Rencontres du Vietnam

Atmospheric Remote Sensing and Molecular Spectroscopy
Satellite Measurements

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Vietnam School of Earth Observation, ICISE, Quy Nhon 2018

OUTLINE

- Basics of atmospheric remote sensing from space
  - Orbit types
  - Instrument types
- Illustration with two CNES missions
  - MERLIN : CH4 measurement with Lidar
  - MICROCARB : CO2 measurement with spectrometer
- Copernicus Atmosphere Monitoring Services

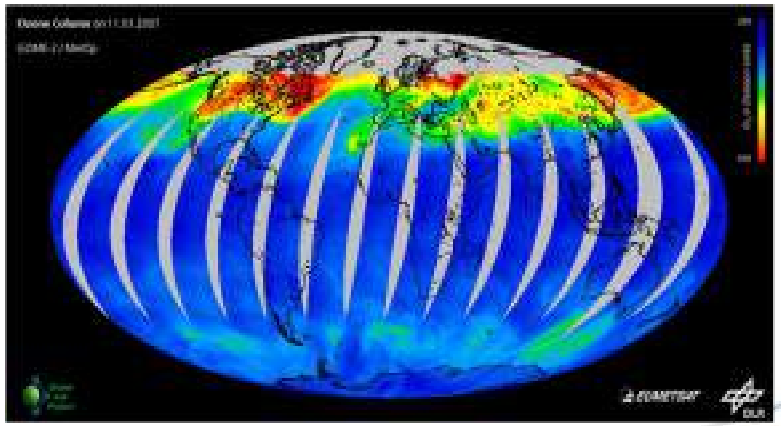
Teacher presentation

Linda Tomasini

- Engineer diploma from French Engineering school in Aeronautics and Space
- Ph.D in Signal processing and Artificial Intelligence, 1993
- Post-doctorate in robotics at Stanford University, California.
- Cryptologist at Thomson-CSF, Paris from 1994 to 1996.
- CNES engineer in Toulouse since 1997:
  - reliability and safety engineer for earth observation missions
  - in charge of human factor for manned space flights aboard International Space Station,
  - in charge of image quality performance for Earth observation satellites
  - in charge of advanced studies for Earth Observation missions (Greenhouse gases observation missions, soil moisture and ocean salinity, high revisit missions like ocean color, air quality measurement, earth magnetic field measurement mission …)
  - in charge of training and international cooperation for space applications
- Hobbies : piano, drawing, vietnamese culture and language.

Why remote sensing from space ?

- Provides synoptic/detailed views of large portions of Earth surface unaffected by political boundaries
- Capability of frequent target acquisition / follow on changing phenomena
- Provides combination of multi-sensors capabilities and create consistent, well calibrated data set
- Capabilities to provide data in a fast manner all over the world
- But only part of a complete integrated data collection system including other sensors and ground infrastructure



Applications of atmospheric remote sensing

- Air quality monitoring
- Numerical Weather forecast (NWP)
- Climate studies
- Greenhouse gases observation
- Ozone layer monitoring
- Sun radiation forecasting (sun power generation)
- Atmospheric corrections for remote sensing

