Altimétrie spatiale

PART II : Vers l'altimétrie de nouvelle génération : du LRM au SAR, altimétrie large fauchée et diffusiométrie radar

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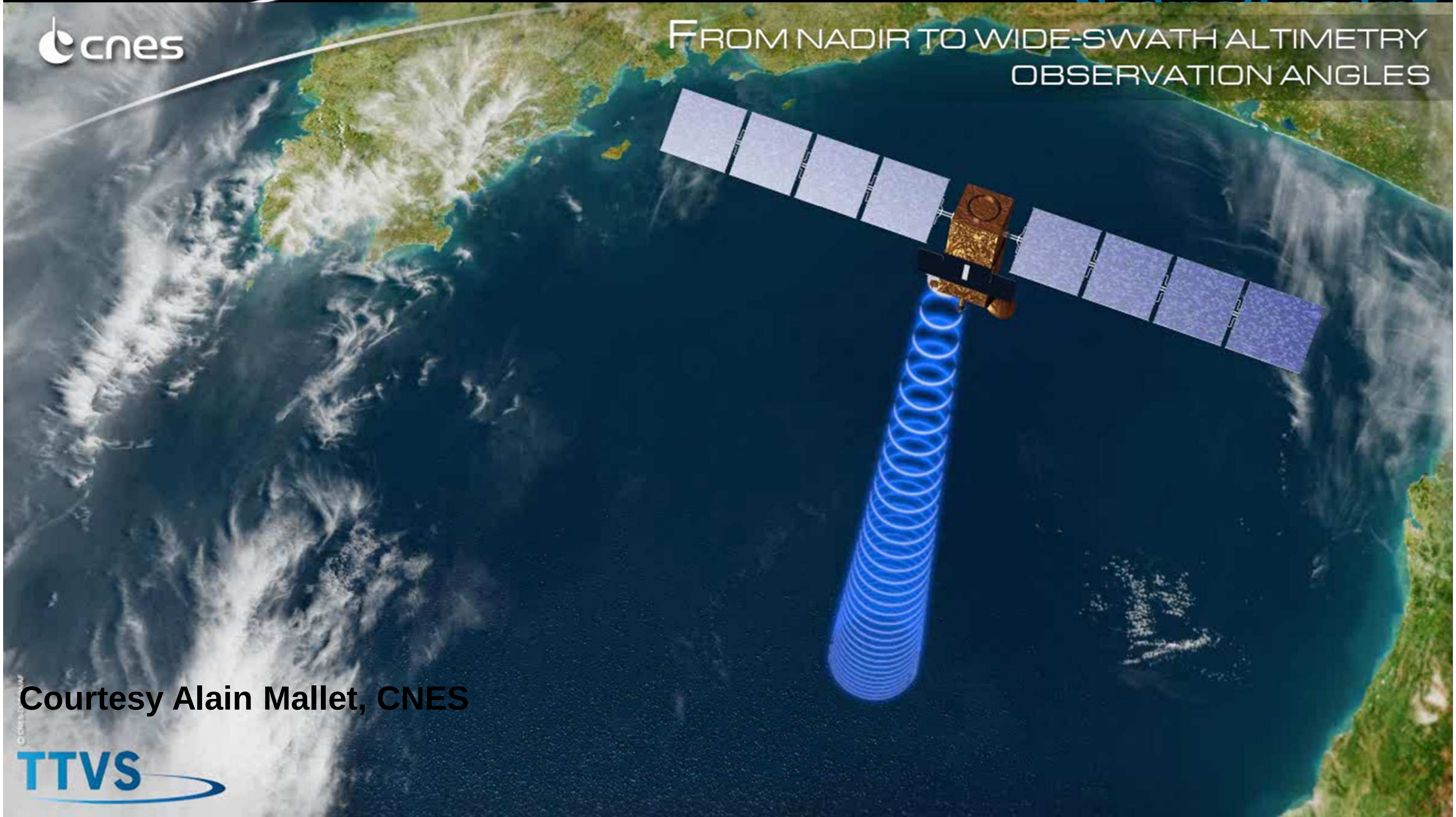
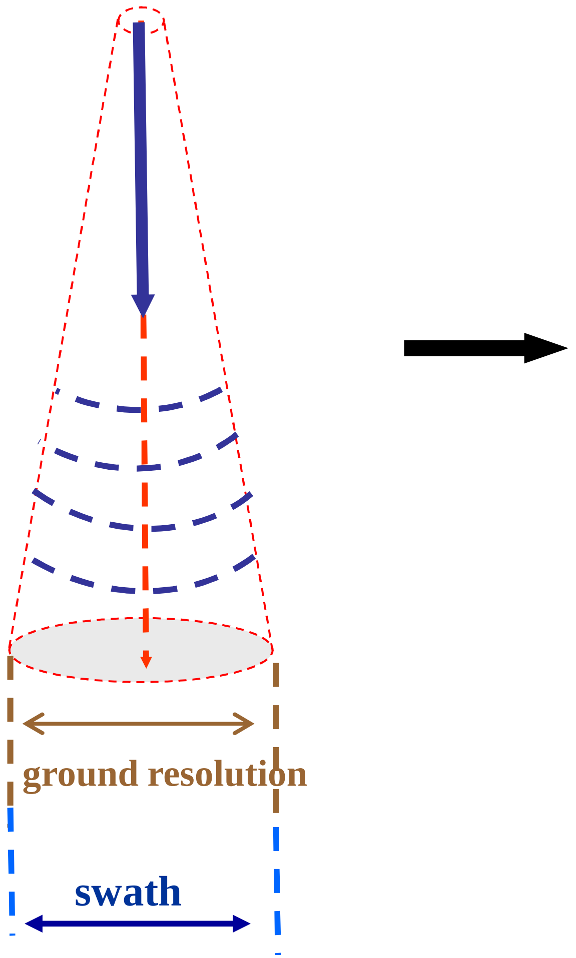
- **Du LRM (Low Resolution Mode) au SAR (Synthetic Aperture Radar)**
- **L’illumination cohérente et l’interférométrie**
- **La physique de la mesure de SWOT**
- **Diffusiométrie radar vent et vagues (exemple de SWIM sur CFOSAT)**

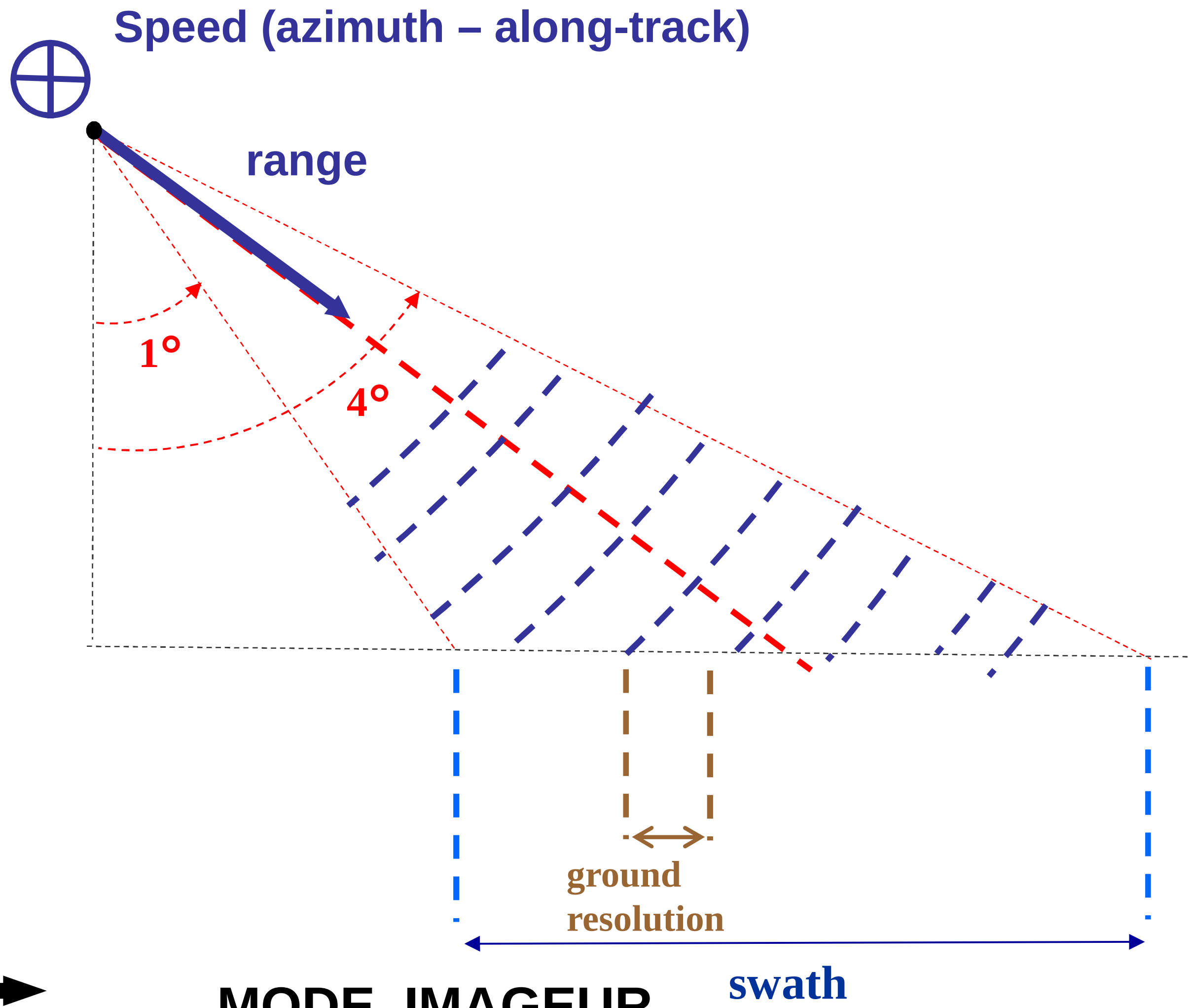


Courtesy Alain Mallet, CNES

De l'OBSERVATION nadir à La large fauchée

→ Illumination Off-Nadir





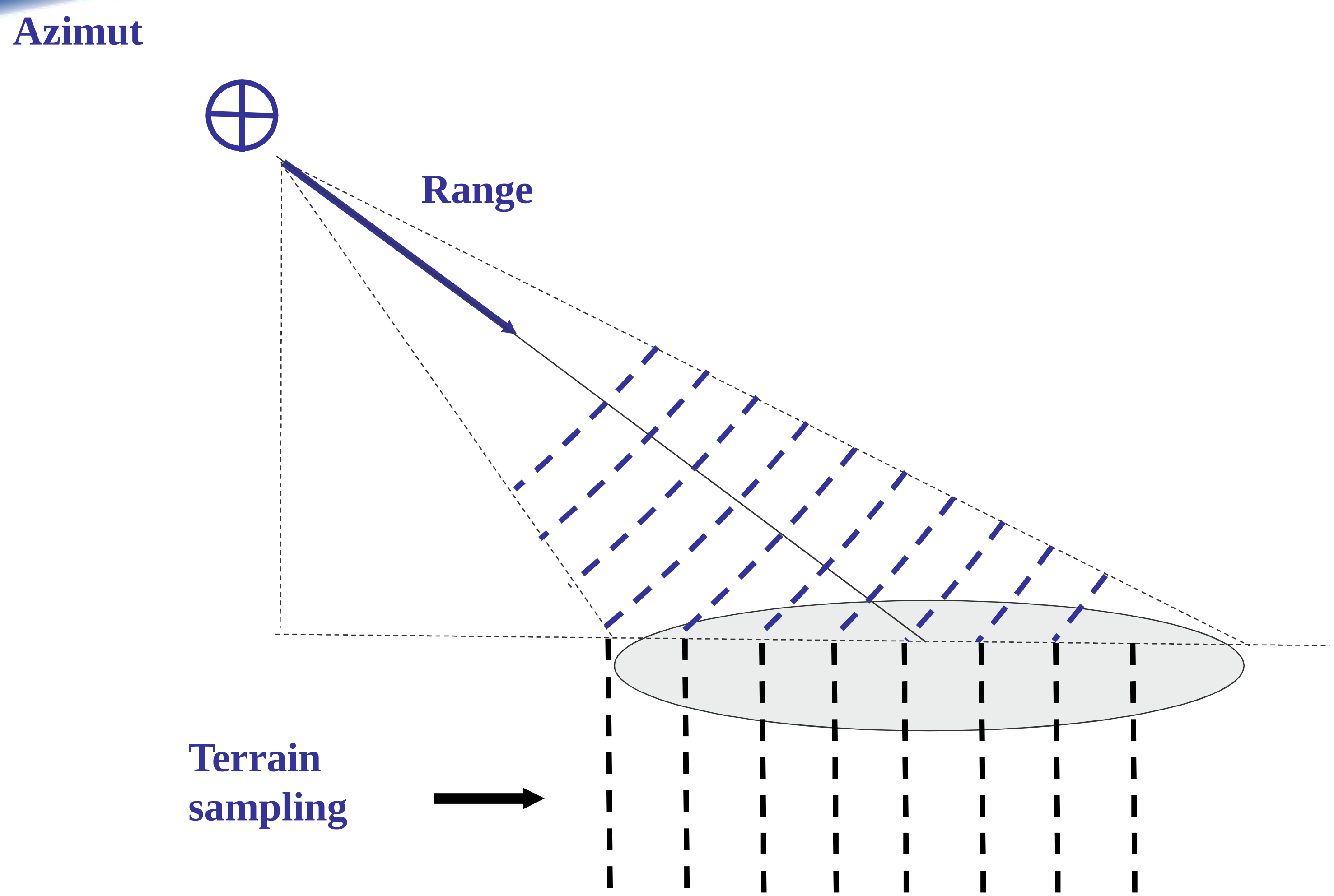
MODE SONDEUR

MODE IMAGEUR

(amélioration résolution across-track, alliée à la modulation de fréquence)

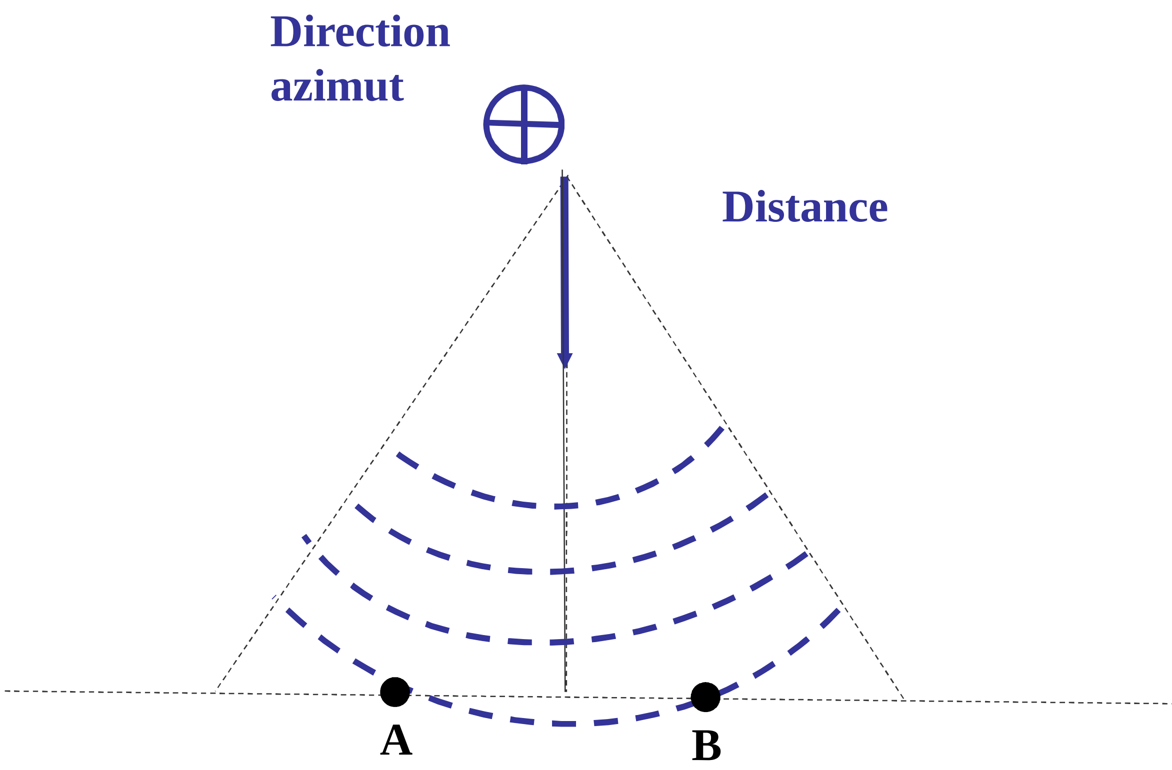
TTVS

Imaging radar geometry



Imaging radar geometry

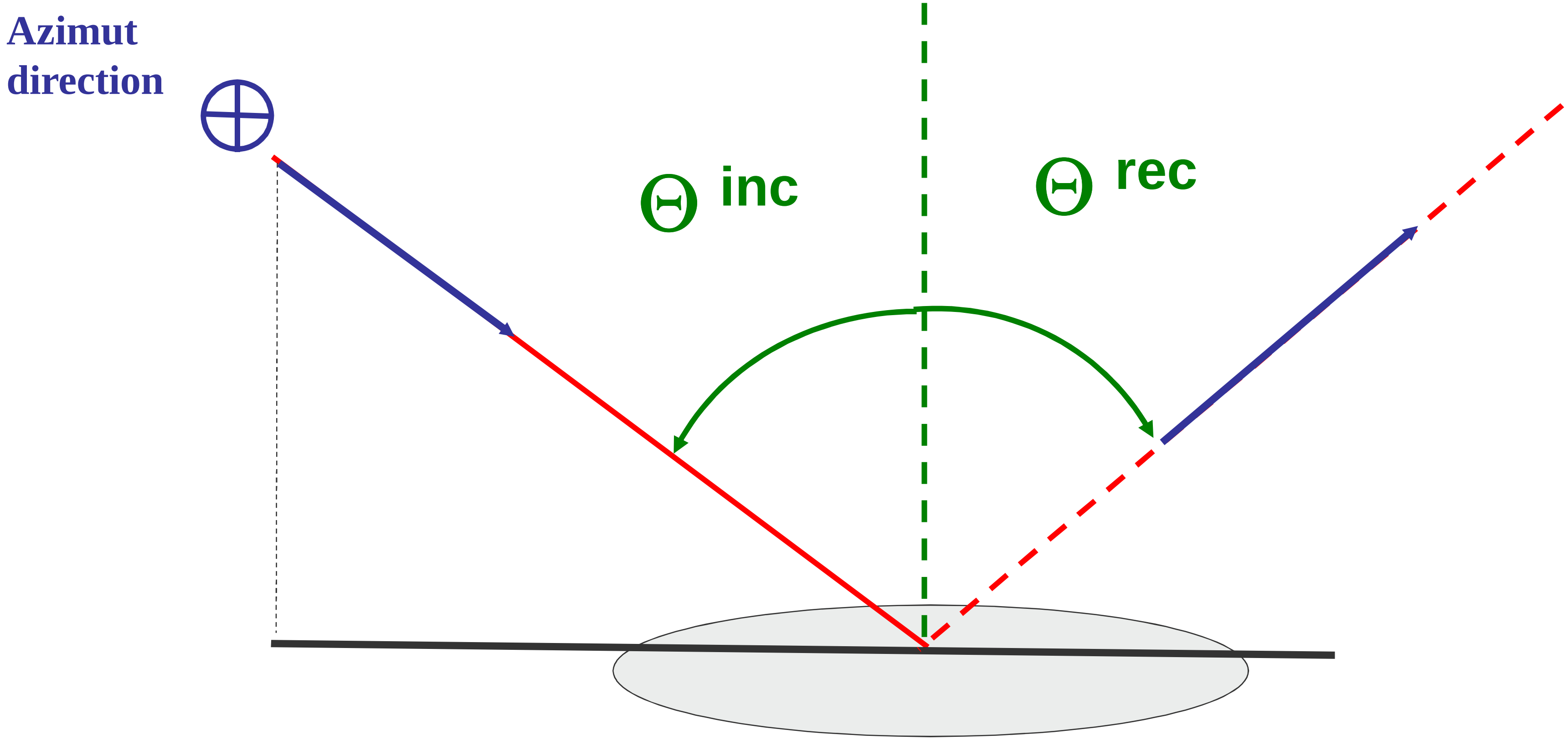
… What if radar were not in slant range ?



A and B are ambiguous (discrimination based on range mesurement)

Imaging radar geometry

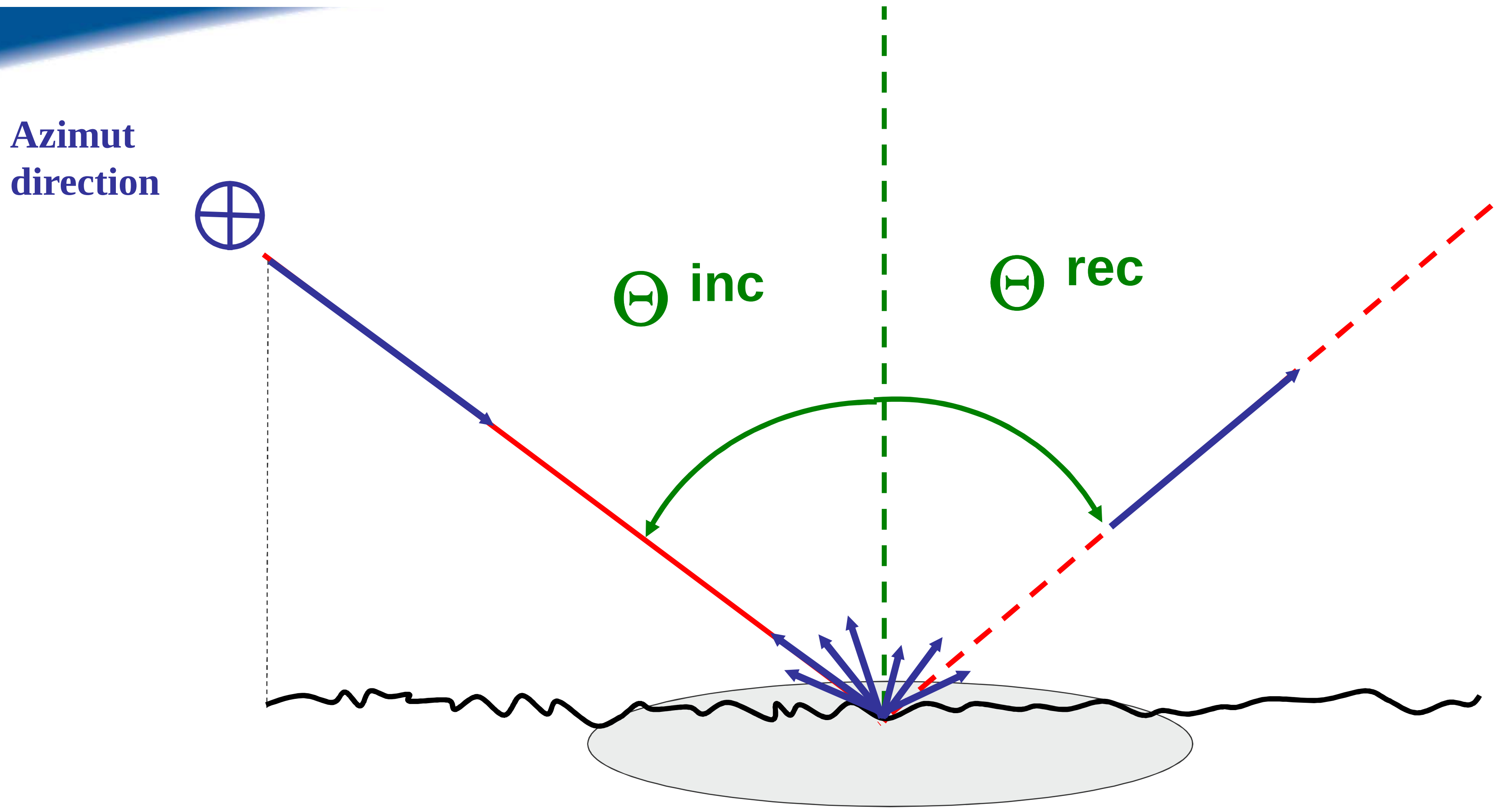
… The radar must be in slant range !



… and the reflected energy propagates in a direction which is not the one of the radar !

Imaging radar geometry

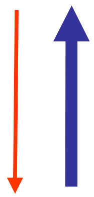
… The radar must be in slant range !



… Only a limited amount of energy is backscattered towards the radar
→critical power budget

Nadir looking vs. Off-Nadir Physics : transmitted power

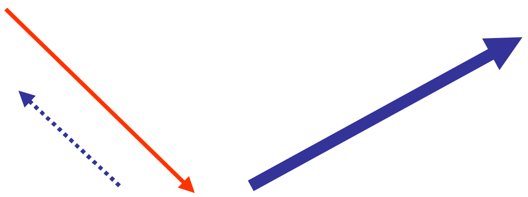
Nadir looking - Ku band



Received signal is strong : Low transmitted power

(Ex : Altimeter Poseidon on JASON ~ 10 W)

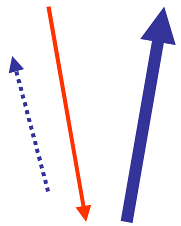
Off-Nadir (~ 30° incidence) – X band



Received signal is weak

(Ex : SAR-Lupe ~ 6 kW !

SWOT (~ 1-4° incidence) – Ka band

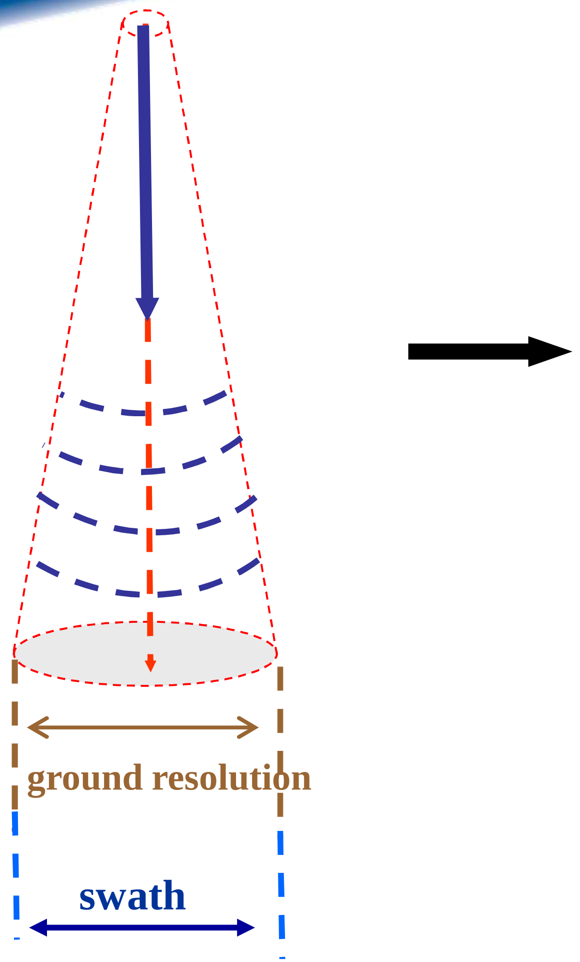


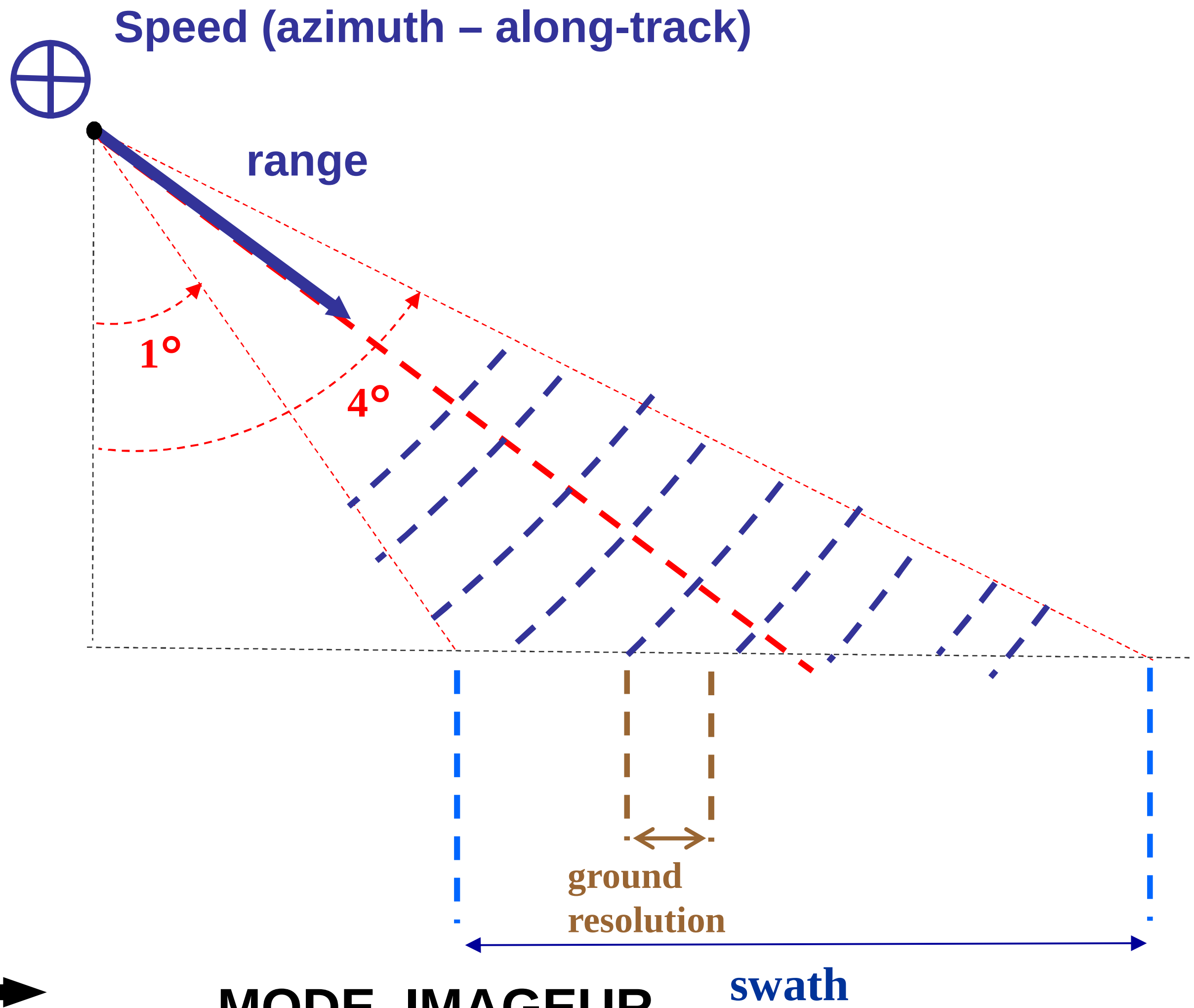
Transmitted power

(~ 1.5 kW)

