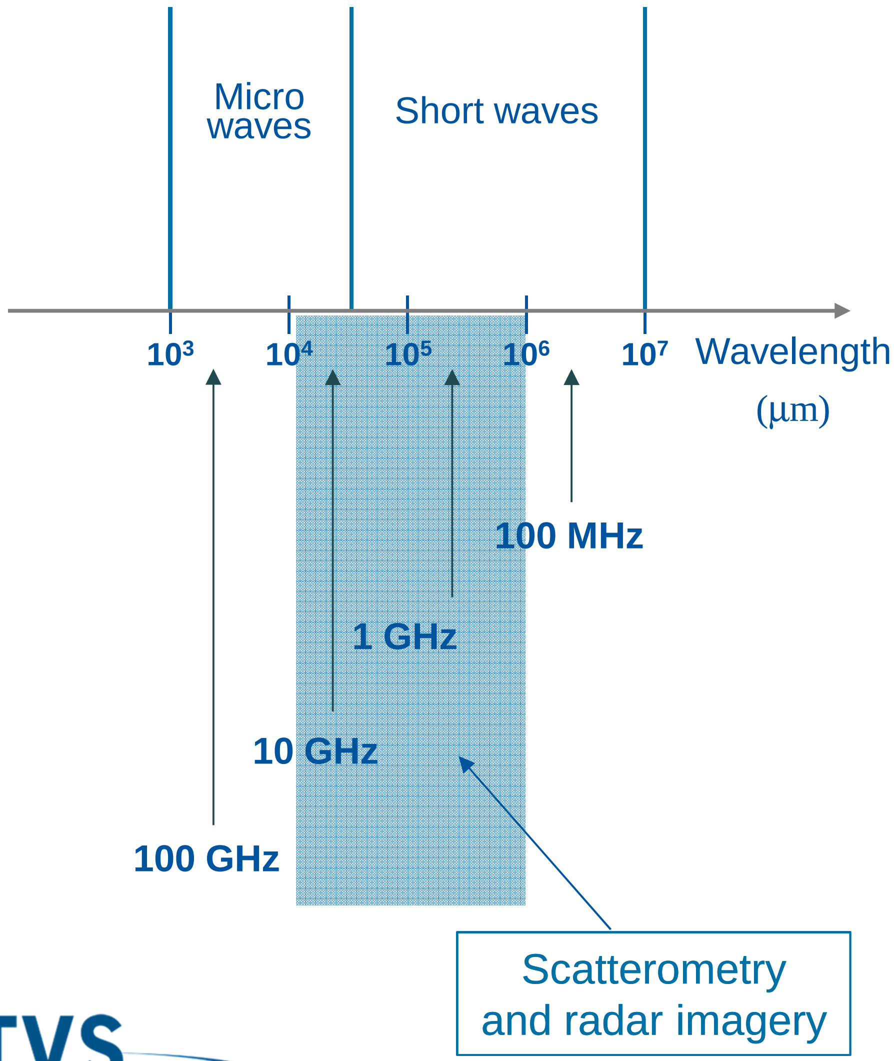
(Nadir transmission - JASON)



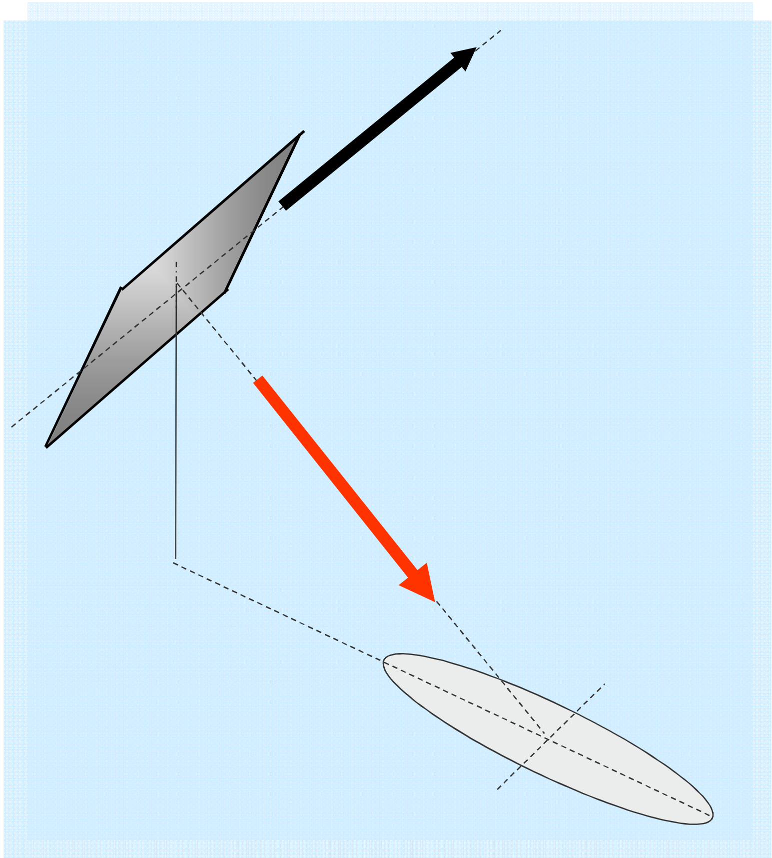
to 13 GHz to 35 GHz)

Radar scatterometry, imagery
active observation

The electromagnetic spectrum

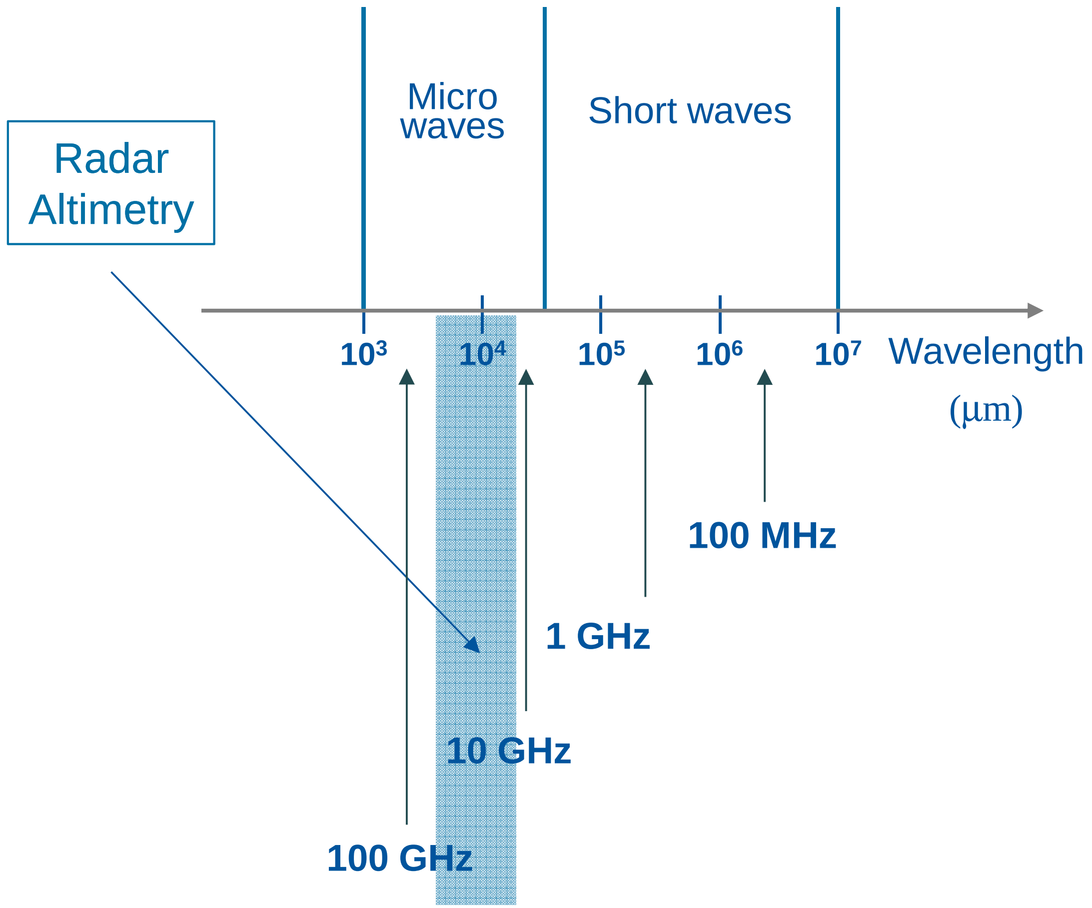


Off-Nadir transmission - SWIM



to 440 MHz to 13 GHz

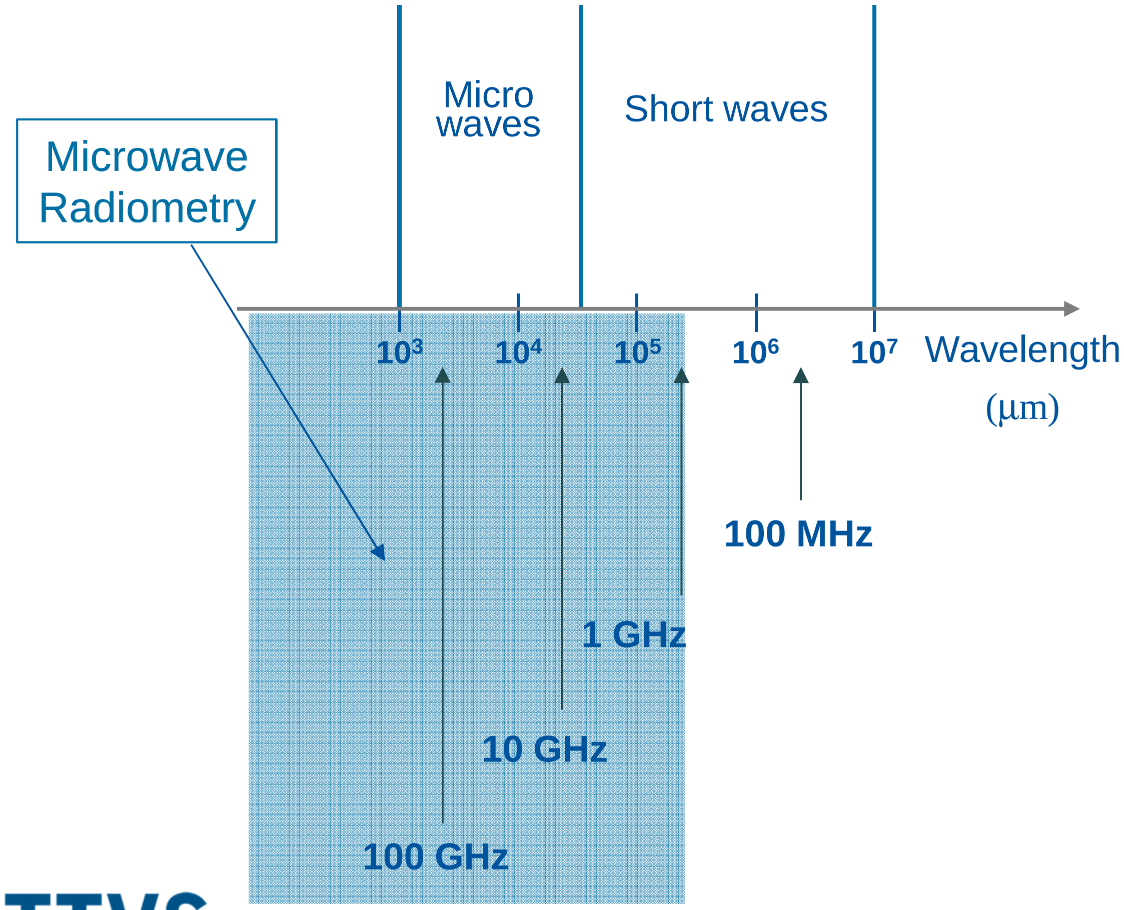
Radar altimetry
active observation



Extension to wide-swath altimetry

35 GHz

Microwave Radiometry
passive observation

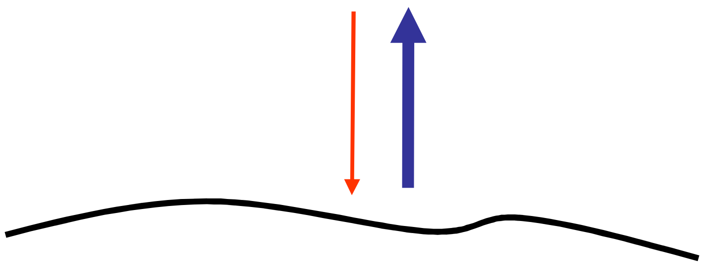


to 1.25 GHz to > 200 GHz

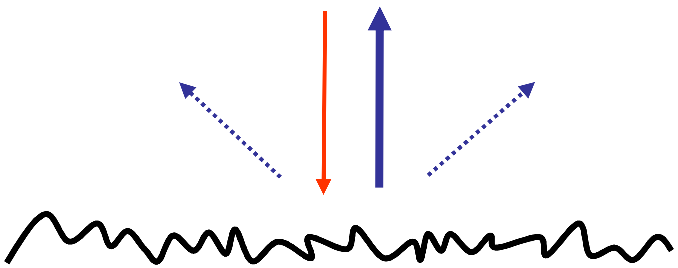
No signal transmission

Nadir looking vs. Off-Nadir Physics

Nadir

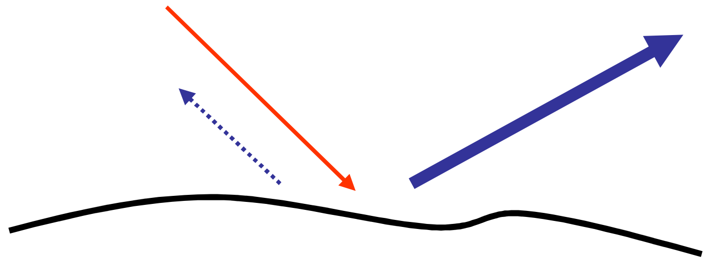


Low rugosity
➔ Strong received radiometry

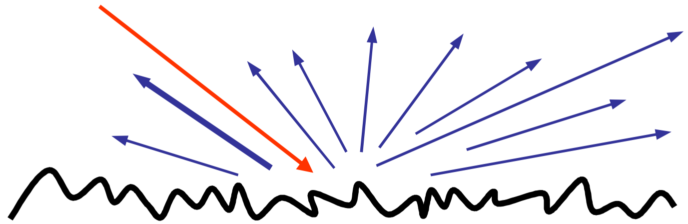


Strong rugosity
➔ Lower radiometry

Off-Nadir



Low rugosity
➔ Low received radiometry



Strong rugosity
➔ stronger radiometry

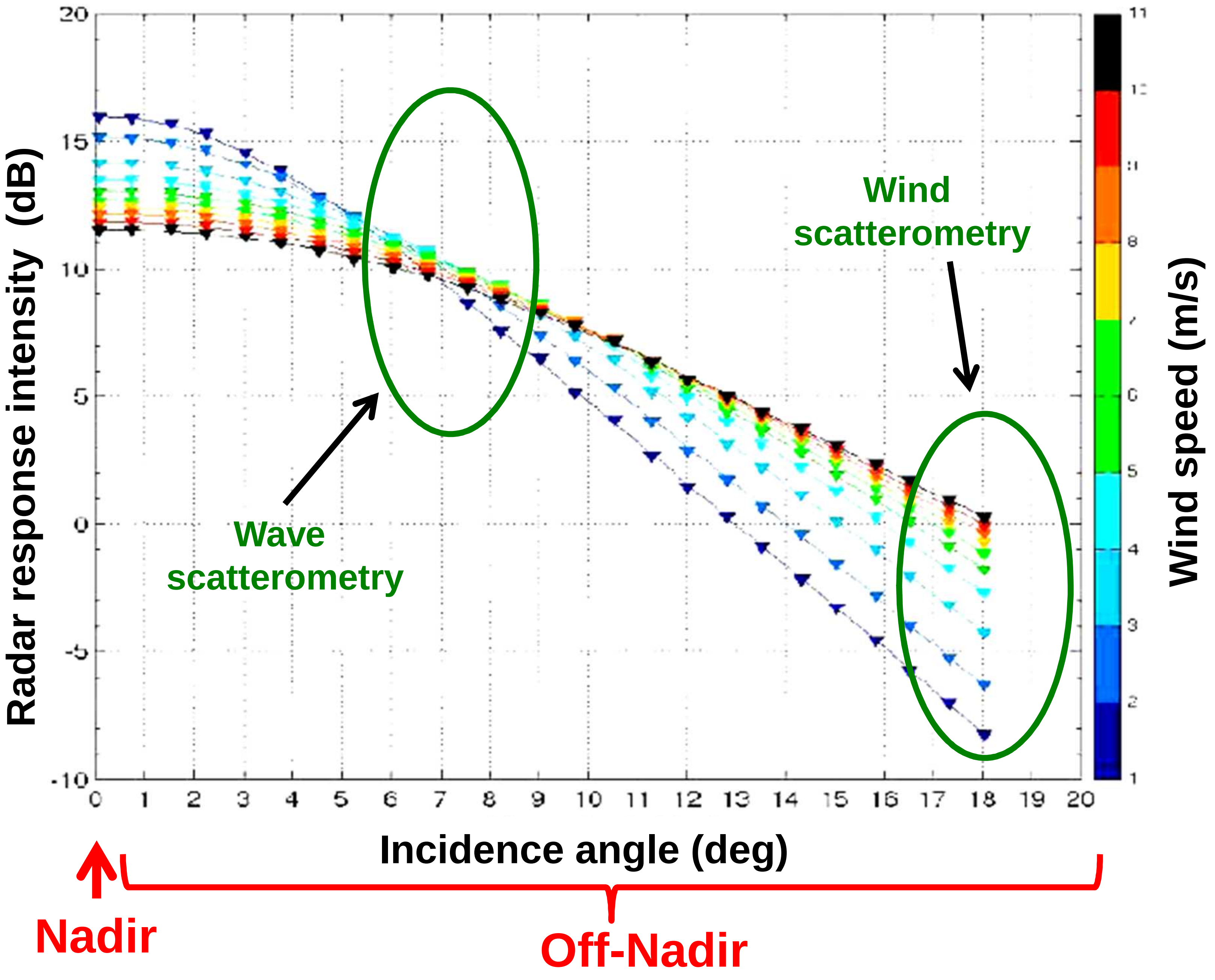
Exemple of off-nadir (TDX images) over water areas

- higher wind → + water roughness → + backscattering

Courtesy D. Desroches et al. (CNES / Altamira

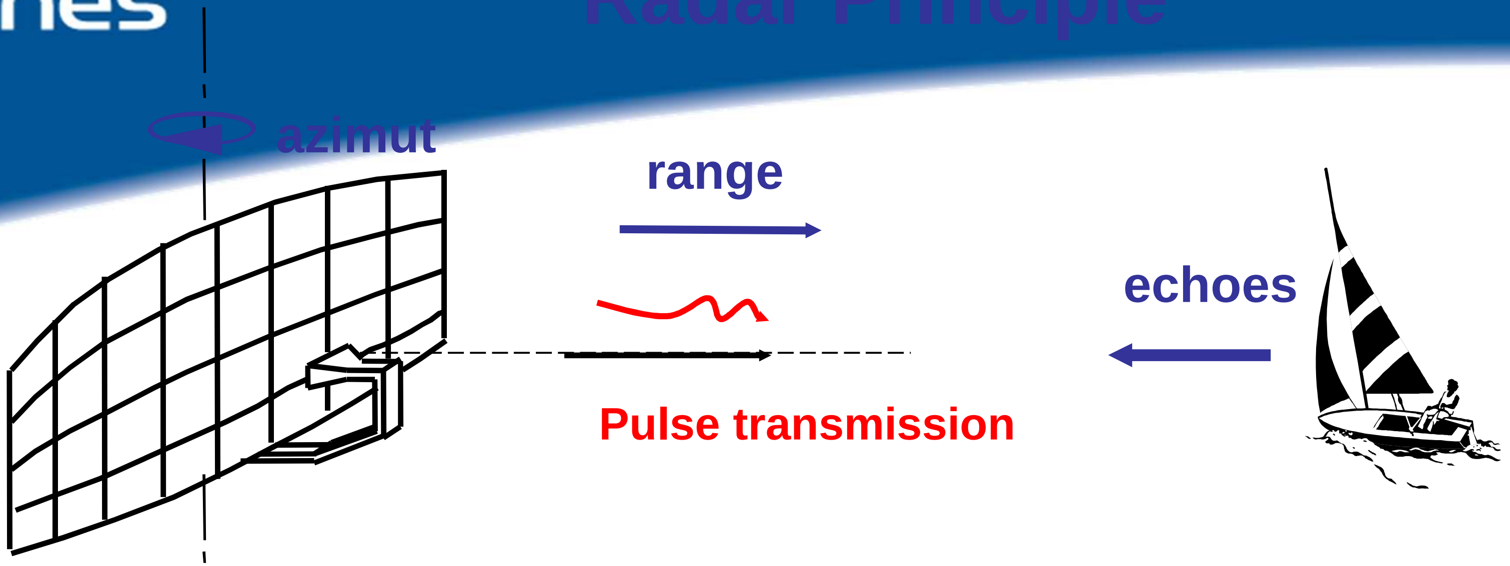
altamira INFORMATION

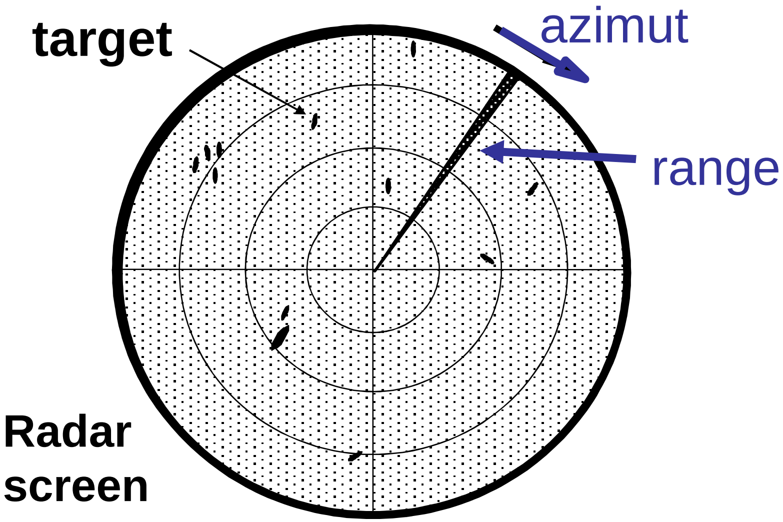
From Nadir to Off-nadir active observation : Wave and wind scatterometry