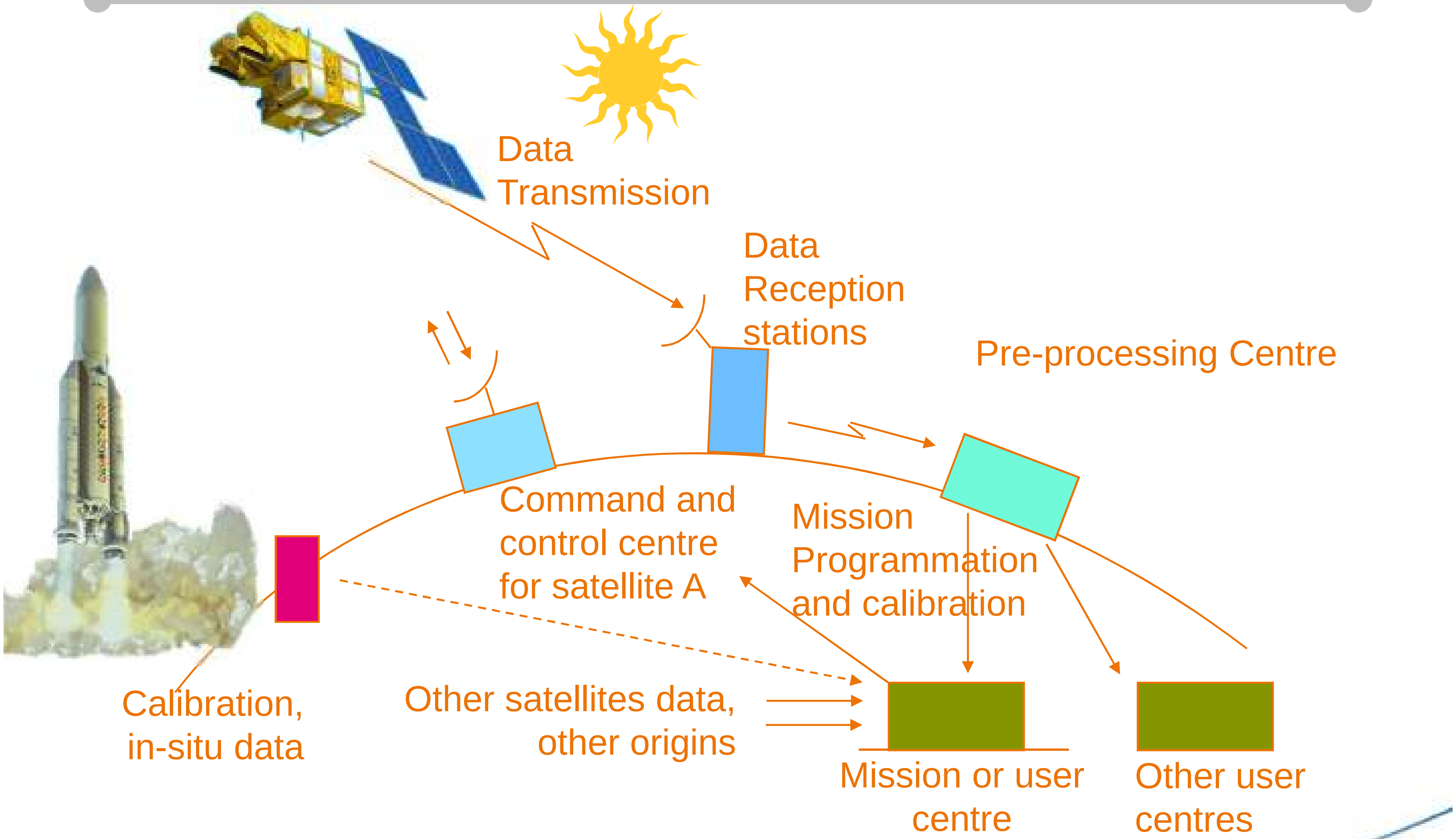
➢ See Copernicus Atmospheric Monitoring Services

www.Atmospheric.Copernicus.eu

But…

- Impacts of ionosphere and atmosphere crossing
- Indirect measurement of the physical phenomenon
  - Atmospheric chemical composition deduced from absorption effects on solar rays
  - Gravity variations deduced from satellite orbit perturbations
- Hostile environment
  - radiations, thermal conditions, isolation
- Observation from far distance
  - Spatial resolution
  - Observability / commandability
  - Sensors calibration all along mission duration
- Infrastructures
  - High reliability of space segment required
  - Launch is costly