De l'OBSERVATION nadir à La large fauchée

→ Illumination Off-Nadir



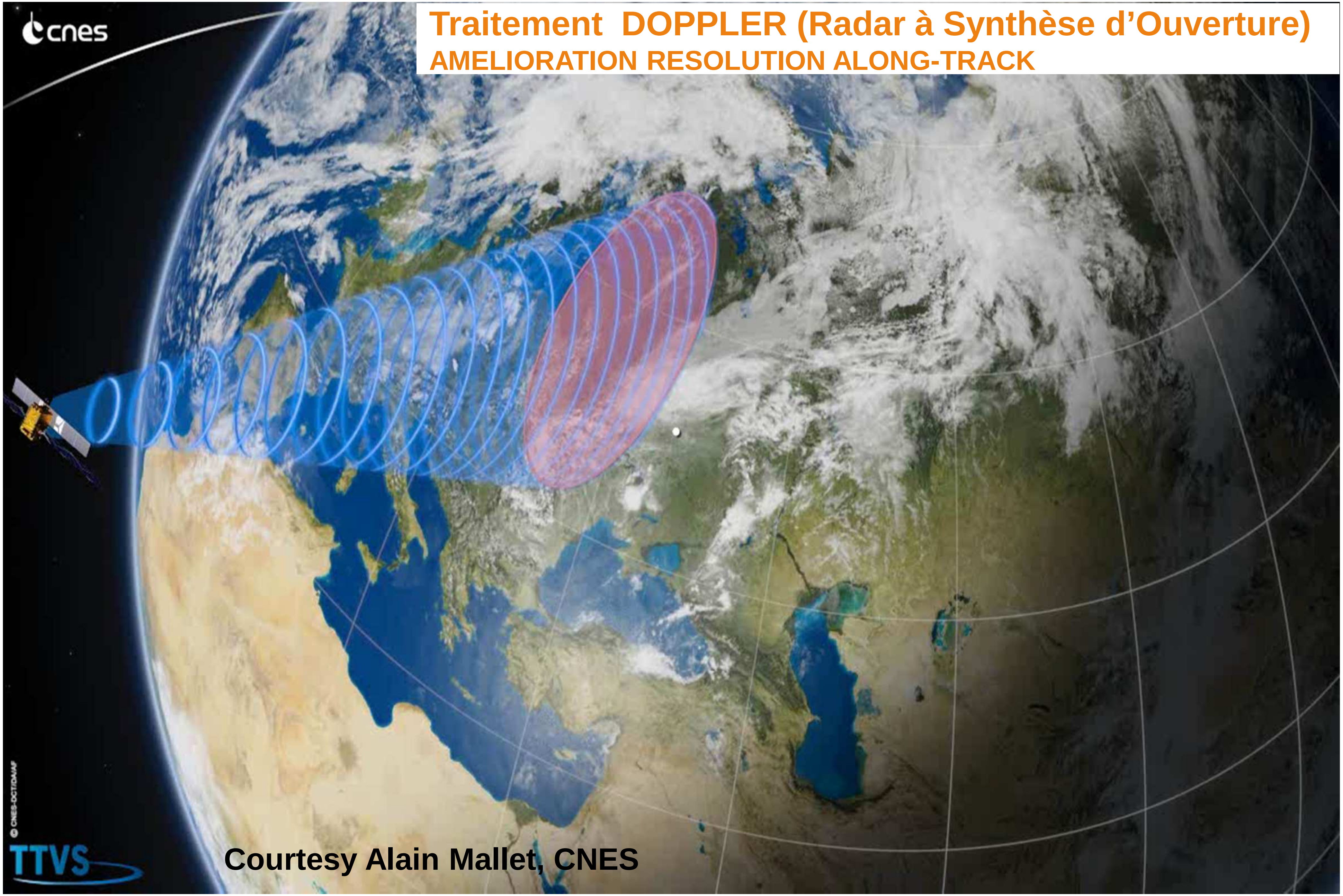


MODE SONDEUR → **MODE IMAGEUR**

(amélioration résolution across-track, alliée à la modulation de fréquence)

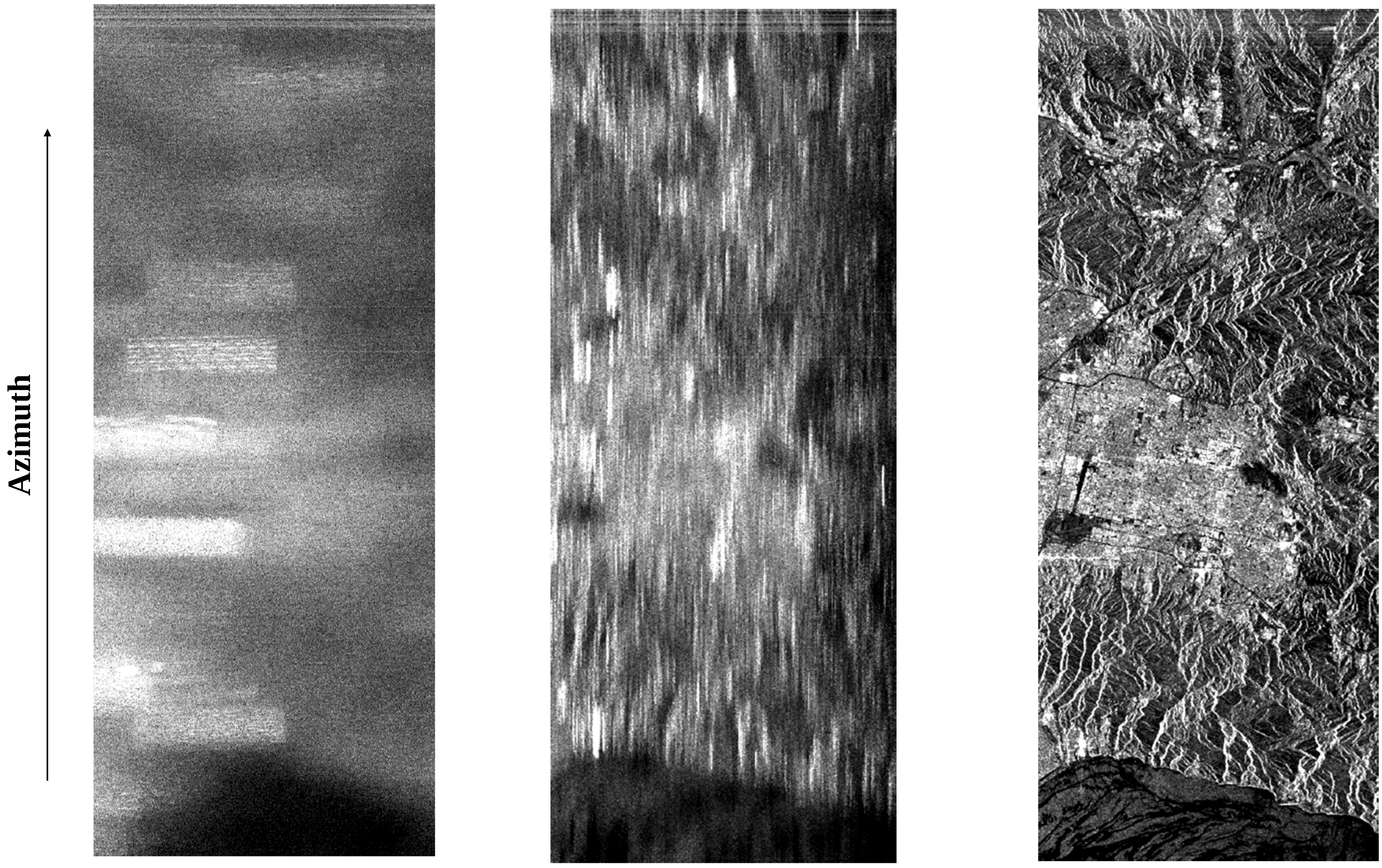
Traitement DOPPLER (Radar à Synthèse d’Ouverture)

AMELIORATION RESOLUTION ALONG-TRACK



Courtesy Alain Mallet, CNES

SAR Image synthesis in action



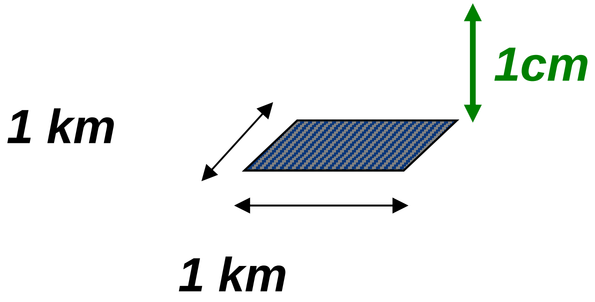
Raw Image

Range Compression

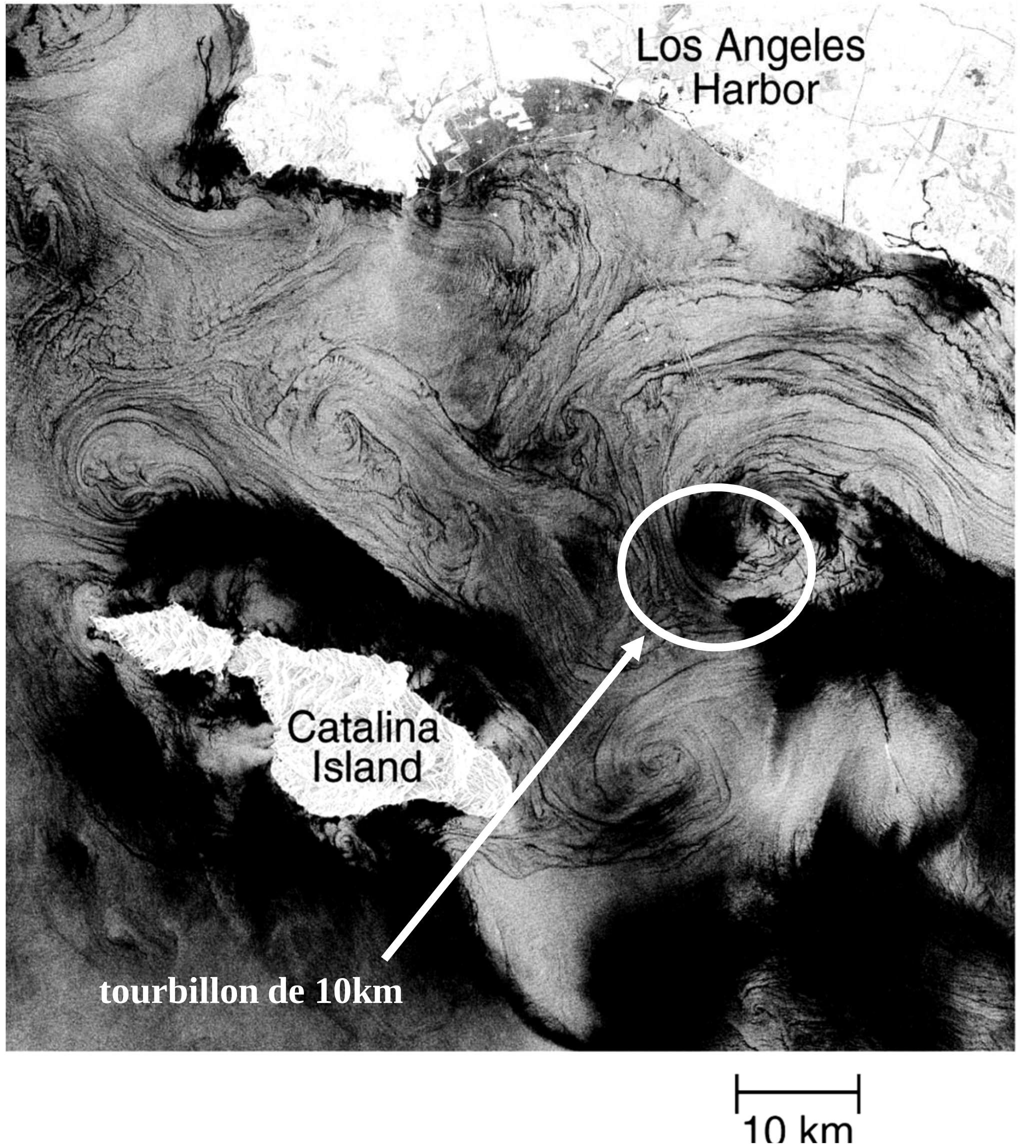
Resolved Image

Wide Swath Altimetry for HR oceanography

OCEANOGRAPHIE HAUTE RESOLUTION



RADARSAT - December 26, 1998



Existant : ~ qq cm sur 7 km x 7 km

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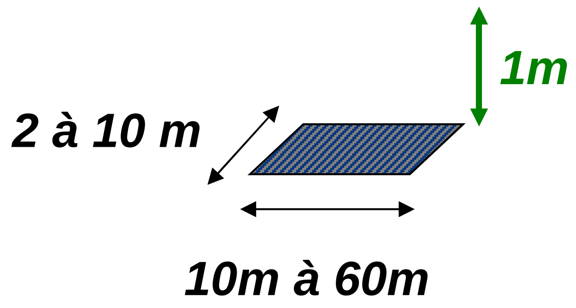
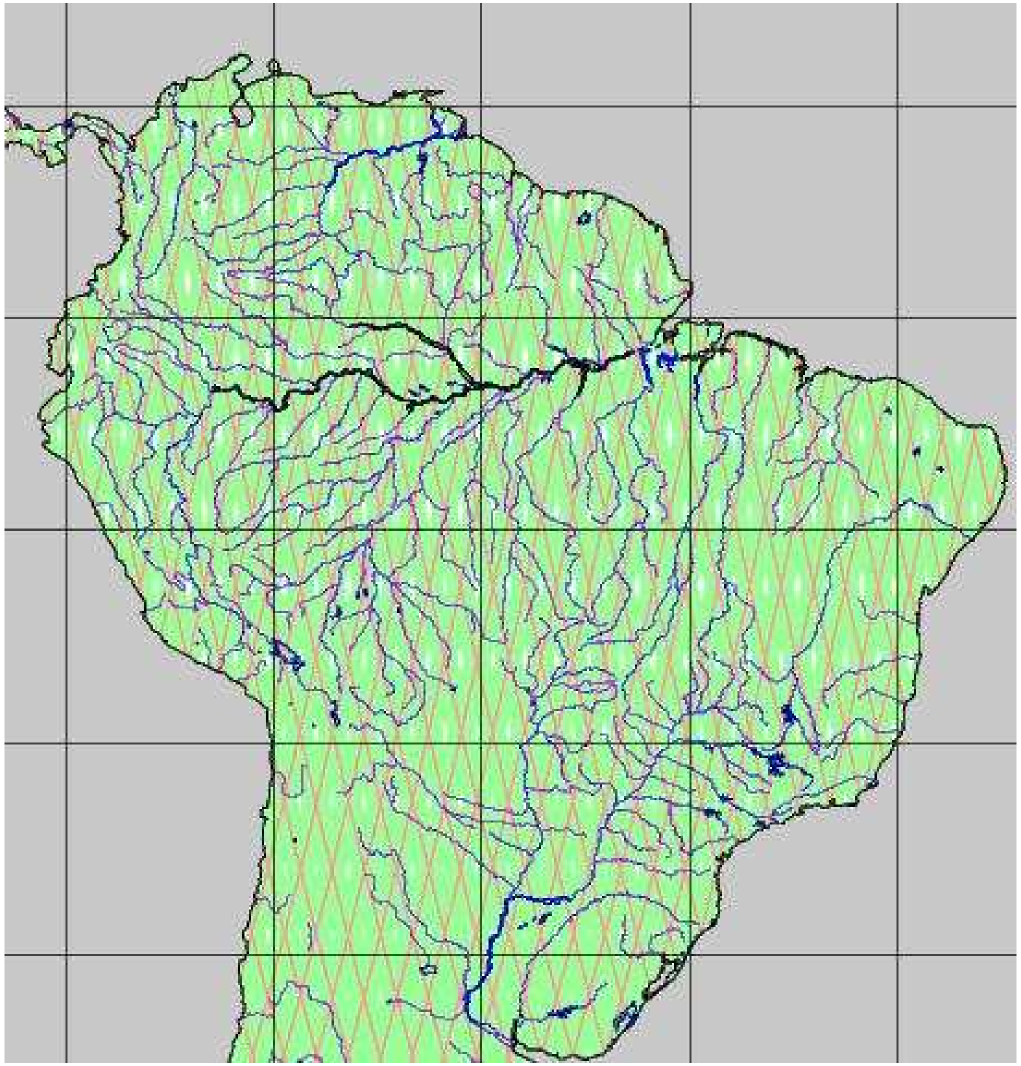
Wide Swath Altimetry for hydrology

HYDROLOGIE

CONTINENTALE





Existant : ~ qq cm sur 7 km x 7 km

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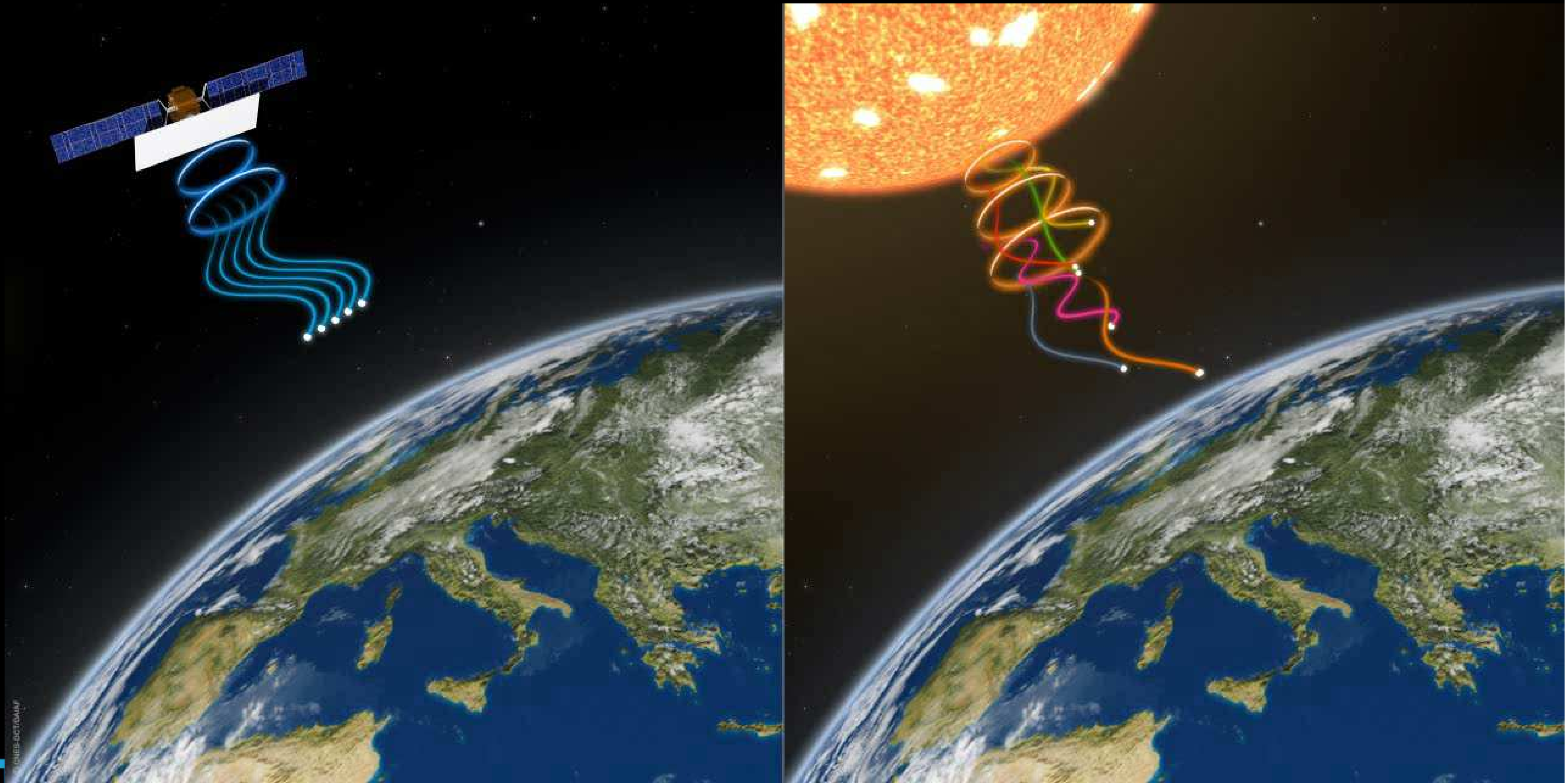
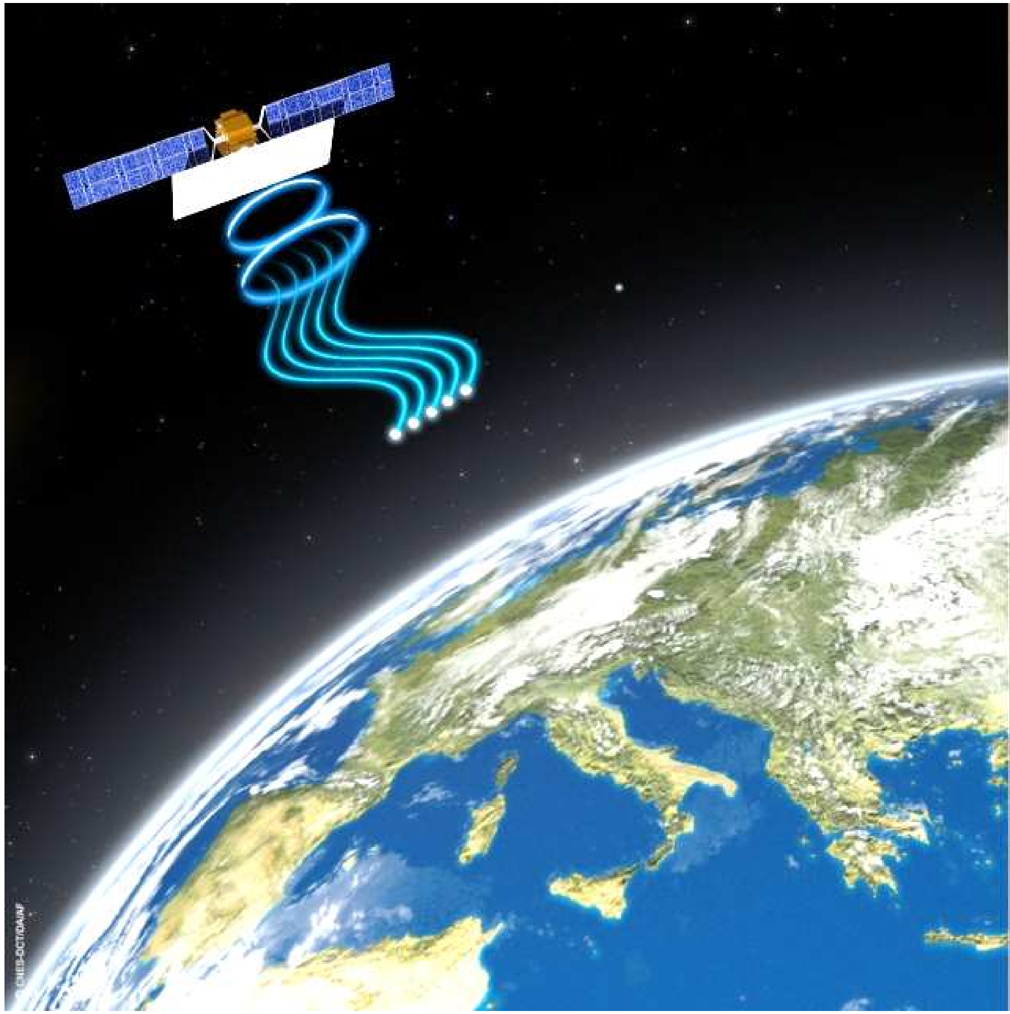
Coherent versus incoherent illumination

For coherent illumination, the in-phase photonic vibration allows for the use of the radar signal phase information

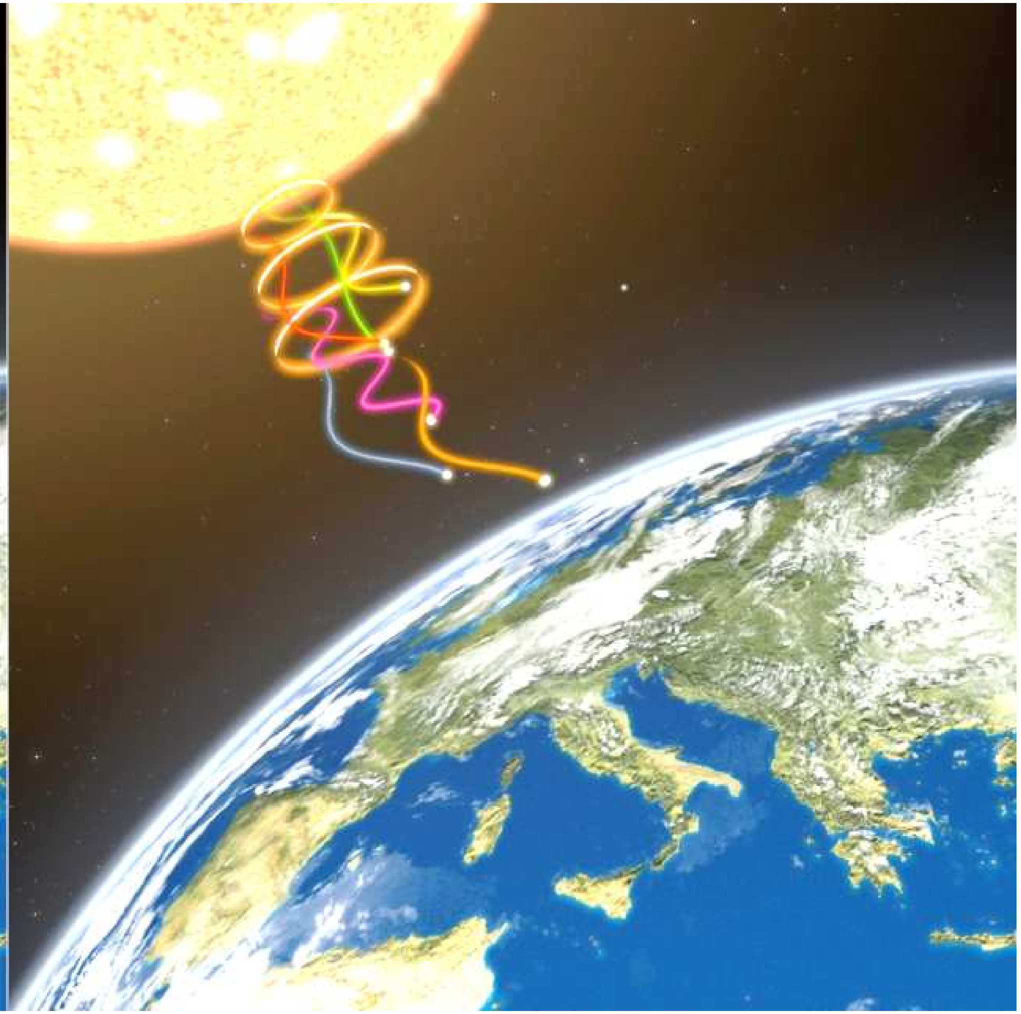


Coherent Illumination, non coherent illumination

… On the spartan organisation of the radar wavelength !

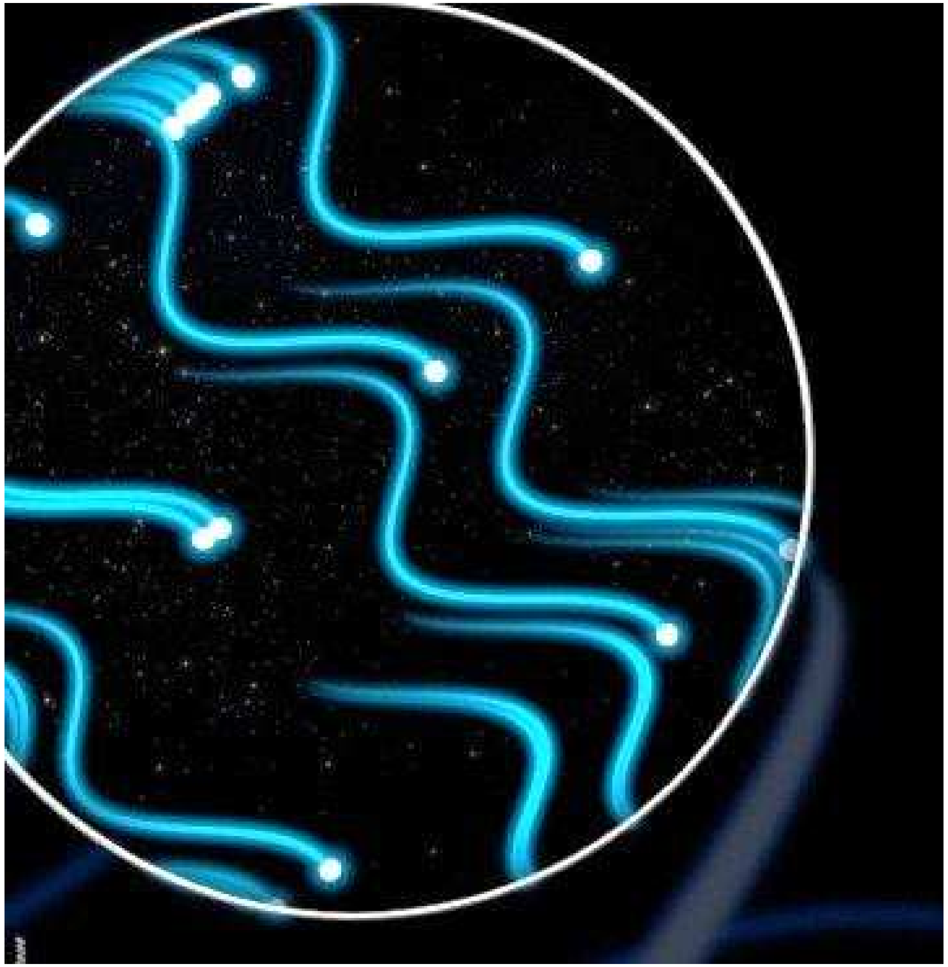


Radar illumination (or laser)



Natural illumination

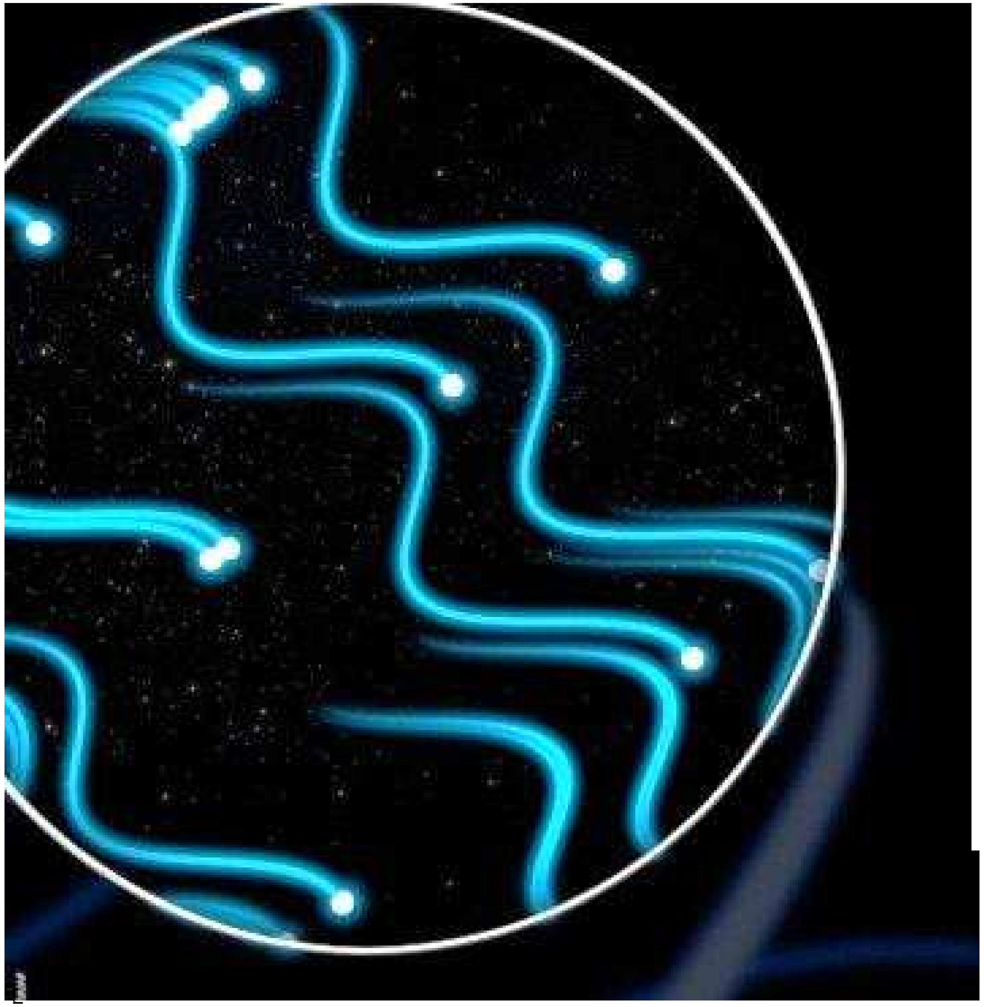
Coherent Illumination, non coherent illumination
… On the spartan organisation of the coherent wave !