Radar Fundamental

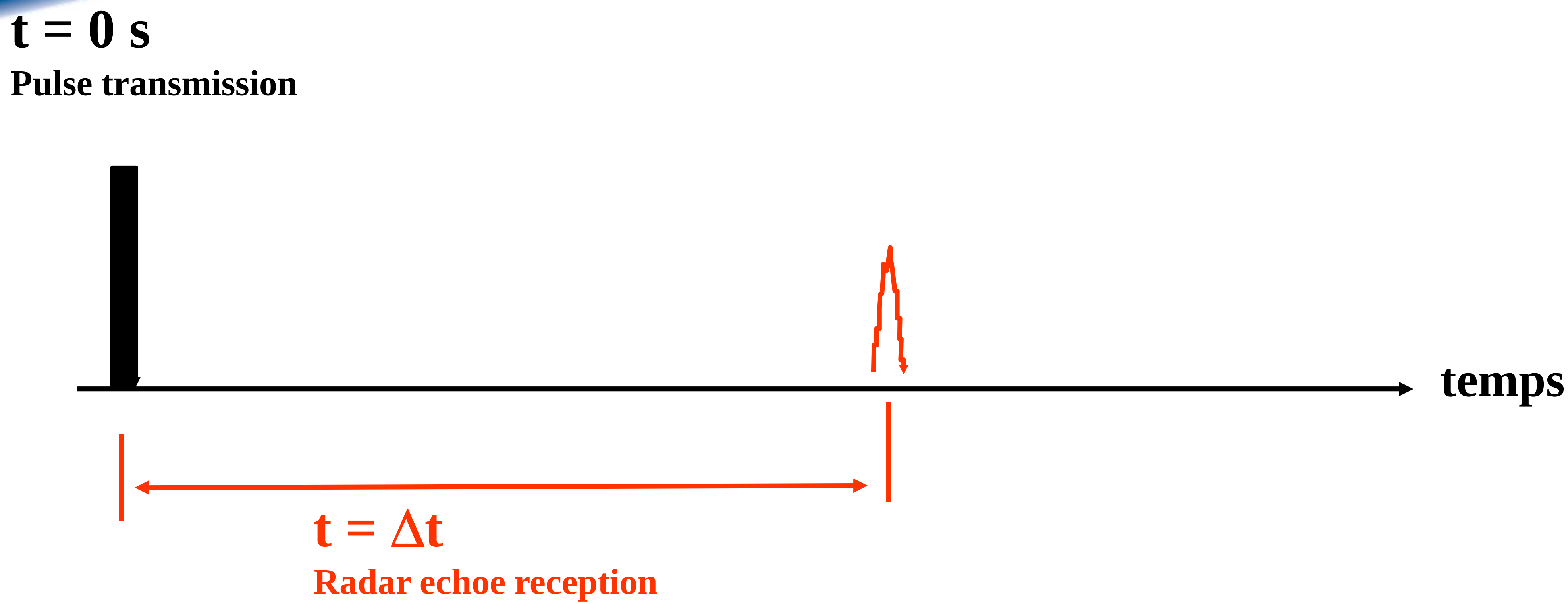
Radar Principle





• **Time difference between pulse transmission and echoe reception gives a range information**

Radar Principle : chronogram of an « ideal pulse » (Dirac Pulse)

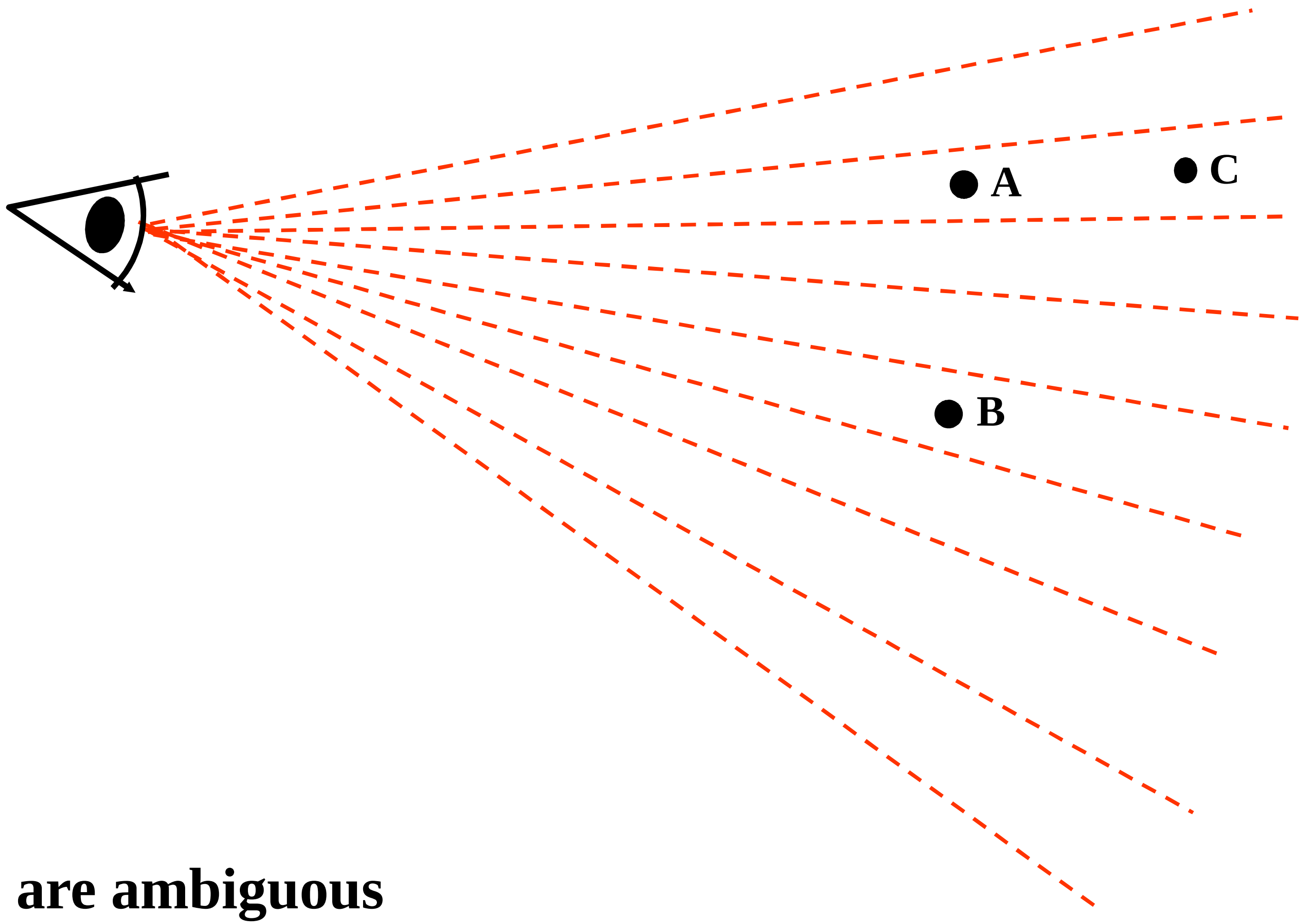


→ **Radar target range : d = c.Δt/2**

→**Time measurement transformed into a range information**

Our world as seen by :

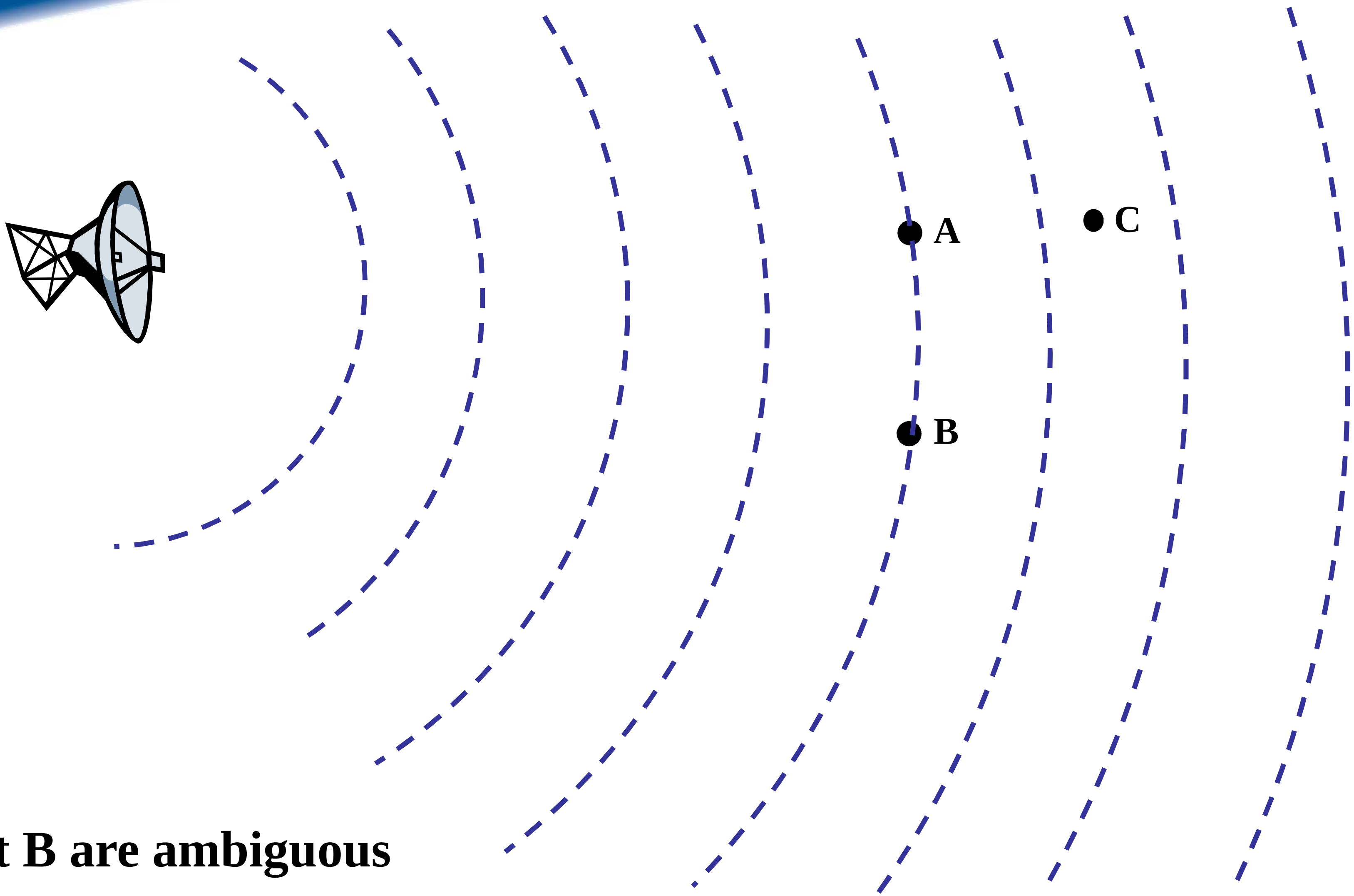
→ Optical vision : angular sampling



A et C are ambiguous

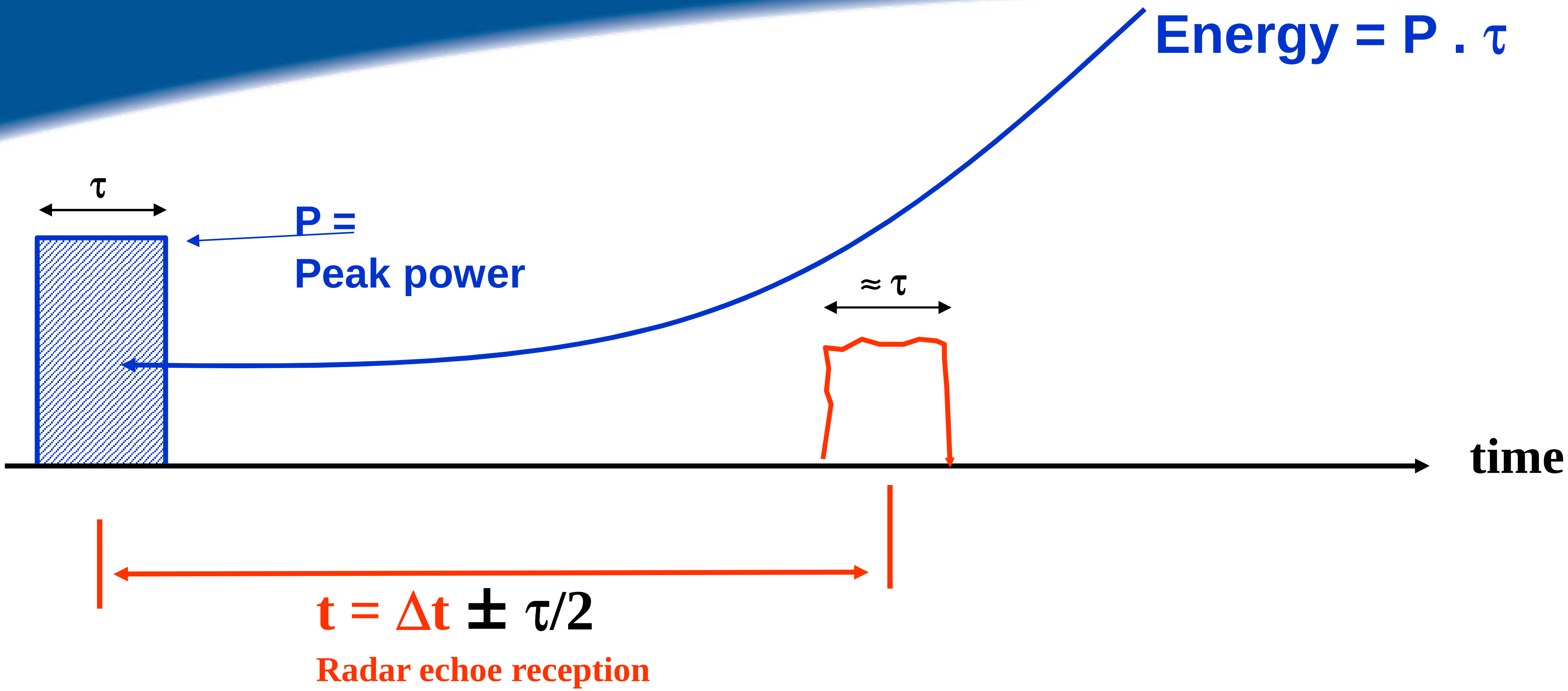
Our world as seen by :

→ radar vision : range sampling



A et B are ambiguous

Real pulse, width τ



→ Radar – Target range : $d = c.\Delta t/2 \pm c.\tau/2$

→Time measurement = range information + uncertainty (τ)

Range resolution = uncertainty on range discrimination →

$$\pm\, c \,.\, \tau / 2$$

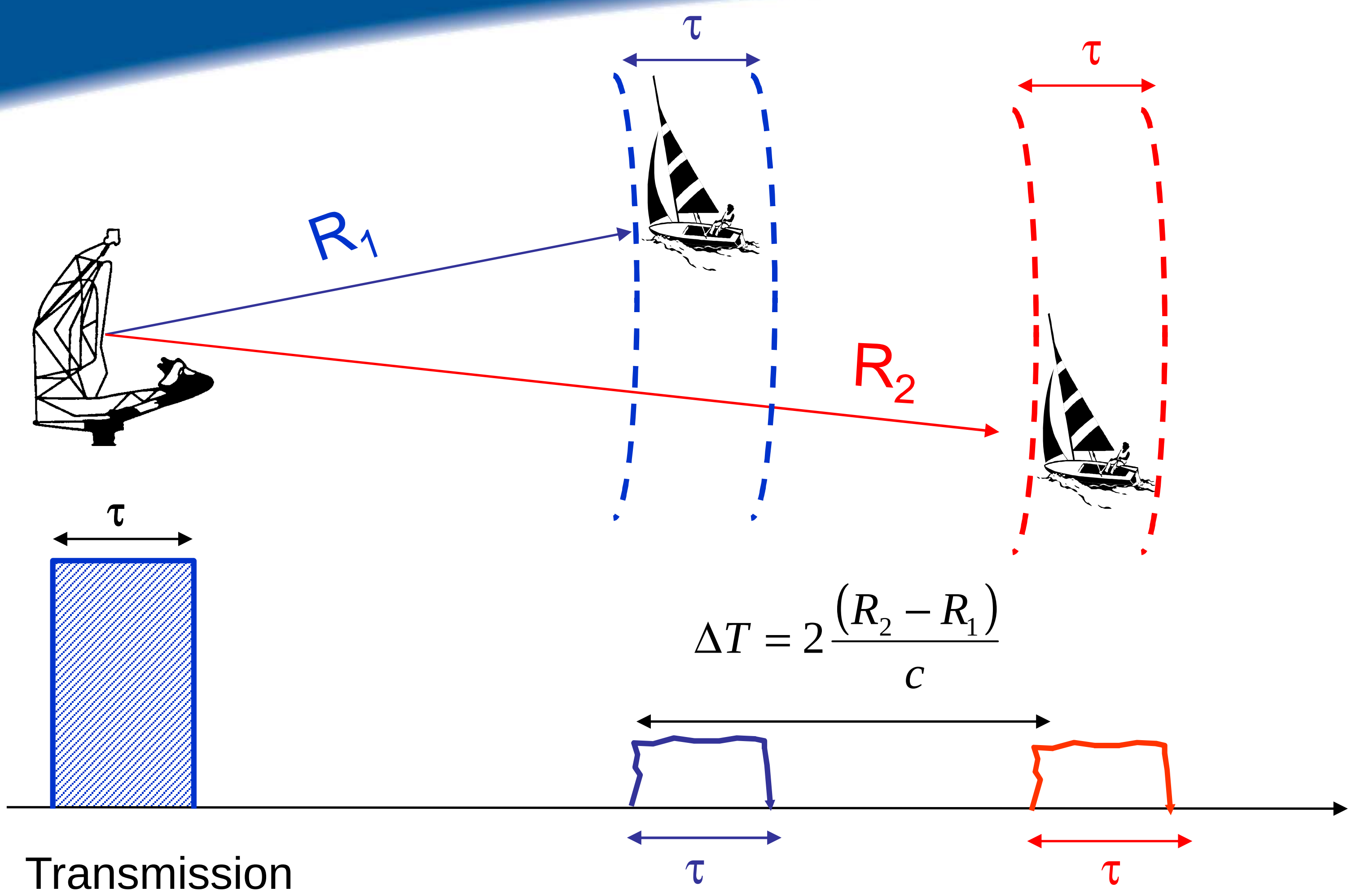
3×10^{8} m/s

30×10^{-6} s

$$\underbrace{3 \times 10^{8}\ \text{m/s} \qquad 30 \times 10^{-6}\ \text{s}}_{}$$

4500 m !

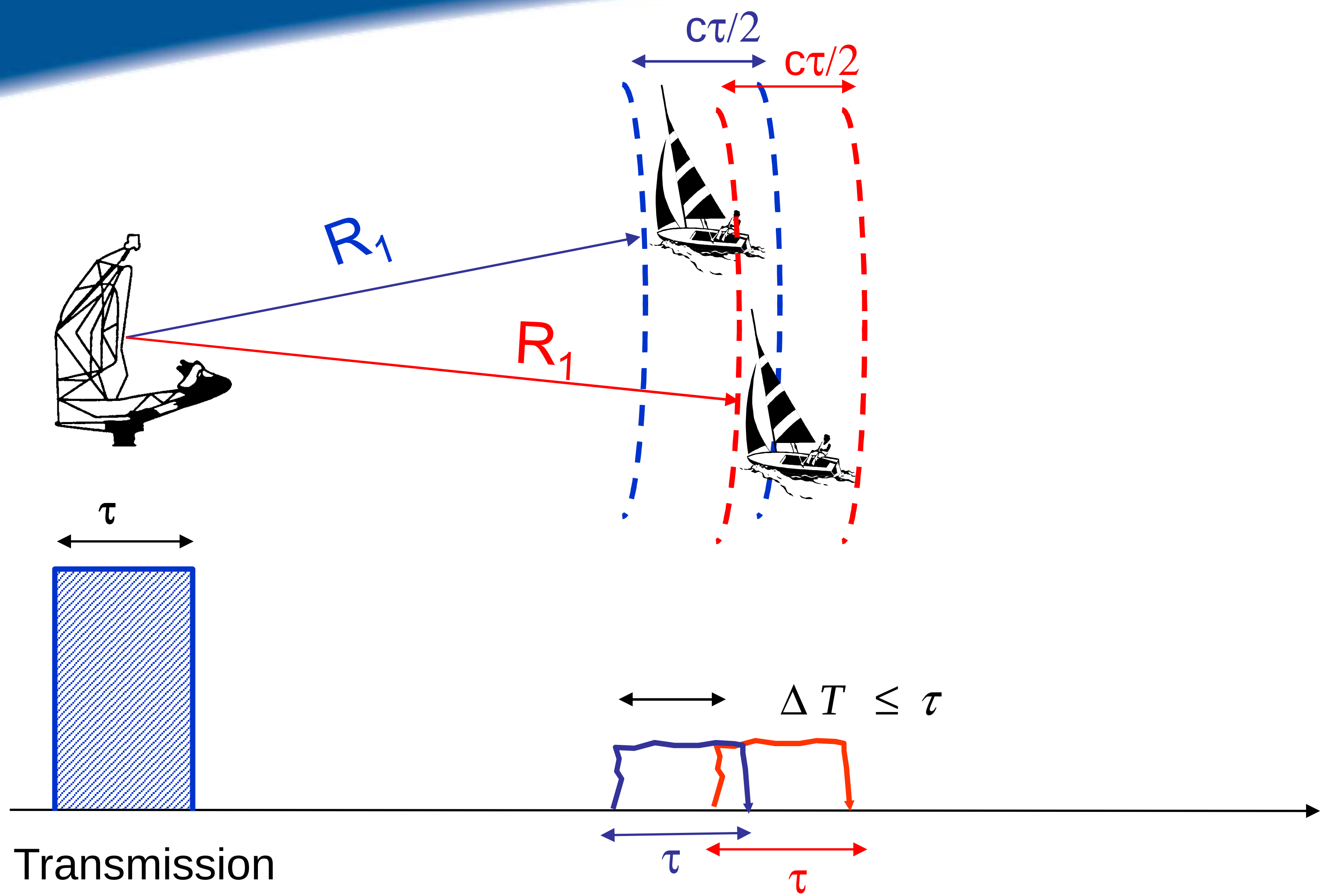
Range resolution = uncertainty on range discrimination