Space system overview

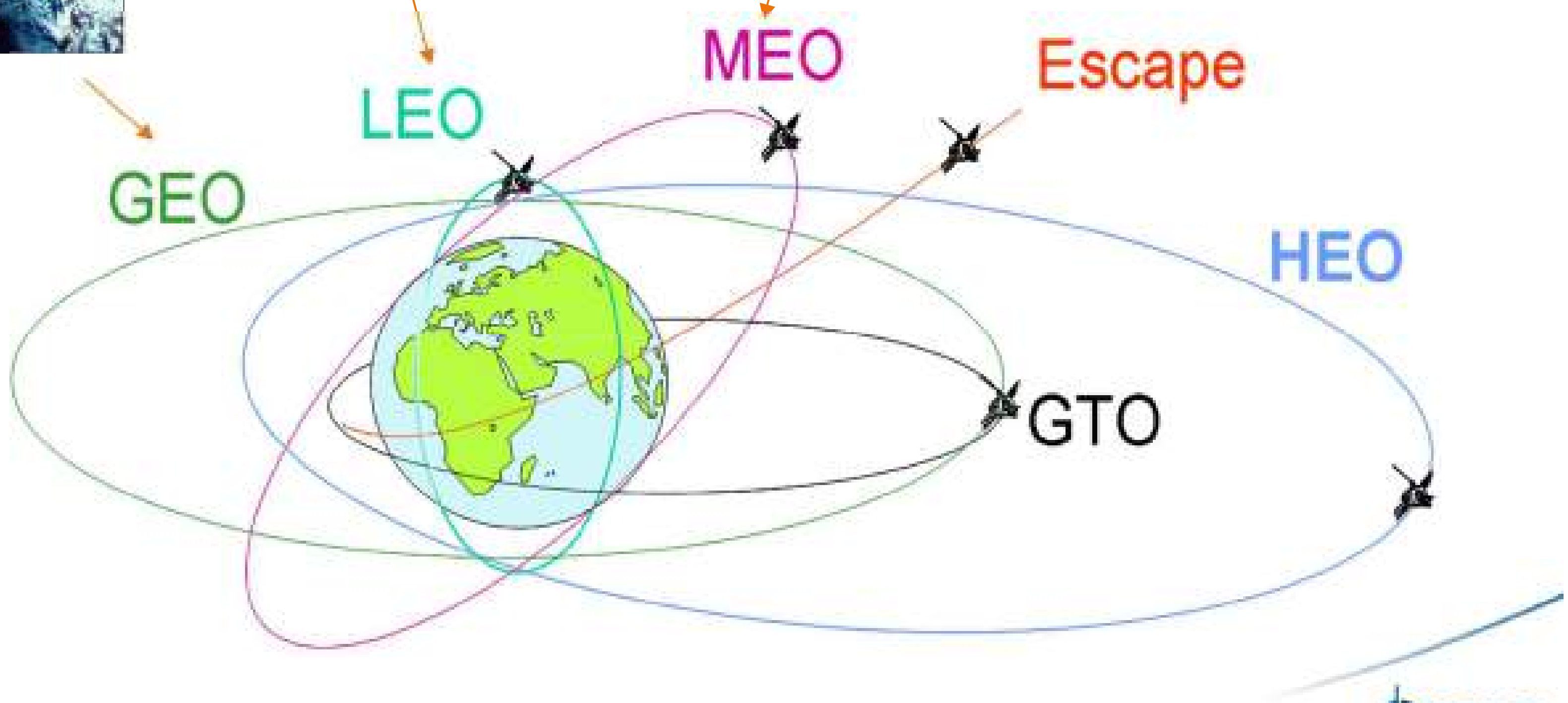


Different viewpoints

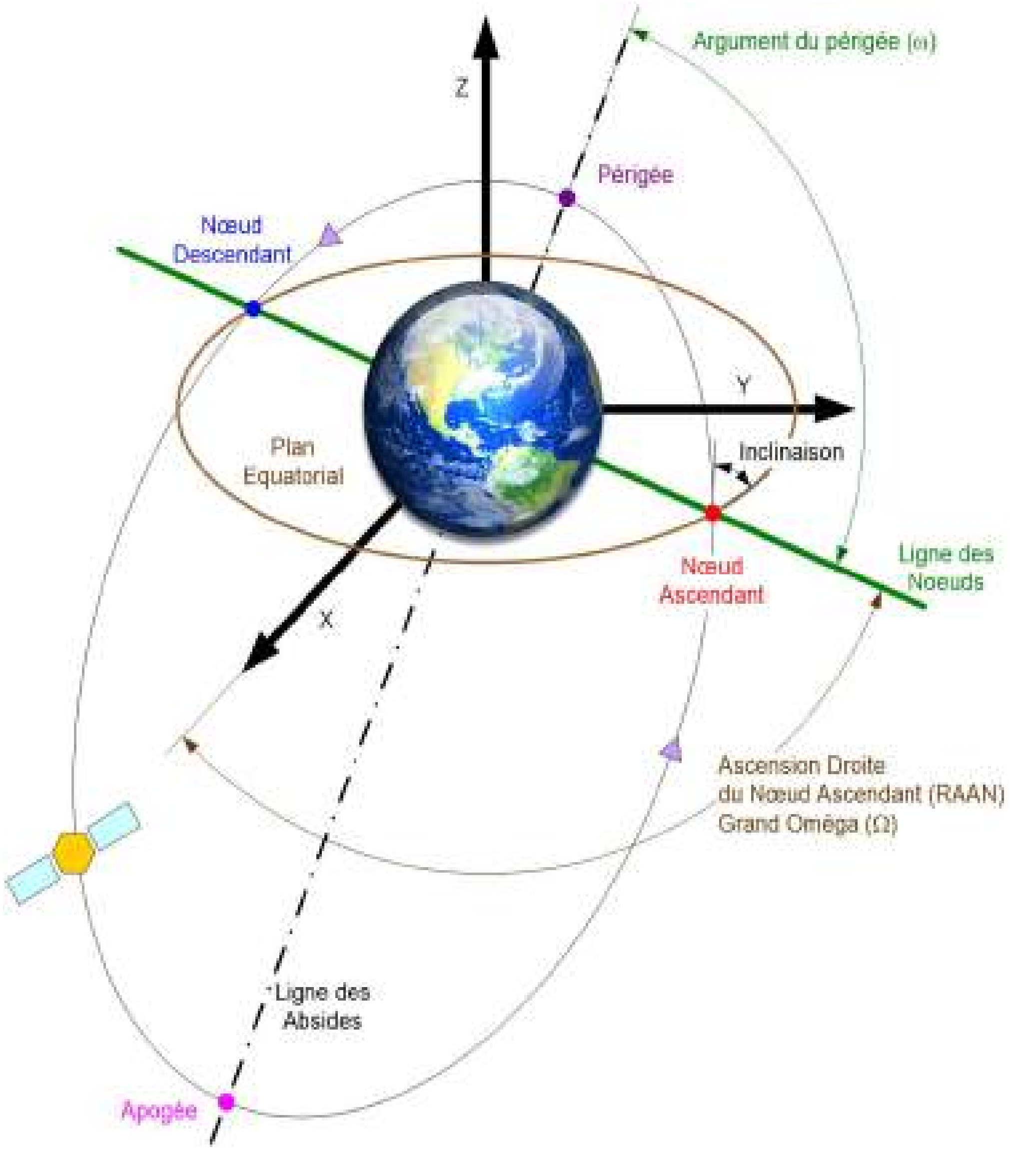
Weather Forecast :
Meteosat, 36000 km

Satellite imager :
Spot-5, 800 km

Ocean Altimeter :
Jason-2, 1300 km



Orbital elements