Radar (or laser) illumination
COHERENT

Natural illumination
INCOHÉRENT

The phase of the coherent wave



© CNES - All

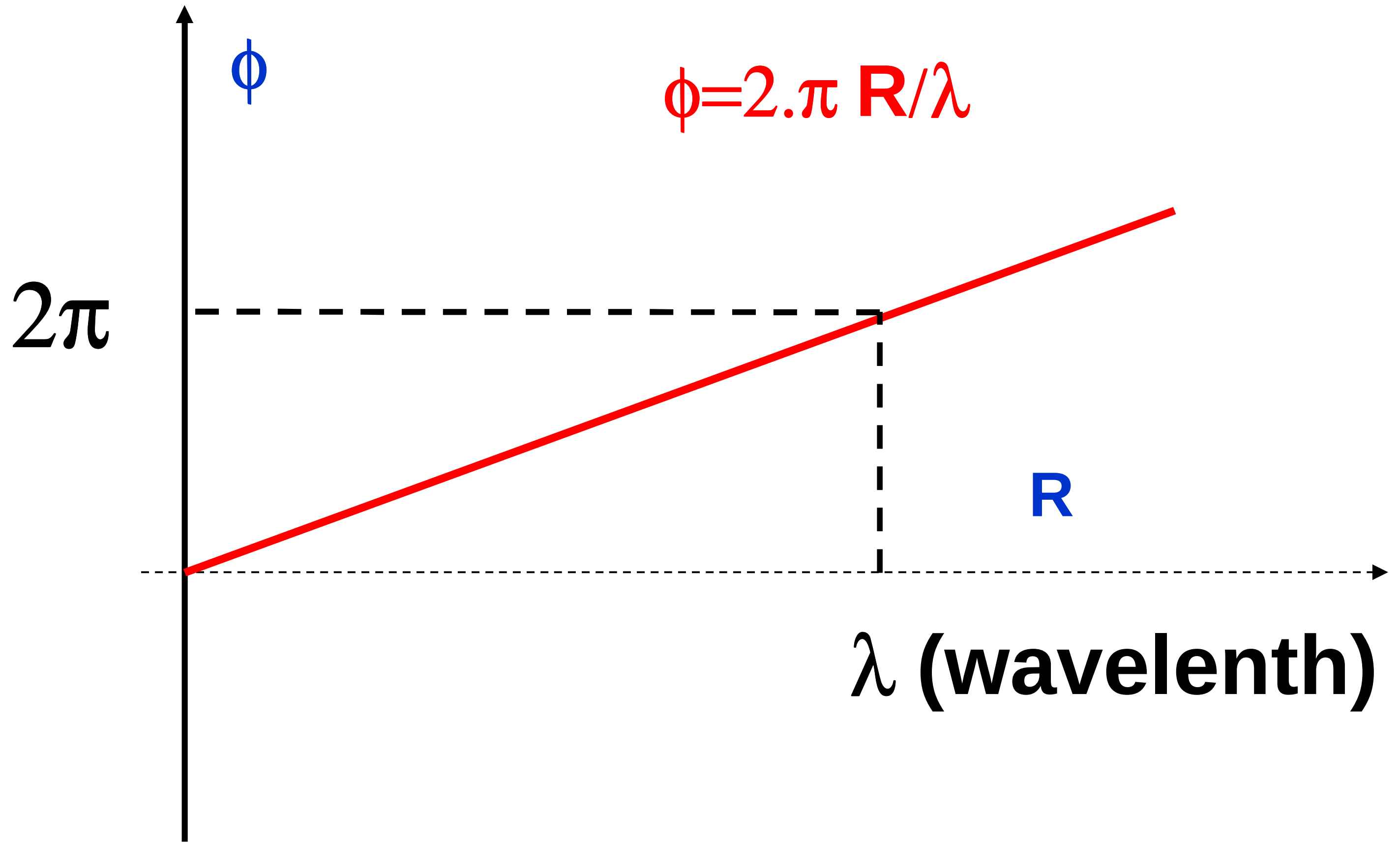
Rayonnement radar (ou laser)

Phase (i.e. vibration state) of
one photon =

Same as the phase of any photon

➔We can define the
« Phase of the wave »,
as the phase state common
to every photon of the wave.

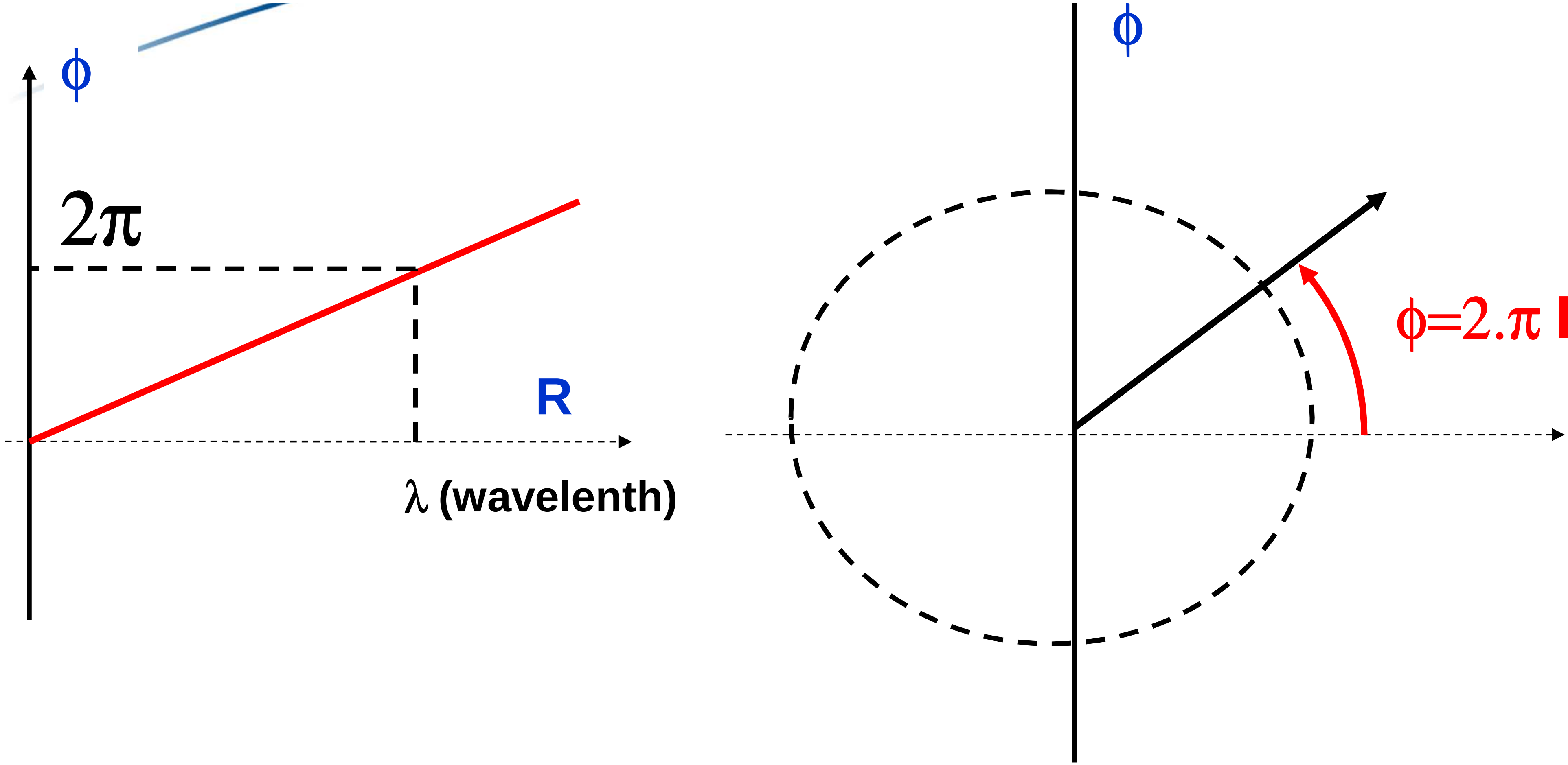
The phase of the coherent wave



The phase state is a function of

the distance R covered by the wave

Phase of the coherent wave / Phase of the radar signal



Phase of the wave ➔ Phase of the radar signal

The wave Phase is « wrapped » by the radar measurement

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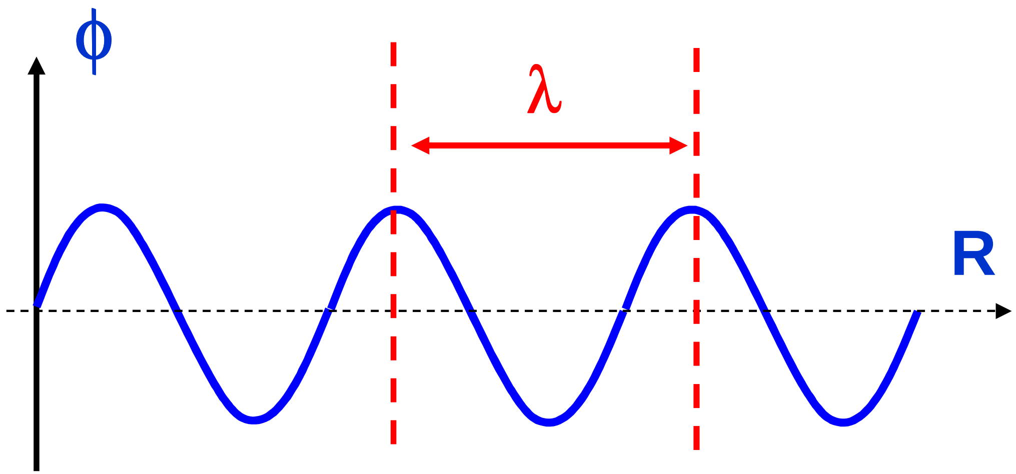
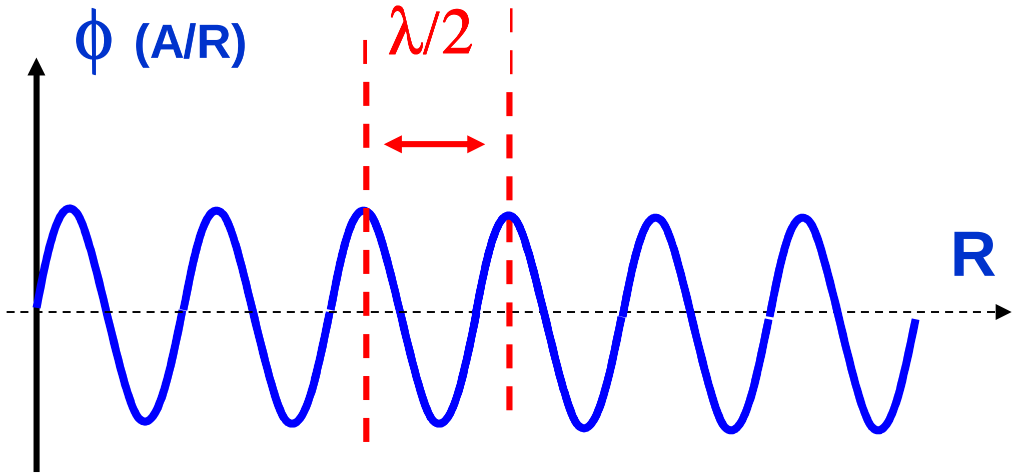
Coherent Illumination: the phase of the radar wave



The phase of the radar signal (modulo 2π) takes the same value at two locations separated by the range λ (wavelength)

TTVS

Coherent Illumination: the phase of the radar wave



… Actually : the range λ/2 when accounting for the round trip distance

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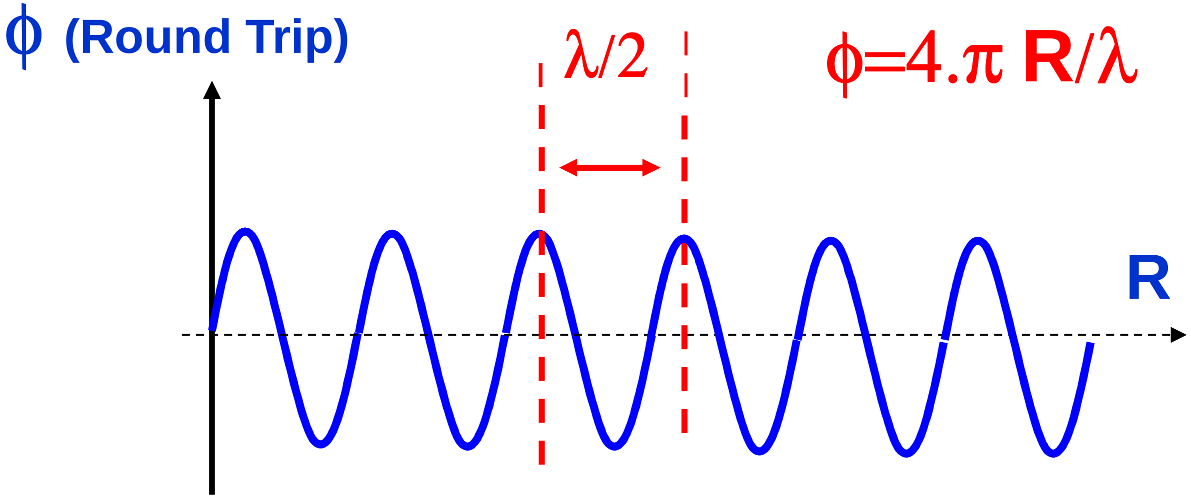
Coherent Illumination : the phase of the radar wave



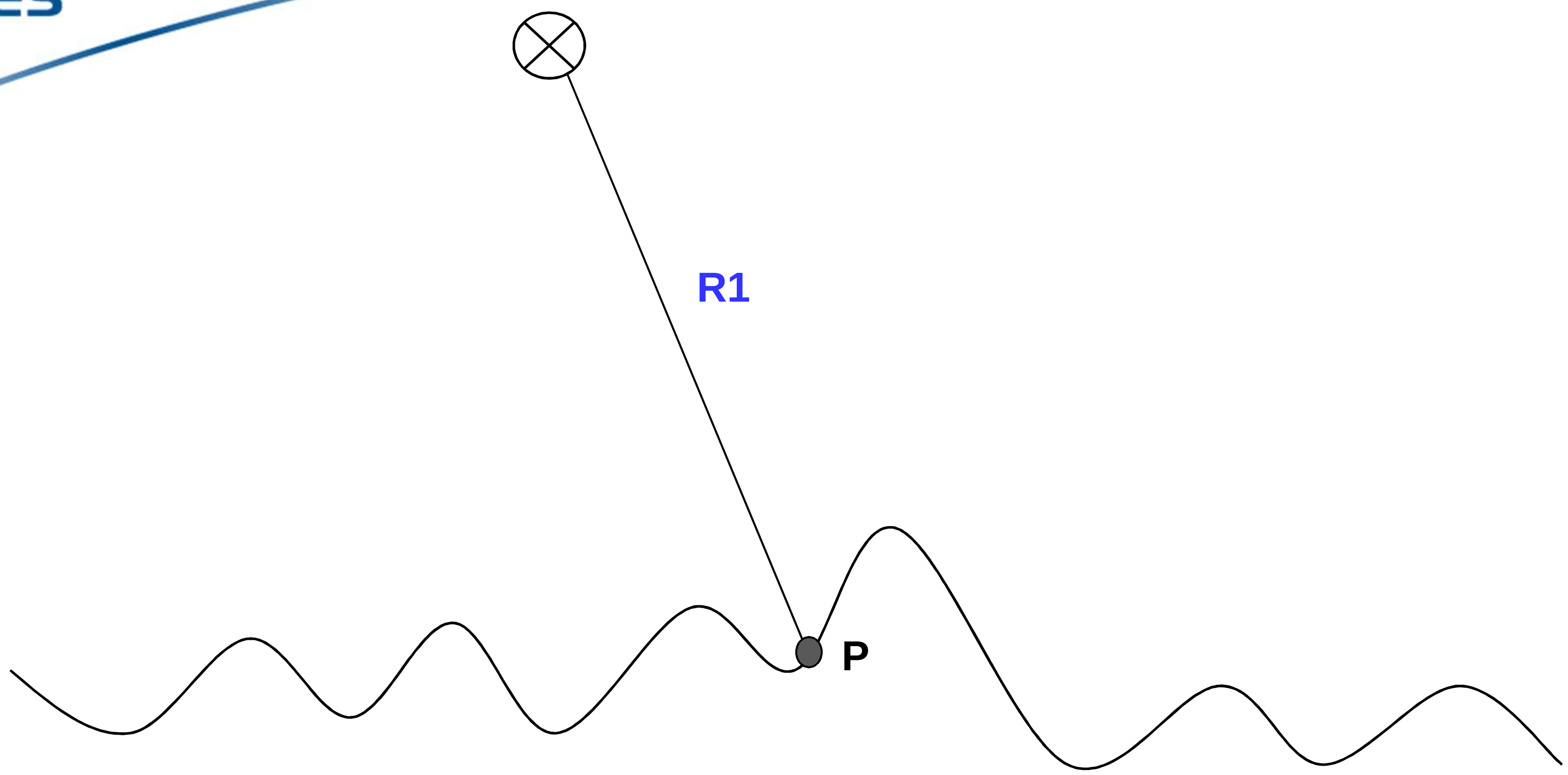
$\phi = 4.\pi\, R/\lambda \mod (2.\pi)$

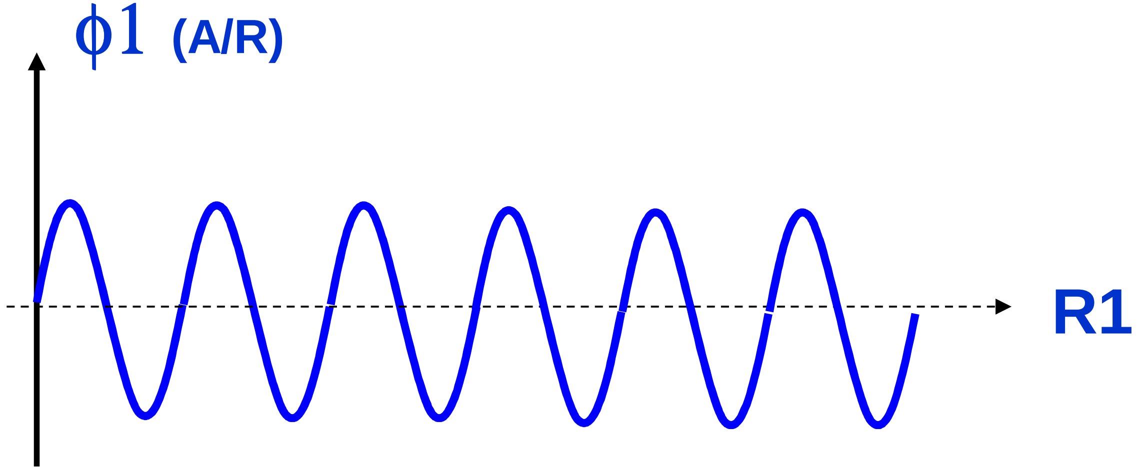
Can we infer the range R from the knowledge of the phase ϕ ?

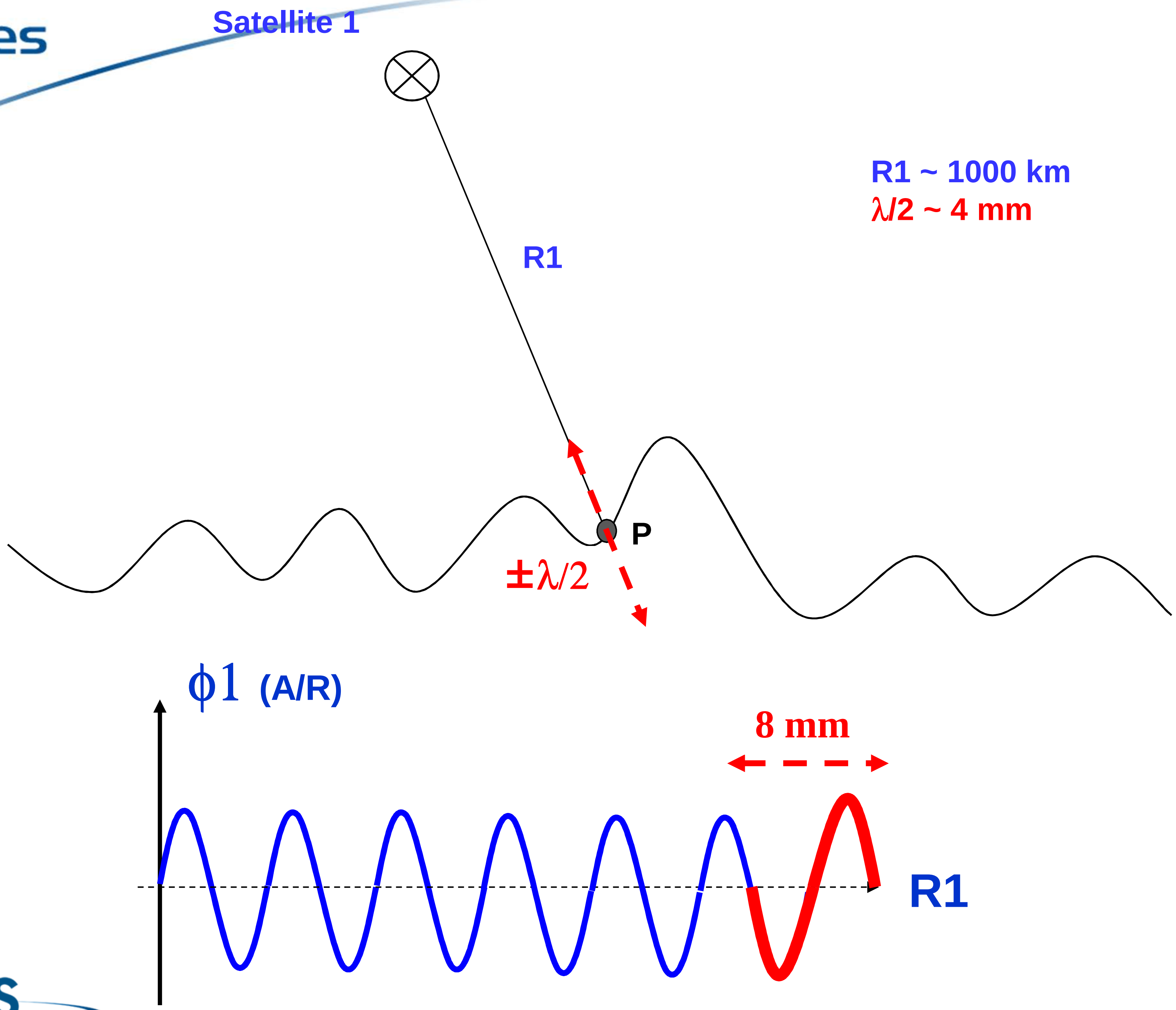
… Quite difficult, as it would require to determine the number N of λ/2 segments over the range R very precisely

Ex : Bande Ka : λ/2= 4 mm→ N=R/(λ/2) ~ 1000km /4 mm ~2.10^8

… and moreover to assume that neither the atmosphere nor the wave / surface interaction corrupt the phase

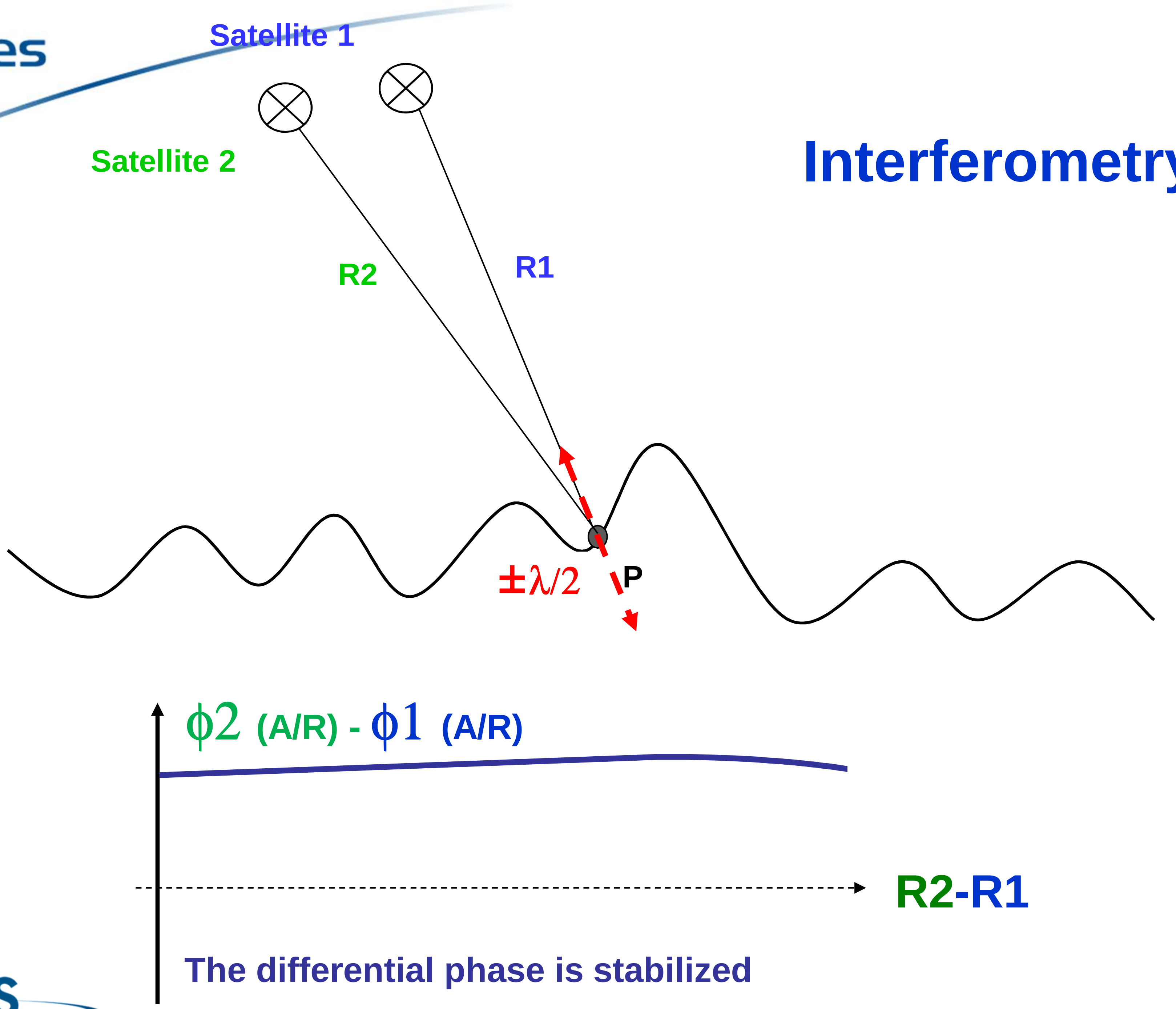

Satellite 1
R1
P


$\phi 1$ (A/R)
R1



Satellite 1
R1 ~ 1000 km
λ/2 ~ 4 mm
R1
P
±λ/2
ϕ1 (A/R)
8 mm
R1

Interferometry



The differential phase is stabilized

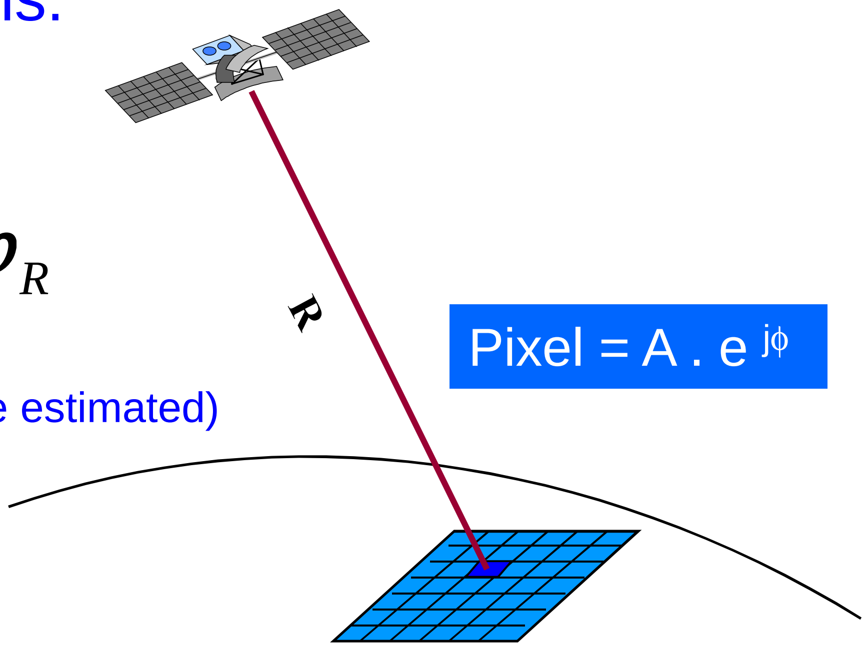
Principle of interferometry

- Each image pixel contains two terms:
  - Amplitude: A
  - Phase:

$$\varphi_{pixel} = \varphi_{specific} + \varphi_R$$

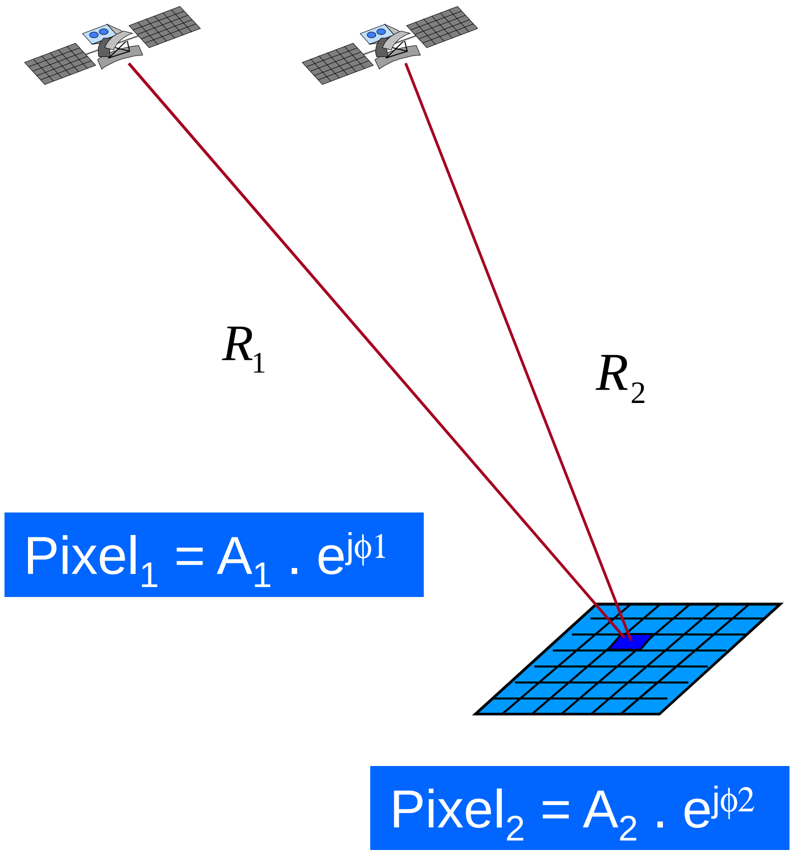
$\varphi_{specific}$ (wave / surface interaction cannot be estimated)

$$\varphi_R = \frac{4\pi}{\lambda} R$$



➡ Absolute phase cannot be used as information

Principle of interferometry



- If two images with unchanged ground conditions

$$\varphi_{specific\_1} = \varphi_{specific\_2}$$

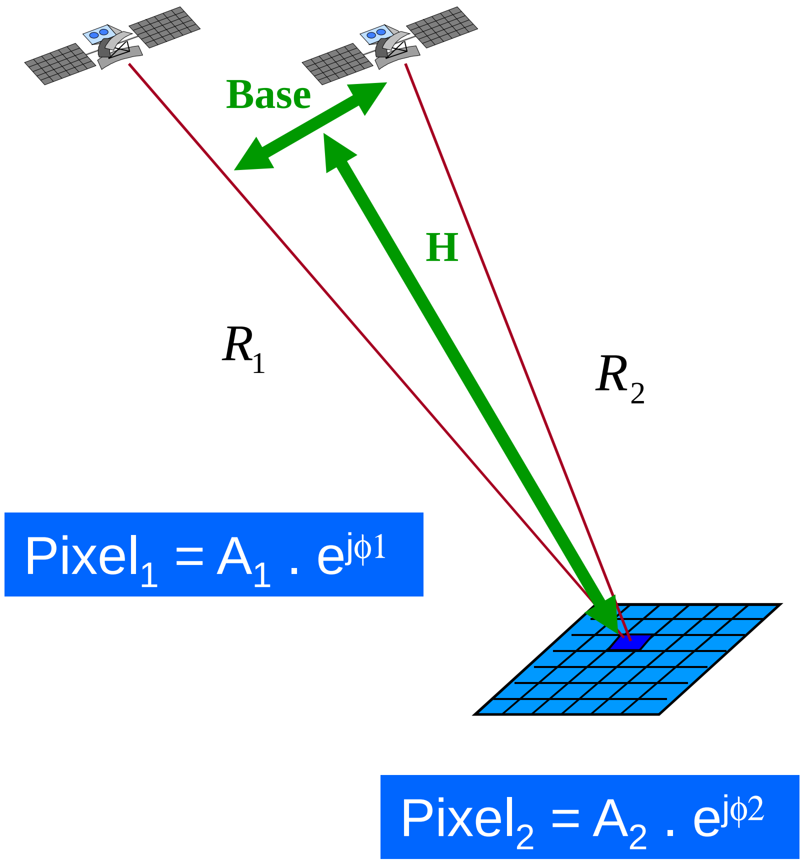
$$\Rightarrow \Delta\varphi = \varphi_2 - \varphi_1 = \varphi_{R_2} - \varphi_{R_1}$$

$$\Delta\varphi = \frac{4\pi}{\lambda}(R_2 - R_1)$$

- Image of $\Delta\varphi$ = interferogram = image of distance differences

If : $(R_2 - R_1)$ varies of $\frac{\lambda}{2}$ $\Rightarrow \Delta\varphi$ varies of 2π (one fringe)