Discrimination if :

$$\Delta T \geq \tau \Leftrightarrow \Delta R \geq c \cdot \tau / 2$$

Range resolution = uncertainty on range discrimination

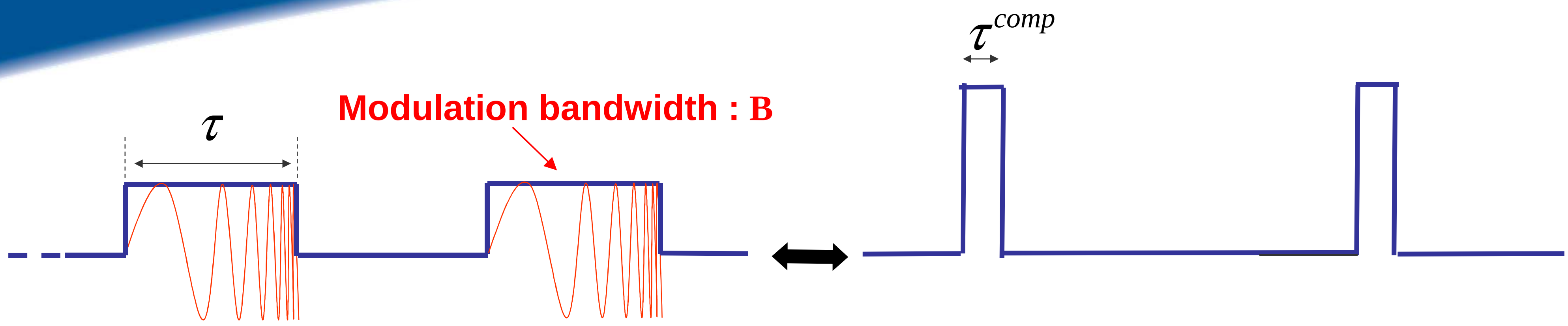


Non discrimination : $\Delta R \leq c \cdot \tau / 2$


cnes
Detection
© CNES-DCT/DA/AF
TTVS

Range resolution enhancement

→ Long pulse frequency modulation ⟷ Pulse compression



τ = long pulse duration

τ^{comp} = short pulse duration =1/B

$$c\tau / 2 \rightarrow c / 2 / B$$

← Range resolution After processing

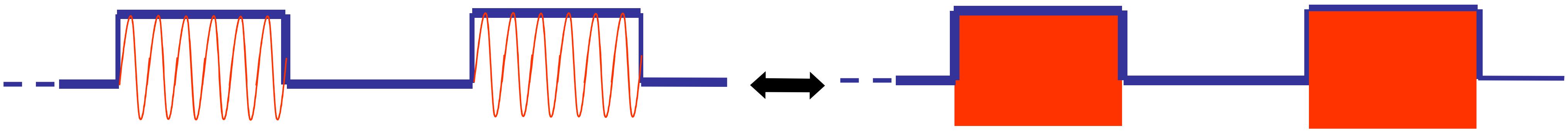
$$15\ km \rightarrow 0.47\ m$$

(JASON : τ=100µs, B=320 MHz

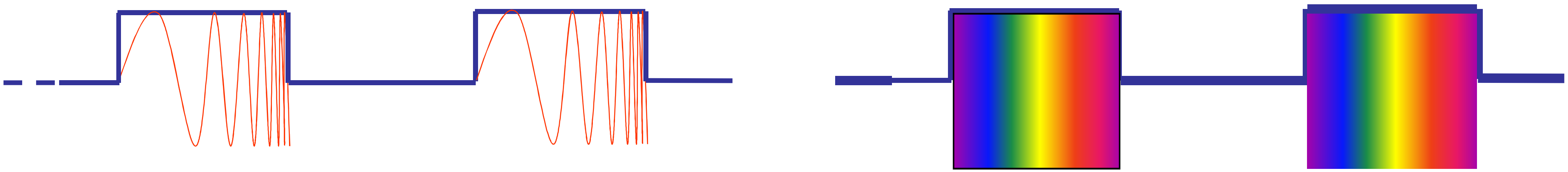
A naïve interpretation of pulse compression … (1/2)

➜Frequency modulation is kind of a pulse « coloring »

Monochromatic wave : 1 ray, 1 « color »

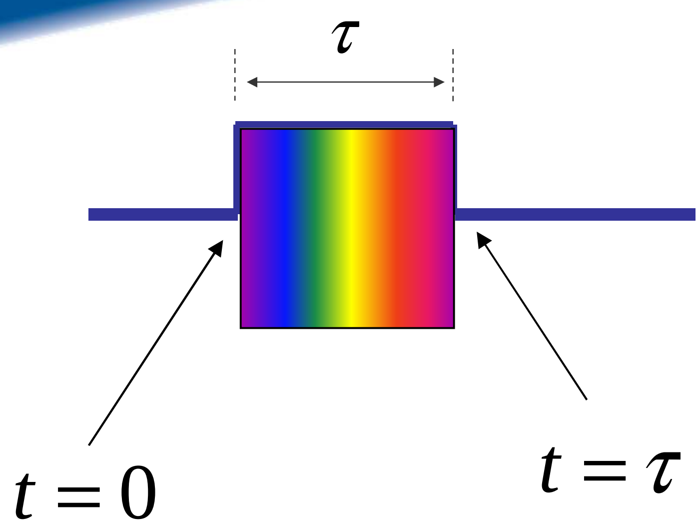


Frequency modulated wave = « colored » wave



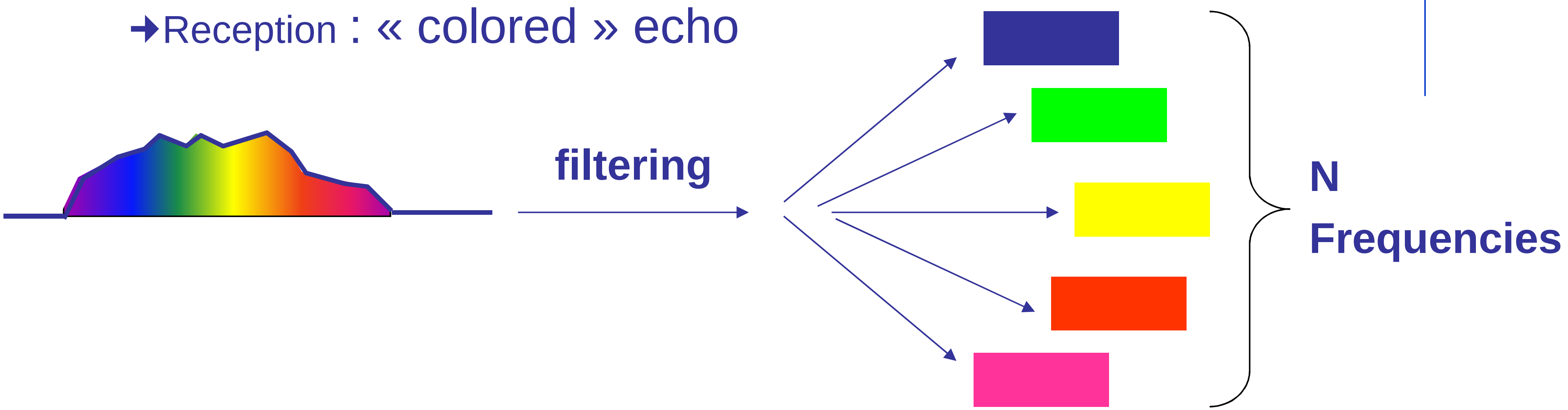
A naïve interpretation of pulse compression … (2/2)

➜Transmitted pulse (Energy : $E=P_c.\tau$, Pc : Peak power)

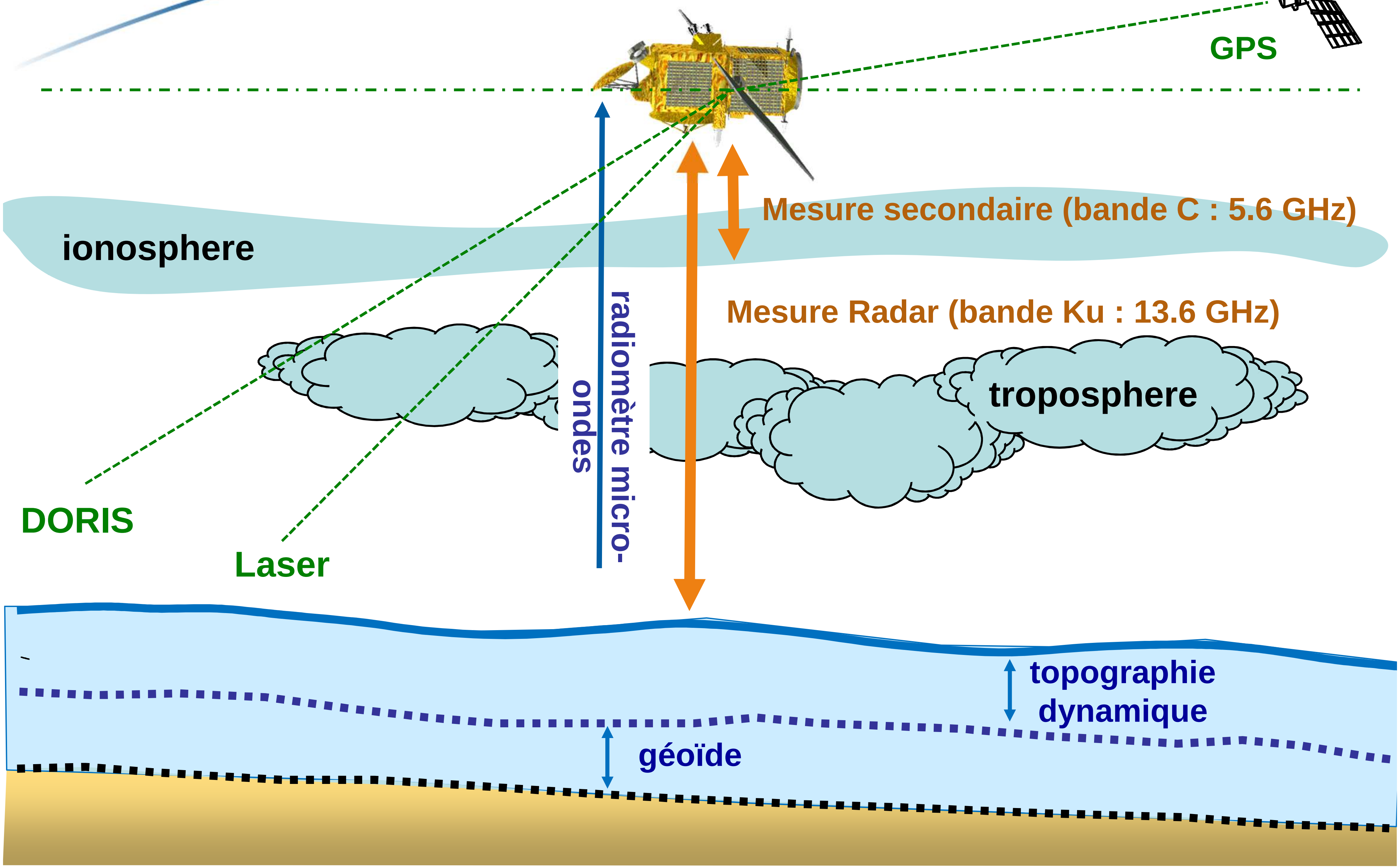


Temporal resolution : τ / N

➜Reception : « colored » echo



L’ALTIMÉTRIE RADAR « NADIR » (« SINCE 1992 »)



From altimetric range to Sea Surface Height (SSH) : not so easy …

$$SSH = h_{sat} - [h_s + h_i + h_{iono} + h_{dry} + h_{wet} + h_{EM} + h_{otide} + h_{stide} + h_{ol} + h_{ptide} + h_{baro}] + \varepsilon$$

where :

h_{sat} : satellite height above the reference ellipsoid (radial orbit component)

h_s : instantaneous distance between the altimeter antenna and ocean surface

h_i : instrumental corrections

h_{iono} : ionospheric correction

h_{dry} : dry tropospheric correction

h_{wet} : wet tropospheric correction

h_{EM} : EM-bias correction

h_{otide} : ocean tide correction

h_{side} : solid Earth tide correction

h_{ol} : ocean loading correction

h_{ptide} : pole tide correction

h_{baro} : inverted barometer correction

ε : random and systematic remaining errors

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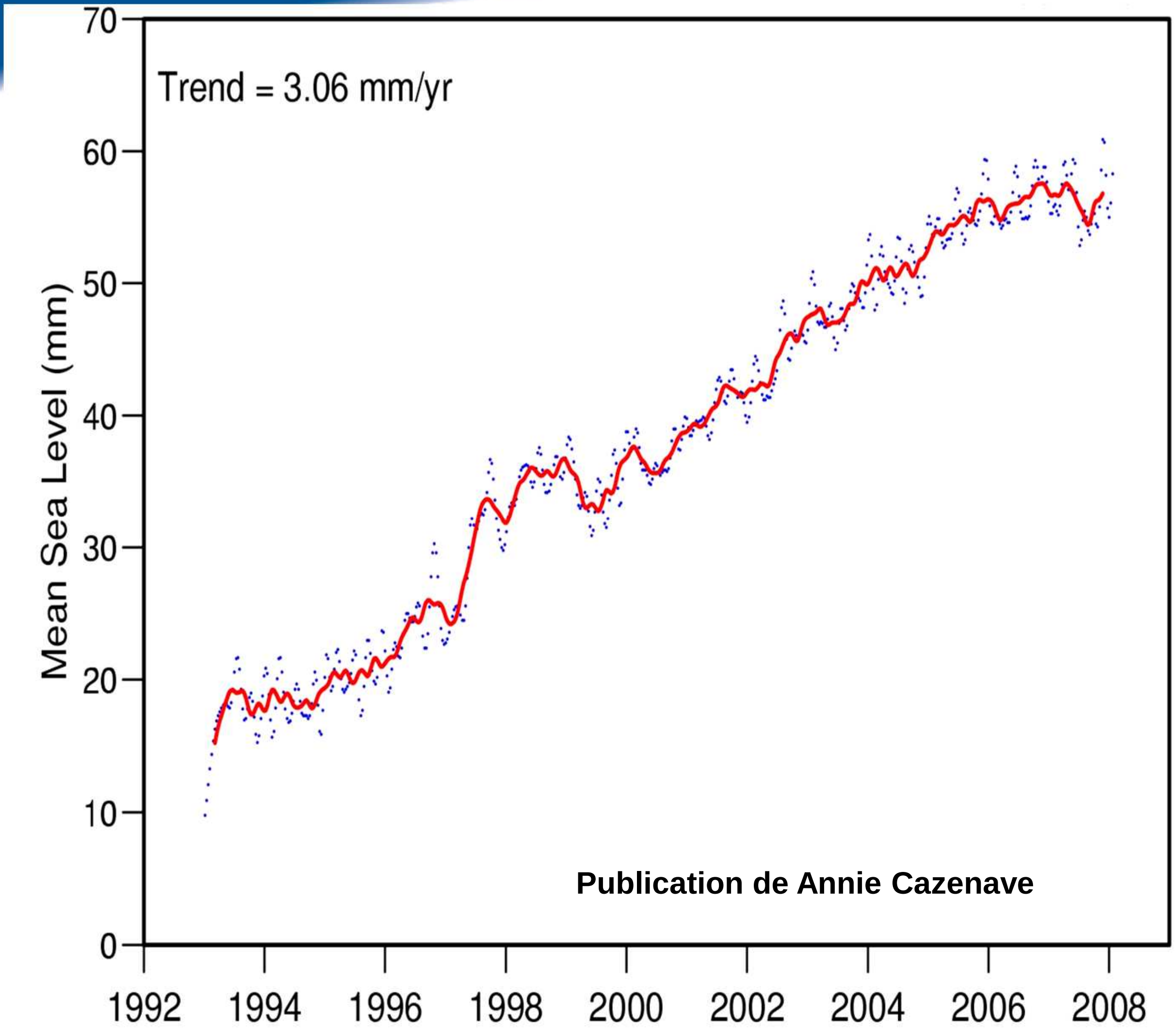
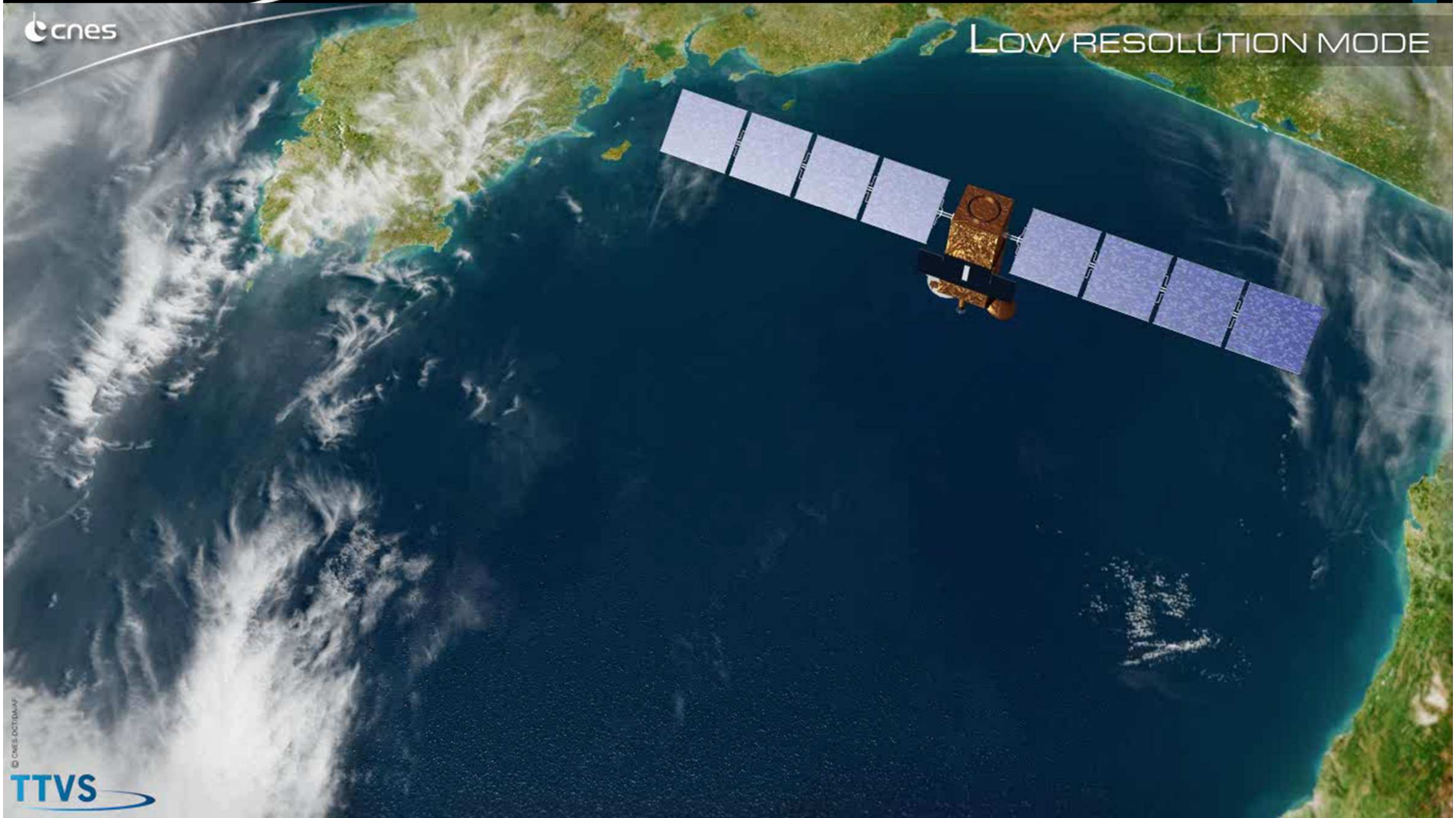
Mean Sea level evolution : 1993-2007 (TOPEX and JASON data take)