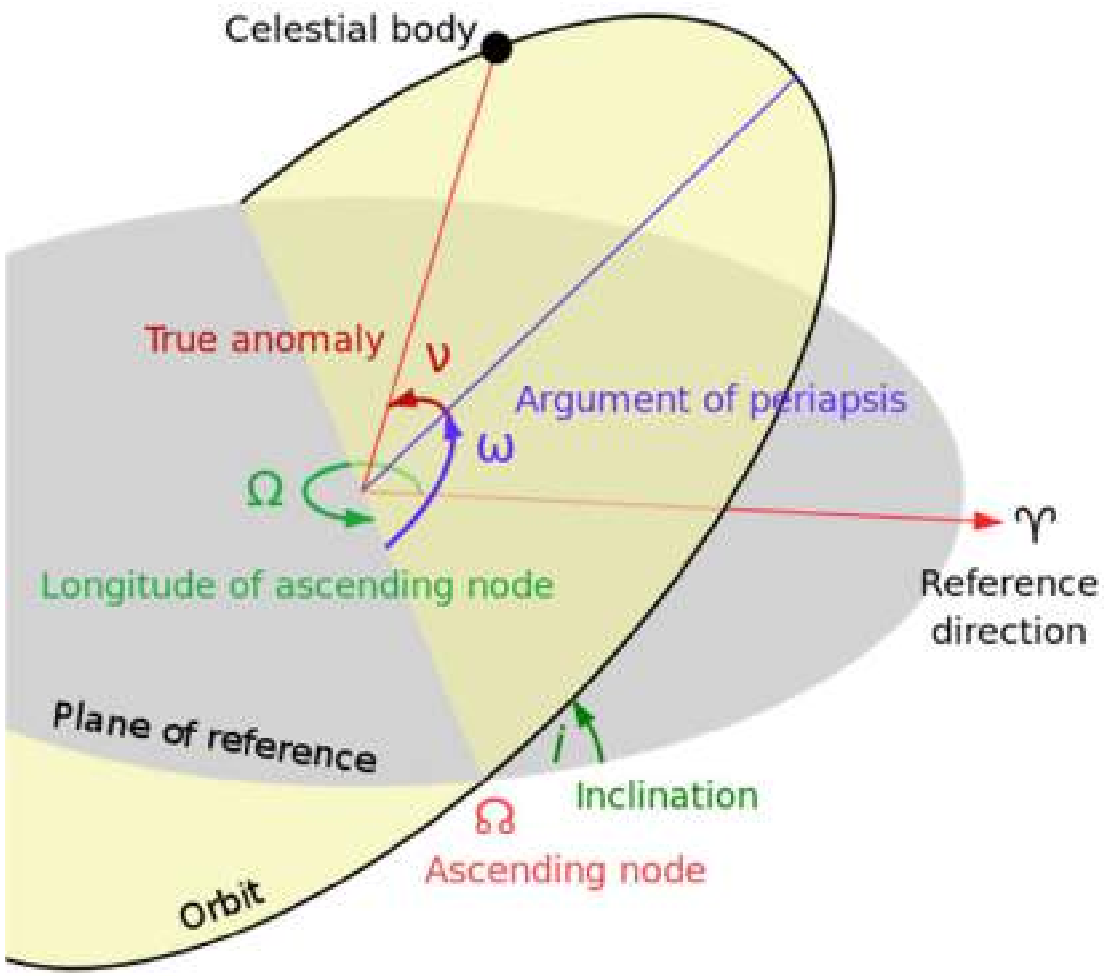


Inclination : angle between orbital plane and equatorial plane

Ascending Node (AN) : orbit point where satellite crosses equatorial plane from South to North

Line of Nodes : Intersection of orbit plane and equatorial plane.