Principle of interferometry



Interferometry is not stereoscopy

Phase Base/H << « Optical Base/H »

10^{-5} 10^{-1}

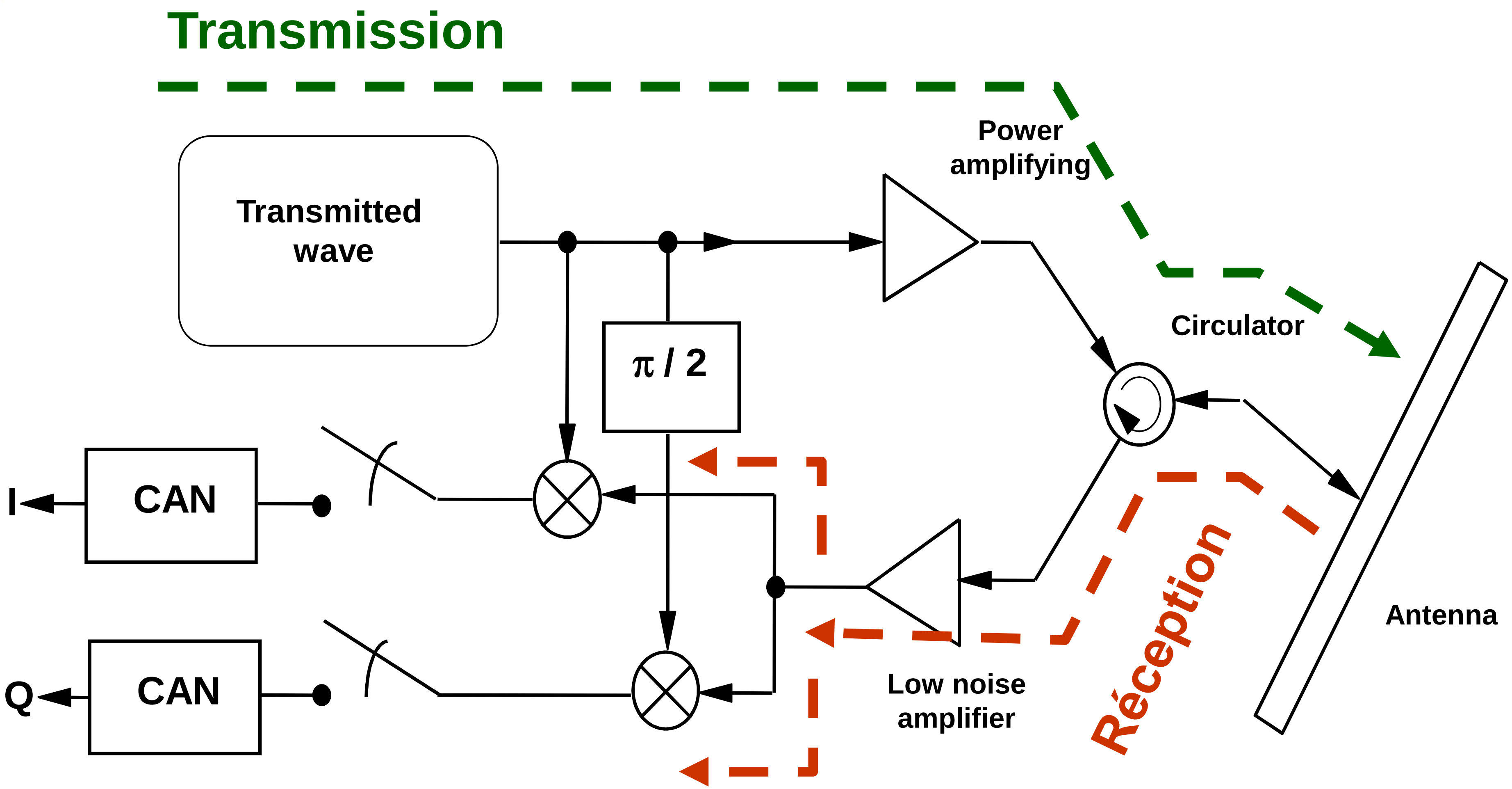
SWOT :
Base=10m, H=1000 km

SPOT :
Base=100 km, H=1000 km

Variation de phase

Déformation géométrique

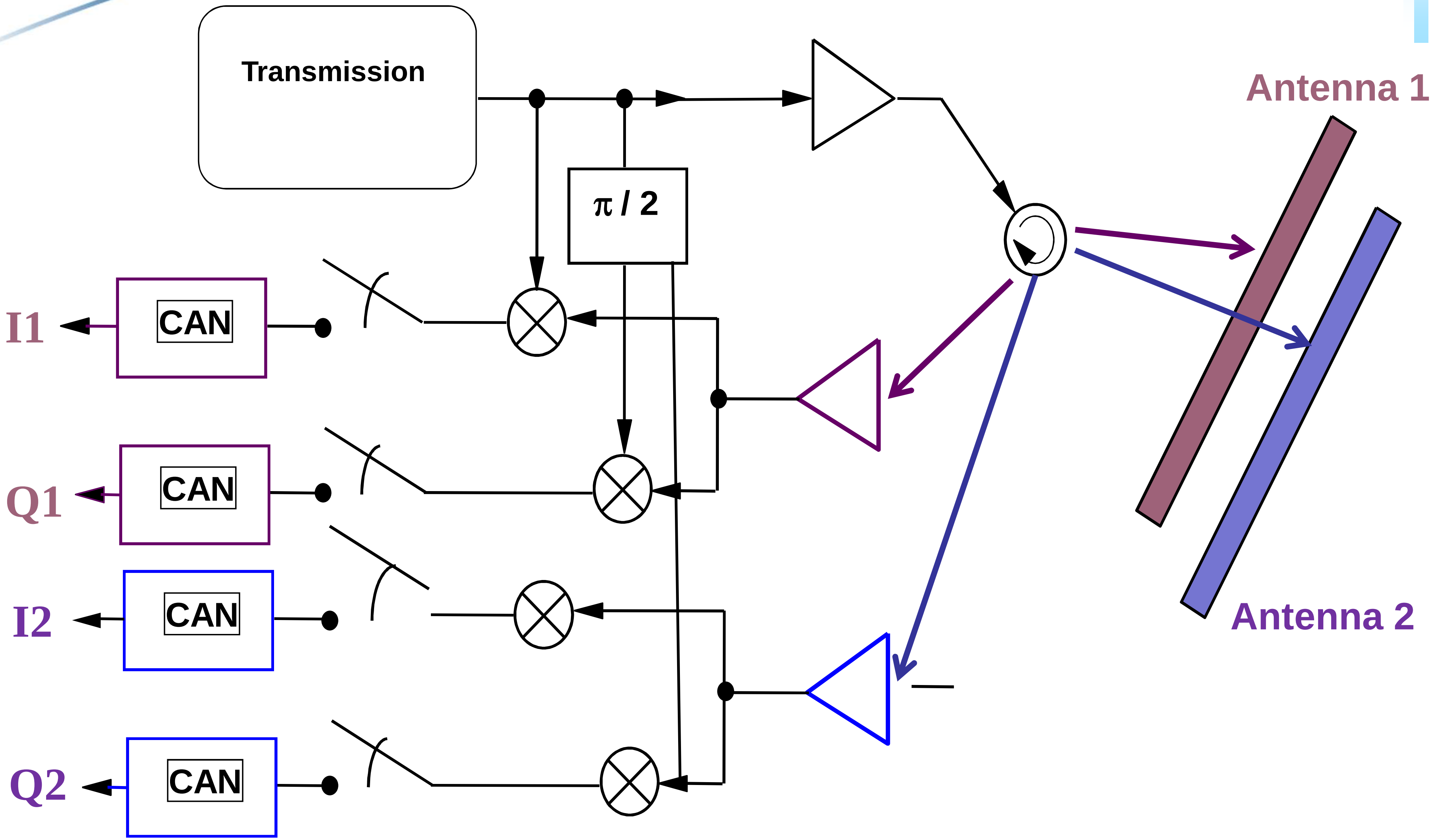
Radar signal measurement / Phase measurement



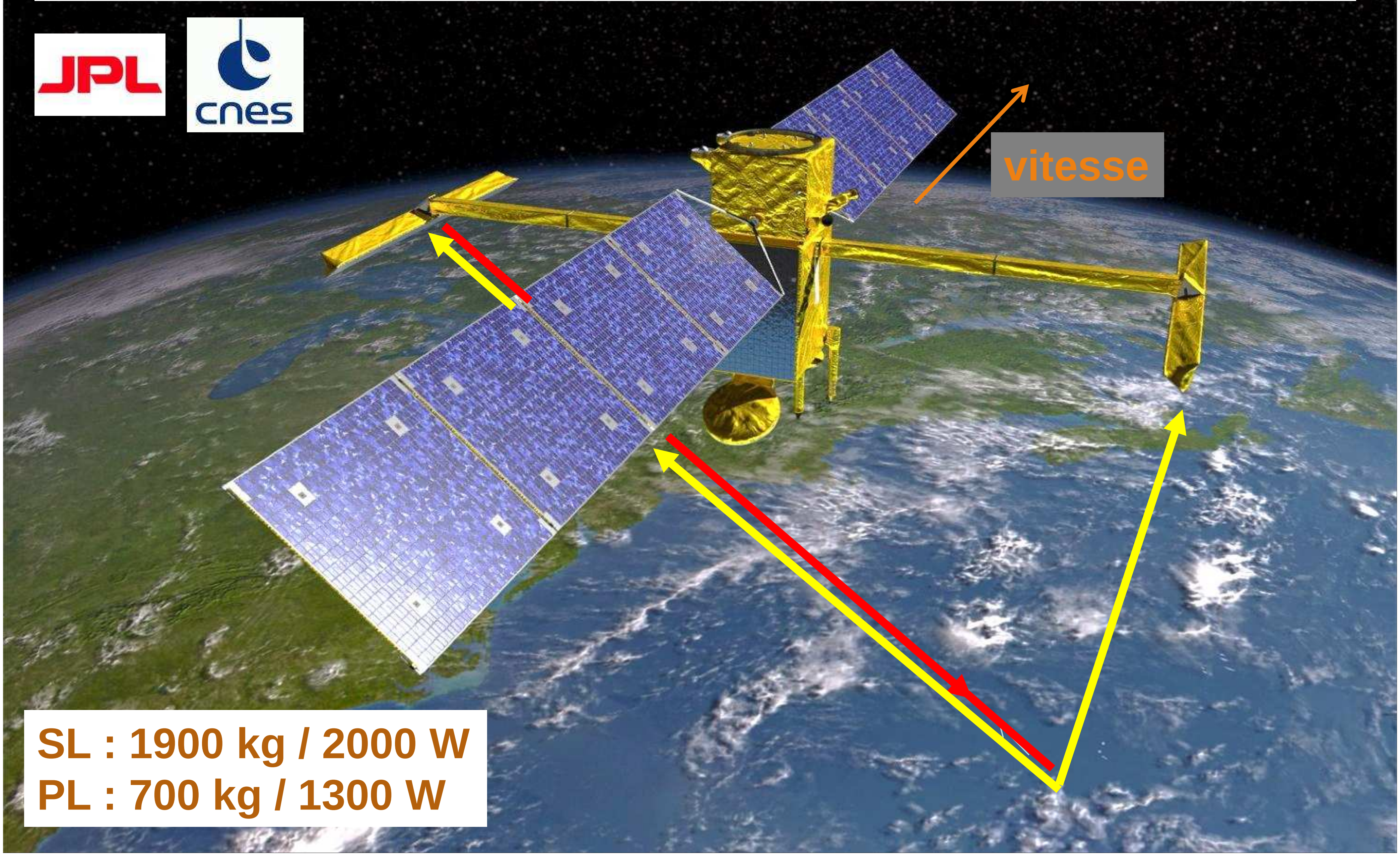
1 image pixel = I + j. Q (complex number) = radiometry + phase

A radar signal is a « two-layers » signal, including a radiometric layer and a phase layer

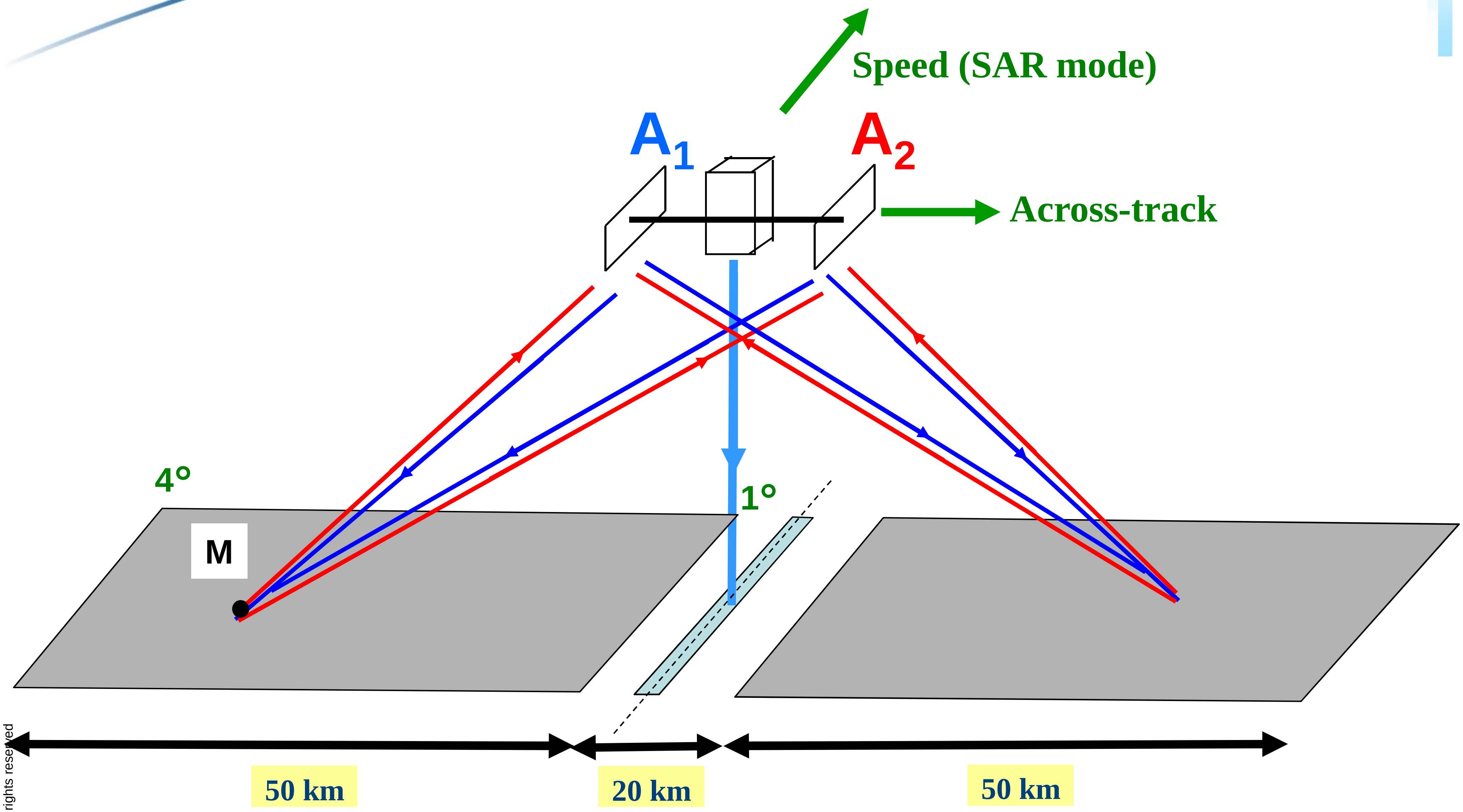
Interferometric Radar chain



SURFACE WATER AND OCEAN TOPOGRAPHY (SWOT)

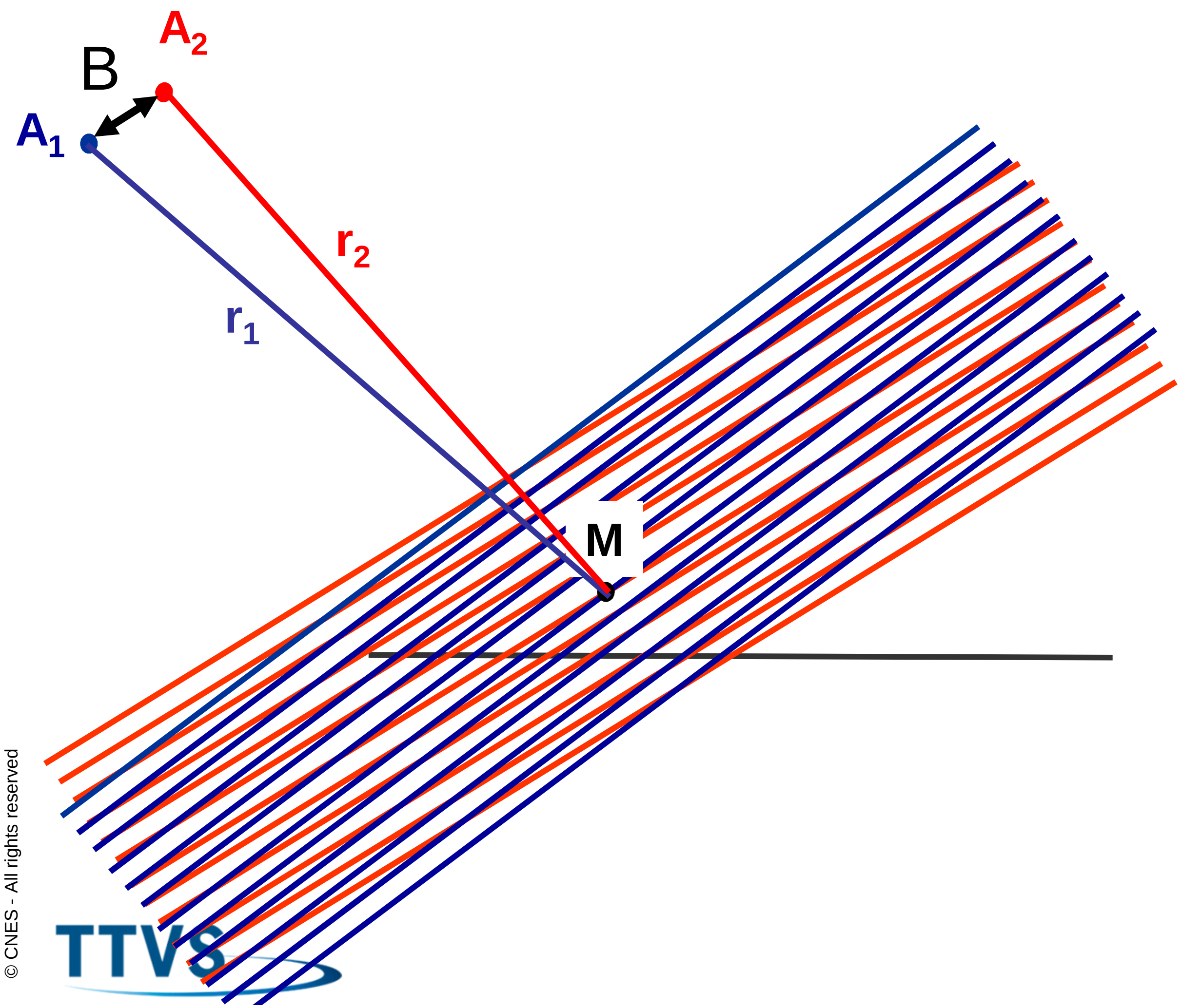


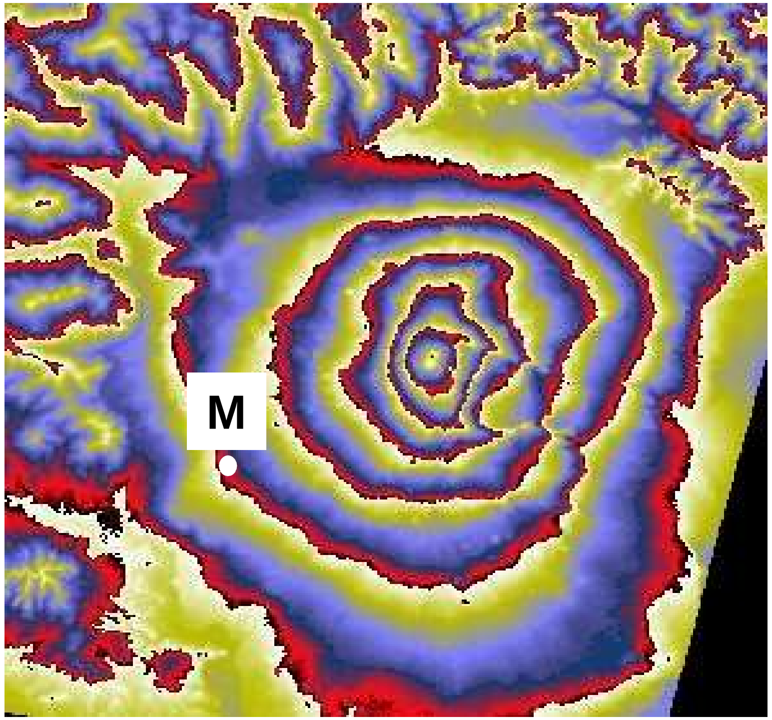
SWOT ACQUISITION



Sensibilité topographique et baseline interférométrique

Baseline / wavelength : B/λ (= 1000)



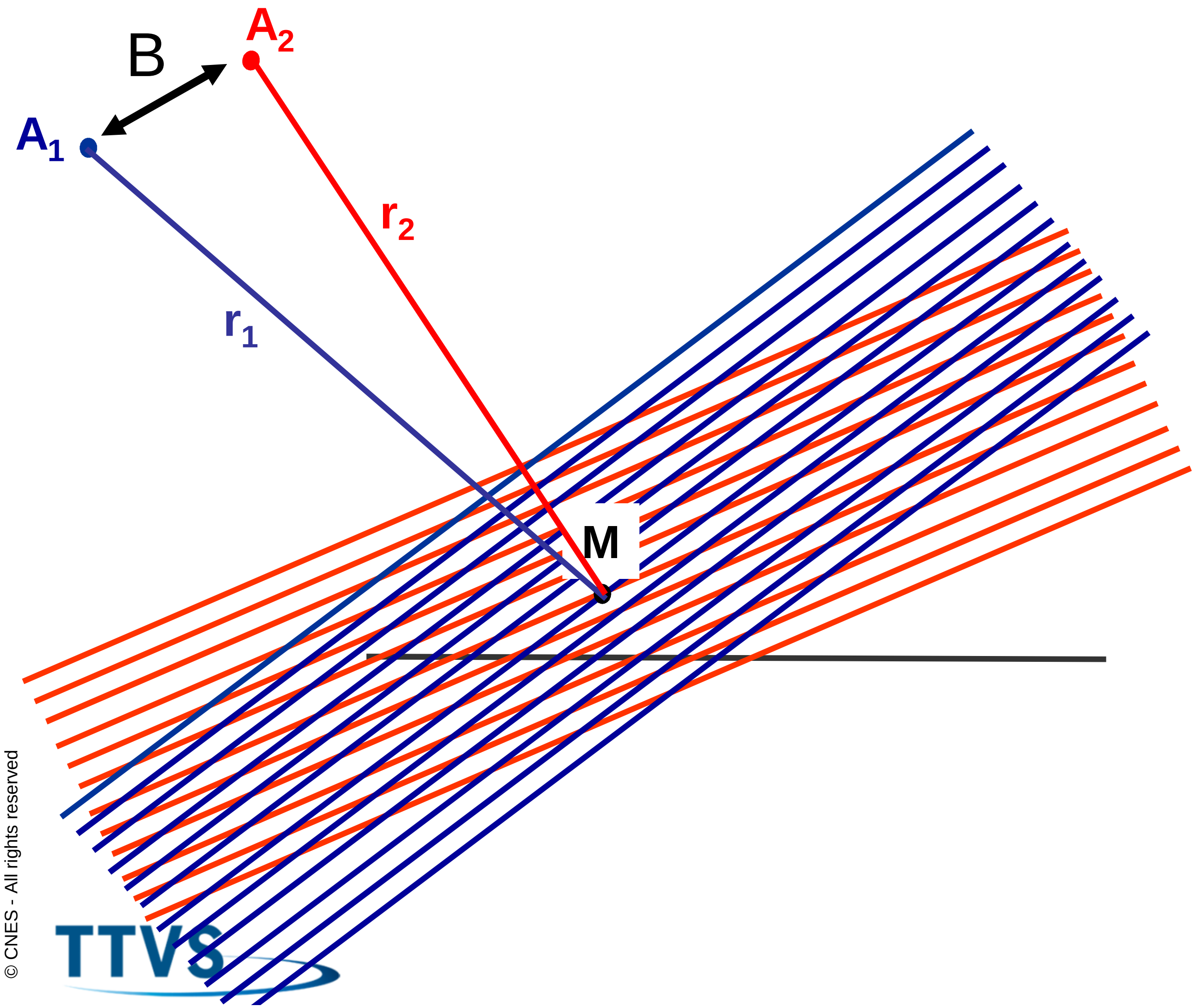


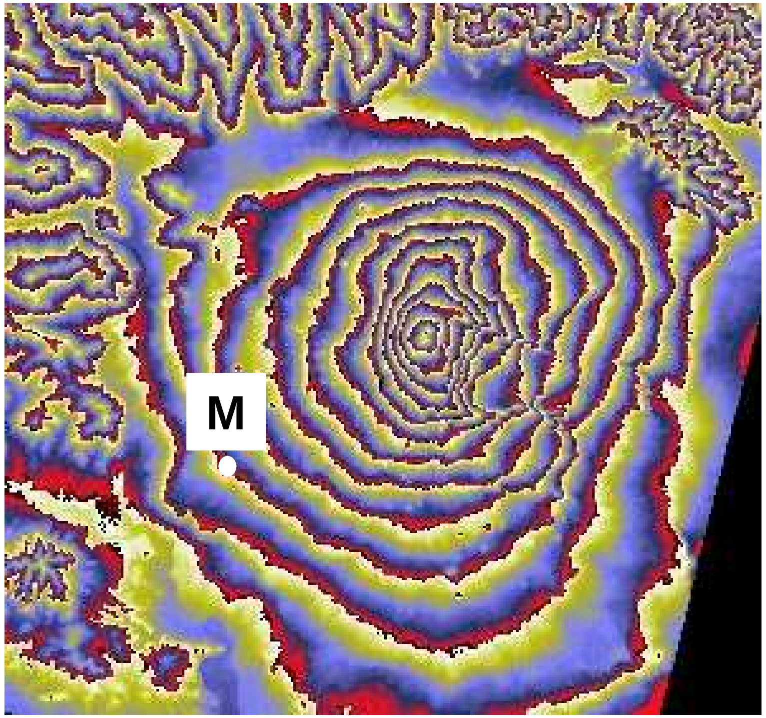
Iso-altitude line (r_1-r_2)

→ Height measurement

Sensibilité topographique et baseline interférométrique

Baseline / wavelength : B/λ (= 2000)





Iso-altitude line (r_1-r_2)