3 mm / year


LOW RESOLUTION MODE
cnes
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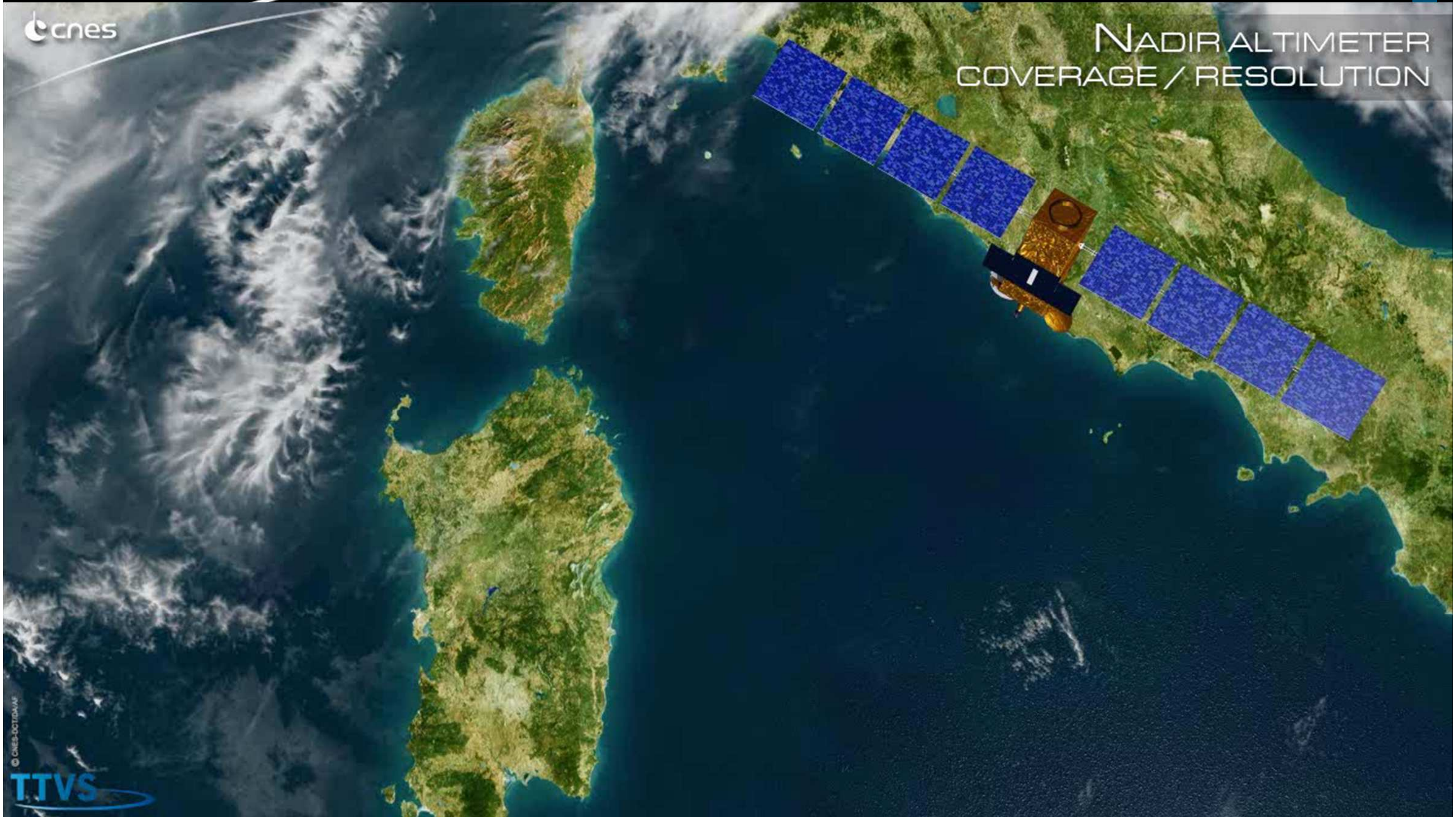
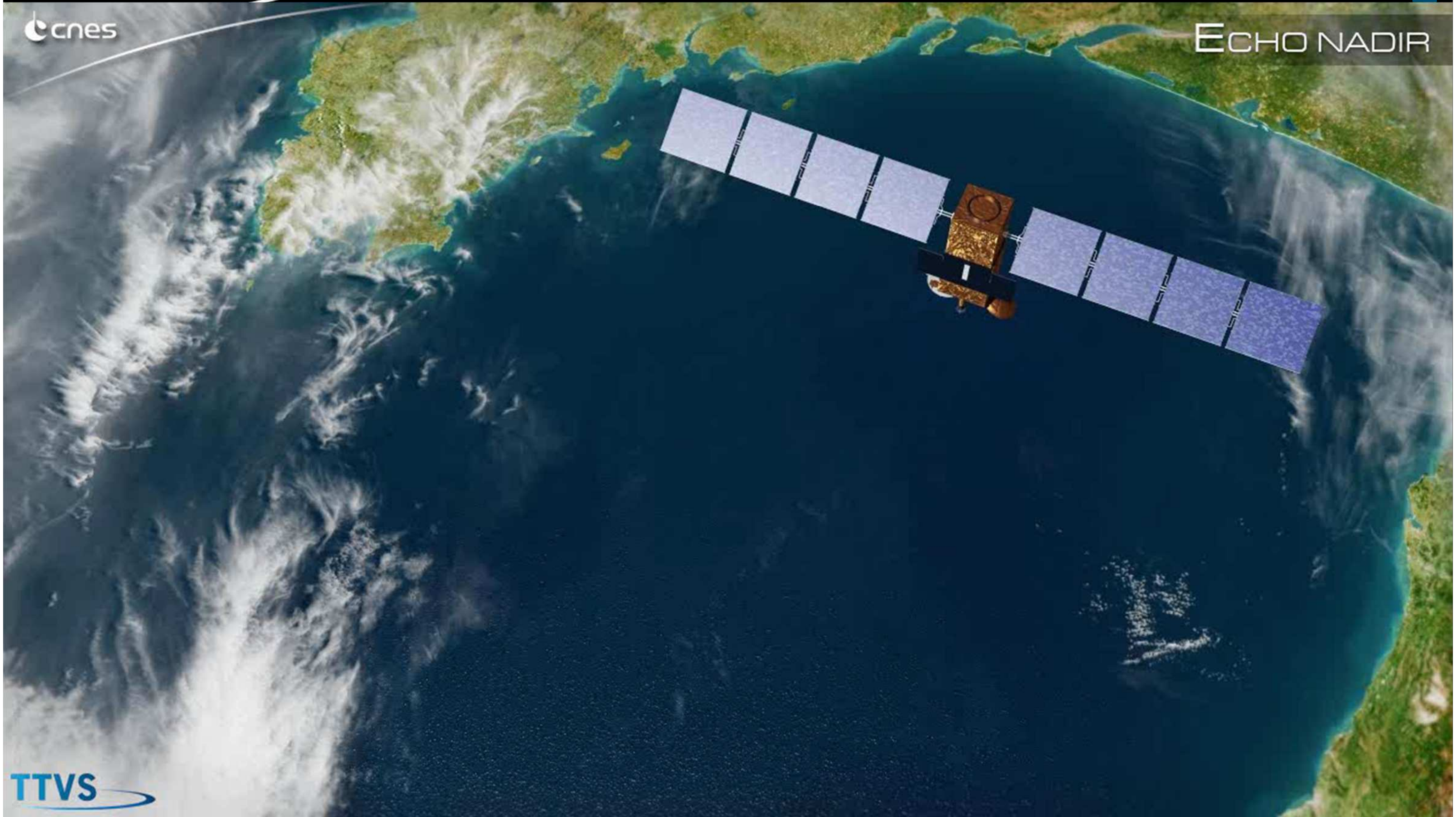
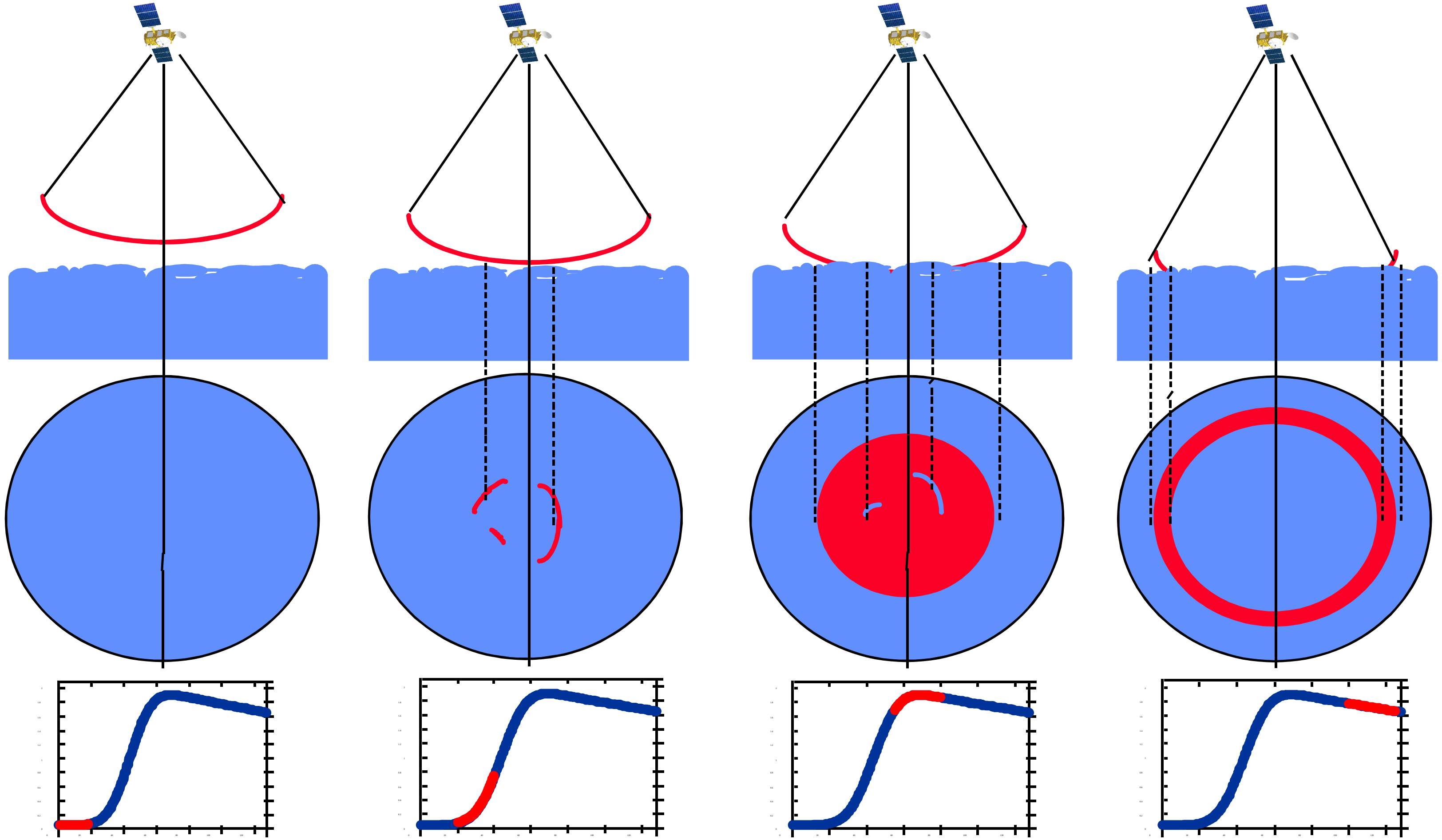
Nadir altimeter coverage / resolution




ECHO NADIR

Echo Formation: Sea state impact

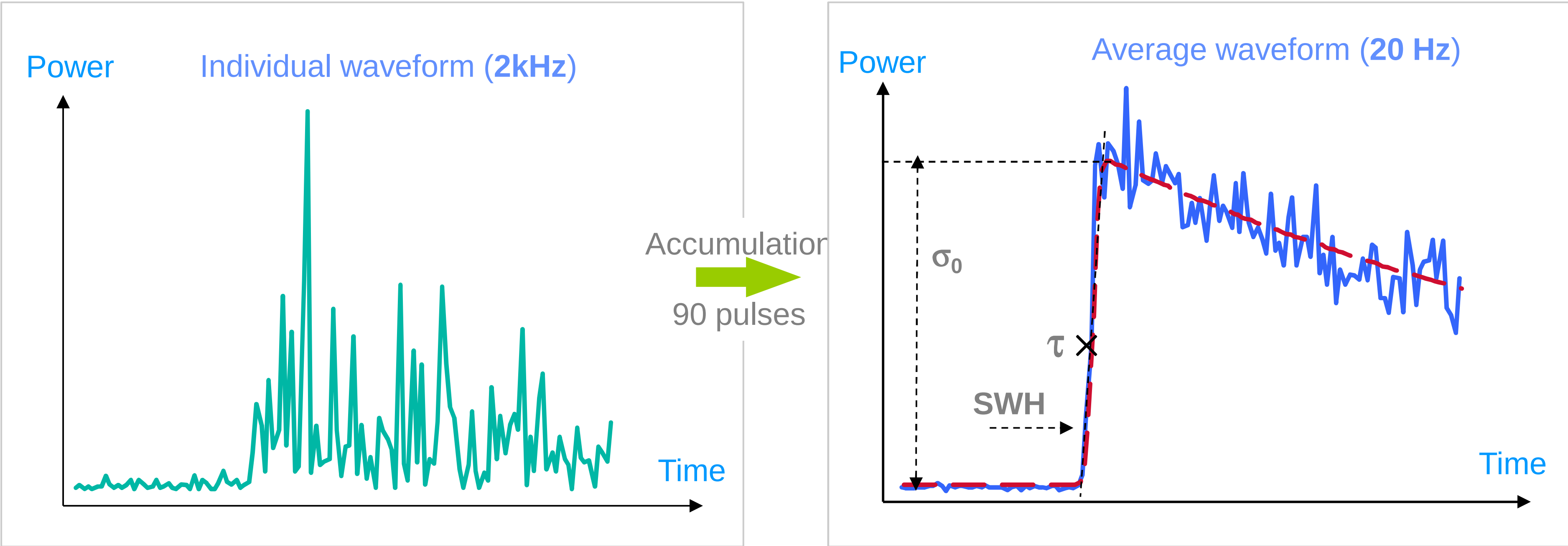
Le radar altimètre: modèle d'écho de Brown



Formulation théorique à partir des caractéristiques du radar et de l'état de mer

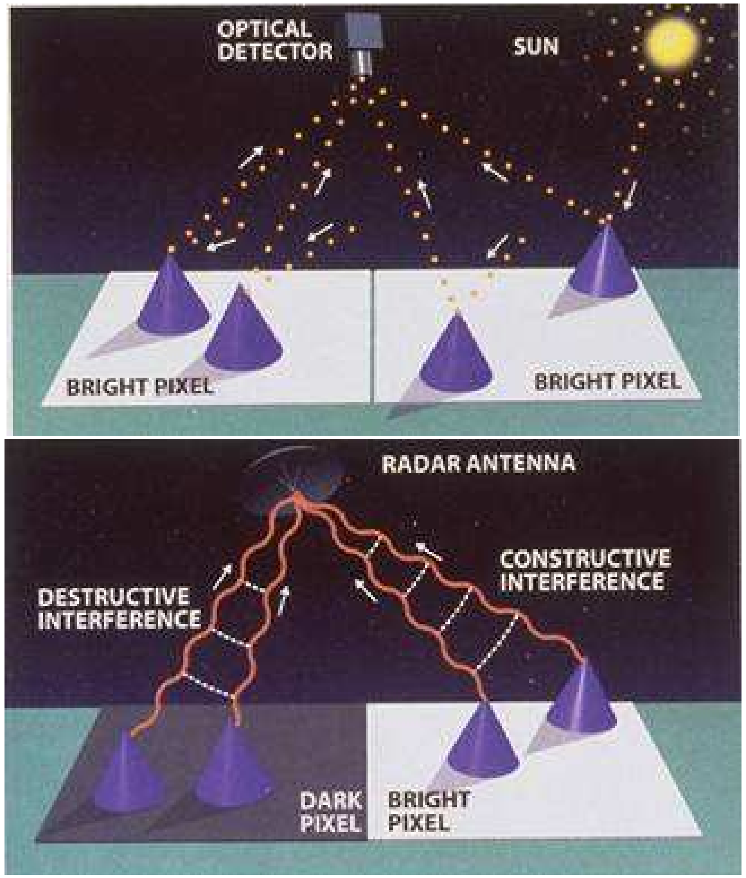
Averaging individual echoes

- The signal is affected by the “speckle” linked to sea surface properties



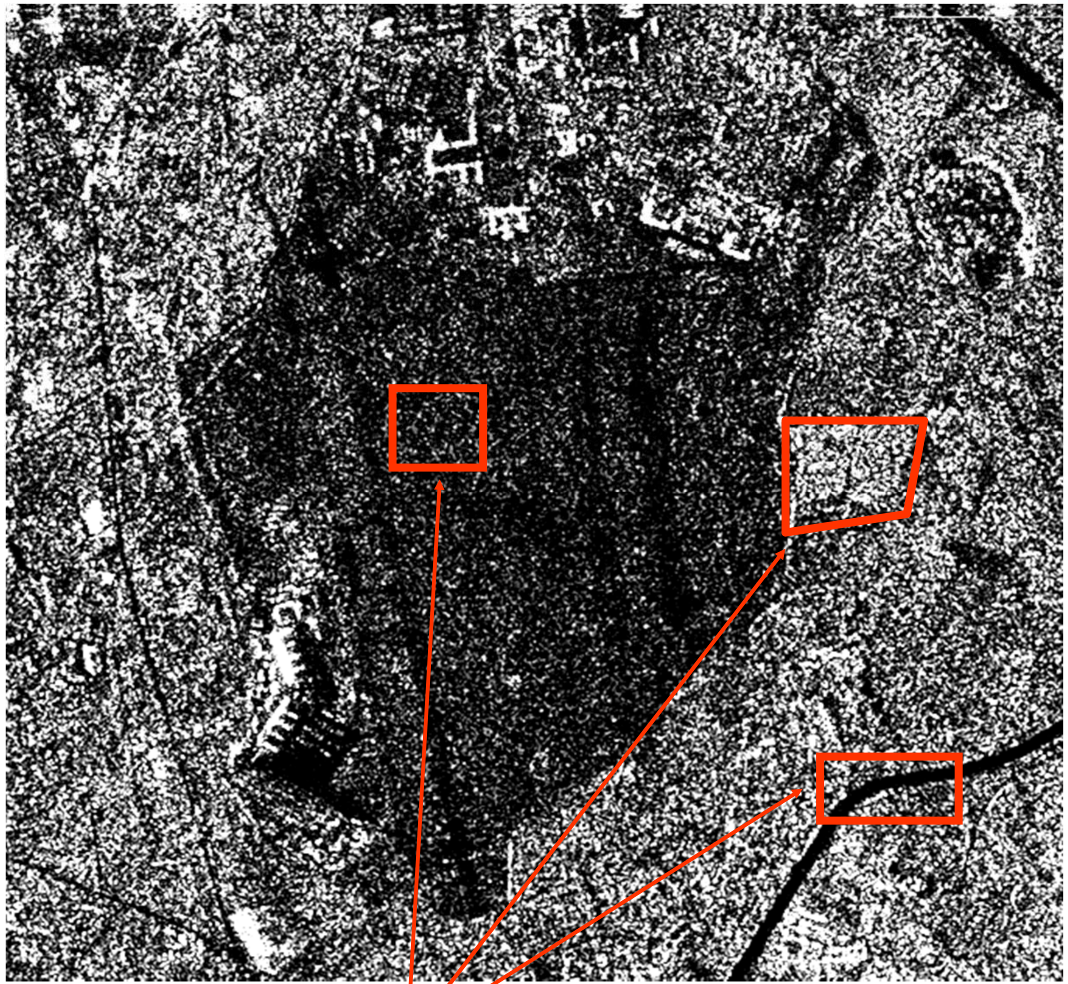
-> After integration of ~100 elementary echoes,
the return power spectrum signal can be fitted with Brown’s model

Speckle noise and coherent light



© Scientific American

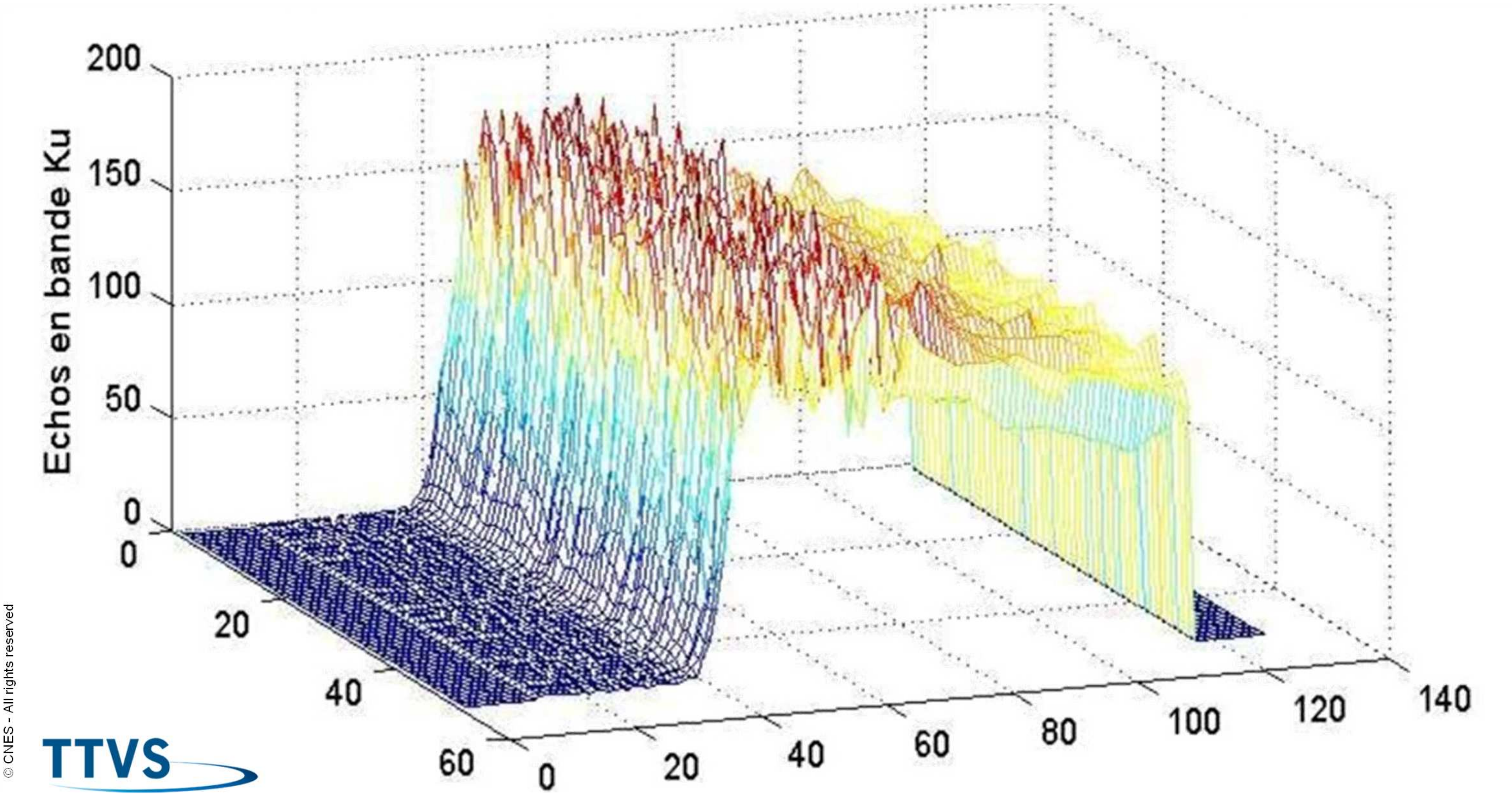
- “Random light: deterministic result ...”
- “Deterministic light: random result!”