Argument of periapsis (ω) : angle between ascending node and periapsis


Celestial body
True anomaly
ν
Argument of periapsis
ω
Ω
Longitude of ascending node
♈
Reference direction
Plane of reference
i
Inclination
☊
Ascending node
Orbit

Sun-Synchronous Orbits (SSO)

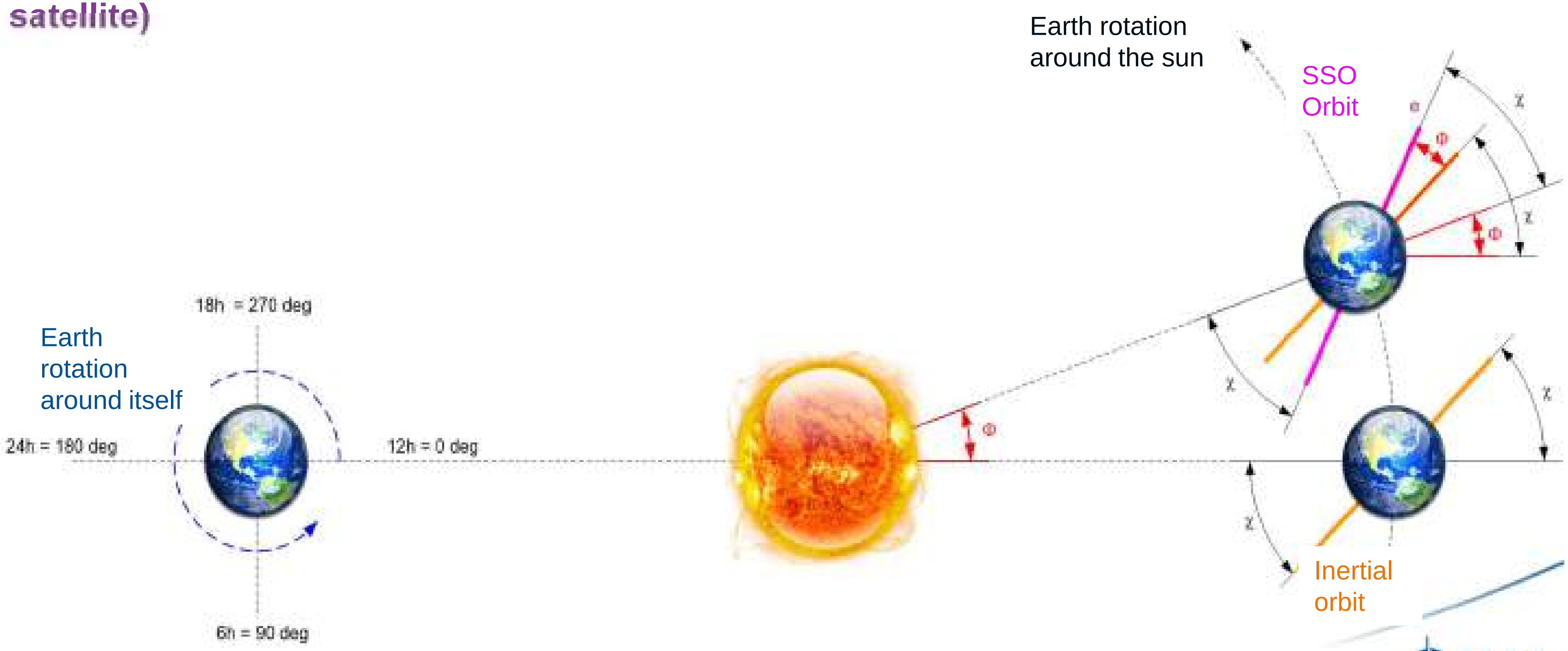
Local Time of Ascending Node (LTAN) : Angle between ascending node and sun direction

Sun-Synchronous Orbit : Angle (X) between sun direction in equatorial plane and nodes line is constant