→ Height measurement

TTVS

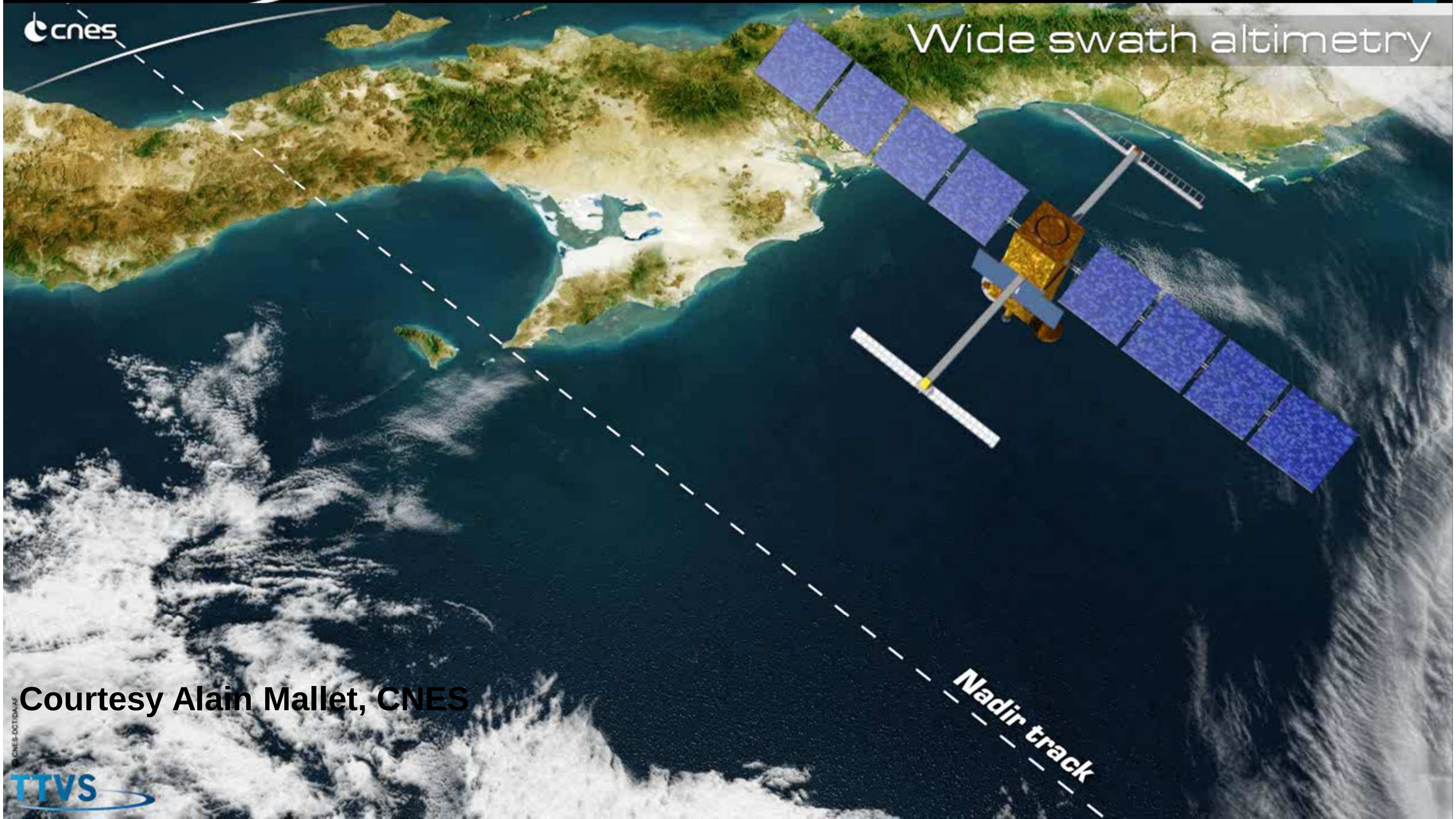
Sensibilité topographique et baseline interférométrique

- Interferométrie = Mesure de hauteur
- Sensibilité topographique ↗ qd : B/λ ↗
- B/λ ↗ qd : λ ↘ (plus facile que ↗ B ! – longueur mât)

→ Transition Bande Ku vers Bande Ka (Gain en sensibilité : 2.6)

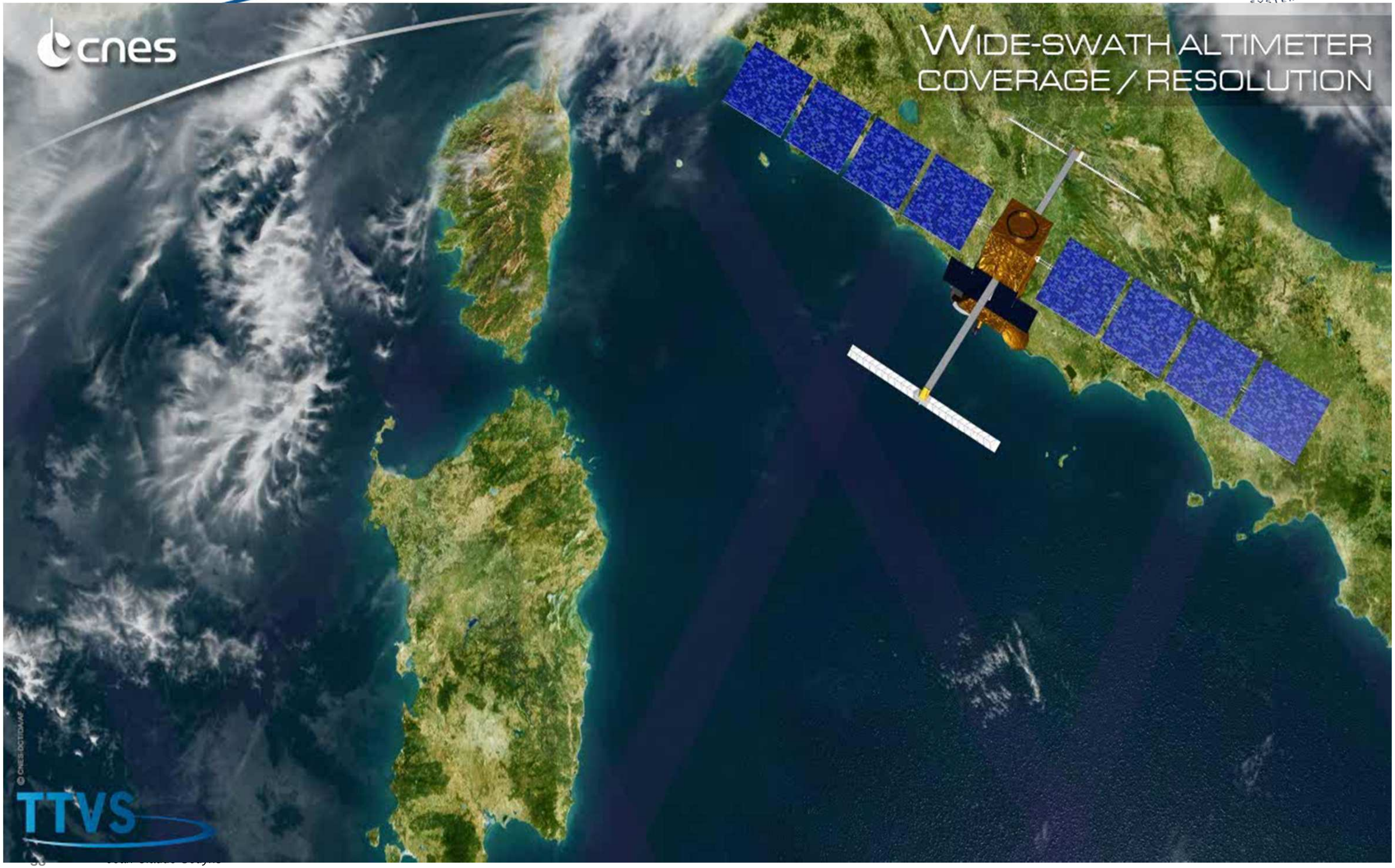
- … En bénéficiant de l'héritage AltiKa

TTVS

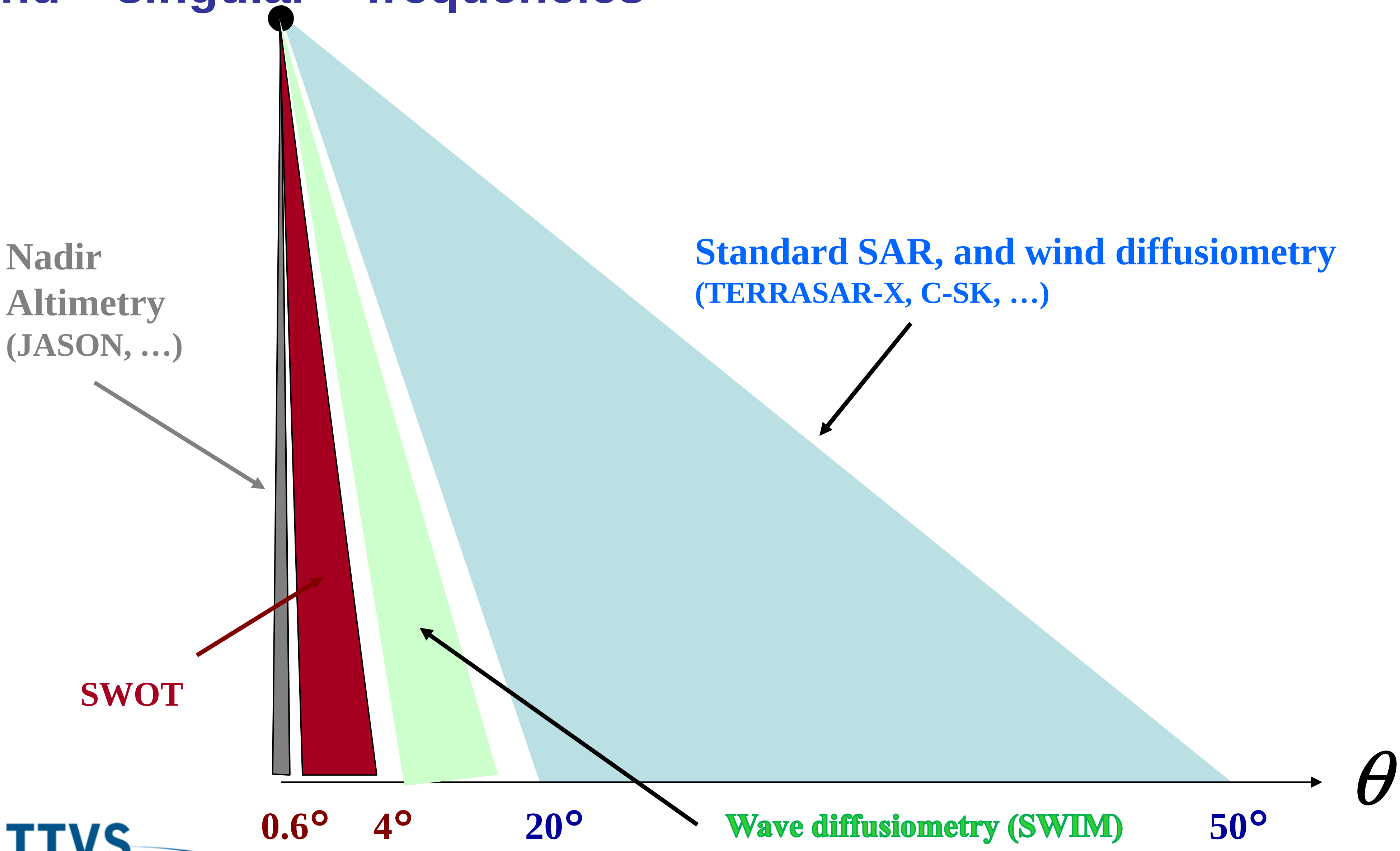


Courtesy Alain Mallet, CNES

SWOT (couverture / résolution)



SWOT geometry : The territory of uncharted incidences … and « singular » frequencies



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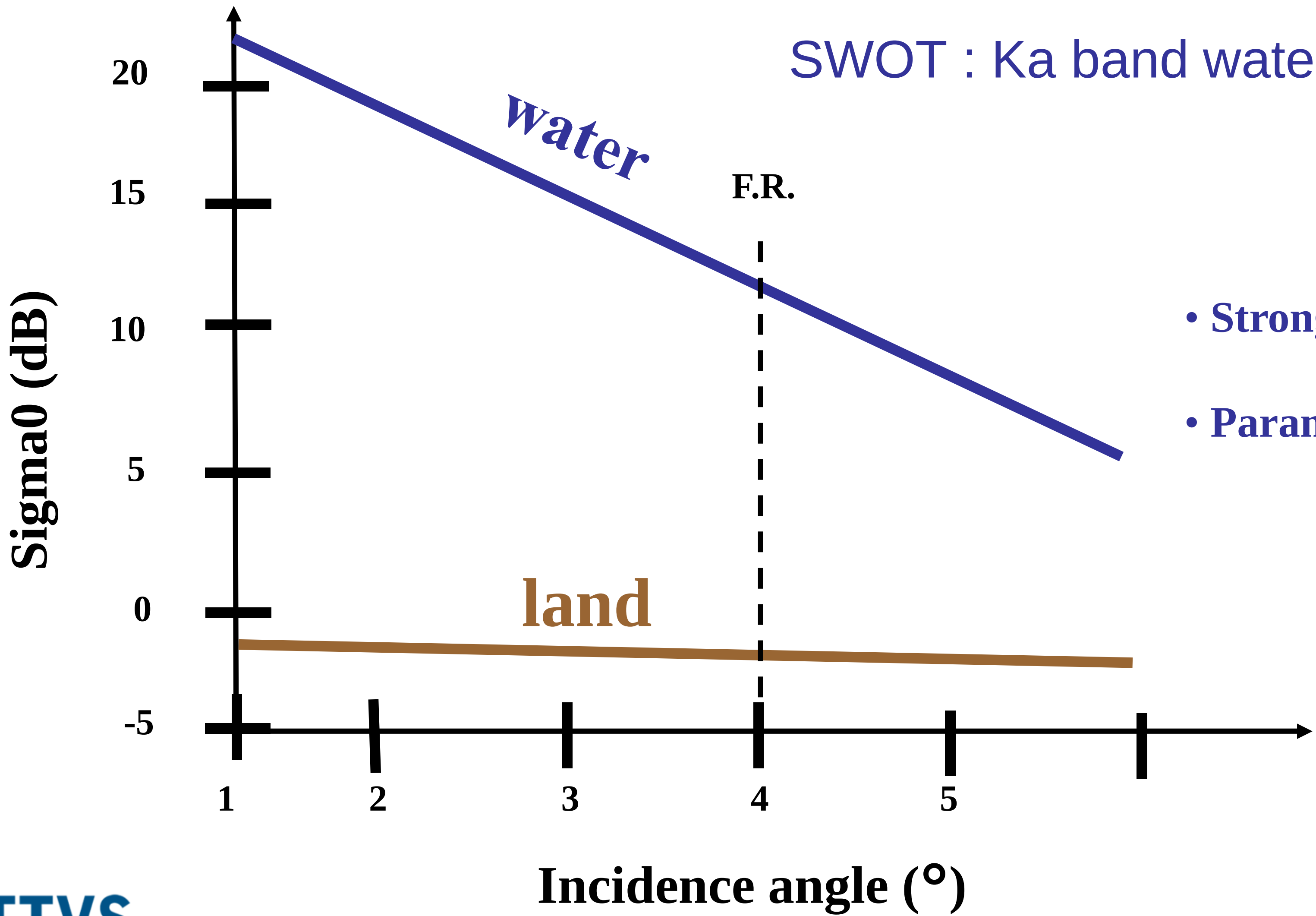
SWOT physics : challenging the contrast between water and soil …



SWOT : Ka band water / land contrast

- Strong contrast (> 10 dB)
- Parameter dependant

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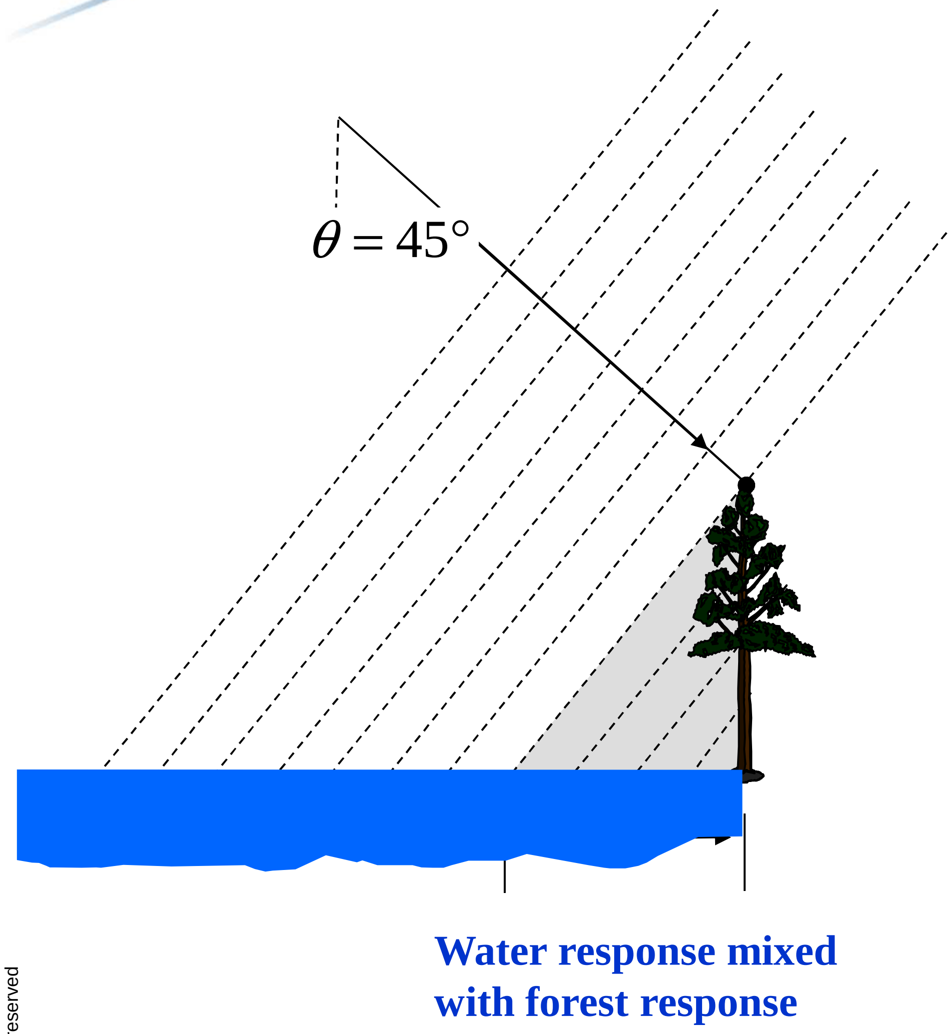
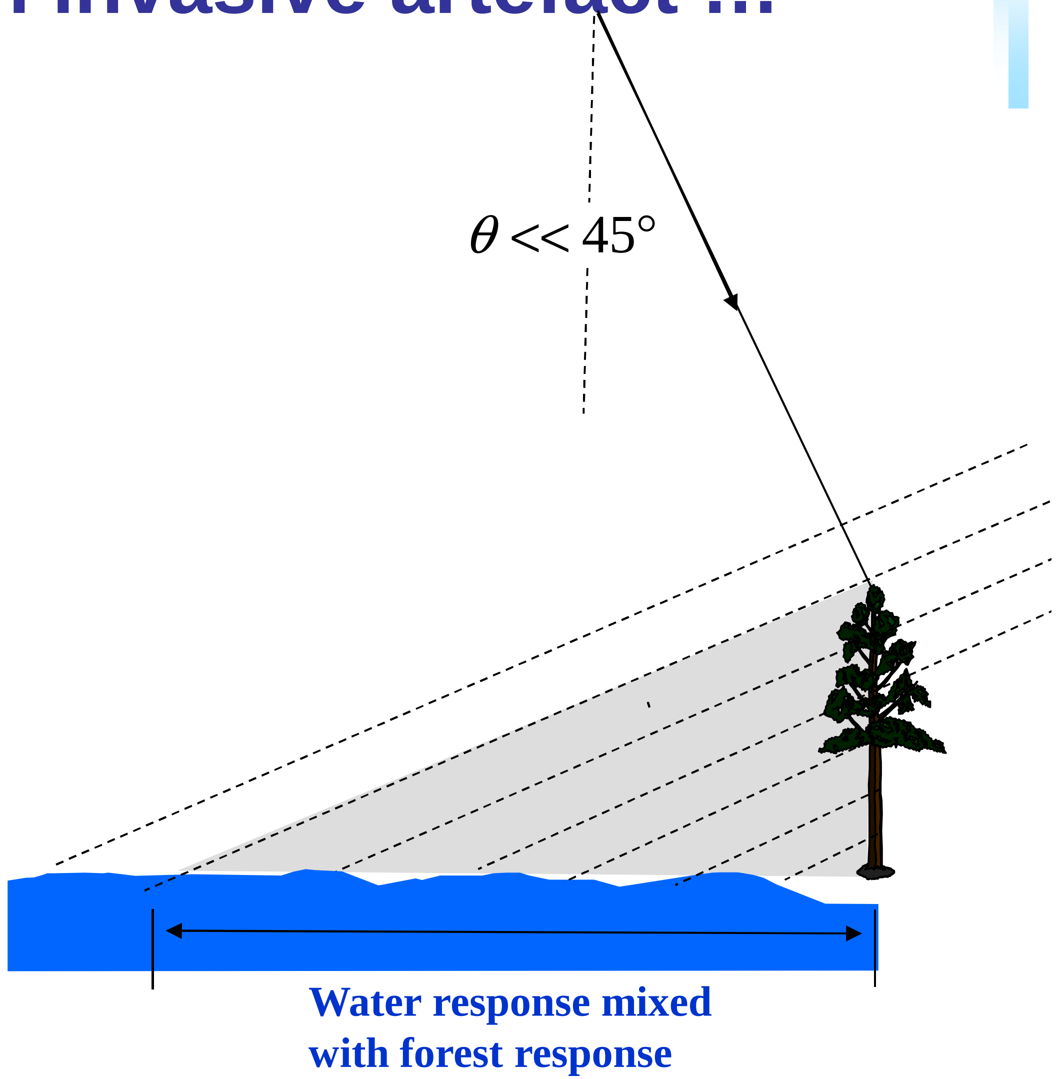
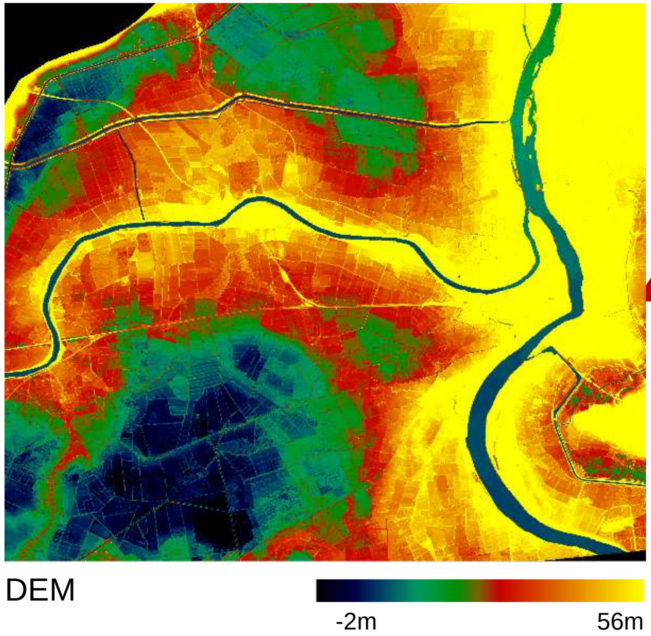
The layover on SWOT, an invasive artefact …





LAYOVER ↗ when θ ↘

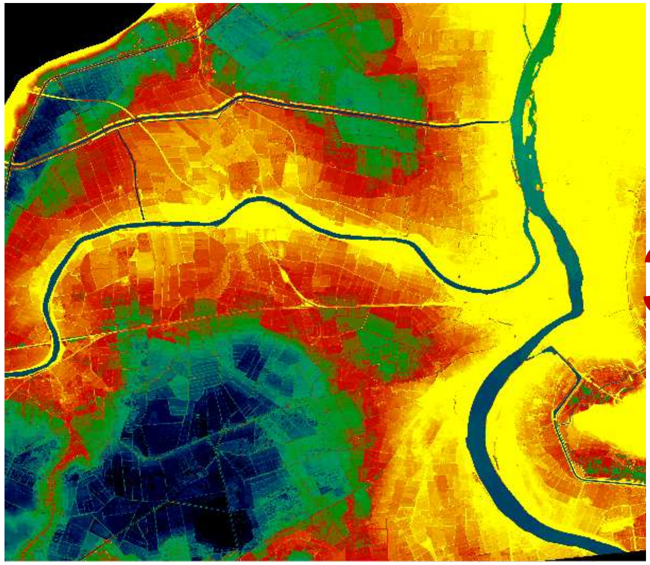
SWOT Layover (4° → 1°)



4°

Layover zones

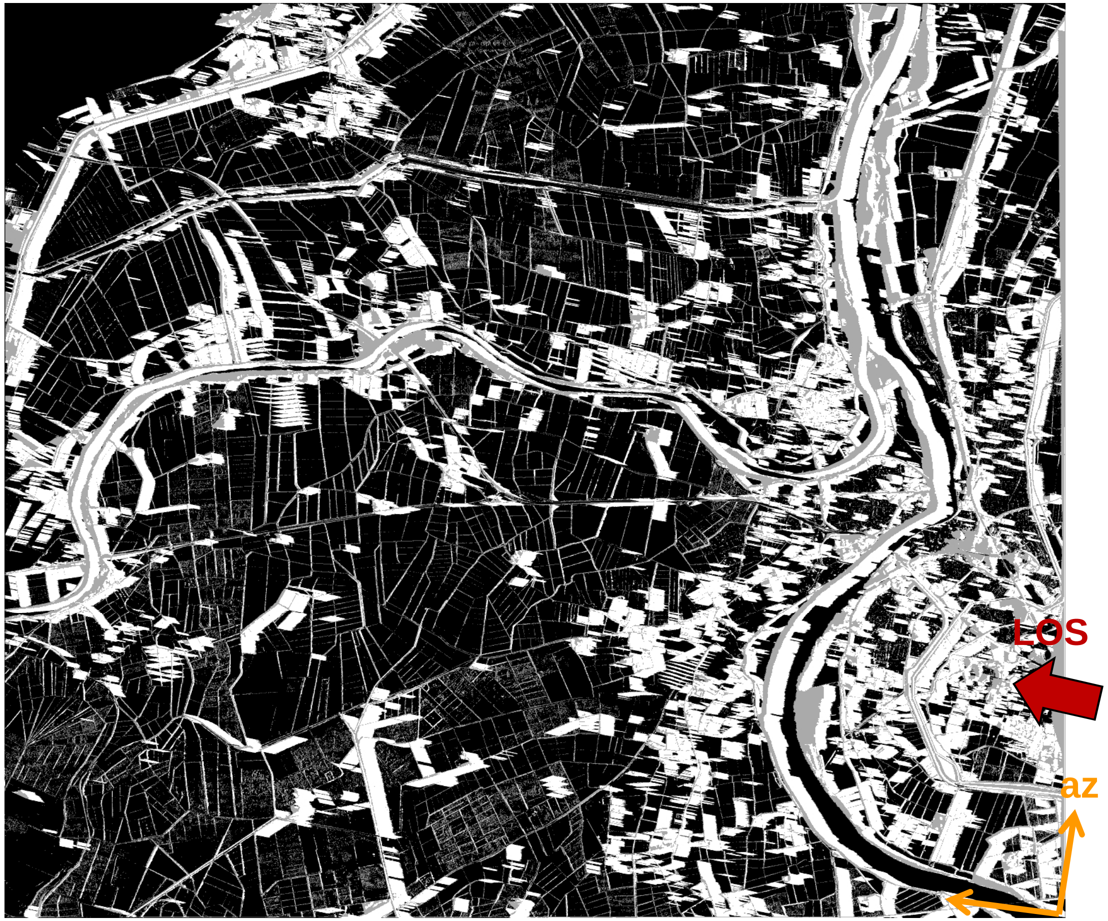
SWOT Layover (4° → 1°)



DEM

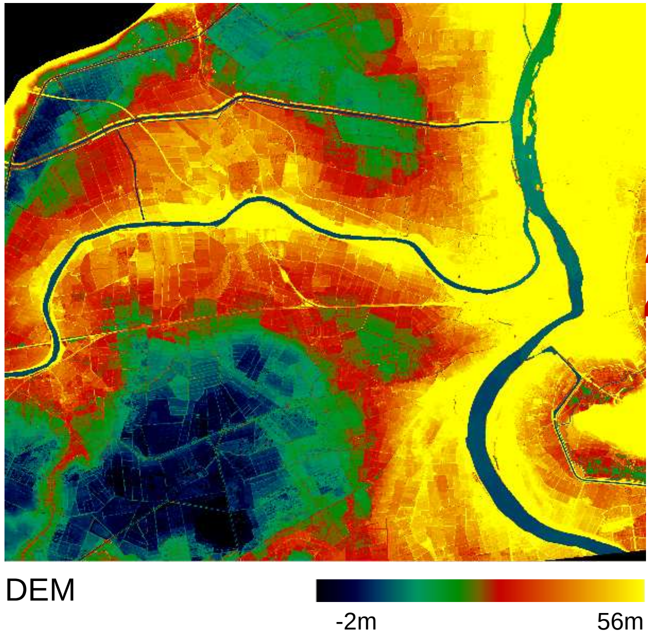
-2m 56m

3°



Layover zones

SWOT Layover (4° → 1°)

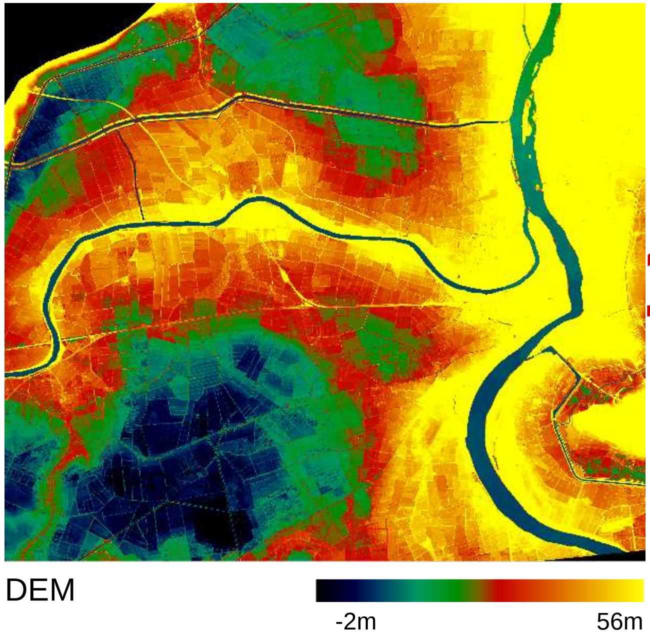


2°

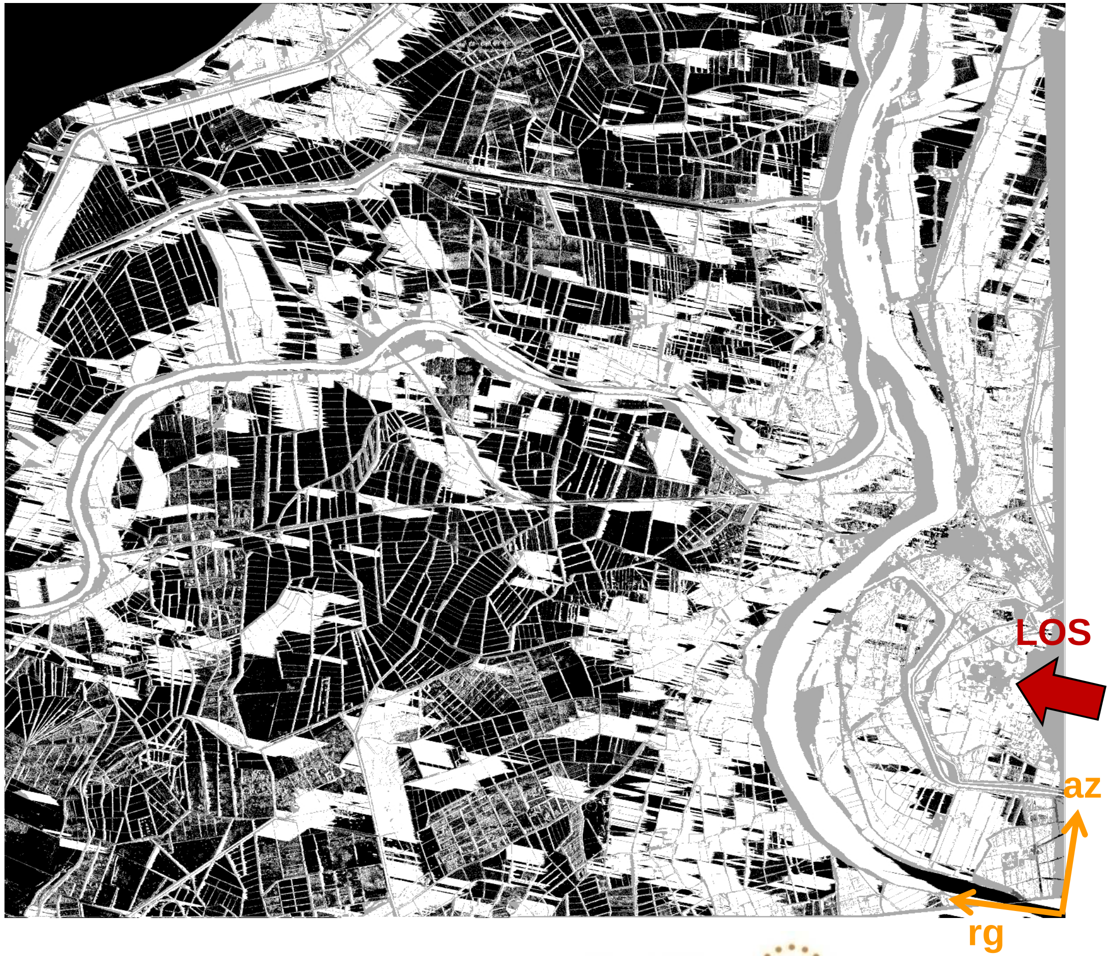
Layover zones

SWOT Layover (4° → 1°)