RSAT standard image

Speckle is a deterministic phenomenon that can be modeled as a multiplicative random noise

Formes d'ondes acquises par l'altimètre Poseidon-2 (Jason-1)



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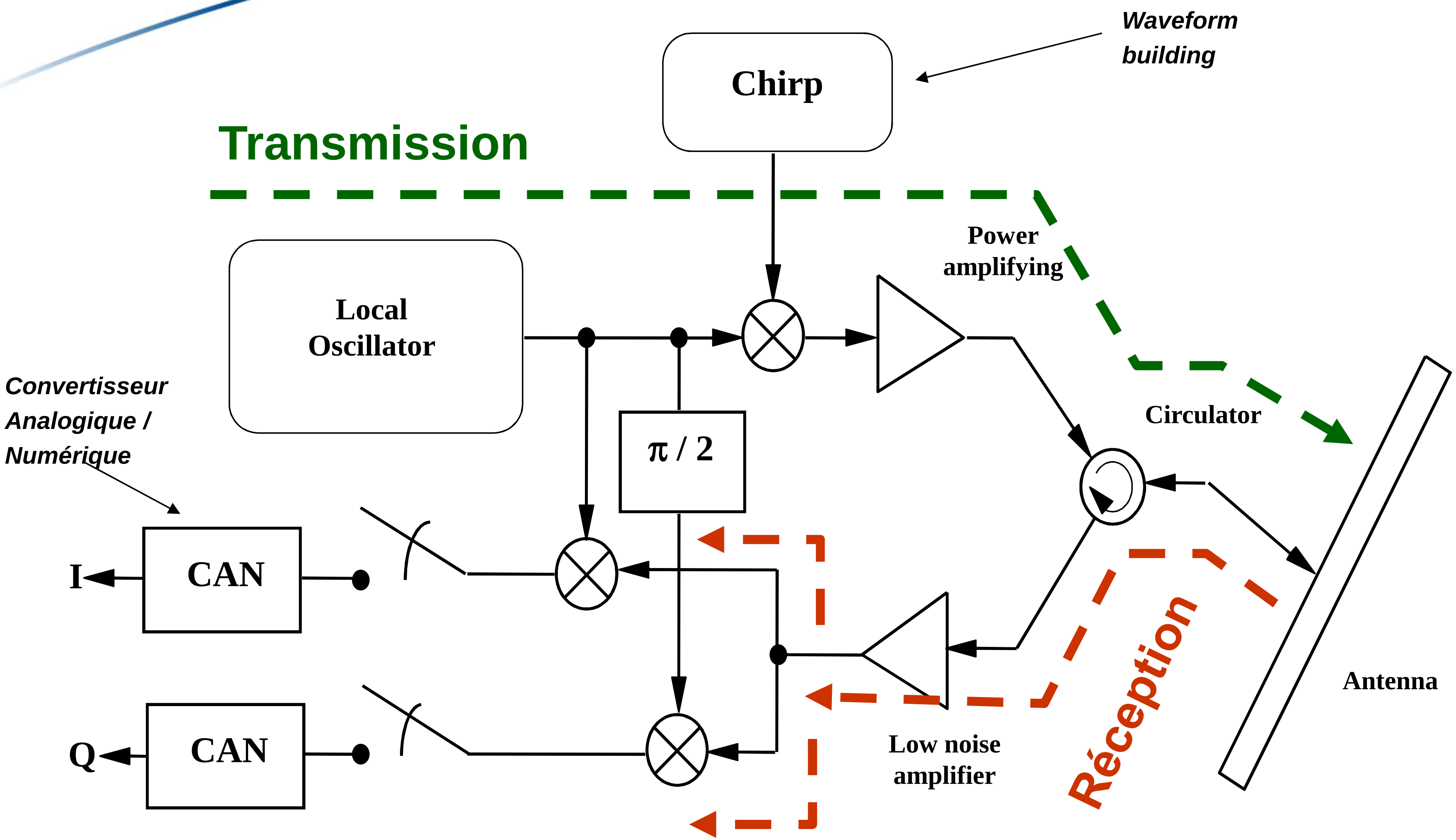
Architure altimètre

On the complex nature (amplitude, phase) of radar data

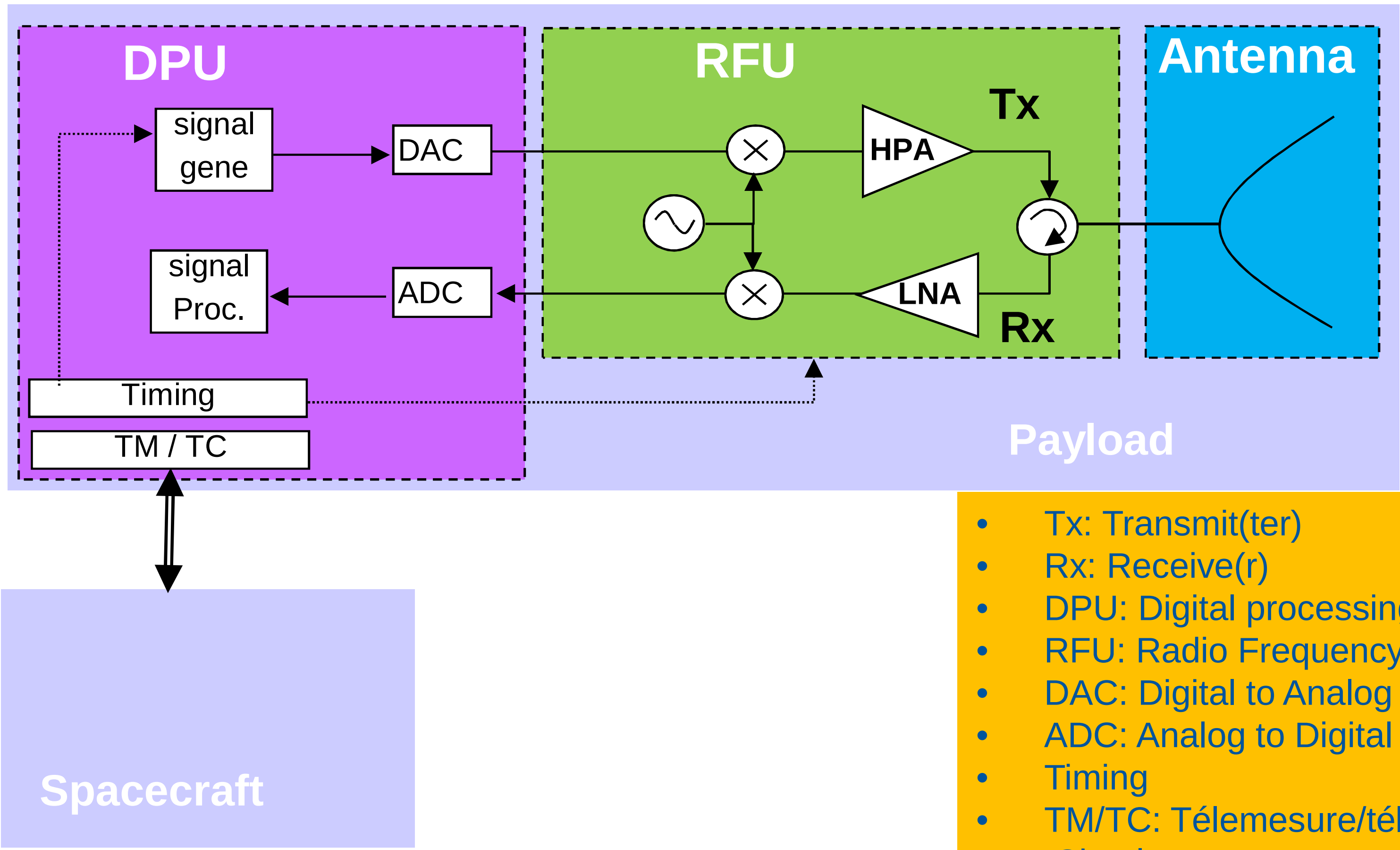


1 image pixel = I + j. Q (nombre complexe) = amplitude + phase

Nadir altimeter : Architecture principle

Three main subsystems

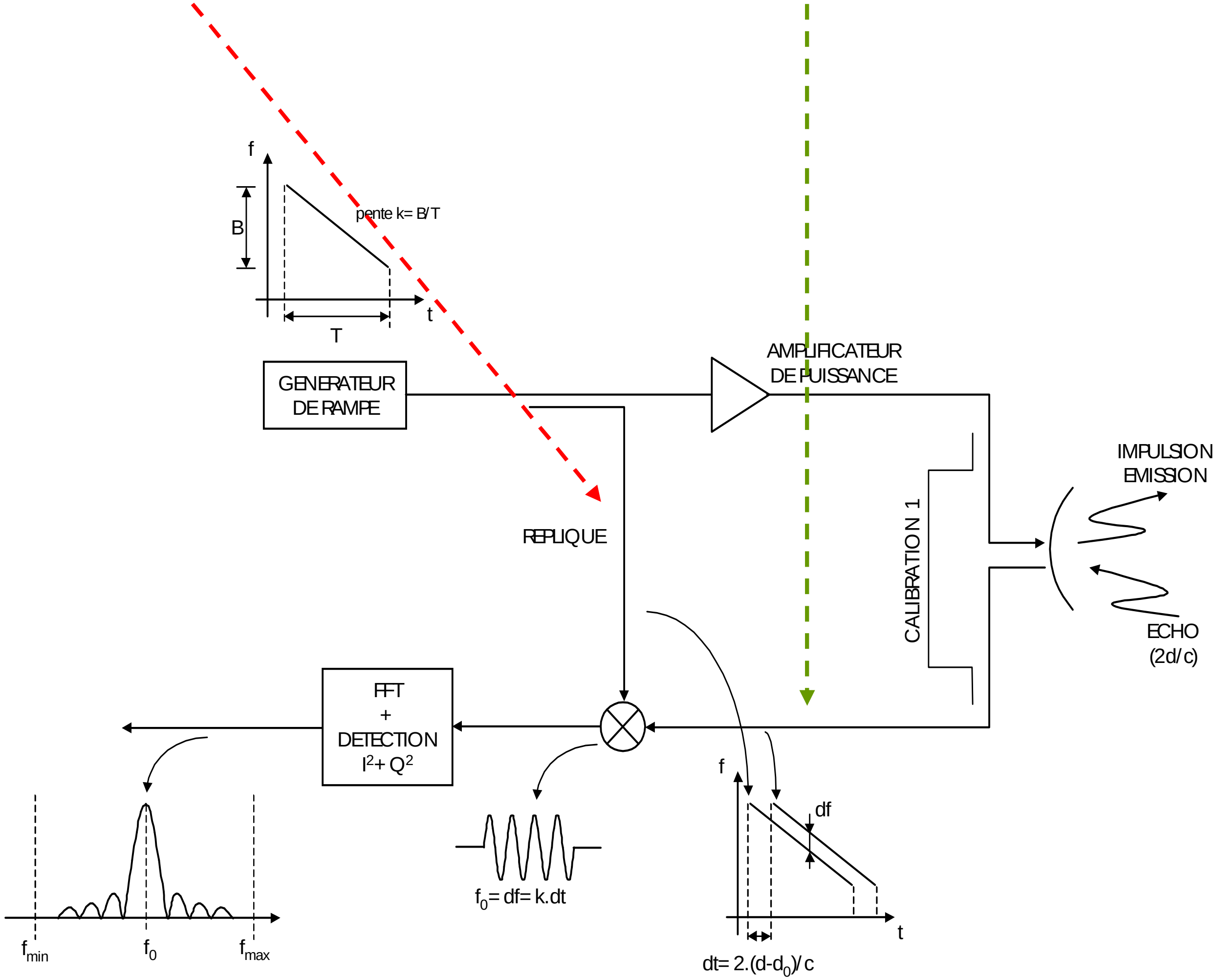
- Digital Power Unit
- Radio Frequency Unit
- Antenna subsystem



- Tx: Transmit(ter)
- Rx: Receive(r)
- DPU: Digital processing Unit
- RFU: Radio Frequency Unit
- DAC: Digital to Analog Converter
- ADC: Analog to Digital Converter
- Timing
- TM/TC: Télemesure/télécommande
- Circulator

Principe de fonctionnement POSEIDON-3

Technique de « Full Deramp » → Nécessite de synchroniser l'émission d'une réplique avec la réception de l'écho à quelques nanosecondes près



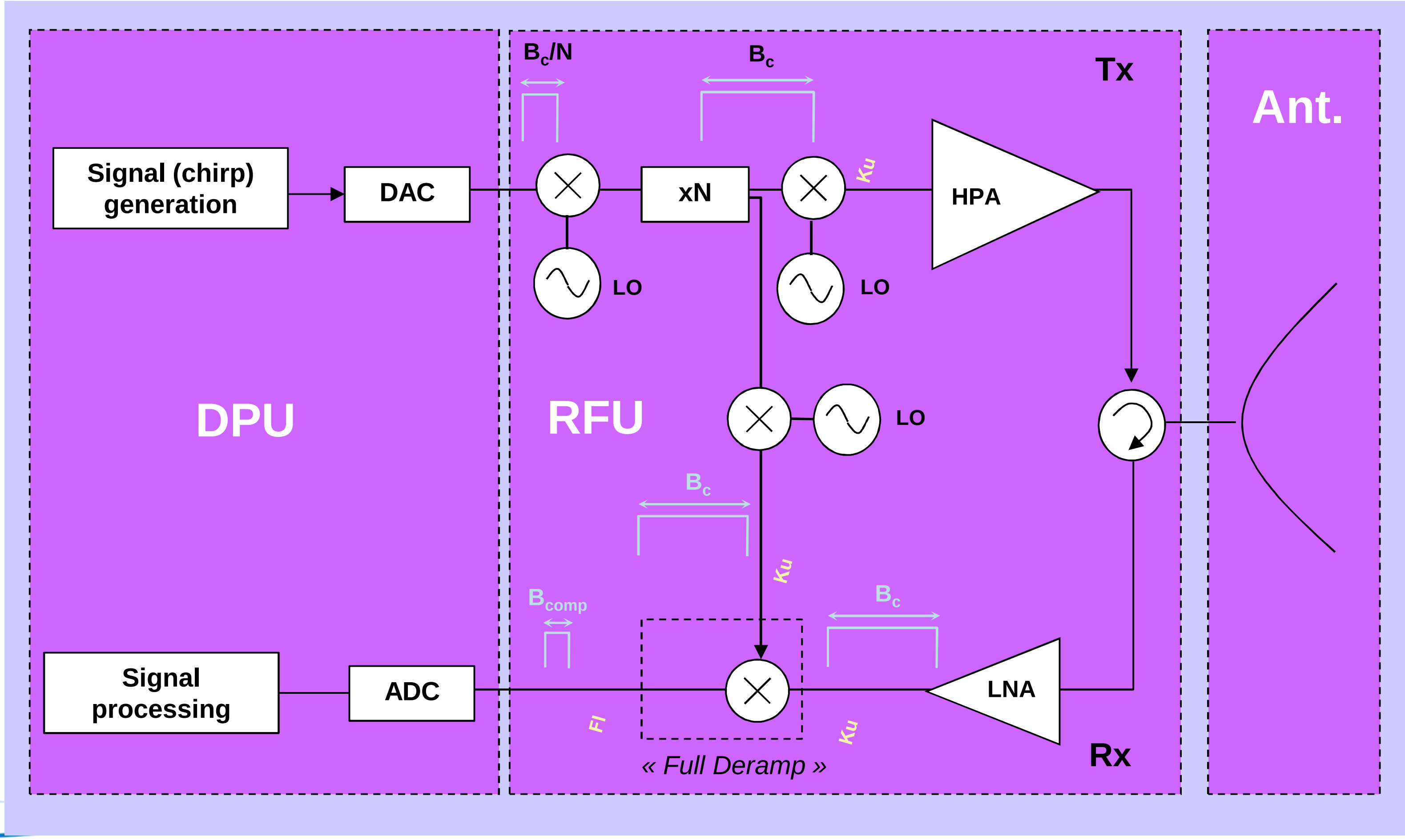
Bande passante : **320MHz**

→ résolution distance « instrument » : **0.47cm**

Altimétrie Nadir : Architecture traditionnelle, dite « analogique »

Architecture with

- Bandwidth extender
- Analog chirp compression
- Mixers
- LOs



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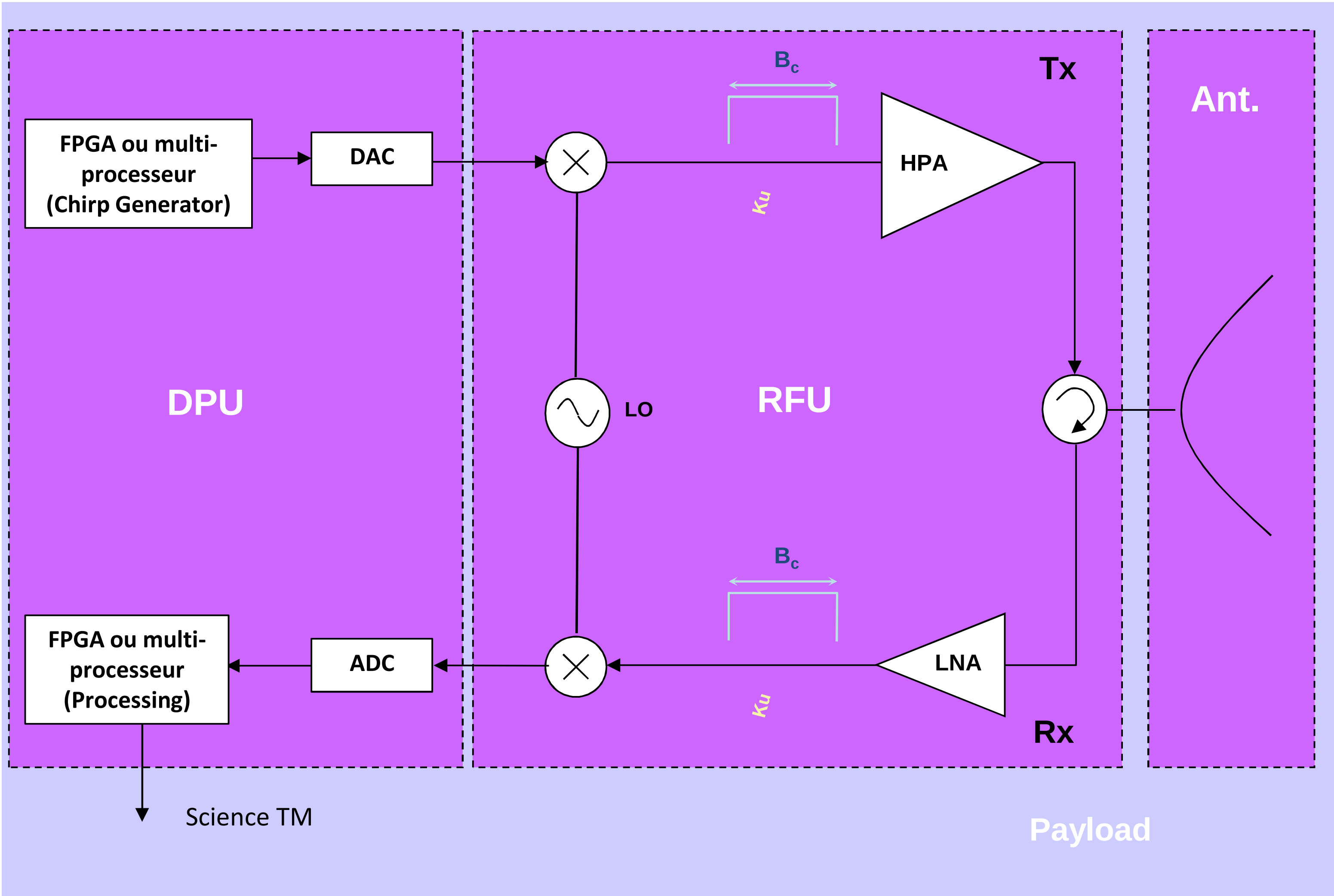
Altimétrie Nadir : Perspective de « passage au numérique »

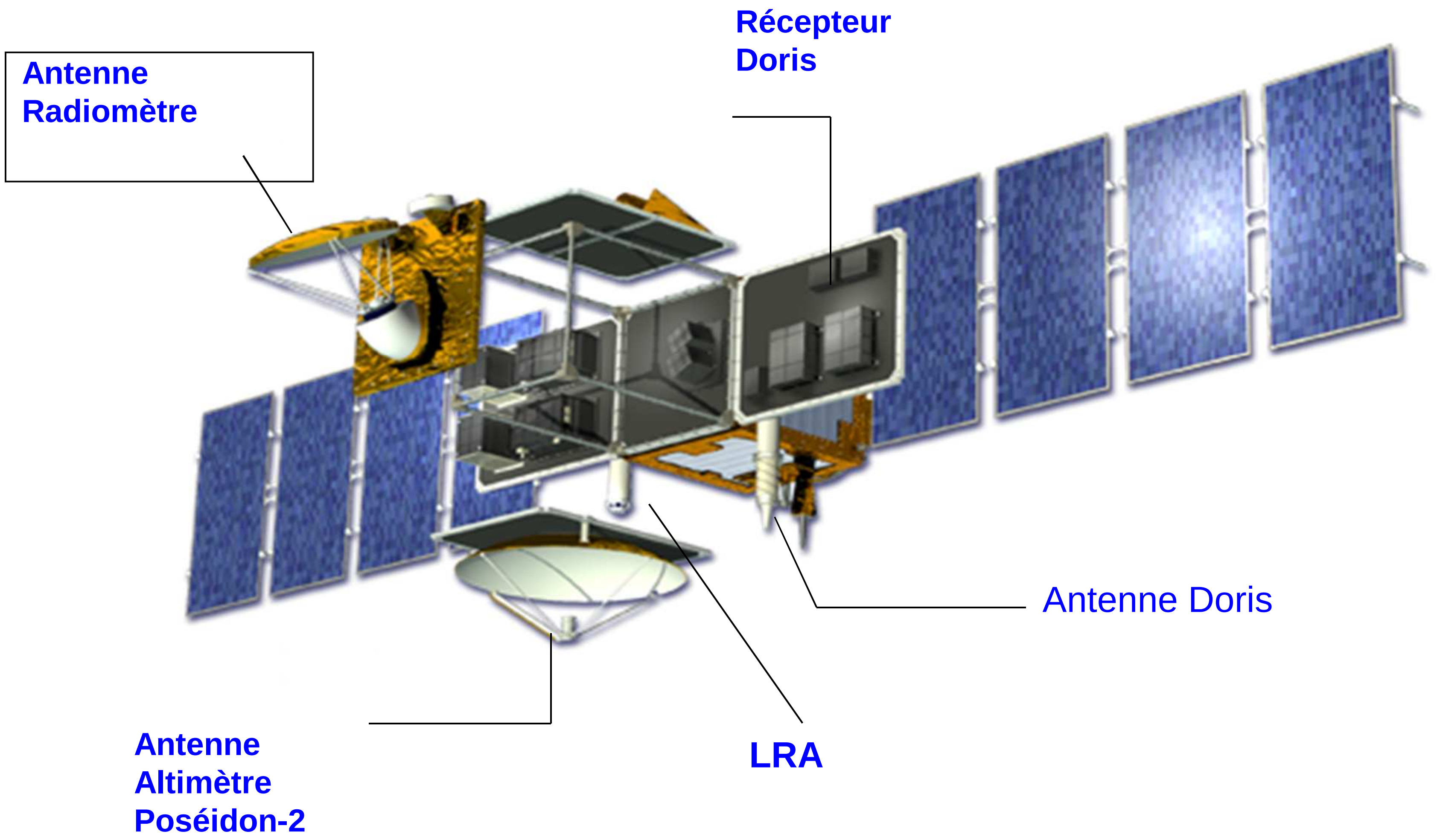


Architecture simplifiée pour futurs altimètres


Jason 3
2013
OSTM/Jason 2
2008
Jason 1
2001–Present
TOPEX/Poseidon
1992–2006

TTVS

JASON: éléments de la charge utile (ici Jason-1)



Poseïdon on JASON

Parameter	Poseidon2 / Jason1	
	Ku	C
Mean orbit altitude	1347 km	
Orbit inclination	66°	
Altimeter band	13.575 GHz	5.3 GHz
Pulse bandwidth	320 MHz	320 / 100 MHz
Altimeter PRF	1.8 kHz	300 Hz
Antenna aperture	1.3°	3.4°
Altimeter Link budget (req.)	10 dB	9 dB
Peak power	7 W	16 W
Vertical resolution	47 cm	
Pulse duration	110 µs	
Echo averaging (altimeter)	50 ms	
Spectrum analyser (altimeter)	128 points	
Antenna diameter	1.2 m	
Data rate	~ 20 kbits/s (compression)	
Mass	2 x 25 kg	
Power consumption	75 W (Ku + C)	