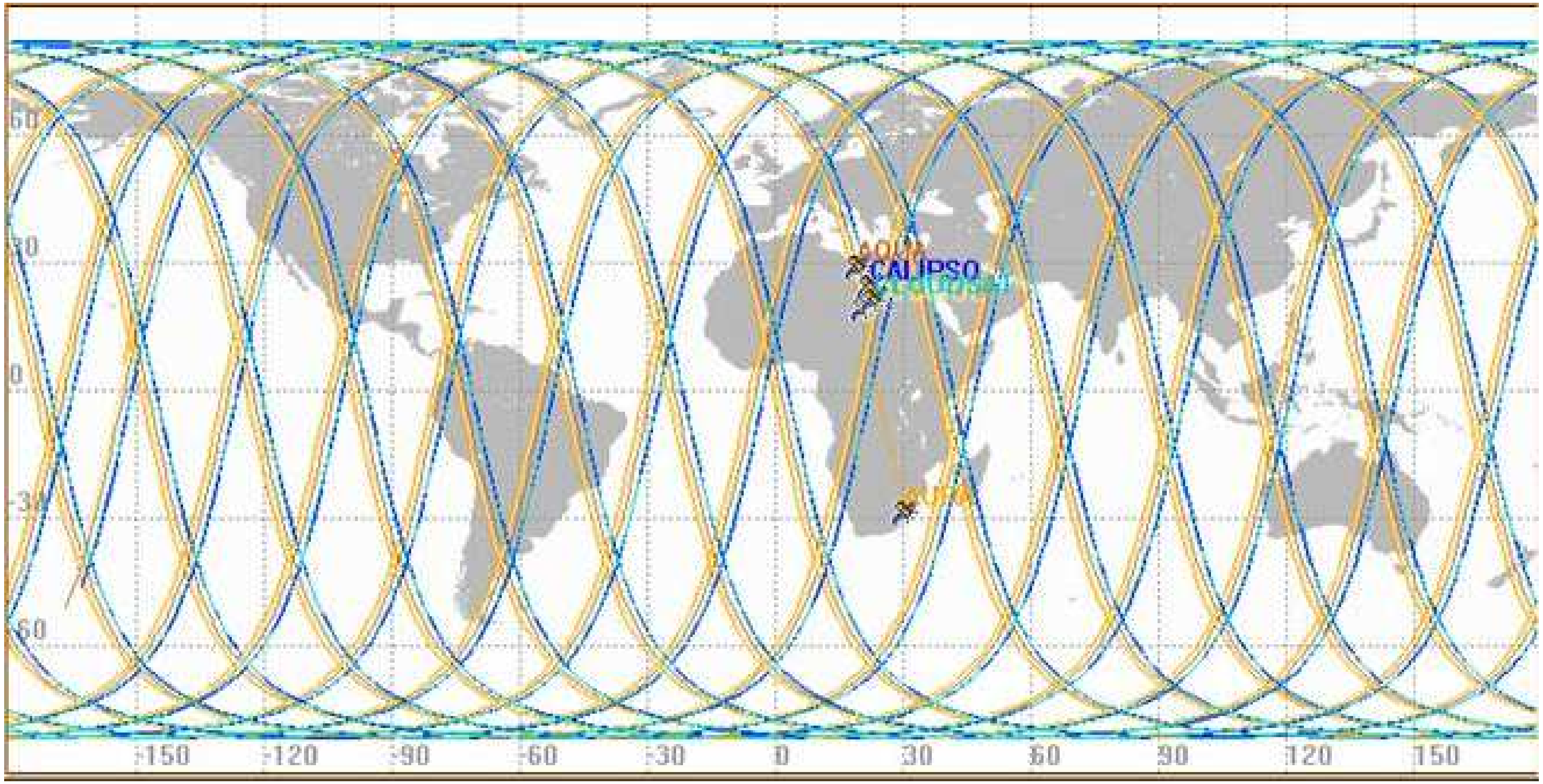
➔ Local Time of Ascending Node is constant

➔ Sun illumination of the satellite projection on Earth is constant and depends on the satellite position on its orbit (at first order)

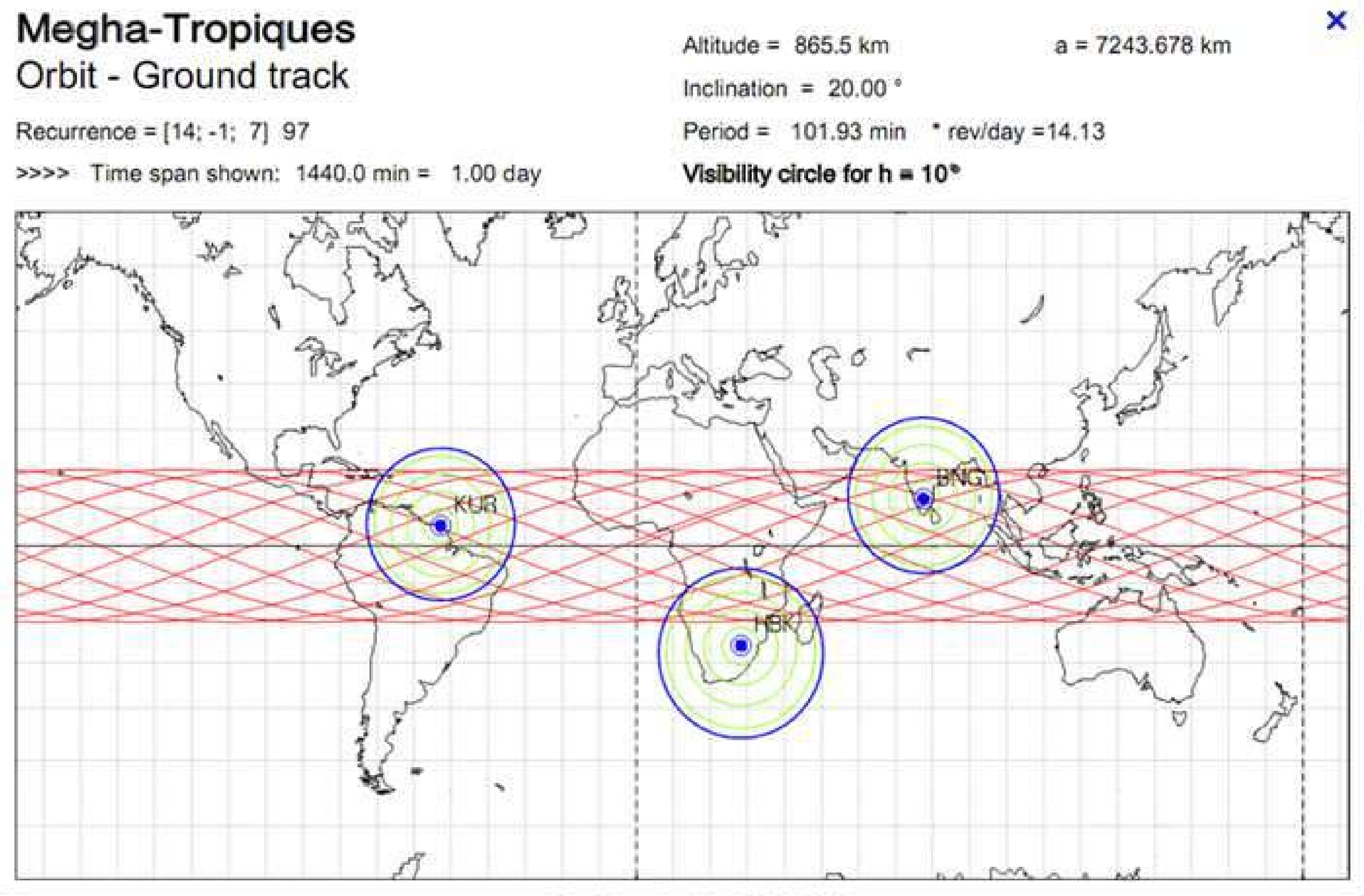
A non sun synchronous orbit is a deriving orbit (ex : Meghatropiques, Singapore TeLEOS satellite)