Lay-over impact reduced tks to strong Water / Land contrast



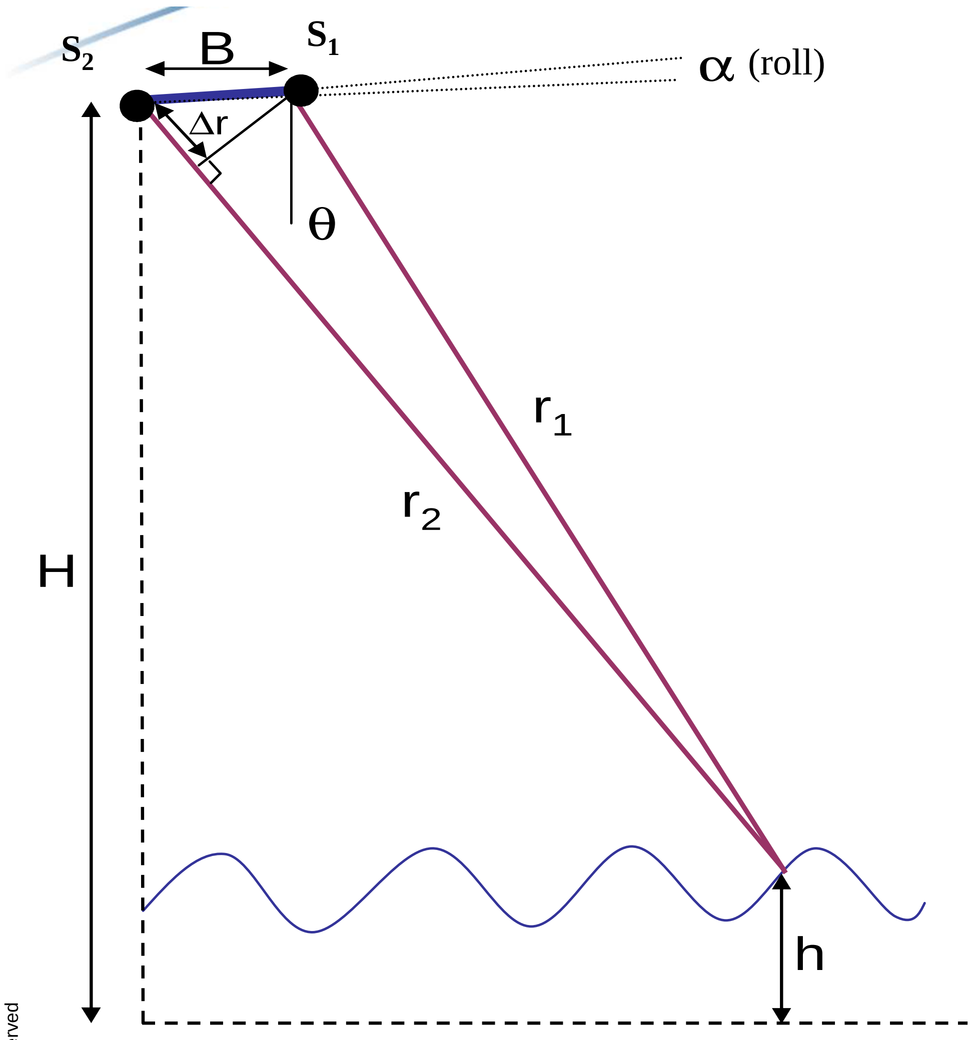
1°



Layover zones

Courtesy Alain Mallet, CNES

SWOT geometry seen from the engeneering team)



Base deformation restitution

↕

Base

SNR, calibration, power budget, …)

↕

Interferometric phase

$$h = f(H, B, r_1, \Phi, \alpha)$$

Orbit ↕ **POD (Doris, GPS, …)**

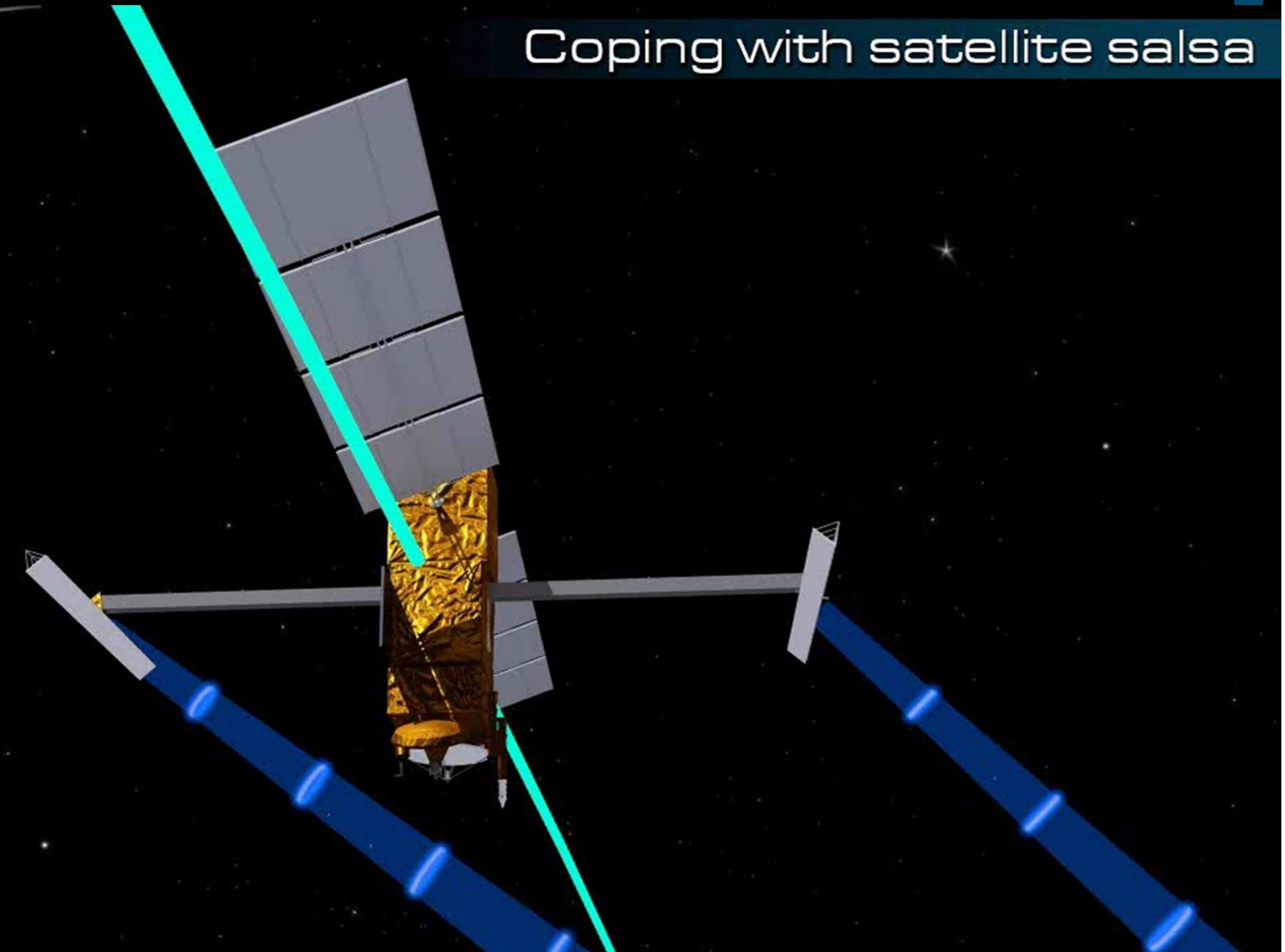
'Time' ↕ **USO (Oscillator)**

'roll angle' ↕ **Roll angle restitution (Calibration)**

$$\Delta r = B.\sin(\theta - \alpha) = \frac{\lambda}{2.\pi}.\Phi$$

Φ : interferometric phase

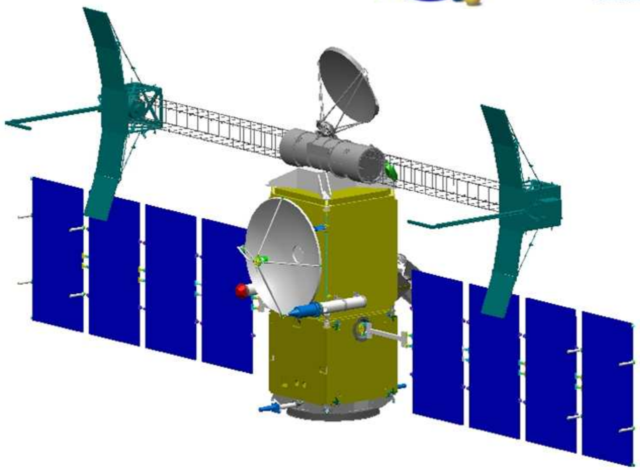
Coping with satellite salsa



KaRIn instrument on SWOT : heritages

- **SRTM** "Shuttle Radar Topography Mission"
  - \- C band and X band, 60 meters mast
  - \- 10 days acquisition in 2000 ➔ global DEM

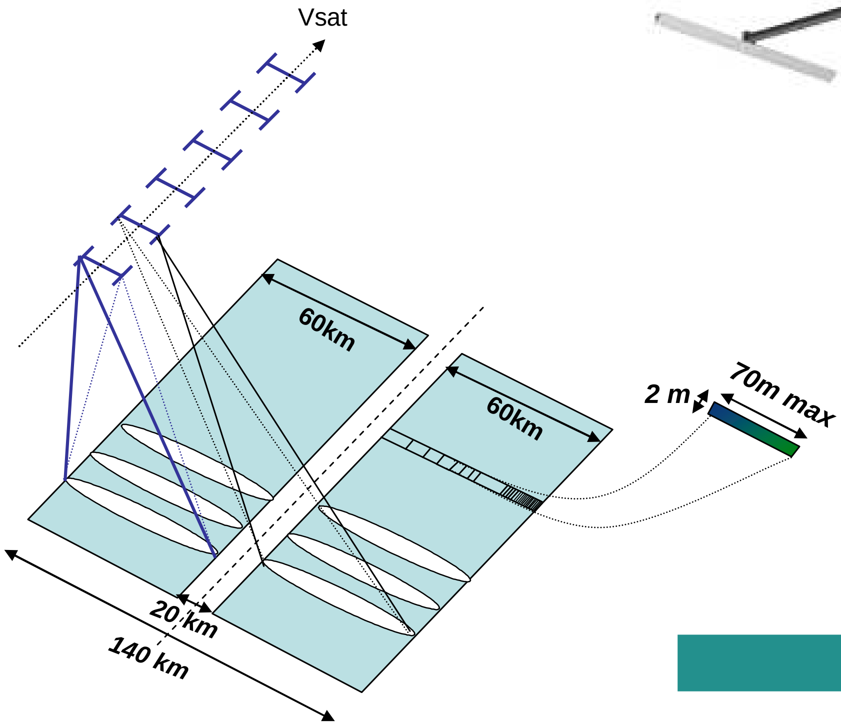
- **WSOA** instrument considered for JASON2
  - \- Ku band, 7 meters mast

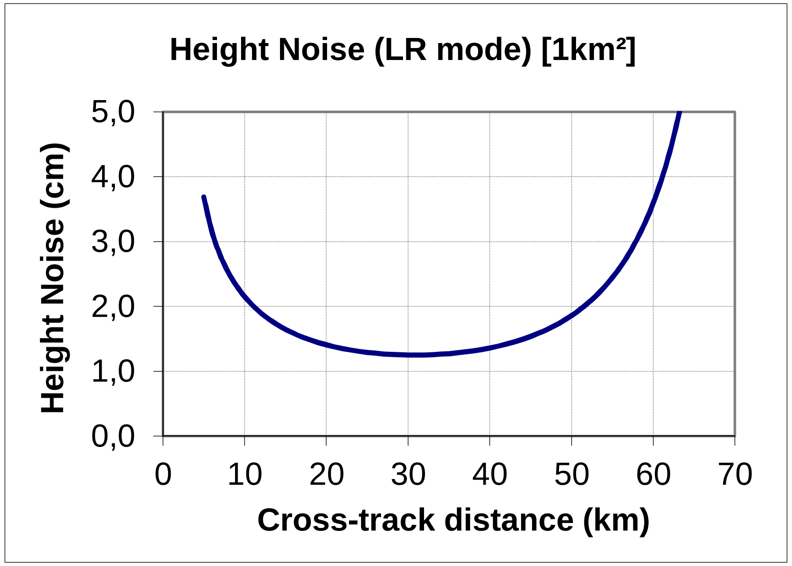


TTVS

KaRIn on SWOT

Acquisition geometry / Ocean height error performances

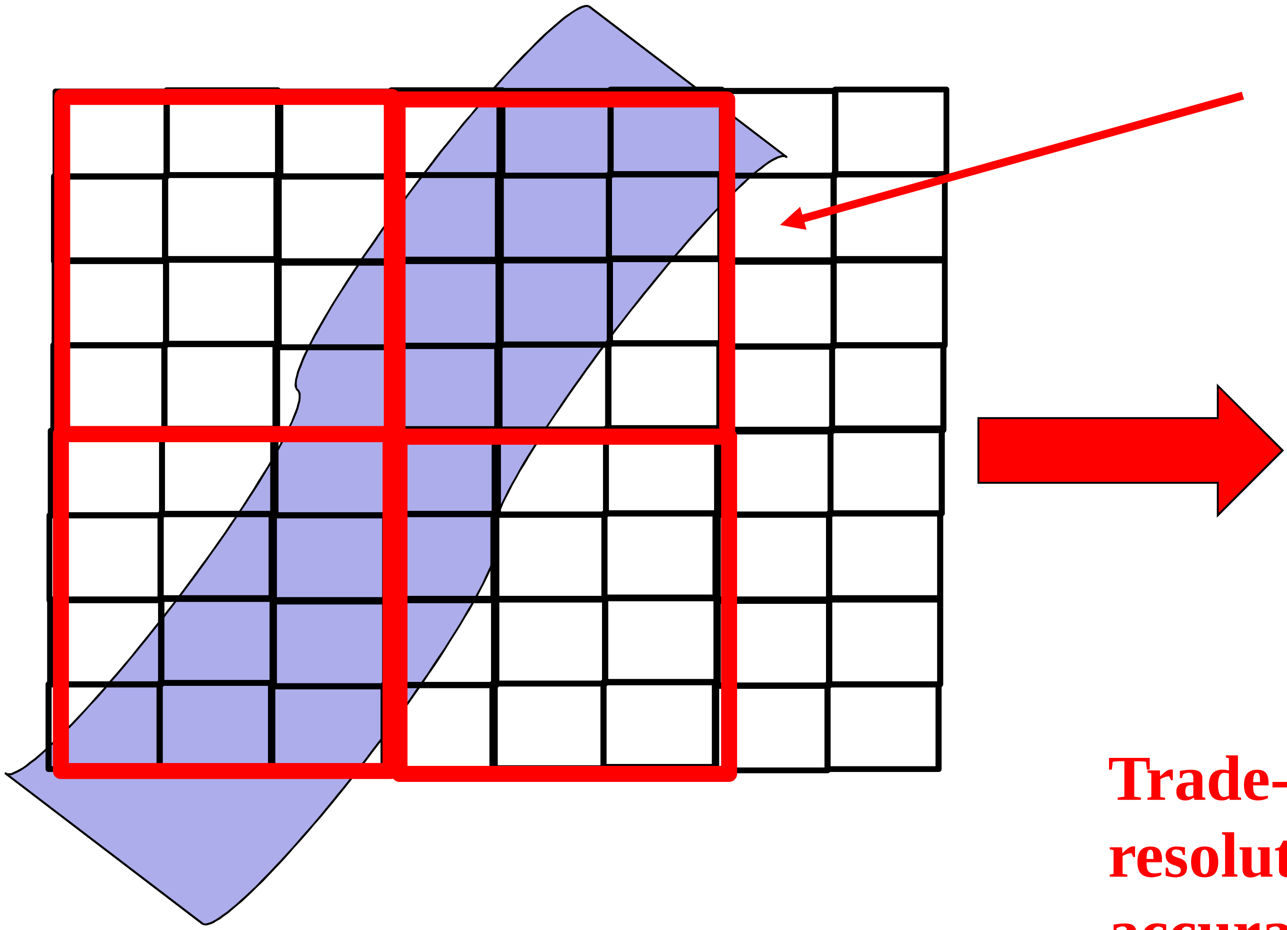




1km² averaging

DEM

➔ Vertical accuracy : if it is not enough …



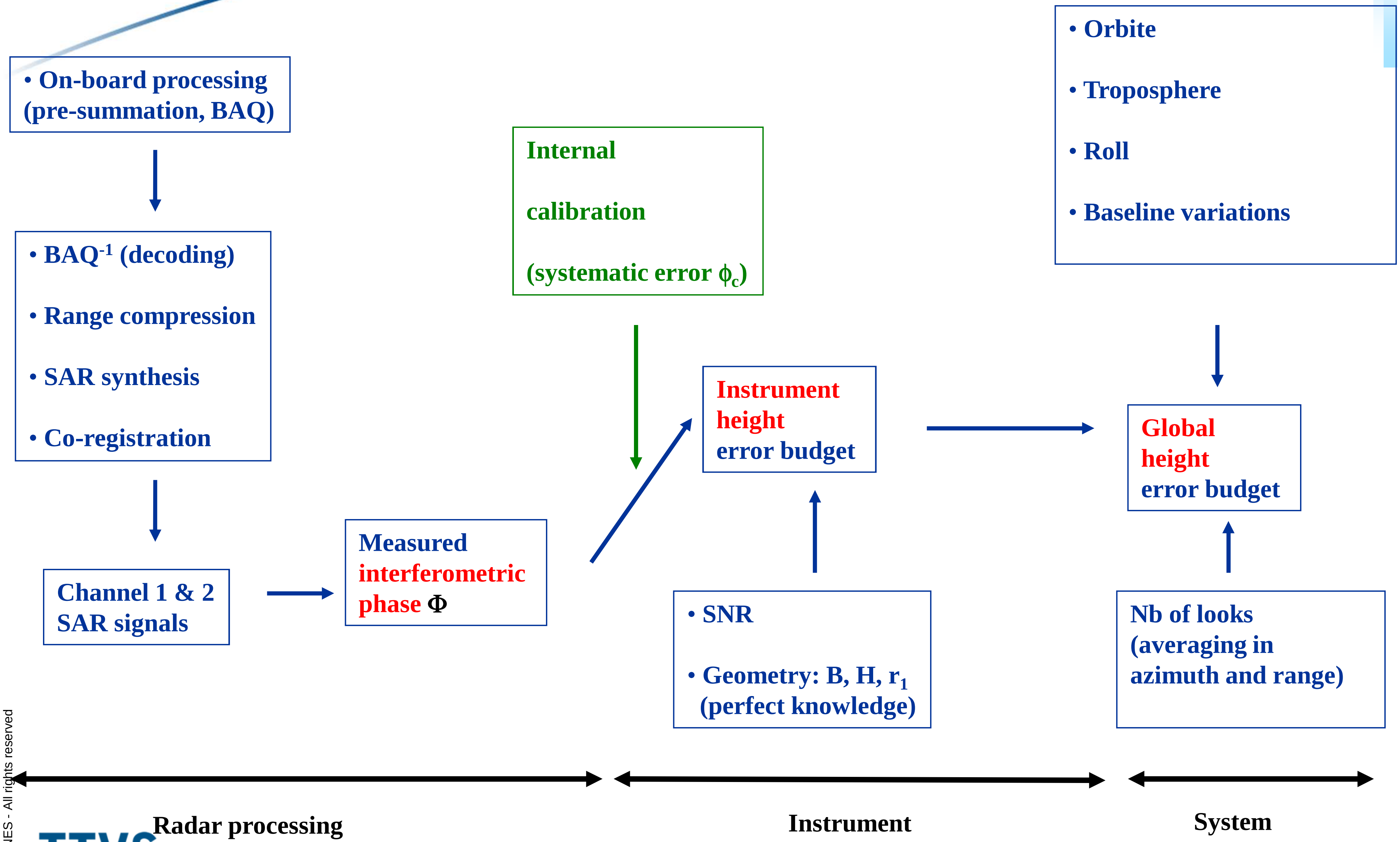
Group on N pixels

$$\sigma_z = \frac{\sigma_\varphi}{2.\pi}.Ea \cdot \frac{1}{\sqrt{N}}$$

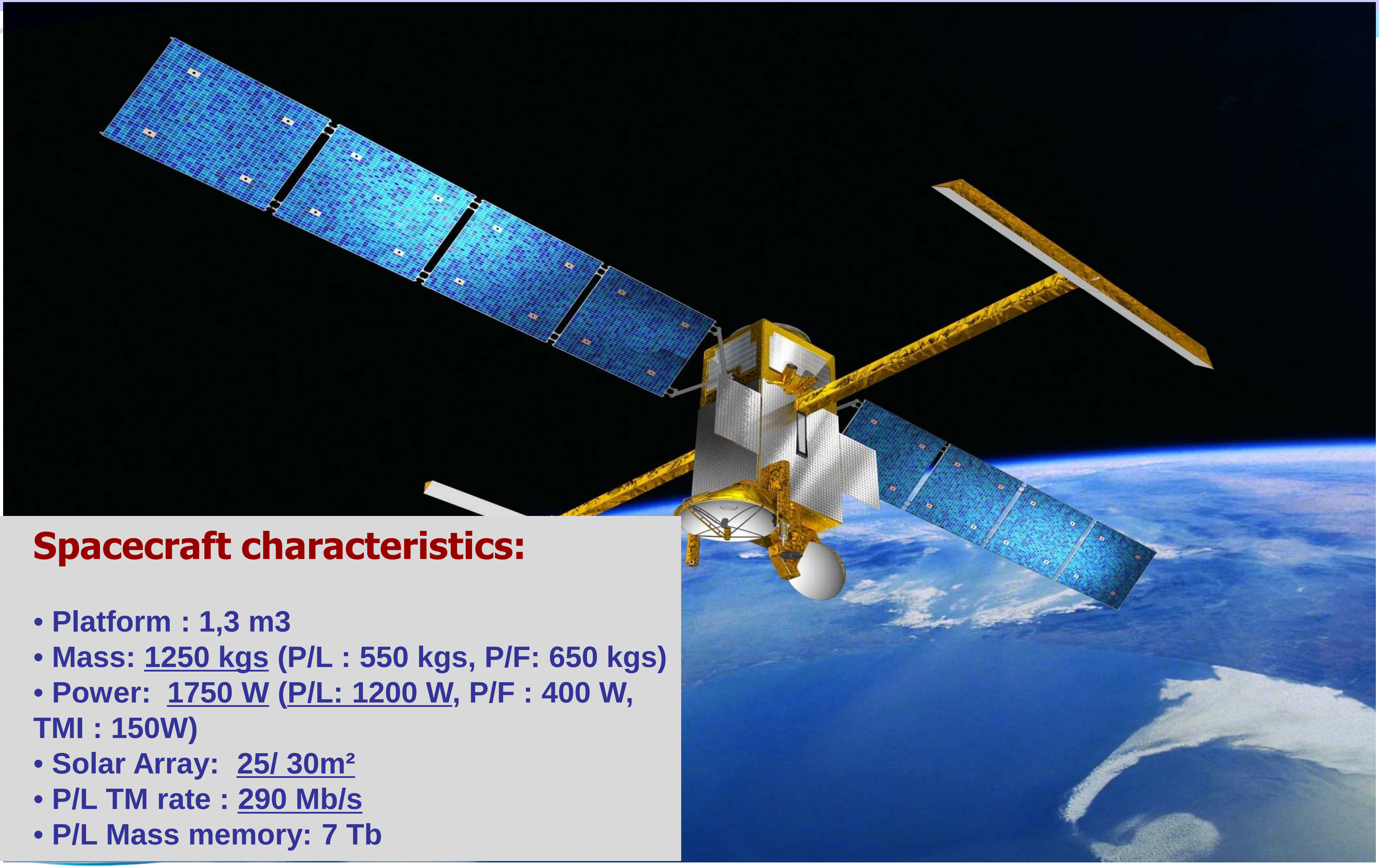
$$\sigma_z = \frac{\sigma_\varphi}{2.\pi}.Ea$$

Trade-off between planimetric resolution and altimetric accuracy on N pixels

The interferometric end-to-end performance



SWOT FOR OCEANOGRAPHY AND HYDROLOGY (NASA / JPL – CNES, 2020)
INTEFEROMETRY FOR WATER AREAS !



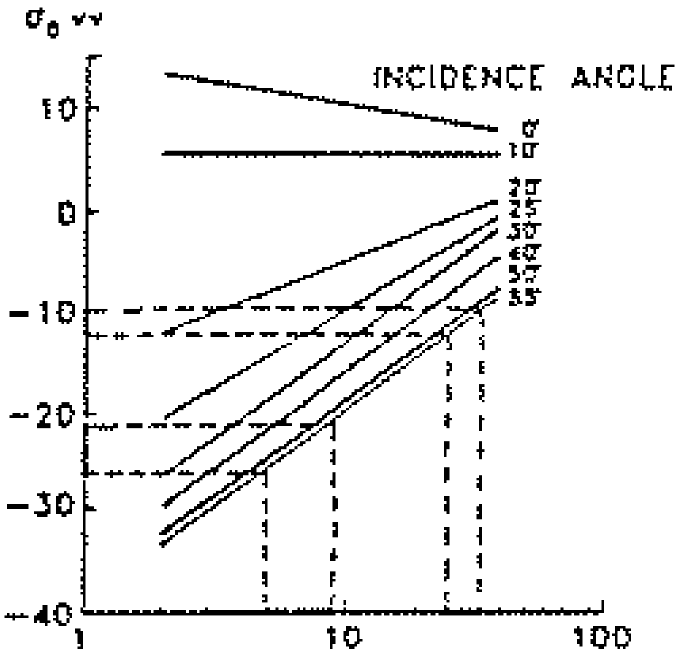
Spacecraft characteristics:

- Platform : 1,3 m3
- Mass: 1250 kgs (P/L : 550 kgs, P/F: 650 kgs)
- Power: 1750 W (P/L: 1200 W, P/F : 400 W, TMI : 150W)
- Solar Array: 25/ 30m²
- P/L TM rate : 290 Mb/s
- P/L Mass memory: 7 Tb

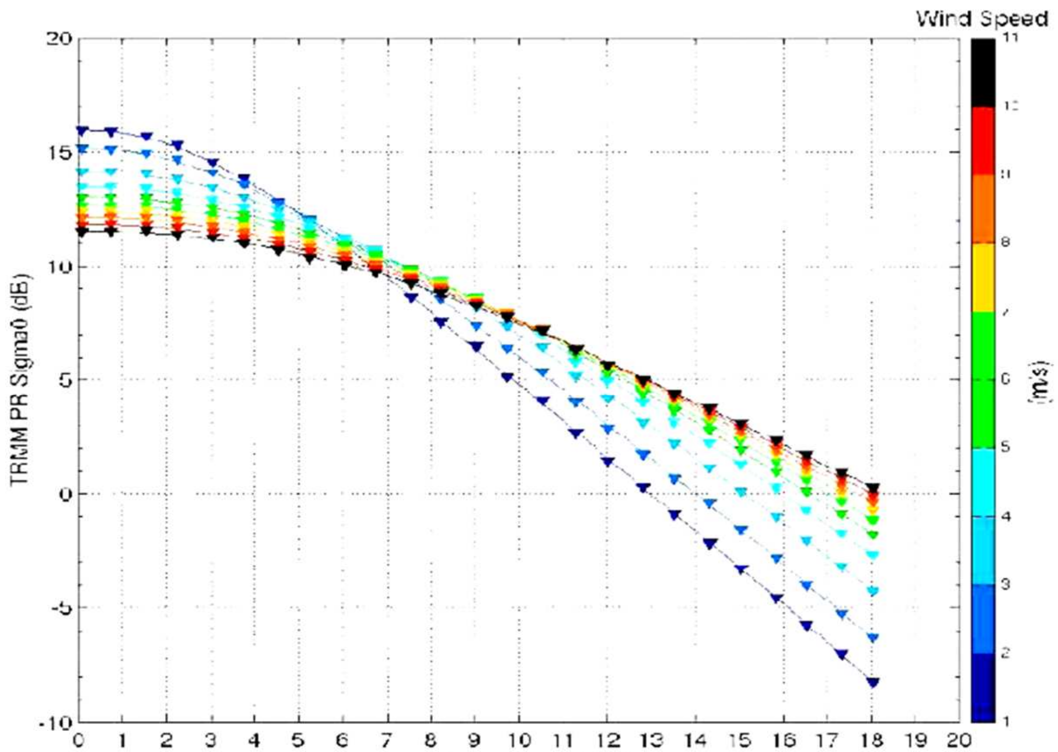
Wave and Wind scatterometry

Wind Scatterometer : principle

As the wind blows over the ocean, the surface is roughened by the generation of capillary waves. These, in turn, modify the surface backscatter (reflected signal or echo) properties.