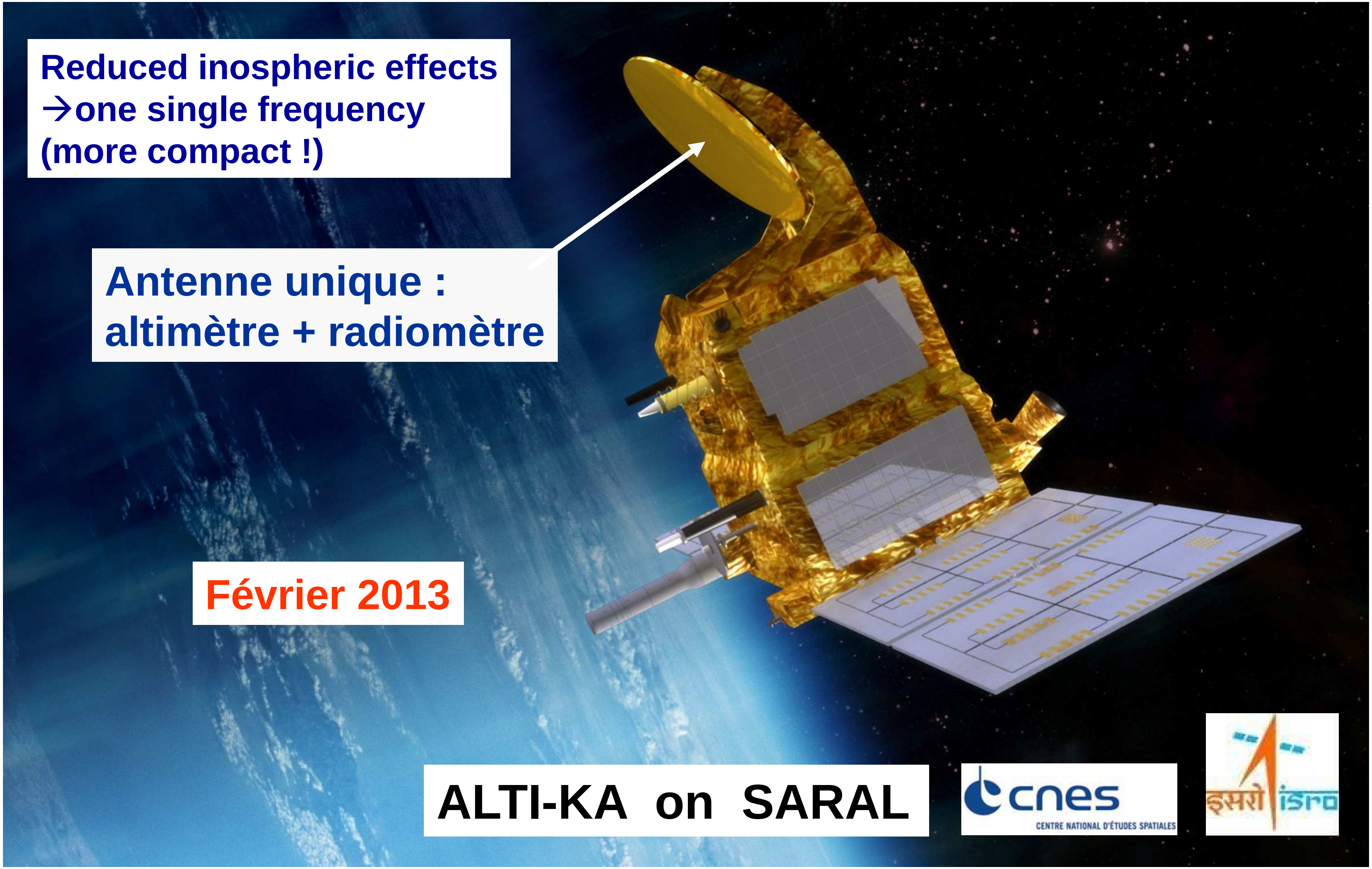
Jason-3

- LA mission de référence
  - ✦ Lancement : mars 2015
  - ✦ Coopération : CNES/NASA/NOAA/EUMETSAT
  - ✦ Orbite : 1336 km / 66° d'inclinaison / cycle de 10 jours / inter trace à l'équateur 300km

- Altimètre nadir conventionnel
  - ✦ Altimètre bande C/Ku POSEIDON-3B
  - ✦ Visée nadir
  - ✦ Une mesure tous les 300m (après intégration bord)
  - ✦ Précision altimétrique centimétrique (~1,4cm @1s)
  - ✦ Résolution spatiale de qques km² (principalement dans ~5km de diamètre pour swh=2m et tache antenne de ~30km de diamètre)
  - ✦ Débit de données faible **(37kb/s) compatible TM bande L**
  - ✦ Instrument (hors antenne) très compact et peu consommant

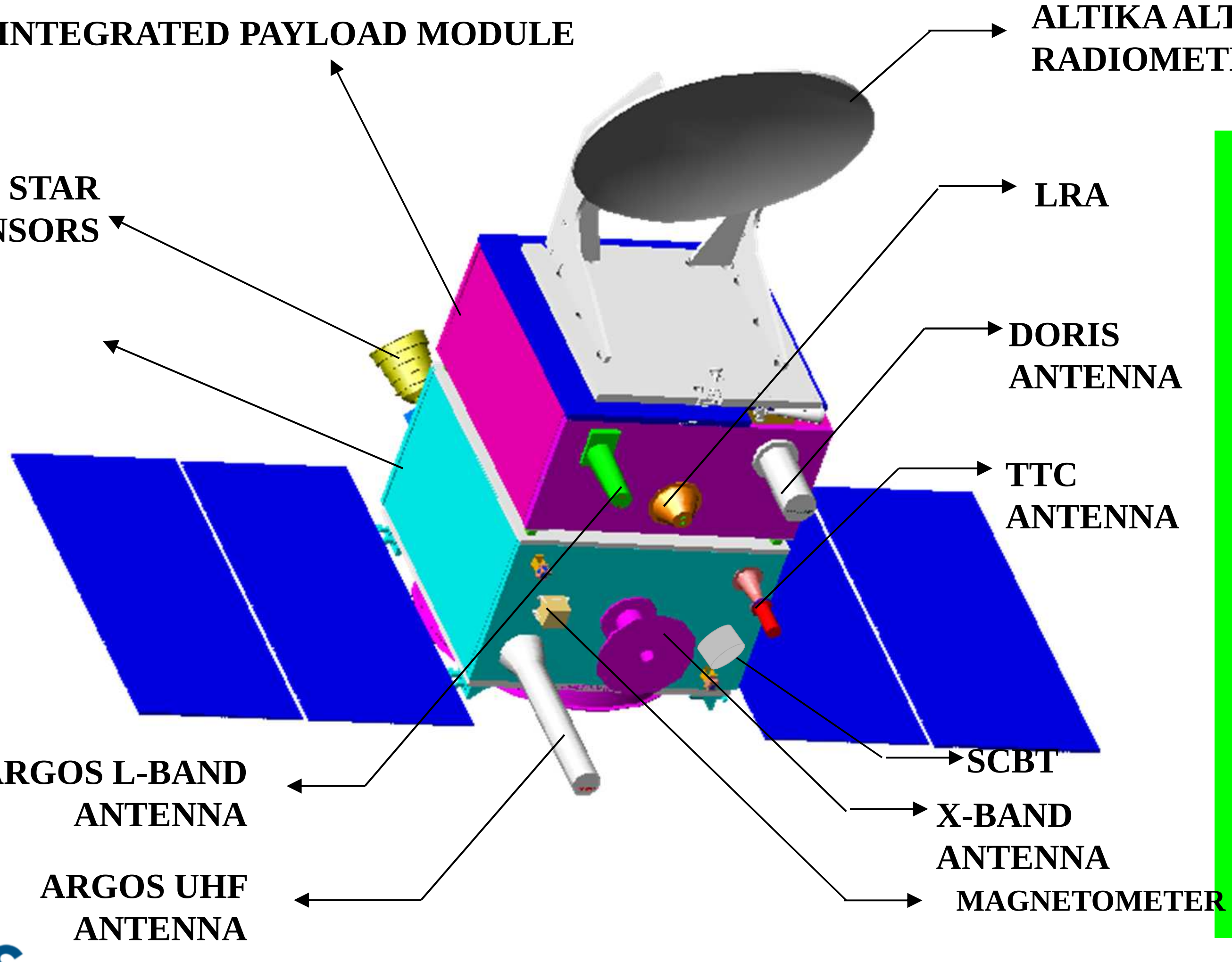
    Masse ~20kg par chaine / conso : ~70W
  - ✦ Antenne: diamètre 1.2m, masse : ~7kg

From Nadir Ku/C to Ka (35 GHZ) : AltiKa - 2011



AltiKa & Argos-3 payloads accommodation on SSB platform : SARAL satellite

AltiKa : Mass = 39 kg, typical consumption = 73 W



SARAL sat. characteristics

 # Mass : 408.6 kg – Dec '12

- SSB platform : 244.8kg
- Payload Module : 163.8 kg

404.916 kg – April '13

 # Power : 570 W (end of life)

- SSB platform : ~ 205 W
- Payload Module: 250 w (peak consumption < 300 W)

 # Size

- ~ 1m x ~1m x 2.7 m
- Solar panels : 1.2m x 1.6m (x2)

Ka band altimetry : AltiKa

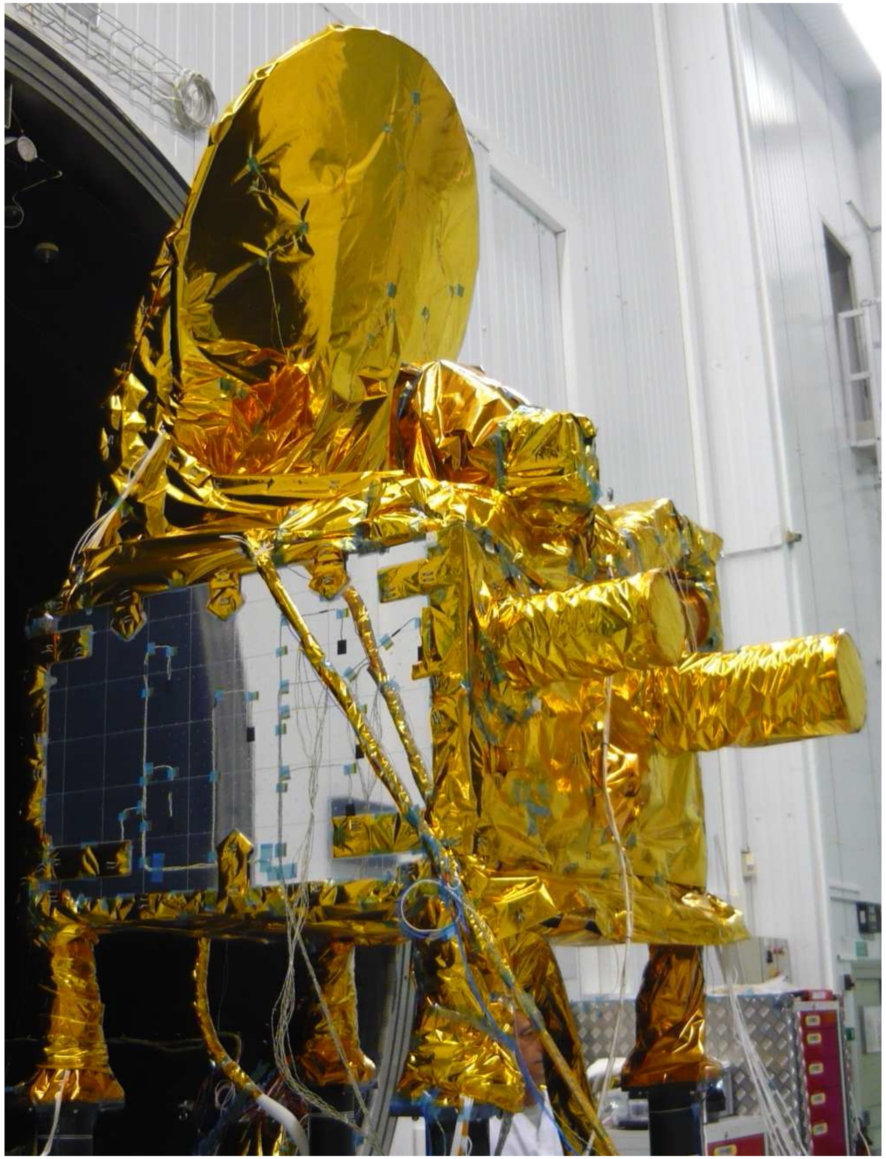
- **Ka-band altimeter**

  - **Developed by Thales Alenia Space- FRANCE (delivery and full validation : 12/09)**
  - **Improved spatial resolution (30 km → 8 km)**
  - **480 MHz bandwidth (improved vertical resolution (~ 30 cm w.r.t. 47cm for J2, 320 MHz)**
  - **Limitations : atmospheric water content (Data loss between 3% and 10%)**

- **Dual-frequency radiometer**

  - **Shares the altimeter Digital Processing Unit and antenna *(compact)***

23.8 GHz +/- 200 MHz & 37 GHz +/- 500 MHz



Performances en vol AltiKa

96 % - 0.1% - 0.9 cm – 0.15 K

- **Acquisition altimètre (mode principal) : 96 % du temps toutes surfaces**
  (recherche de l'écho + temps d'étalonnage < 4%)

- **Perte des données liées à pluie sur océan < 0.1% !**
  (pire cas estimé avant lancement entre **3%** et **10%**)

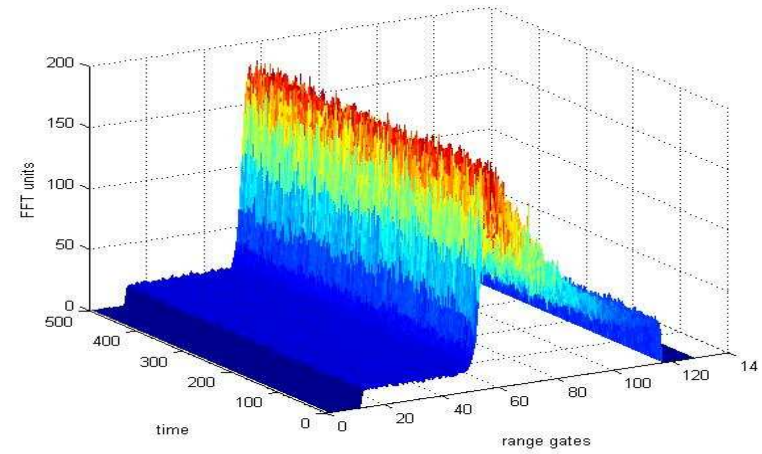
- **Bruit de mesure altimètre pour état de mer standard (2 m) : 0.9 cm**

- **Sensibilité radiomètre (correction troposphérique) : ~ 0.15 K**

Courtesy Nathalie Steunou

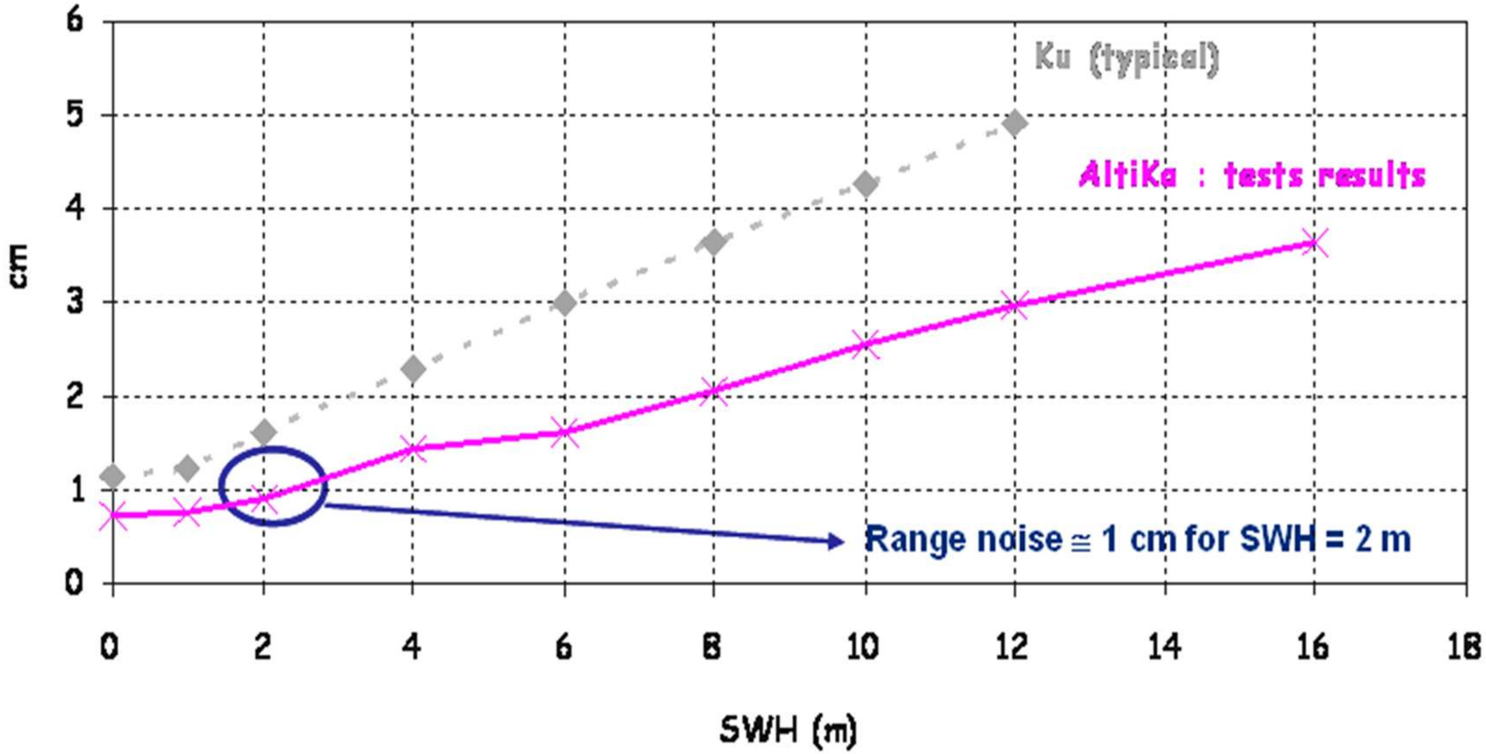
Ka band altimetry : AltiKa

→ Altimeter performances



AltiKa waveforms

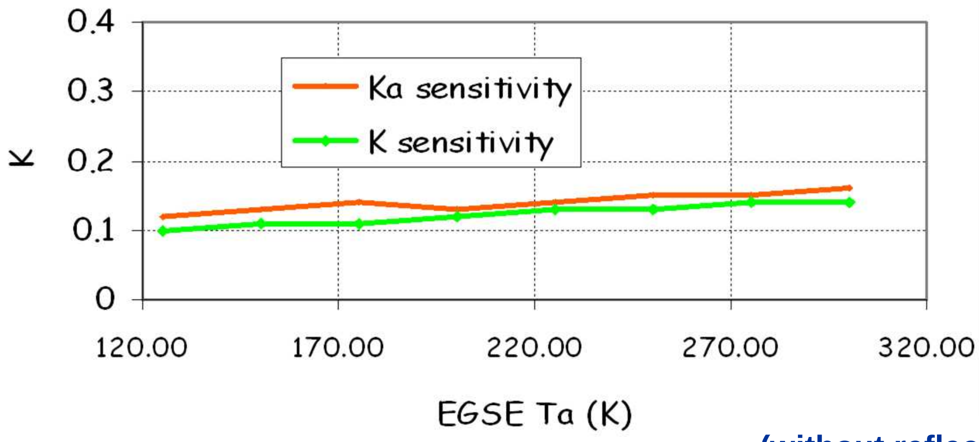
Range noise (1 s) : < 1cm for SWH=2m



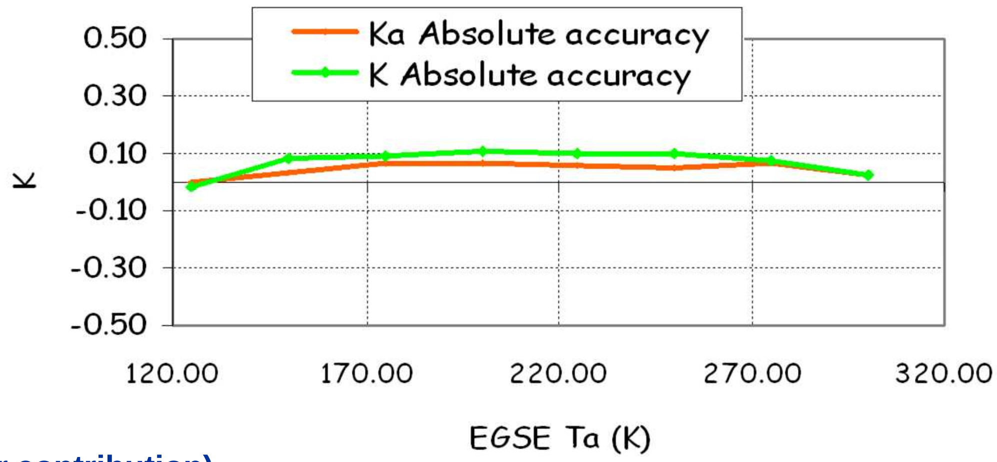
Ka band altimetry : AltiKa

→ Radiometer performances (AIT)

Sensitivity (20°) **0.12 K**



Absolute accuracy (20°) **0.1 K**



(without reflector contribution)

* **Worst case sensitivity : 0.2 K (spec 0.4 K in Ka , 0.3 K in K)** **(0°C, 20°C and 40°C)**

* **Worst case absolute accuracy : < 1.3 K (spec. 3 K)**

AltiKa vs. JASON-2

	AltiKa	Jason-2 (Ku)
Frequency	35.75 GHz	13.575 GHz
Bandwitdh	480 MHz	320 MHz
PRF	~4 KHz (variable)	2 KHz
Antenna Beam / footprint	0.6° / 5.7 km	1.29° / 9.6 km
WF rate	40 Hz	20 Hz