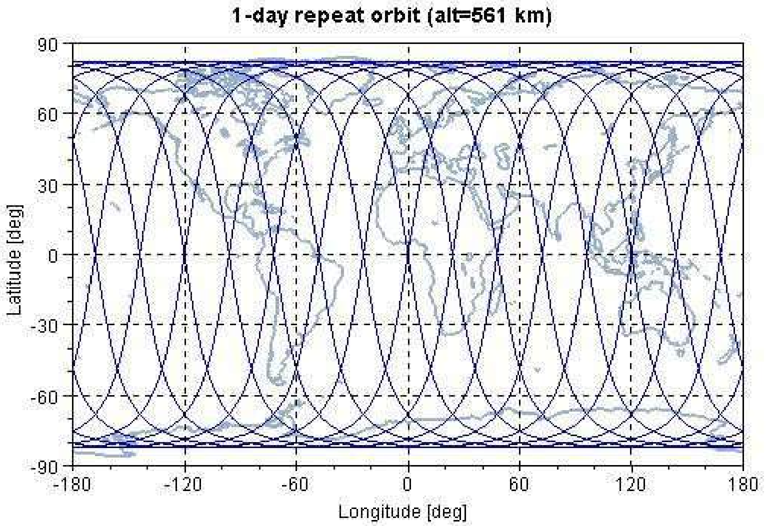
Example of Sun-Synchronous orbit track
A-Train satellites

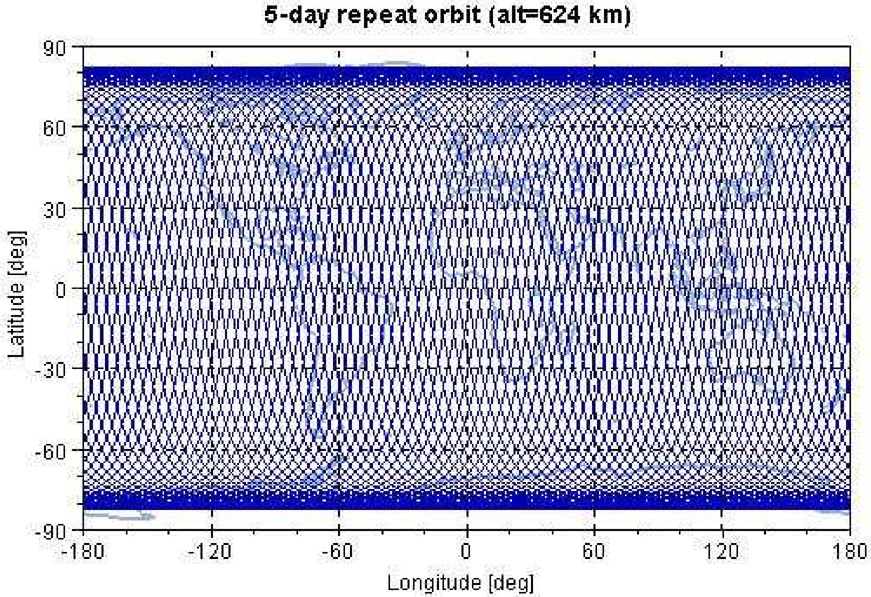


Megha-Tropiques Satellite Orbit



ORBIT SELECTION (Ground track grid)