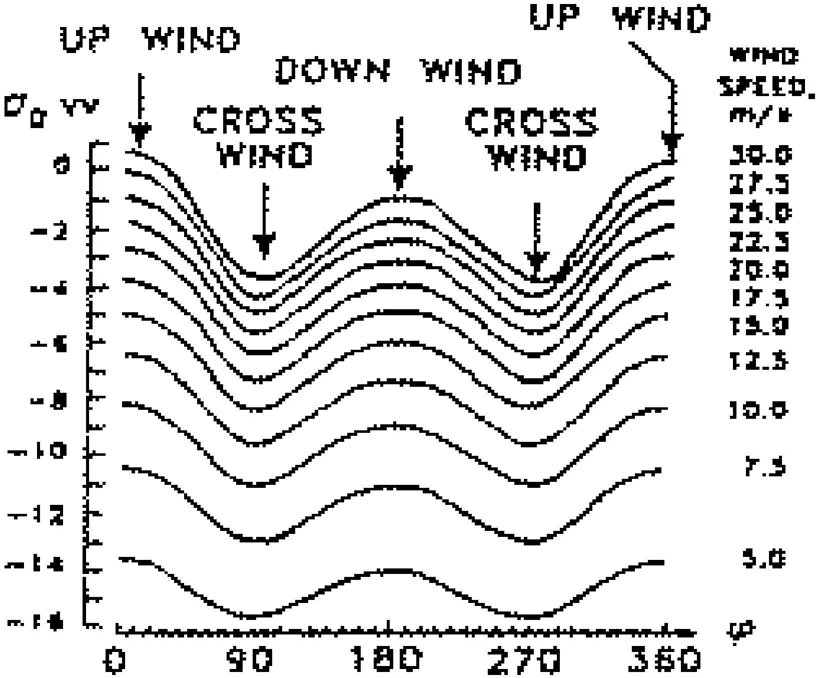


Wind speed (m/s)



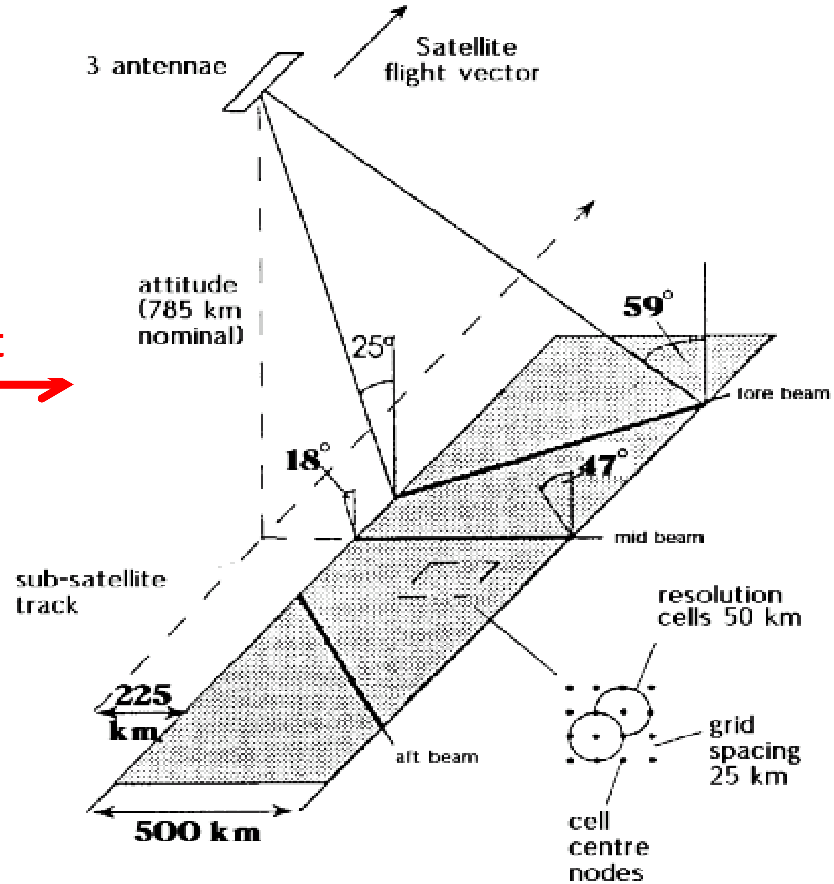
Incidence angle (deg)

Wind Scatterometer : wave impact

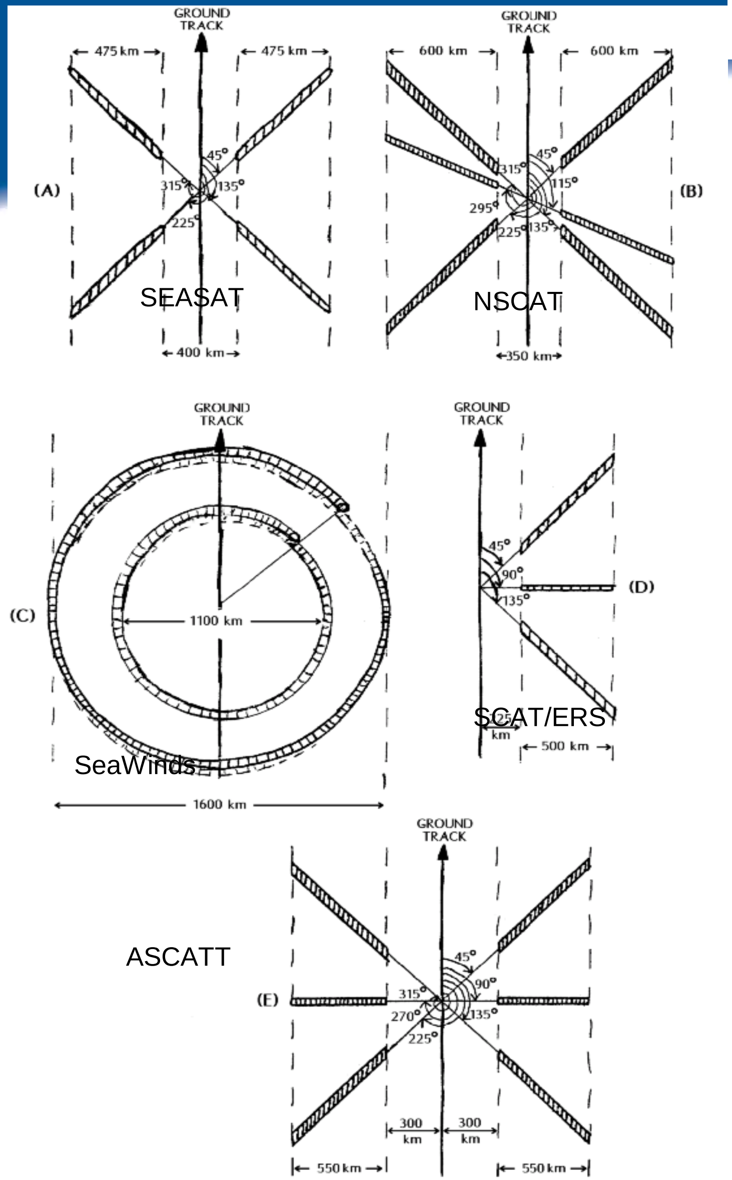


Wind direction (deg.)

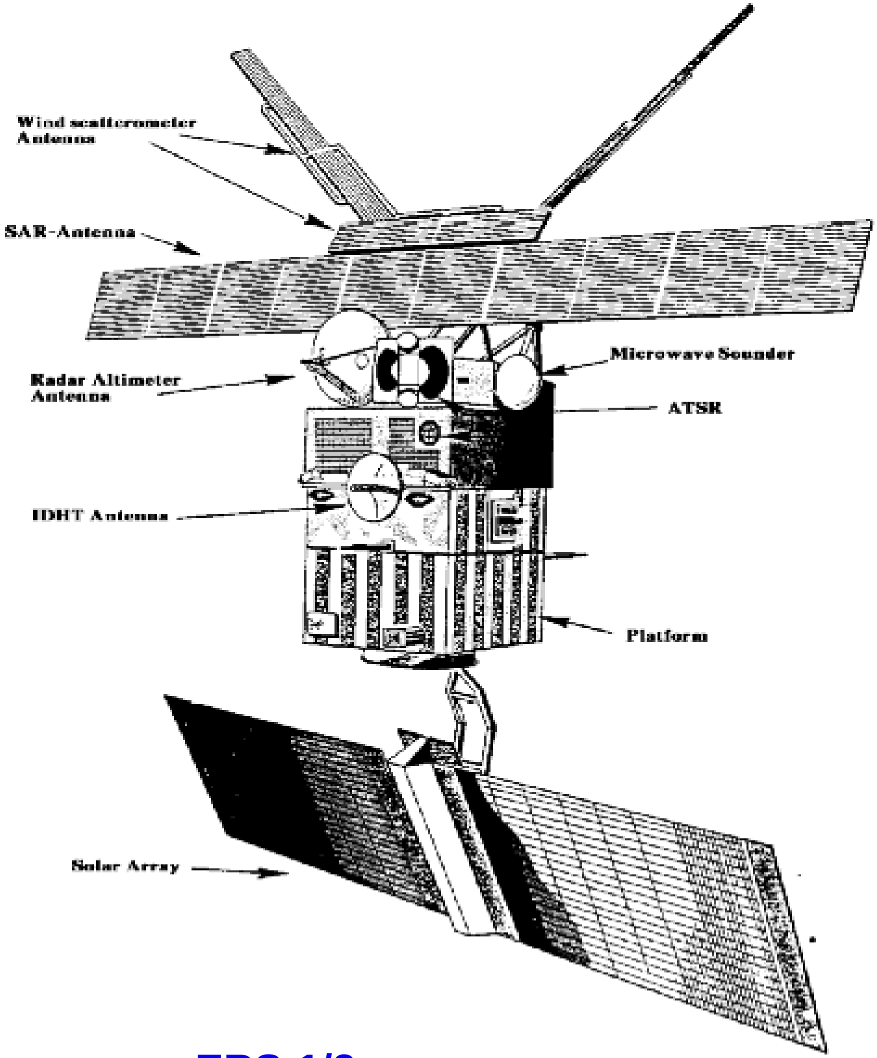
Multi-directional measurement



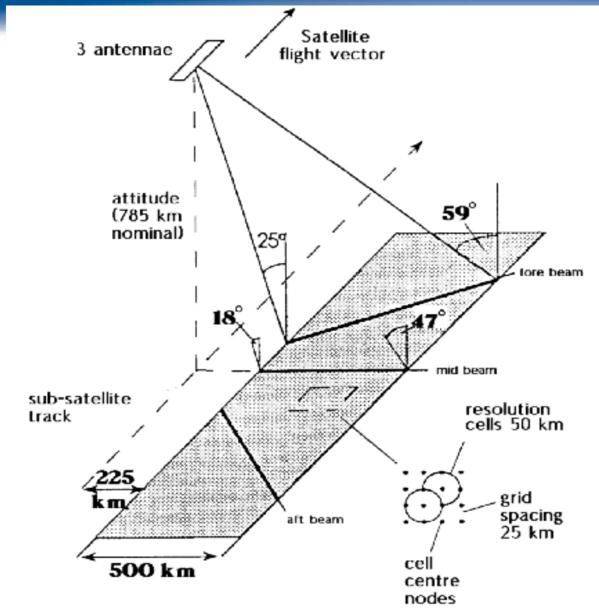
Wind Scatterometer annuary

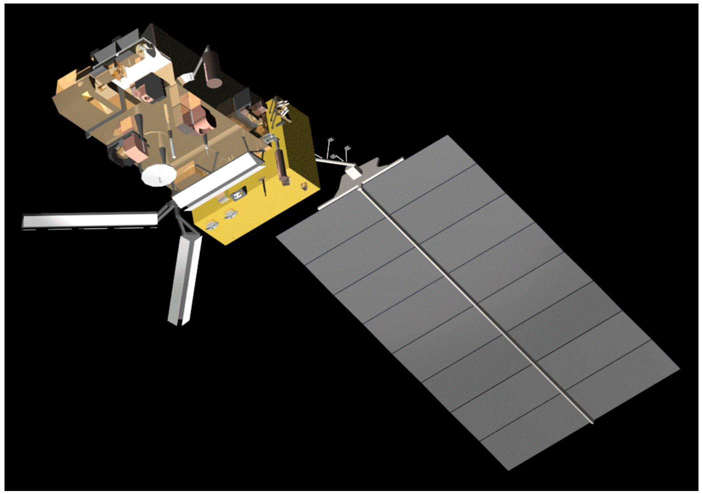


Projects	SEASAT	ERS-1 ERS-2	NSCAT	ASCAT	SeaWinds
Launch	1978	1991,1994	1996	2006	1998/2000
Frequency	14.6 (Ku)	5.3 (C)	13.995 (Ku)	5.3 (C)	13,4 (Ku)
Space resolution (km)	20x60	50x50	25x25	50x50	50 x 50
Swath (Km)	2x500	1x500	2x600	2x500	1800
Antennas	4	3	6	6	1 (2 faisceaux)
Antennas Dimensions(m)	0.15x2.3	0.4x3.6	0.15x3	0.4x4	∅ 1 m
Polarization	VV,HH	VV	VV,HH	VV	?
Peak power (W)	110	5000	120	120	110
Pulse length	4.8 ms	100 µs	5 ms	6 ms	?
Altitude (km)	800	780	820	800	820
Mass (kg)	102	270	235	175	200
Consumption (W)	136	531	275	277	200

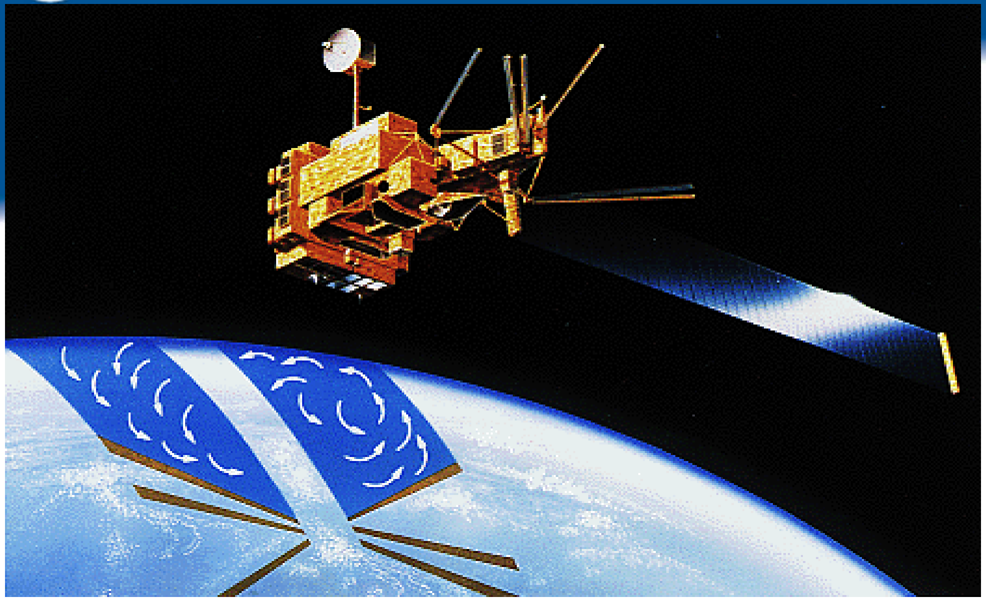


ERS-1/2

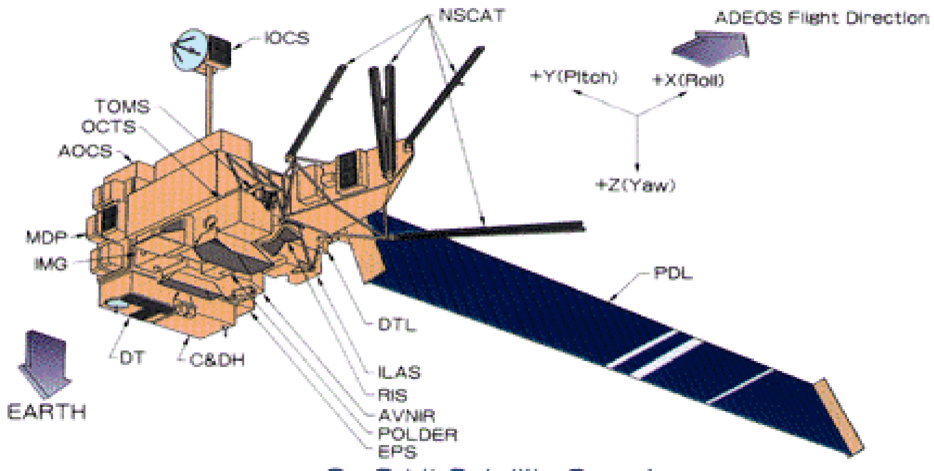




ASCAT / METOP



NSCAT / ADEOS

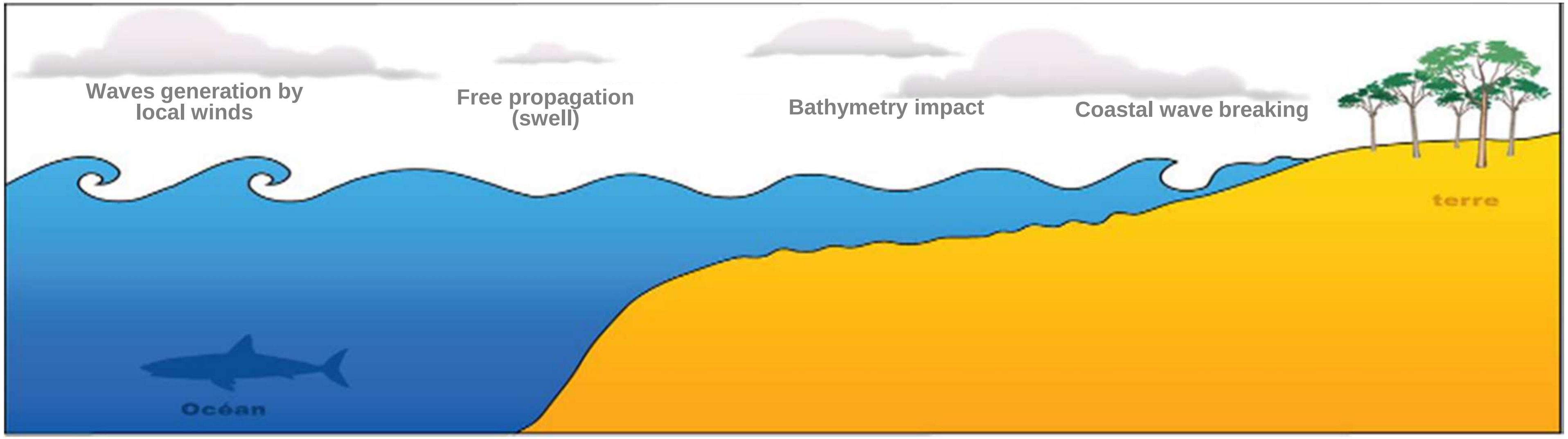


On-Orbit Satellite Overview

SeaWinds / QuikScat

Wave scatterometry

Wave radar scatterometry?



Different kinds of waves corresponding to different sea states

- Wind Sea
- Swell
- Mixed sea conditions

Wave radar scatterometry?

Radar scatterometer

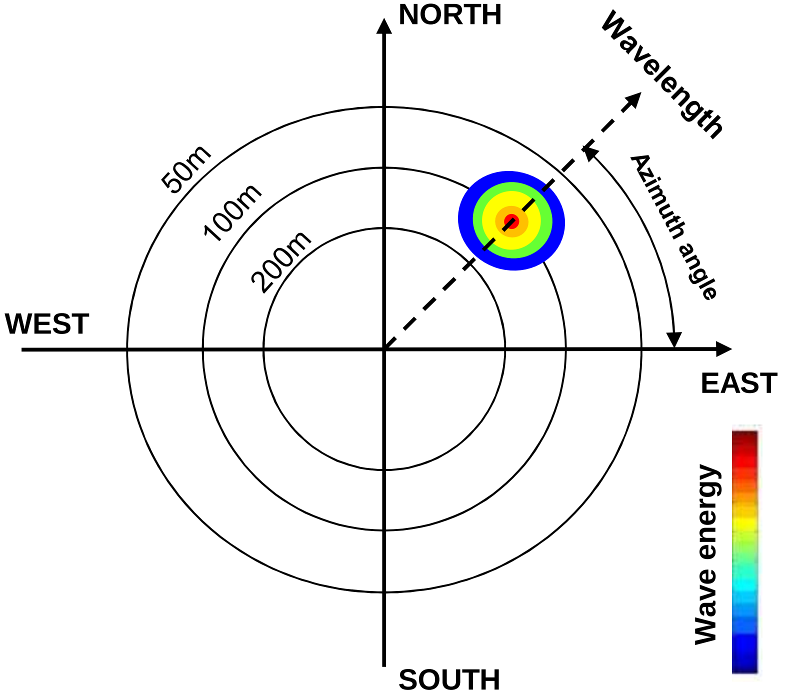
↓

Directional wave spectrum

- Distribution of the waves heights with regards to:
  - their wavelength
  - their propagation direction

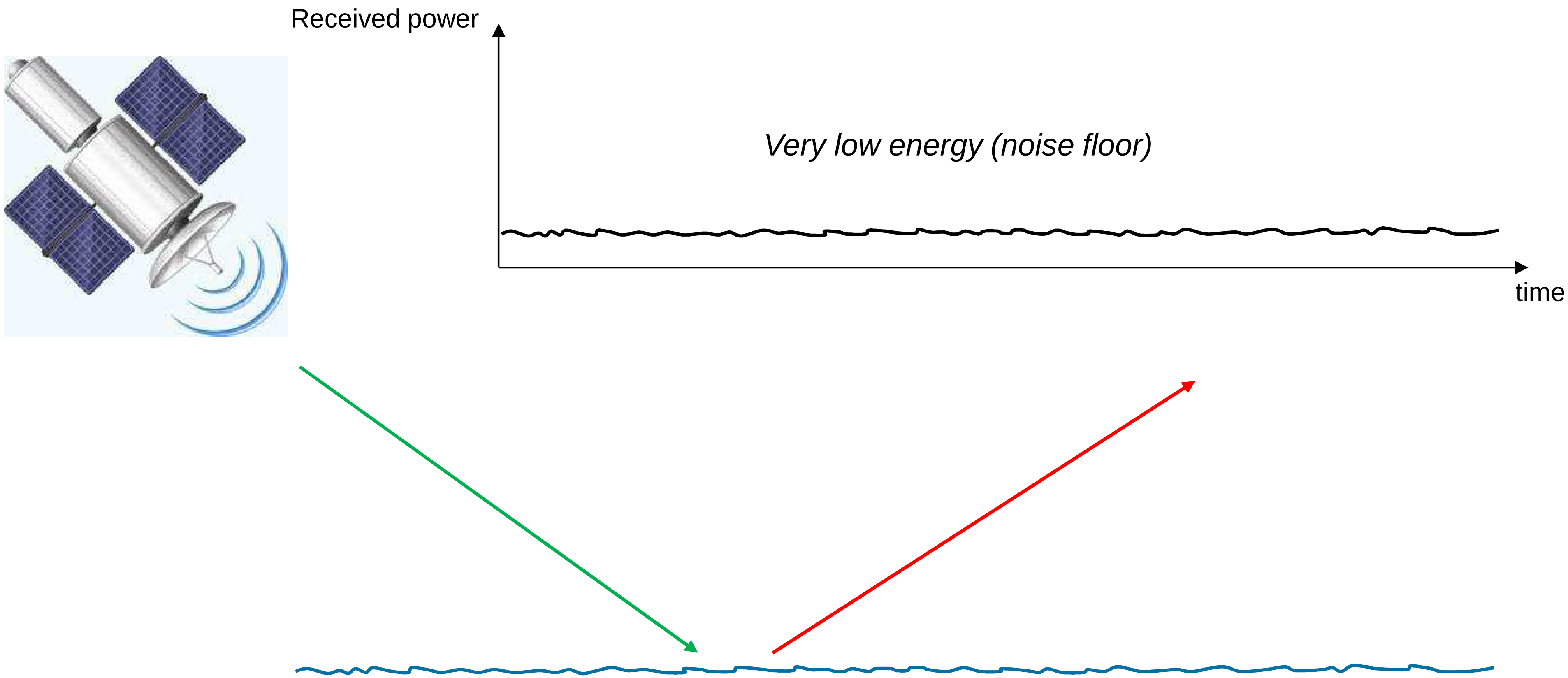
↓

Sea state information through wave characteristics



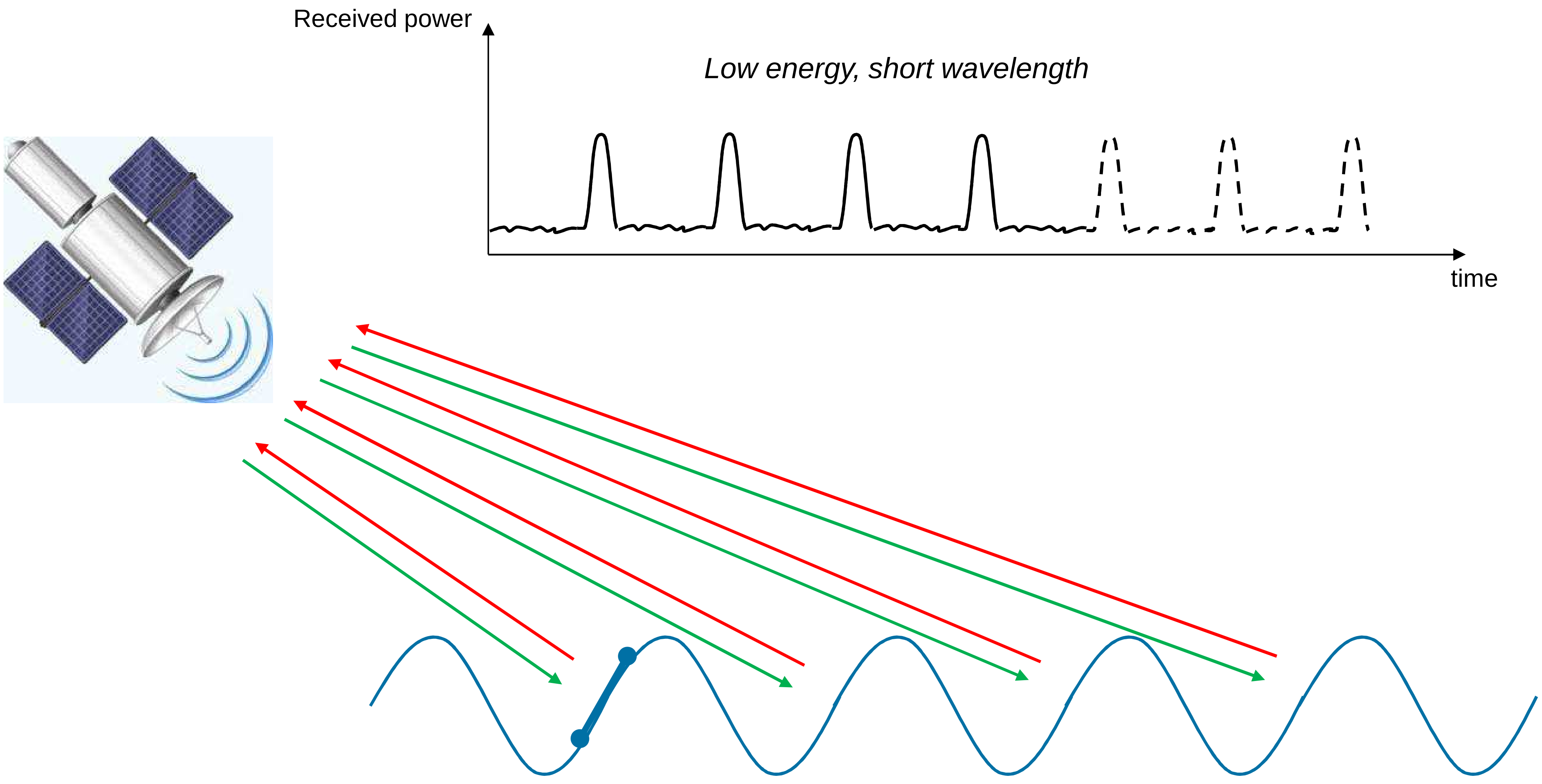
Wave radar scatterometry?

How to characterize the waves with a radar ?



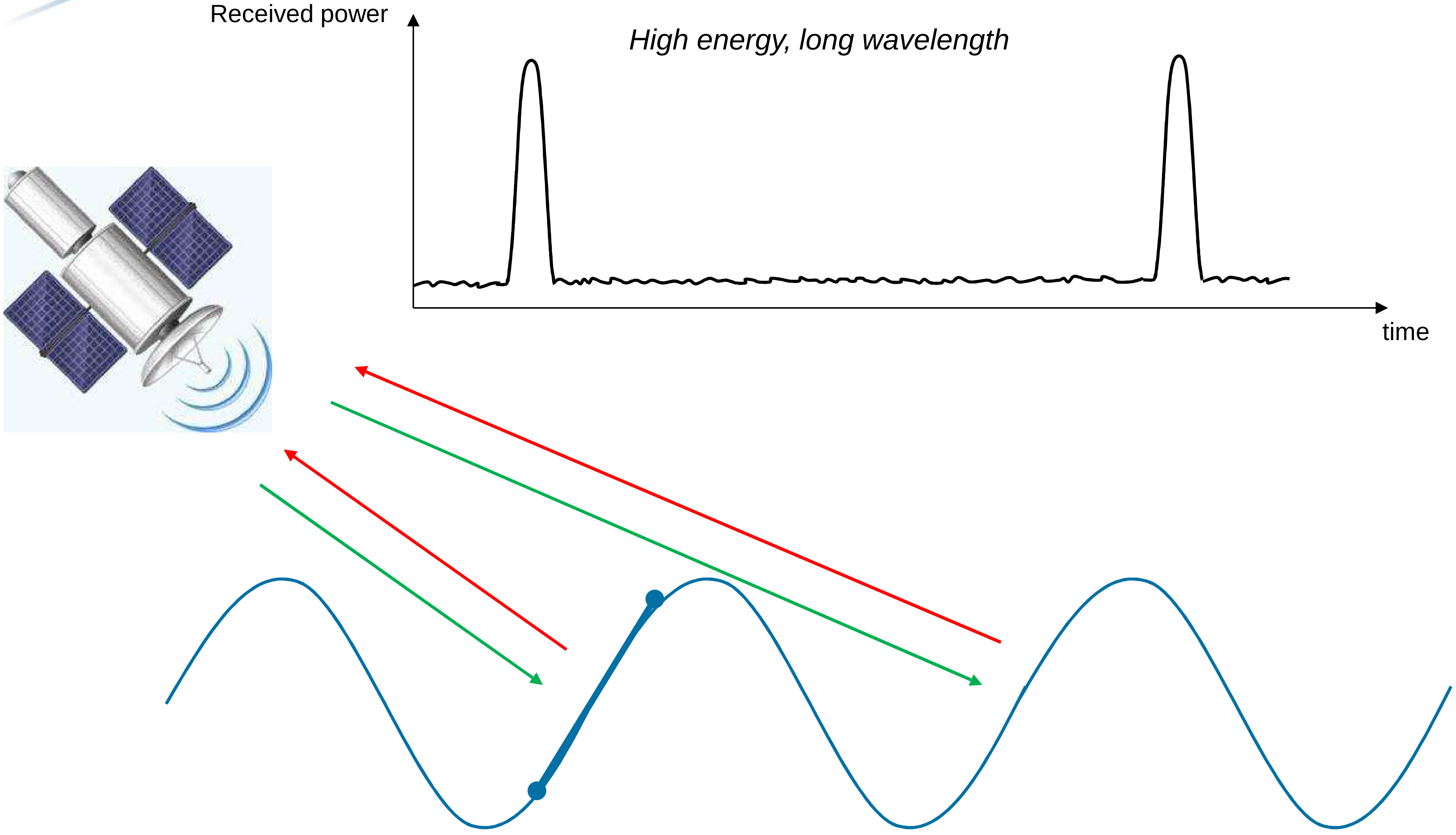
Sea surface: case with no waves

Wave radar scatterometry?



Sea surface: small waves (low heights, short wavelength)

Wave radar scatterometry?