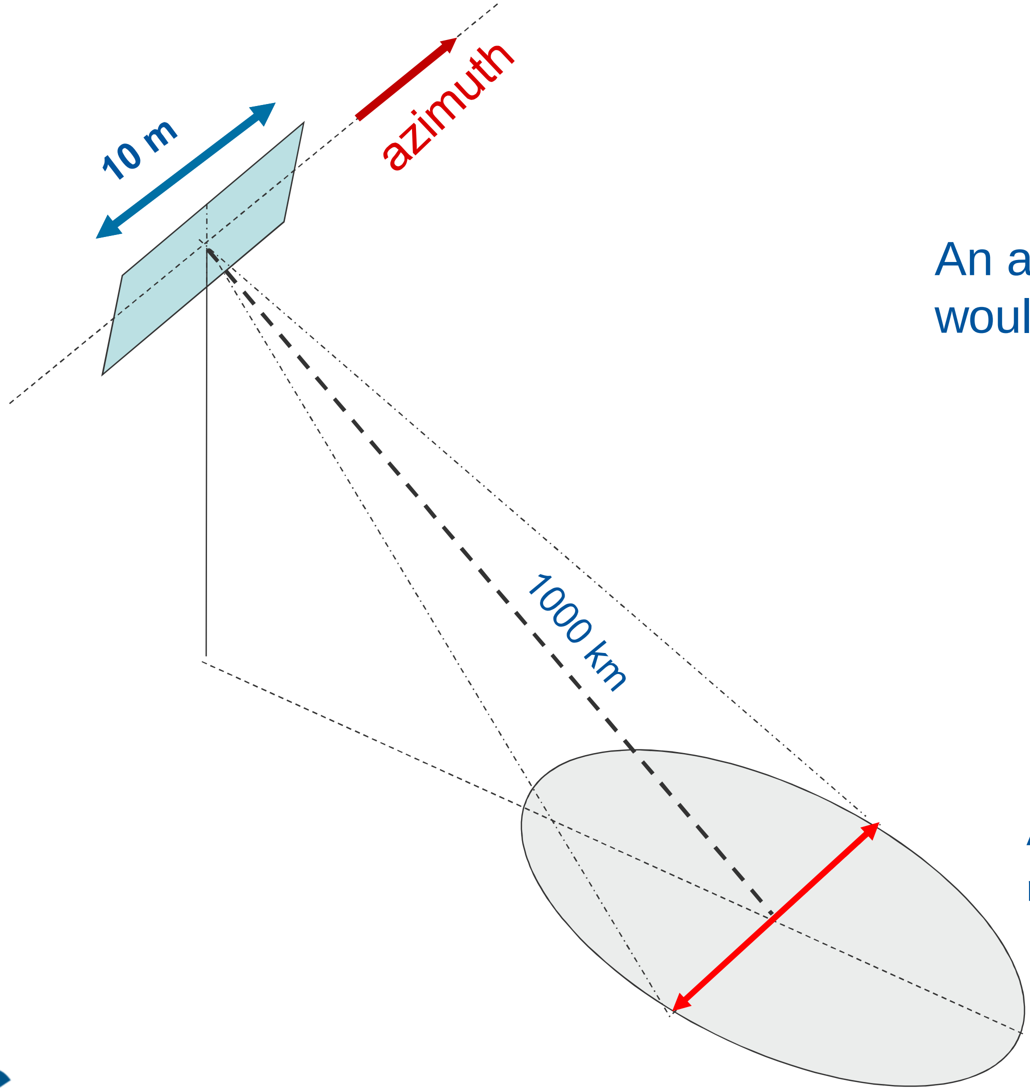
Doppler analysis : a step forward for nadir altimetry

(inspired from SAR imagery …)

Imaging radar geometry : azimuth resolution

- Reminder on antenna scattering
- A wider antenna provides a better resolution

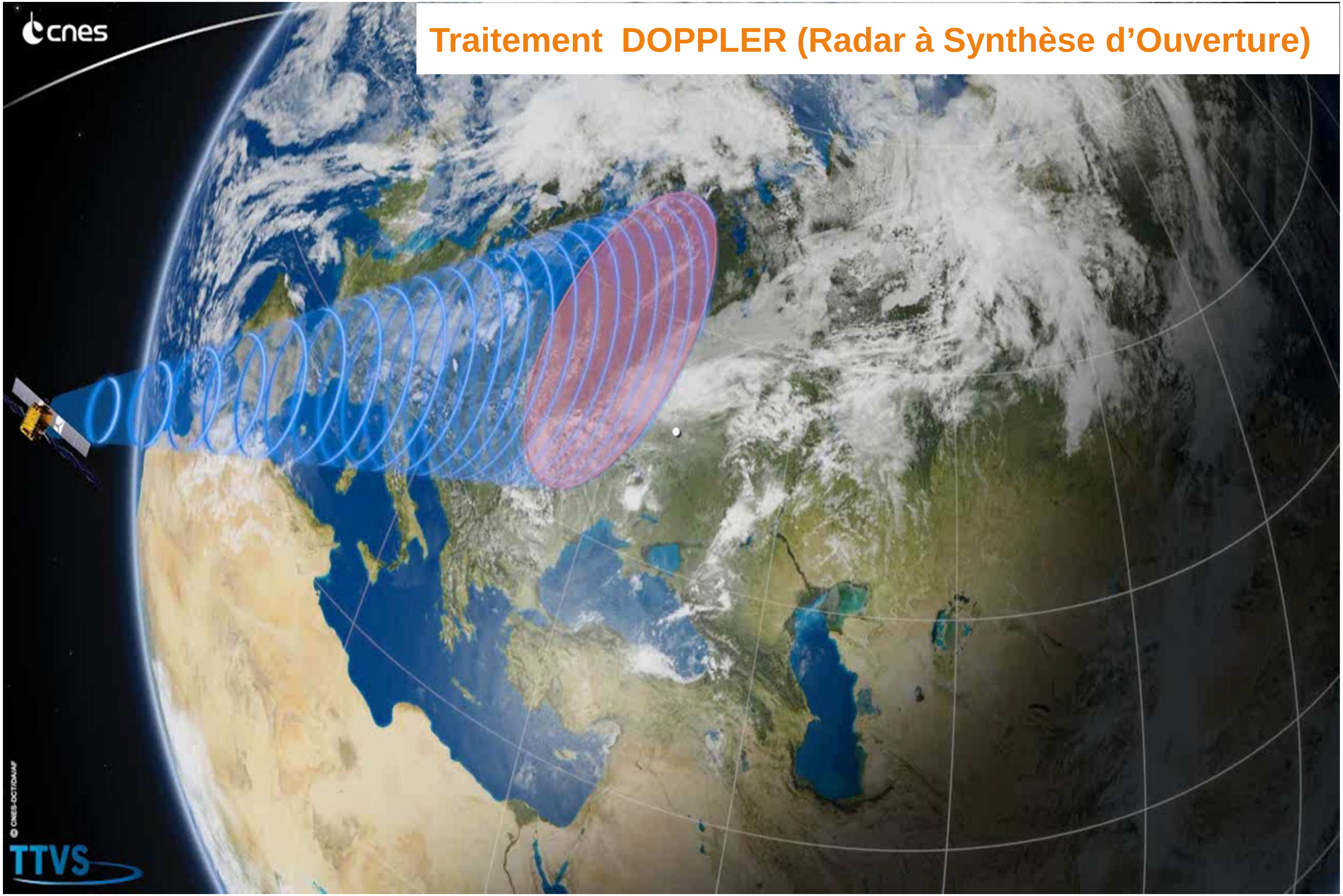
Imaging radar geometry (side-looking): azimuth resolution



An azimuth resolution of 5.6 m would require a 10 km antenna !!

Azimuth resolution = 5600 m @ C band (5.3 GHz)

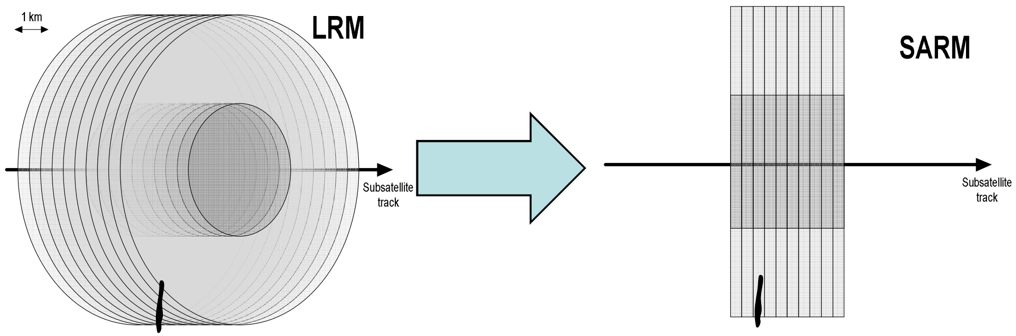
Traitement DOPPLER (Radar à Synthèse d’Ouverture)



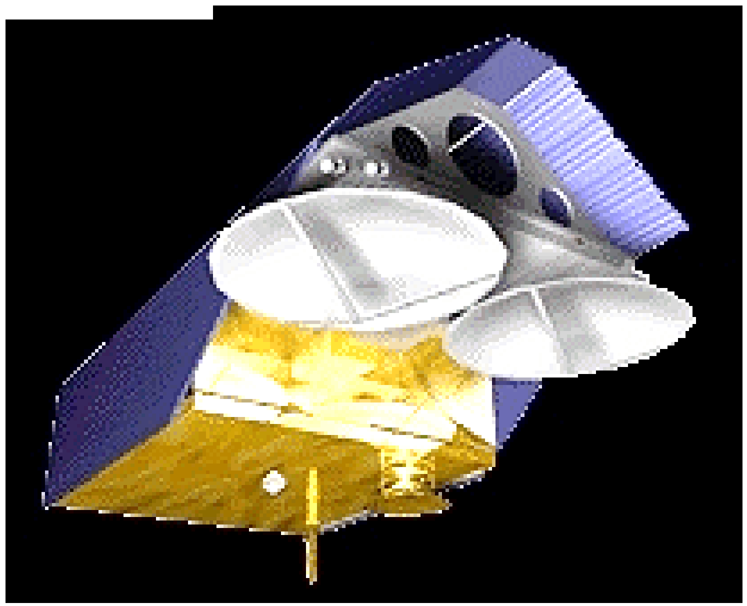
Nadir SAR altimetry

Doppler altimetry : to improve the spatial resolution

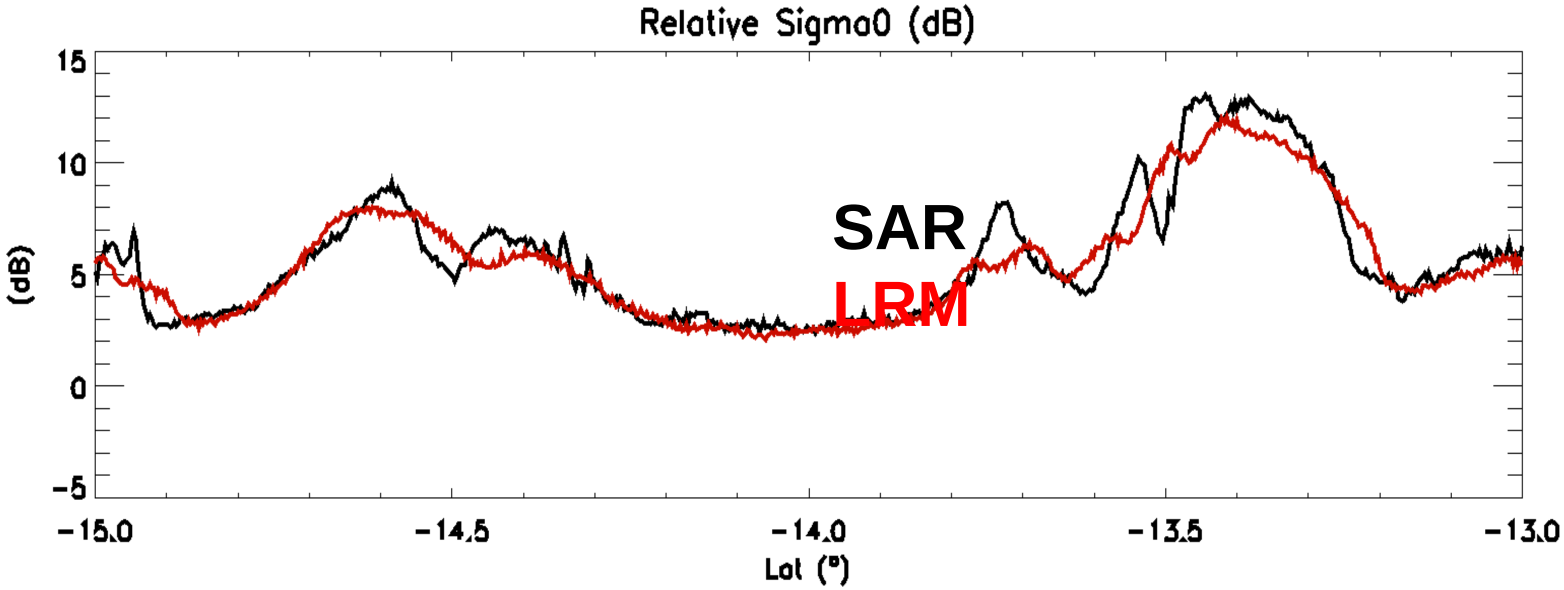
- Close to SAR techniques (imaging radar)
- Nadir pointing + bursts emission
  - Resolution cells = Range / Doppler grid. Resolution 150 – 300 m



- Used in Cryosat 2 ESA mission



Nadir SAR altimetry : comparaison traitement Doppler vs. traitement LRM



CNES : première mondiale dans le traitement de masse des échos Doppler NADIR (CRYOSAT) et inter-calibration avec traitement LRM de référence (« pseudo-LRM ») – F. Boy / N. Picot

TTVS

SENTINEL-3 (Ku/C), 2013
(participation programme ESA)

Sentinel-3

- Programme GMES/Copernicus
  - Lancement : 2015
  - Projet ESA (avec support du CNES sur l'altimétrie)
  - Orbite : 800 km / 98.6° d'inclinaison (héliosynchrone) / cycle de 27 jours / inter trace à l'équateur 104km

- Altimètre nadir avec mode « SAR burst »
  - Altimètre bande C/Ku SRAL
  - Visée nadir
  - Fréquence d'émission des impulsions ~18kHz, réception d'un burst avant émission du burst suivant
  - Traitement des échos avec une synthèse SAR en azimut (synthèse Doppler)
  - Précision altimétrique centimétrique (~1cm @1s en SAR)
  - Résolution azimut de ~300m avec la synthèse Doppler
  - Débit de données élevé **(12Mb/s en mode SAR) nécessite TM bande X**
  - Instrument (hors antenne) compact et peu consommant

    Masse ~25kg par chaine / conso : ~85W
  - Antenne de 1m

Jason-CS / Sentinel6

- Continuité de la série des missions de référence
  - Lancement : 2020
  - Coopération : ESA/NOAA/EUMETSAT + NASA en sous traitance NOAA + support CNES
  - Orbite : 1336 km / 66° d'inclinaison / cycle de 10 jours / inter trace à l'équateur 300km

- Altimètre nadir avec mode « SAR interleaved »
  - Altimètre bande C/Ku POSEIDON-4
  - Visée nadir
  - Fréquence d'émission des impulsions plus élevée (9kHz contre 2kHz précédemment)
  - Possibilité de traiter les échos simultanément de manière conventionnelle (LRM) ou avec un traitement SAR en azimut
  - Précision altimétrique centimétrique (<0,7cm @1s en SAR)
  - Résolution azimut de~300m avec la synthèse SAR
  - Débit de données élevé **(~38Mb/s ou ~20Mb/s avec compression RMC): nécessite TM bande X**
  - Instrument (hors antenne) compact et peu consommant

    Masse ~25kg par chaine / conso : ~110W
  - Antenne : diamètre 1.2m, masse : ~7kg

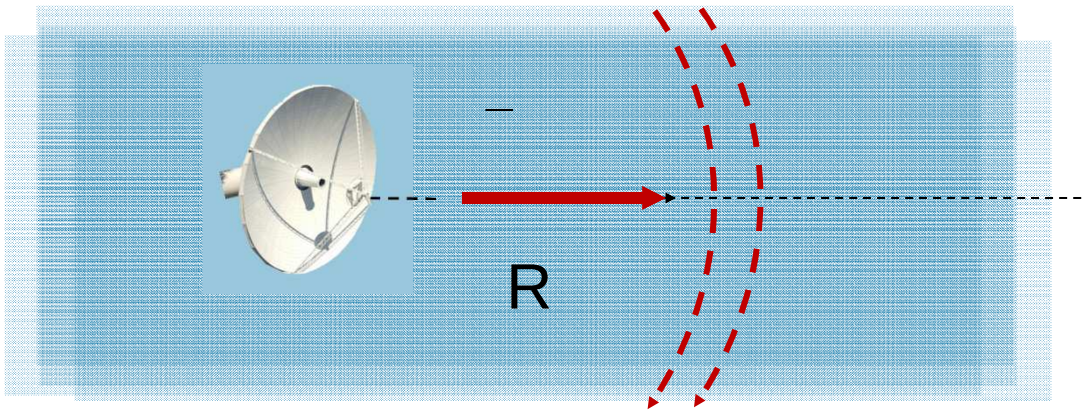
ANNEXES / SUJETS NON ABORDES

* **Active Sounding (radar equation)**

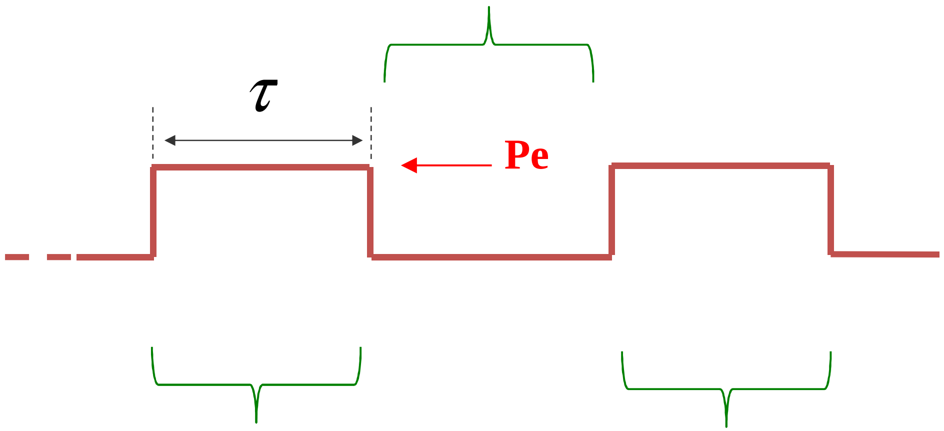
* **Physics of passive radiometry**

Active Sounding (radar equation)

Active Sounding (pulse radar)



Coherent illumination



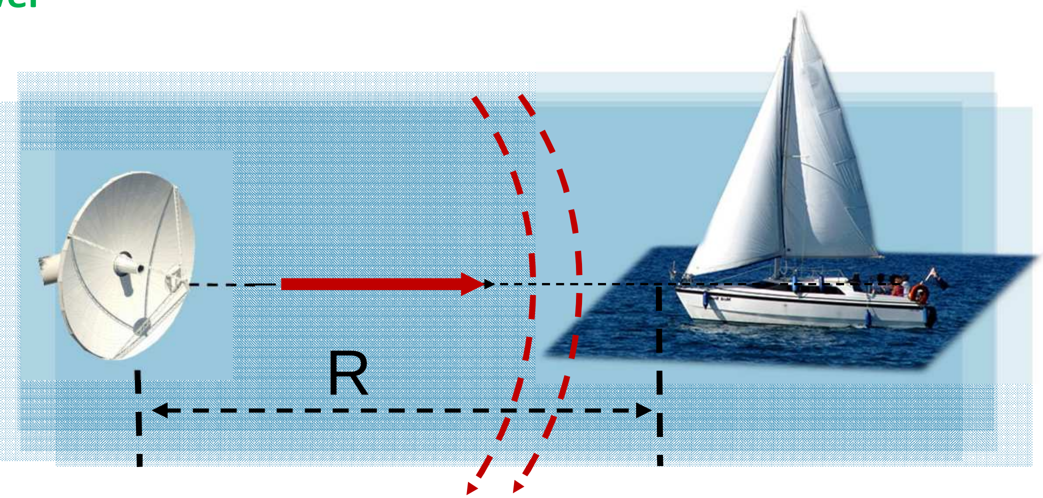
Active Sounding : radar equation (1/4)

- Transmission :
  - Radar transmits a pulse, peak power P_e, antenna gain G_e, range R →
  - Target is illuminated by a power density (in W/m²) :

Peak power

$$dP^{inc} = \frac{P_e \cdot G_e}{4 \cdot \pi \cdot R^2}$$

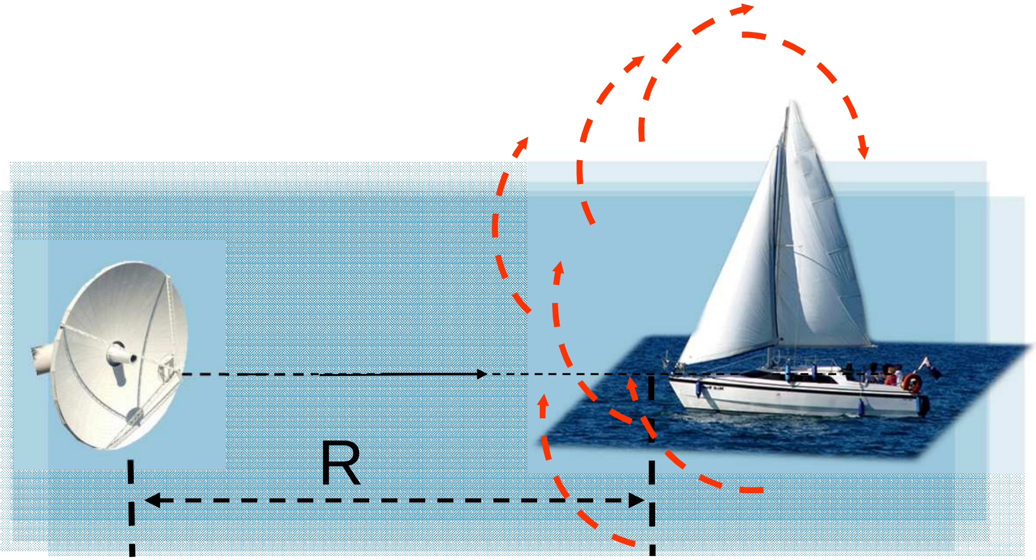
Transmitted power density (in W/m²)



Active Sounding : radar equation (2/4)

- Wave target interaction

$$dP^{s} = dP^{inc} \cdot \frac{\sigma}{4 \cdot \pi \cdot R^2}$$



Active Sounding : radar equation (3/4)