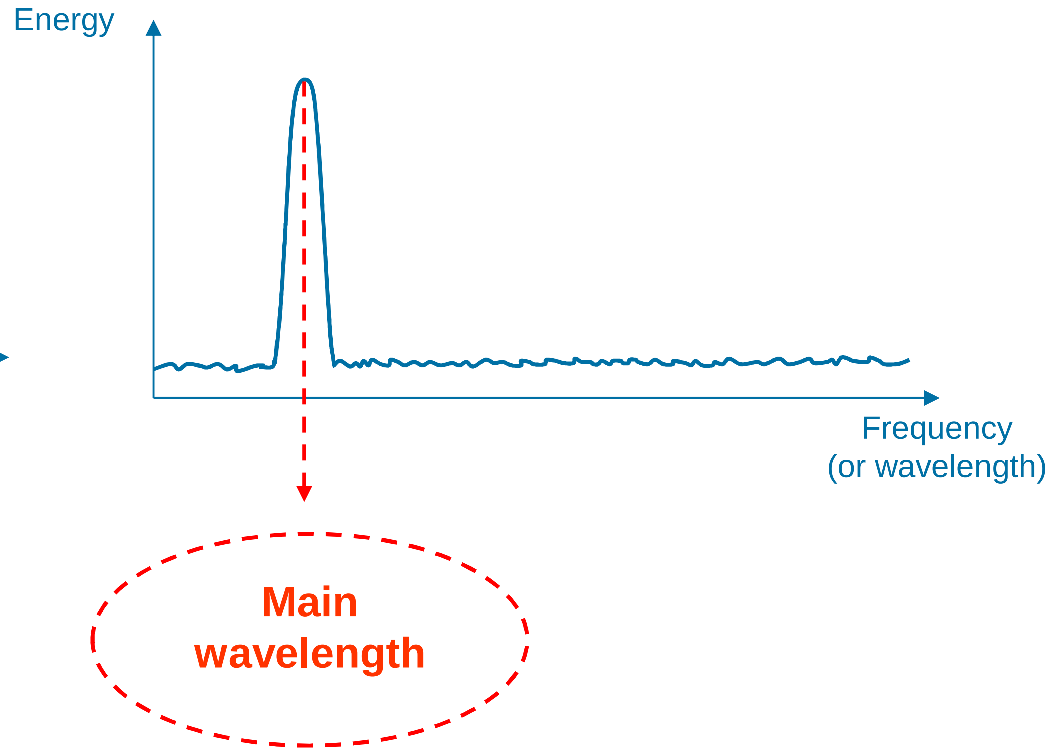
Sea surface: Large waves (high heights, long wavelength)

Wave radar scatterometry?

Received power

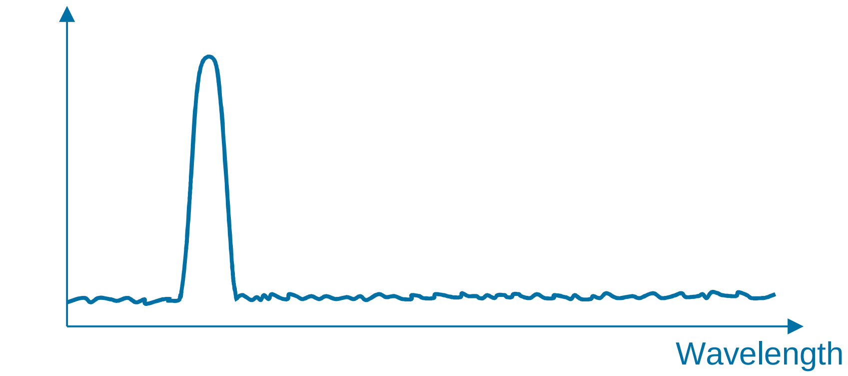
Spectral information

Modulation spectrum



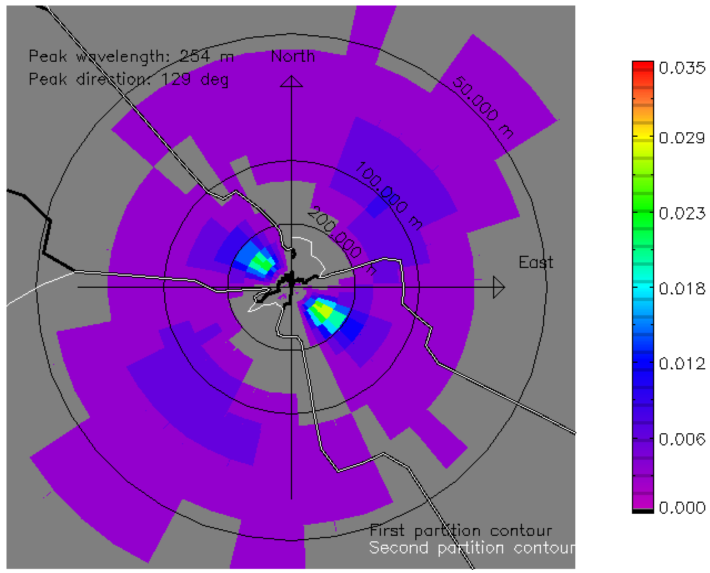
Wave radar scatterometry?

Modulation spectrum



Acquisitions in all azimuth directions

2D Modulation spectrum

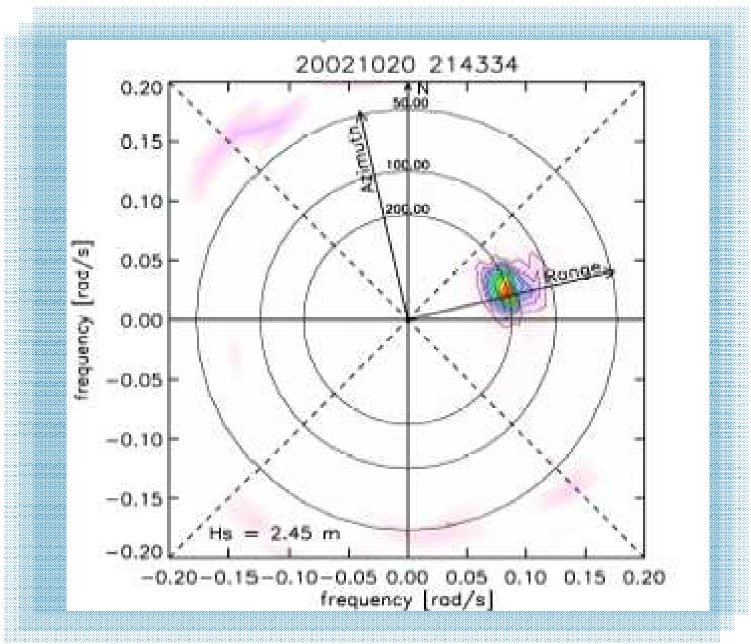


Linear relation

+

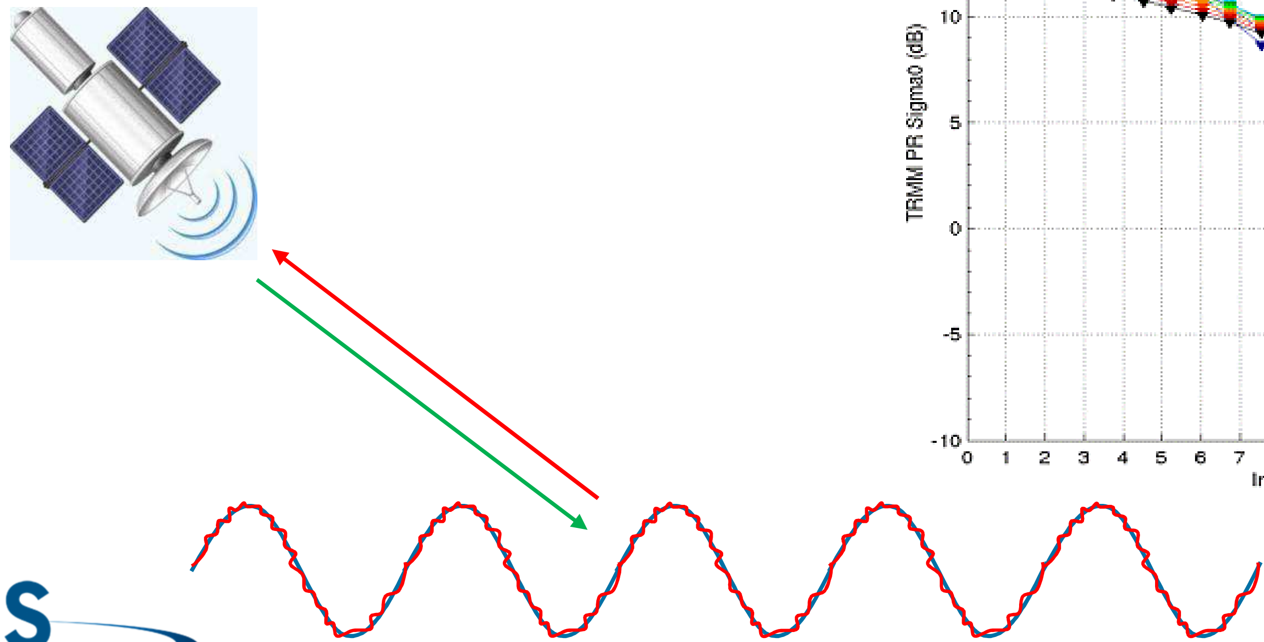
180° ambiguity solving

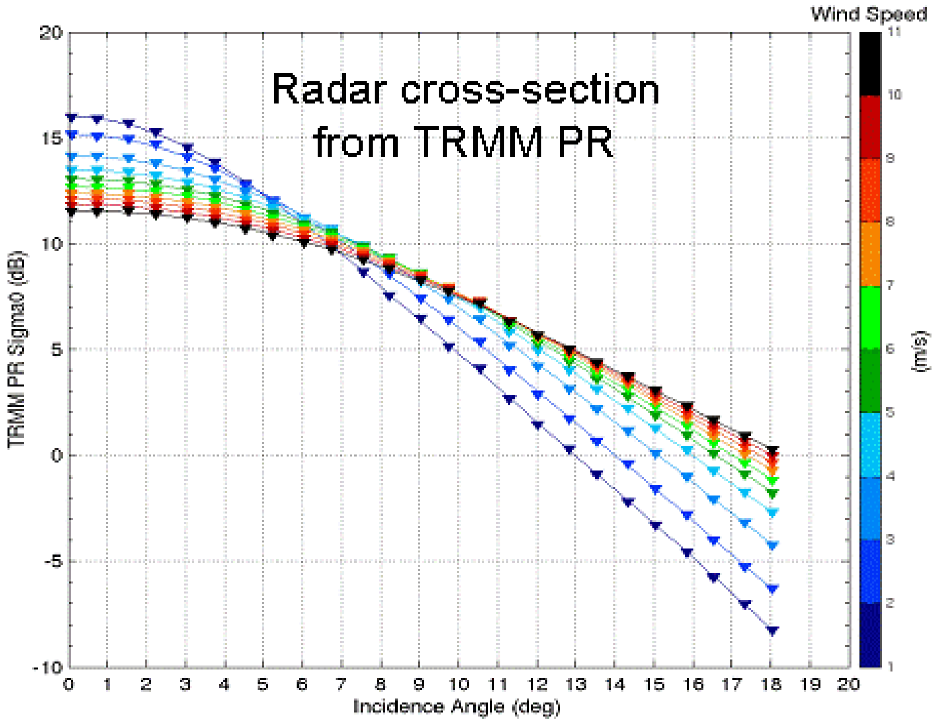
Directional Wave spectrum



Wave radar scatterometry?

- **Received power depends:**
  - On large slopes (waves)
  - But also on surface roughness (generated by winds)
- **Received power depends only on waves around 8° of incidence !**





CFOSAT mission

- **CFOSAT: China France Oceanography SATellite**
- **Oceanographic mission for sea surface monitoring**
  - Wave and wind measurements
  - Backscattering profile
- **Mission mainly dedicated to:**
  - Oceanography
  - Meteorology
  - Climatology

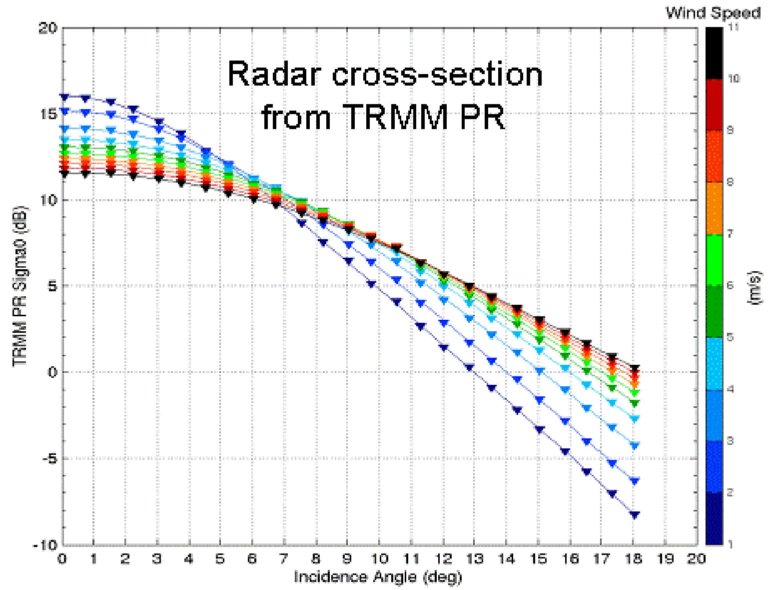
- **Two payloads:**
  - SWIM: wave scatterometer (Surface Wave Investigation and Monitoring)
  - SCAT: wind scatterometer
- **Orbit**
  - Altitude = 519 km
  - SSO (13 days repeat cycle)
- **Mission : 3 years duration**

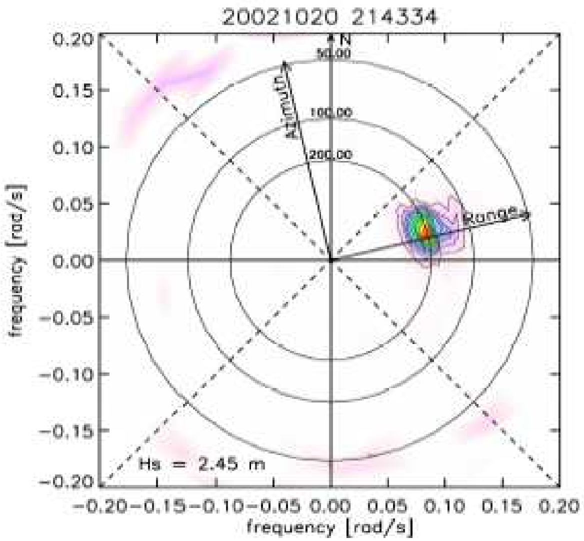
SWIM wave scatterometer

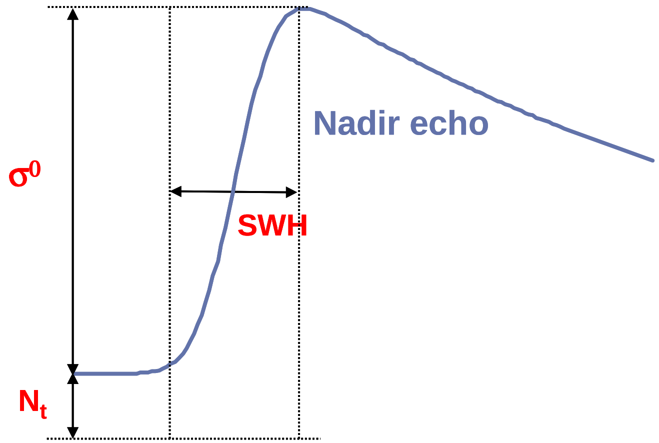
- Measurement of the backscattering coefficient σ^0 in all incidence angles (from nadir to 10°)

- Wave spectrum
  - Modulation depends only on waves around 8° of incidence (use of incidence beams 6°, 8° and 10°)
  - Directional wave spectrum using 360° scans

- Measurement of SWH from nadir echo







Fiche instrument SWIM / CFOSAT

DCT/SI/AR

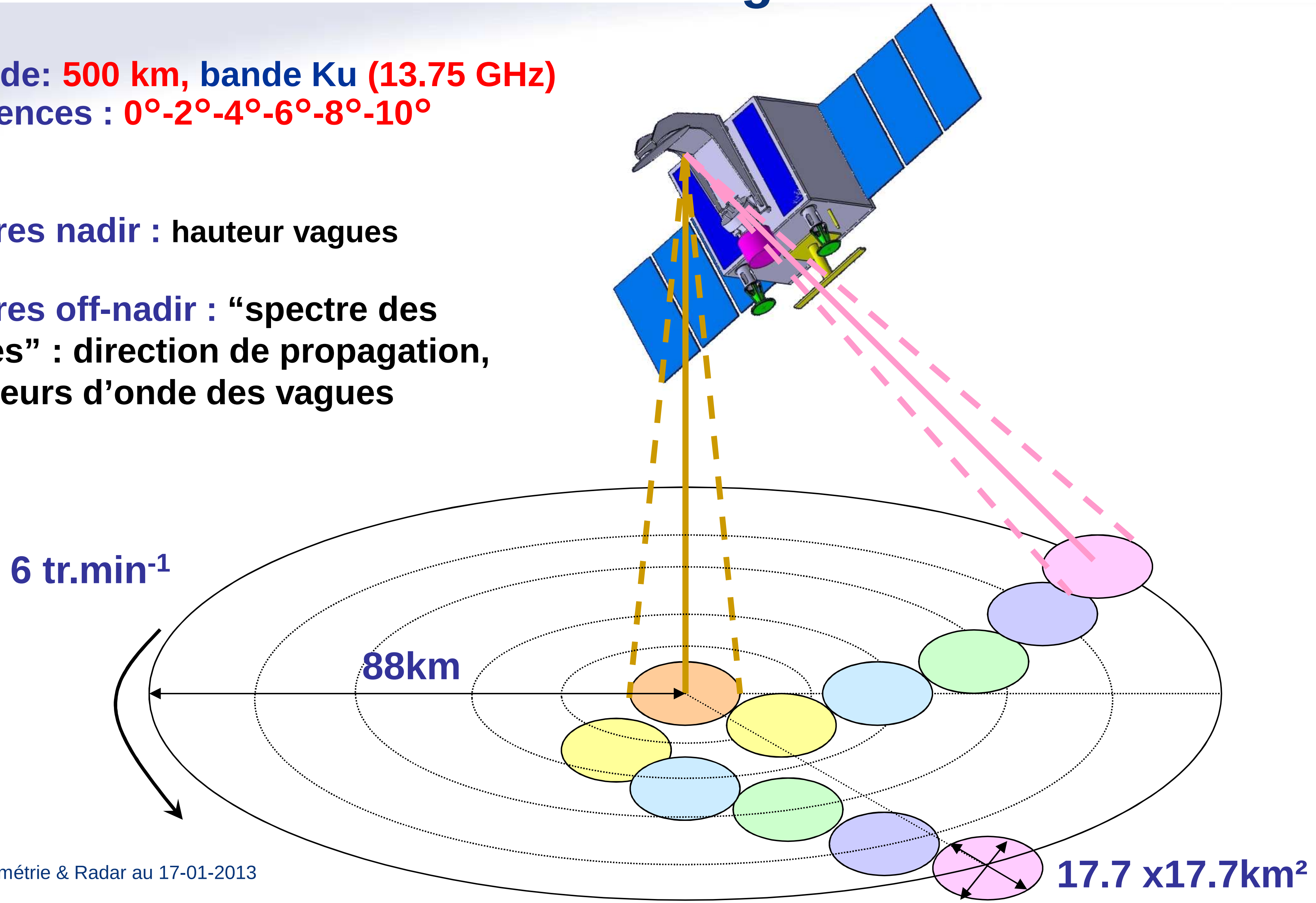
TTVS

SWIM / CFOSAT (2014) –
Diffusiomètre « vagues »

- Altitude: 500 km, bande Ku (13.75 GHz)
- Incidences : 0°-2°-4°-6°-8°-10°

Mesures nadir : hauteur vagues

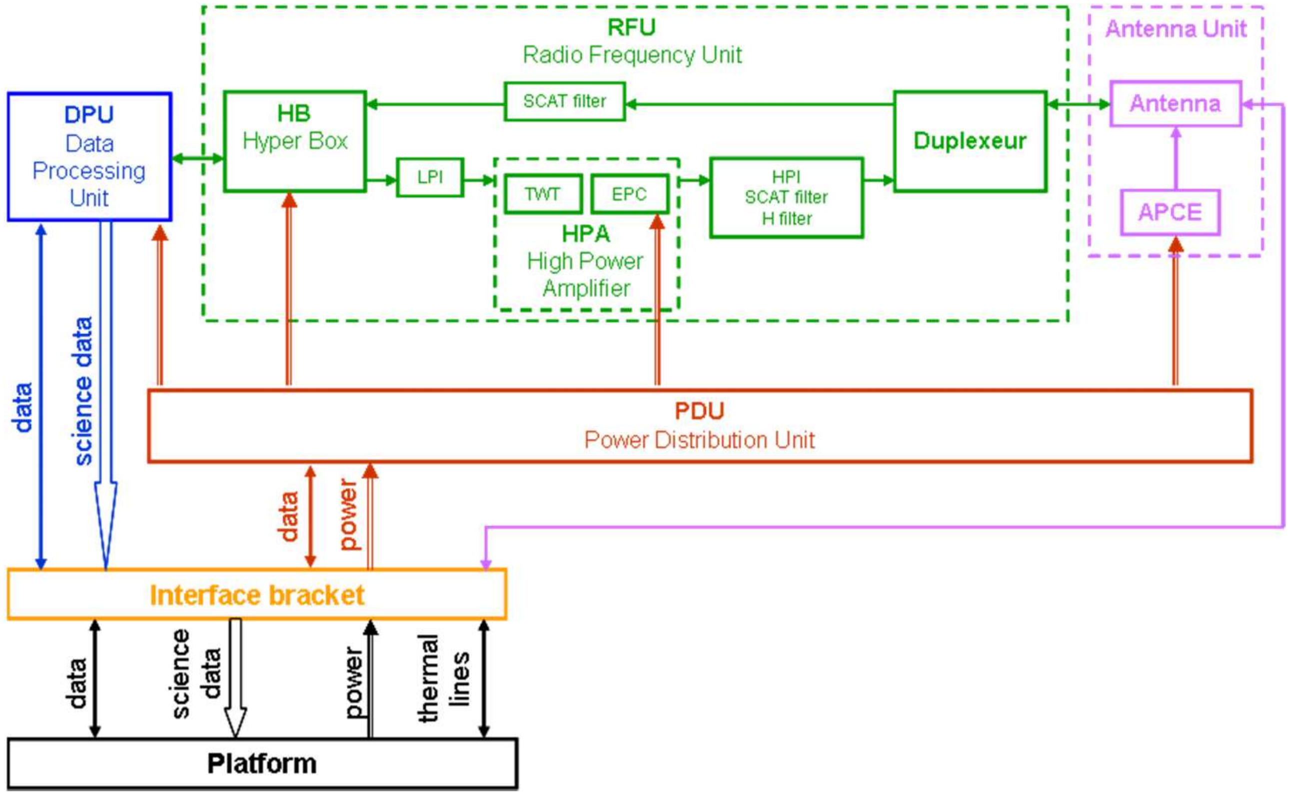
Mesures off-nadir : “spectre des vagues” : direction de propagation, longueurs d'onde des vagues




cnes
CFOSAT
Orbit
Sun synchronous
Local time at descending node
AM 7:00
Altitude at the equator
519 km
Cycle duration
13 days
Satellite mass and dimensions
Mass
600 kg
Primary structure
1.4mx1.4mx1.2m

SWIM instrument

- **SWIM characteristics**
  - **Mass**
    100 kg (including antenna = 50kg)
  - **Consumption**
    220W
  - **Science telemetry data rate**
    1Mbit/s



- **Technological challenges**
  - Antenna mechanism (RMA)
  - On board processing (ASIC)
  - Antenna on-board calibration
  - Platform interfaces (CAN Bus, LVDS)
  - SCAT compatibility

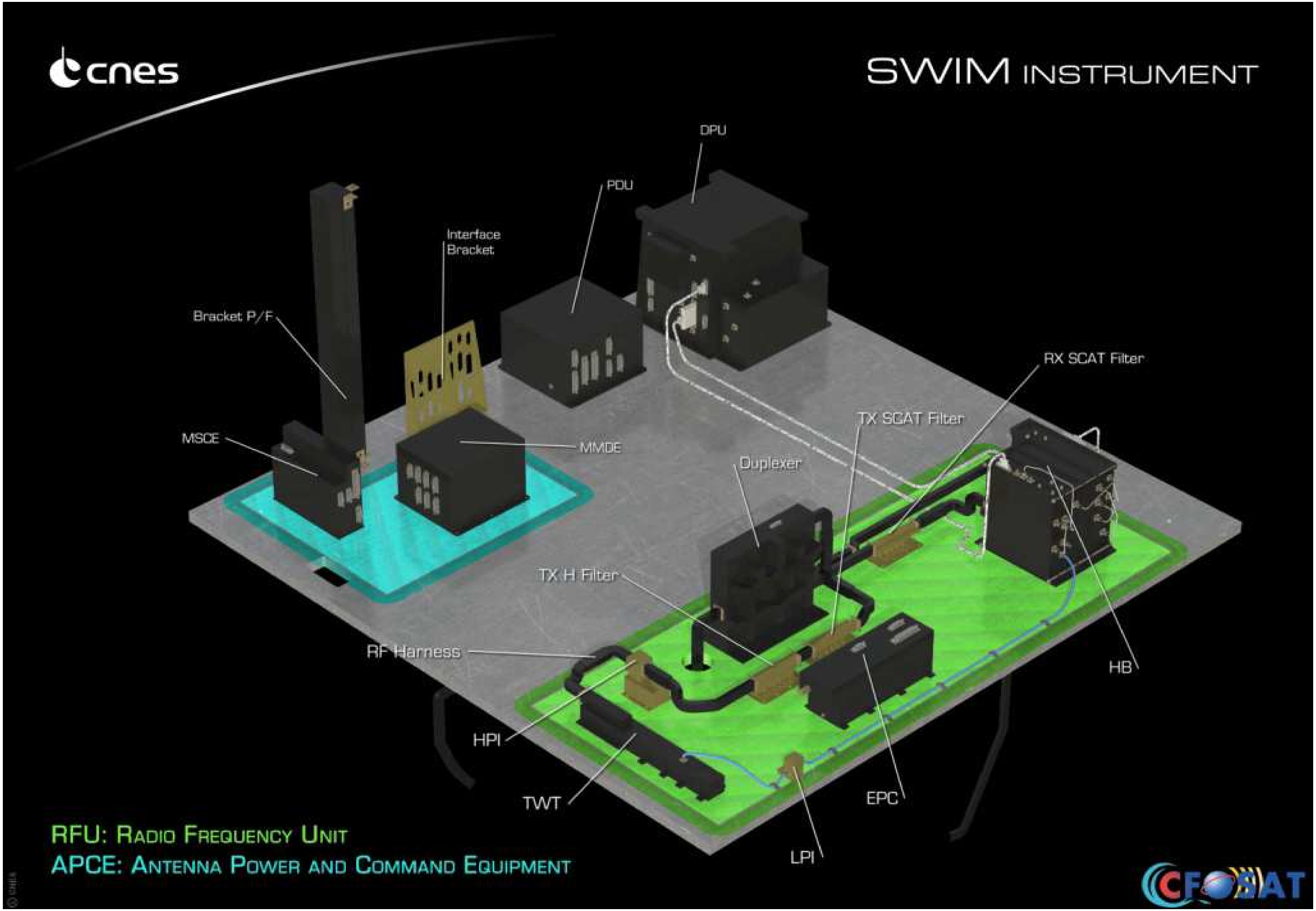
cnes

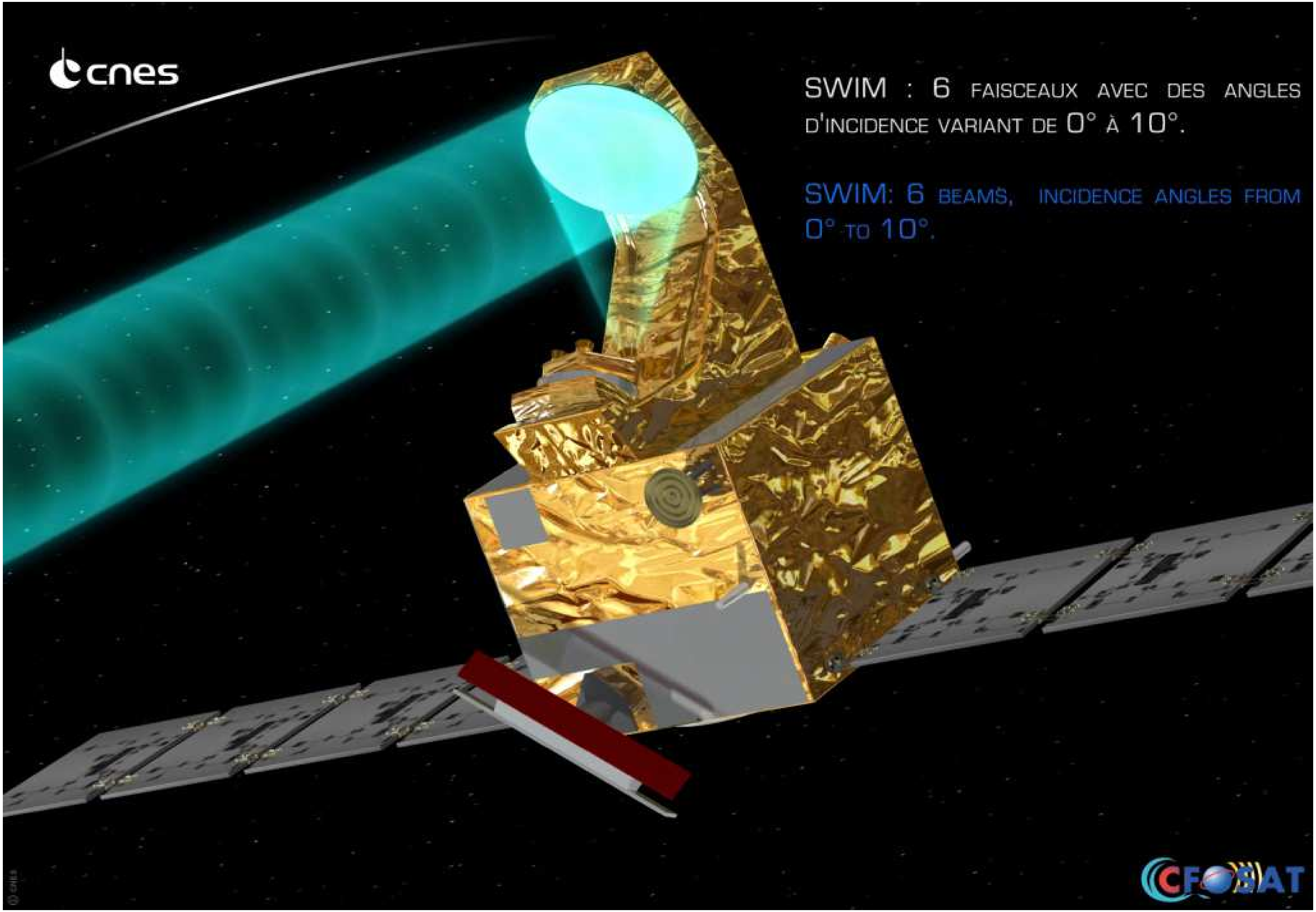
[redacted]

TTVS

Techniques et Technologies des Véhicules Spatiaux

Session 2011 du 19 au 23 septembre et du 21 au 25 octobre


cnes
SWIM INSTRUMENT
DPU
PDU
Interface
Bracket
Bracket P/F
RX SCAT Filter
TX SCAT Filter
MSCE
MMDE
Duplexer
TX H Filter
RF Harness
HB
HPI
TWT
EPC
LPI
RFU: Radio Frequency Unit
APCE: Antenna Power and Command Equipment
CFOSAT


cnes
SWIM : 6 faisceaux avec des angles d'incidence variant de 0° à 10°.
SWIM: 6 beams, incidence angles from 0° to 10°.
CFOSAT

SWIM / CFOSAT