- Reception

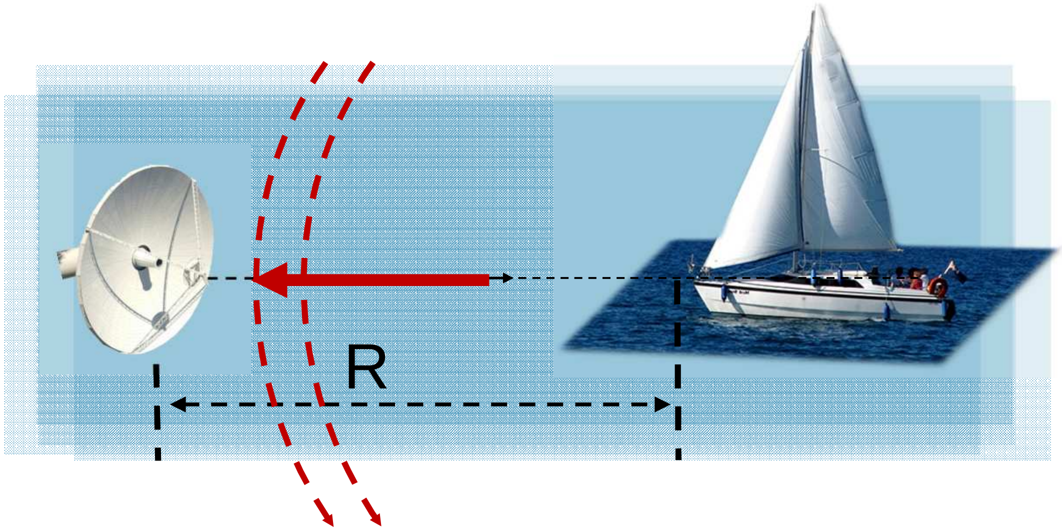
$$P^{rec} = dP^{s} \cdot A_{eff}$$

A_{eff} = Effective surface of the receiving antenna with:

$$A_{eff} = \frac{\lambda^2}{4\pi} \cdot G_r$$

Effective surface

Antenna gain



Active Sounding : radar equation (4/4)

Radar Cross Section (SER)
in m²

$$P^{rec} = P_e \cdot \frac{\lambda^2}{(4\pi)^3} \cdot \frac{G_e \cdot G_r}{R^4} \cdot \sigma$$

Variation in
en λ^2 / R^4

Rem : R = 1000 km
$1/R^4 = 10^{-24}$ …

Bd X, Pe= 1 W, σ= 1m², Pr=10^{-21} W

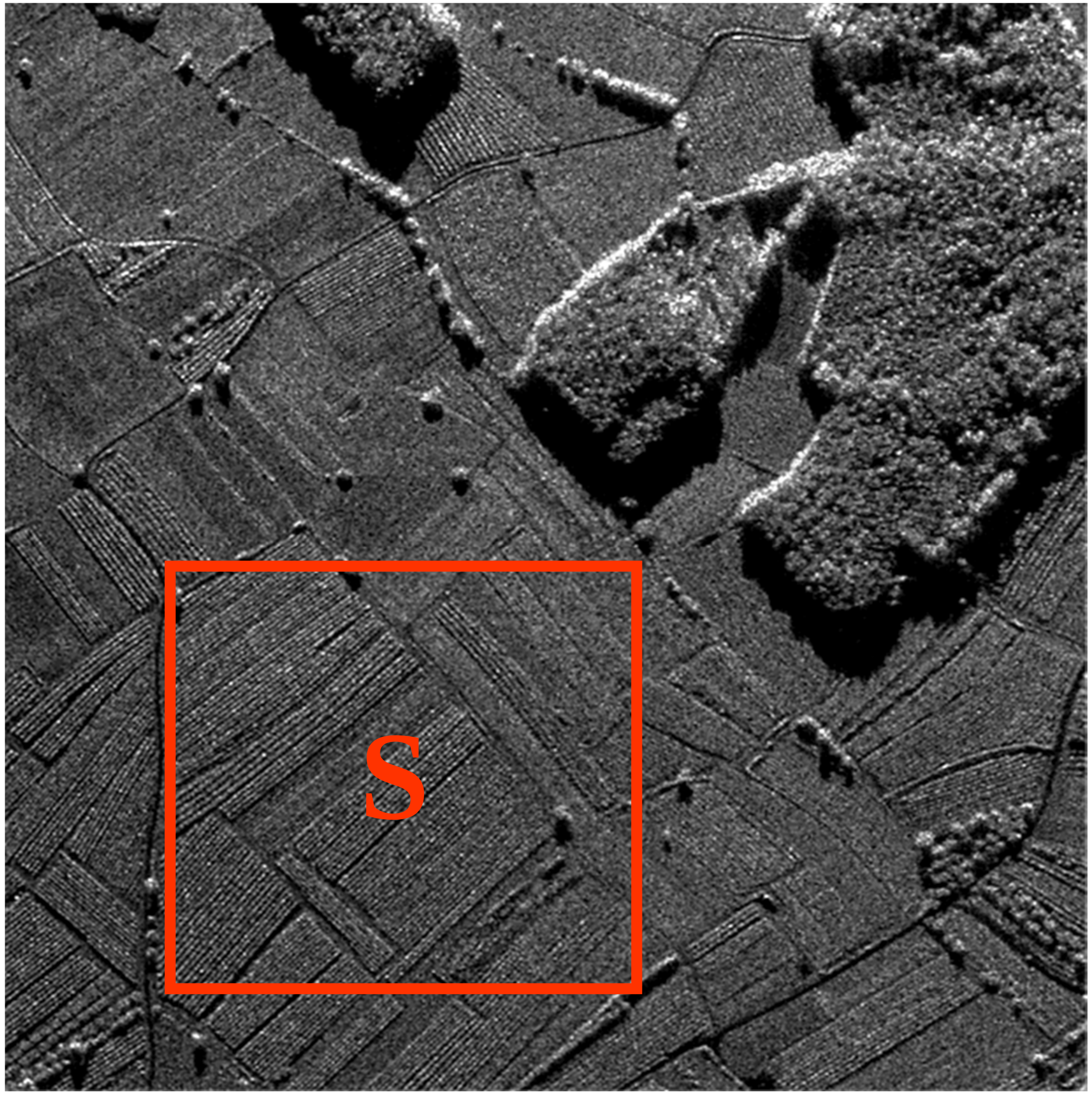
Active Sounding : Radar Cross Section (R.C.S)
➔ Distributed target

m²

$$\sigma^0(dB) = 10 \cdot \log_{10}\left(\underbrace{\sigma / S}\right)$$

m²/m²

dBm²/m²

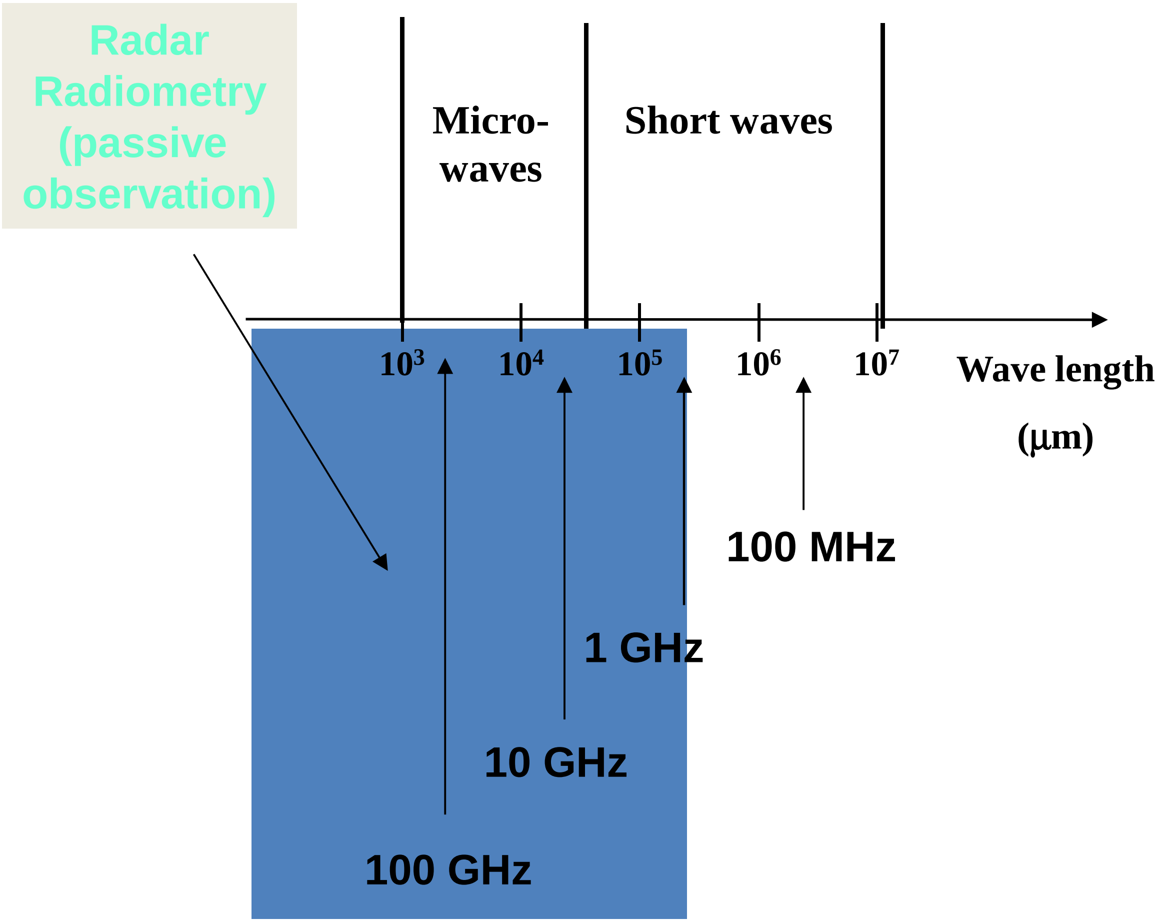


Passive radiometry

SMOS, MEGHA-TROPIQUES …

Abordé cet après-midi

Passive Radiometry



(SMOS : launch / Nov. 2, 2009)

(de 1.25 GHz à > 200 GHz

Passive radiometry Physics

- … On the natural production of electromagnetic scattering

- In low density environment :

- ➔ Atomic or molecular state change generates photons : $E = h \cdot \nu$
- ➔ Generation of an emission line spectrum

single frequency

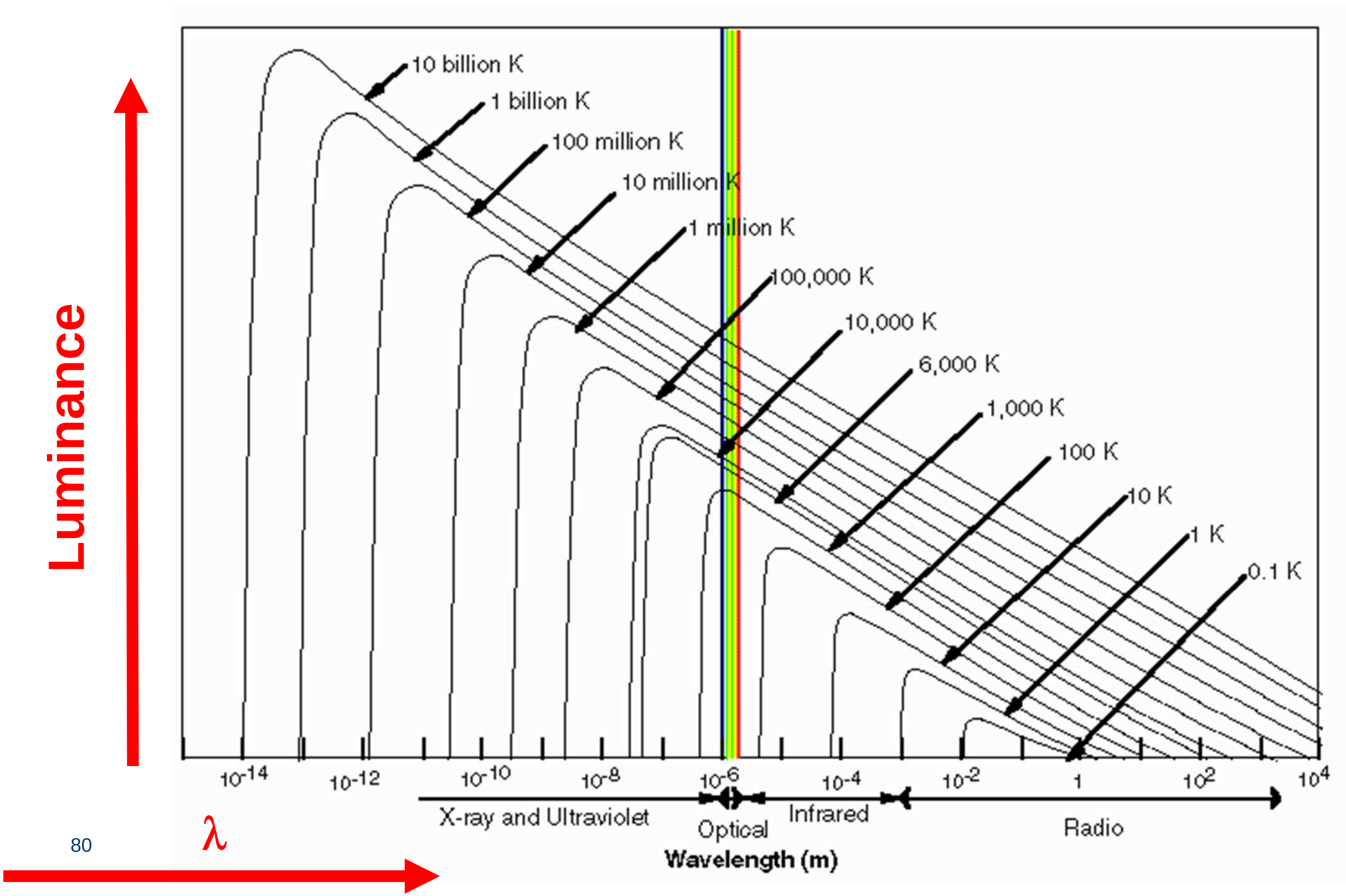
- **In complex and high density environment:**

➔ **Continuous emission spectrum related to the temperature of the observed medium**

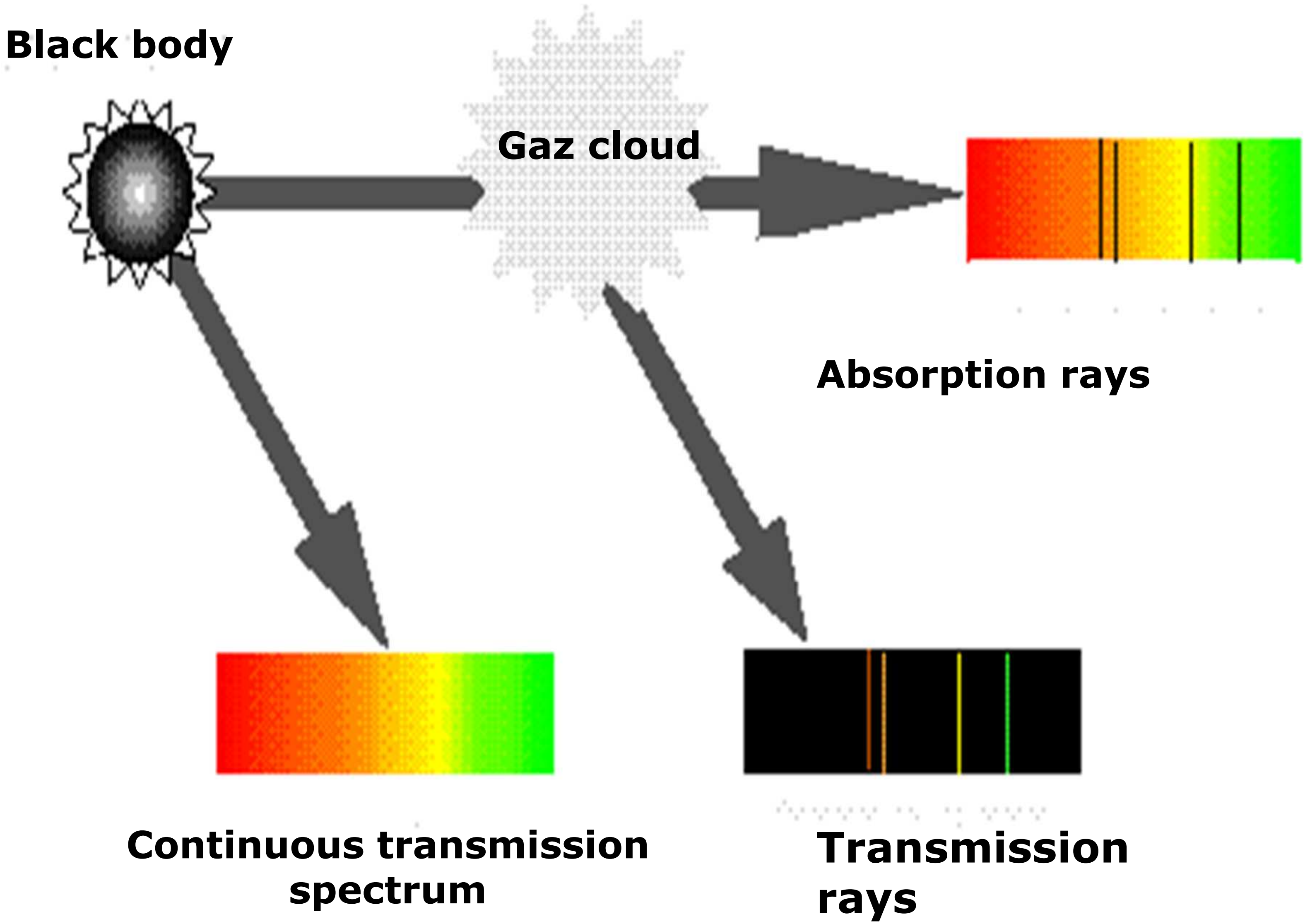
➔ **Higher the physical T° of the body, more energy around short wavelengths is emitted**

➔ **Planck law for the spectral brightness**

Passive radiometry Physics : Planck law



Passive radiometry Physics : KIRCHOFF law



Passive radiometry Physics

After integration on θ, ϕ

Pa = power collected by the antenna

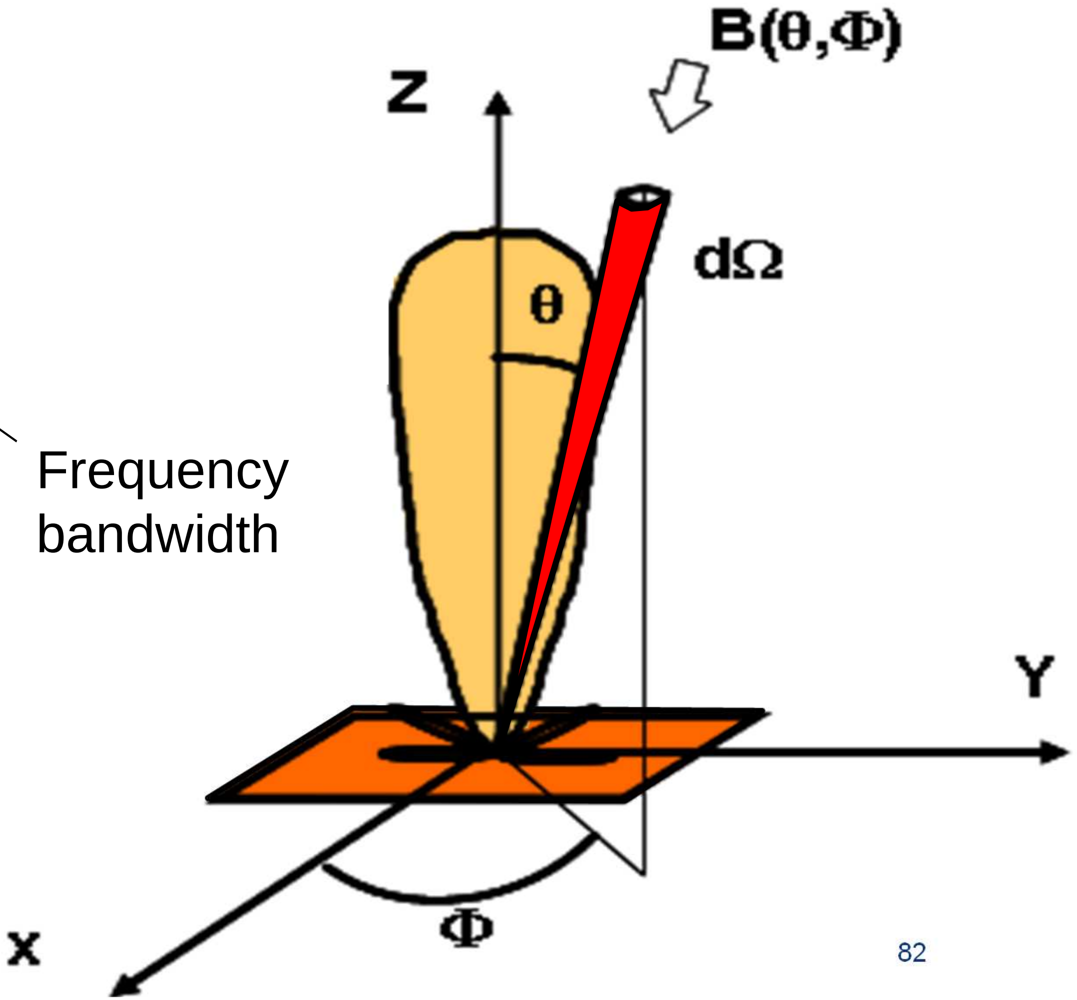
➔ $Pa = k.T_B.\Delta f$

Boltzmann constant

Frequency bandwidth

Brightness temperature

E.M scattering propagating from (θ, ϕ) direction



Passive radiometry Physics

$$Pa = k.T_B.\Delta f$$

Boltzmann constant

Brightness temperature

Frequency bandwidth

$$T_B = \varepsilon.T$$

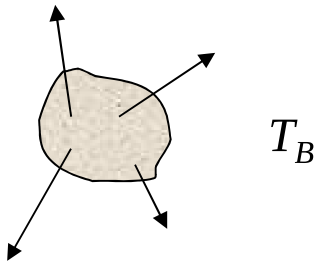
$\varepsilon < 1$
$\varepsilon = 1$ for black body

Emissivité

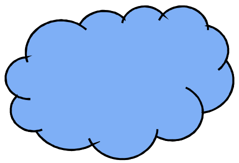
Température physique

ε depends physical properties of the body, frequency, incidence angle, polarisation …

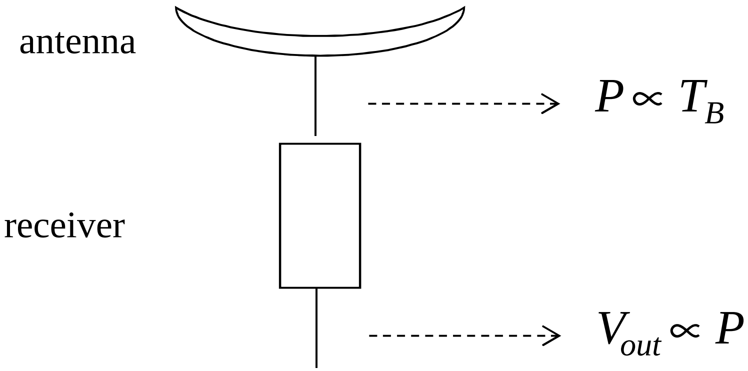
Passive radiometry Physics



Planck's law — **Natural scattering**



Kirchoff's laws — **Filtering**



Noise detection — **Noise (??)**

Noise conversion — **signal**