Phased Orbit with repeat cycle of *Q* days

- Inter-Orbit longitude gap : IO in [23.6°;24.4°] for [500; 650] km sun-synchronous orbits
- Inter-Track longitude gap : IC ~ 24/*Q* °

Cycle duration	1 day	5 days	20 days
longitude gap	24°	4.8°	1.2°
Distance at equator	2671 km	534 km	134 km

Instrument Swath (?) & required coverage (?) => IC

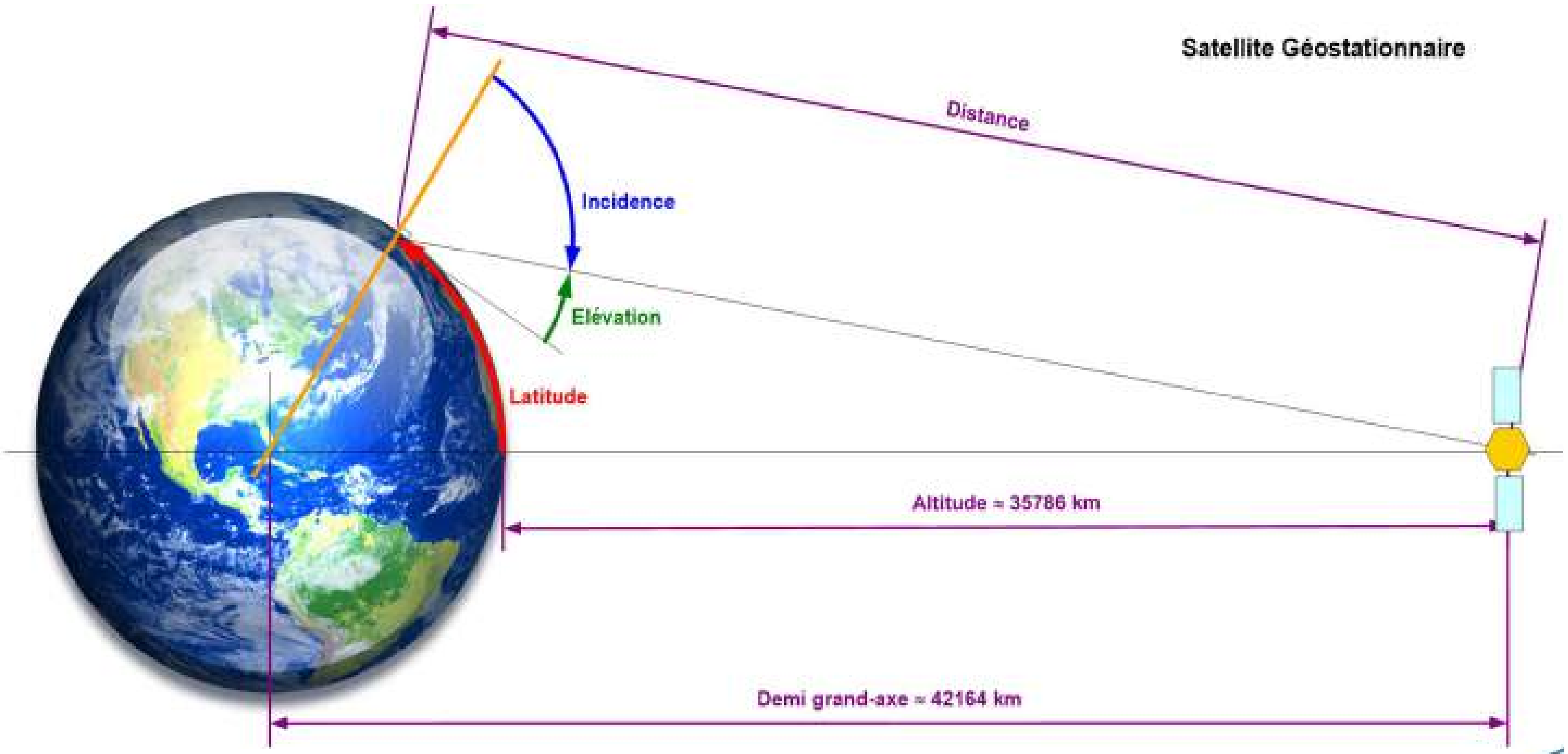
LEO (Low Earth Orbit) Sun-synchronous Orbits

Examples : Aqua-Train satellites, Sentinel 1-2-3-5, METOP, MERLIN, MICROCARB

- Advantages :
  - ✓ Scene and satellite illumination stability
  - ✓ More convenient satellite design (power, thermals)
  - ✓ Low altitude
  - ✓ Global Earth coverage

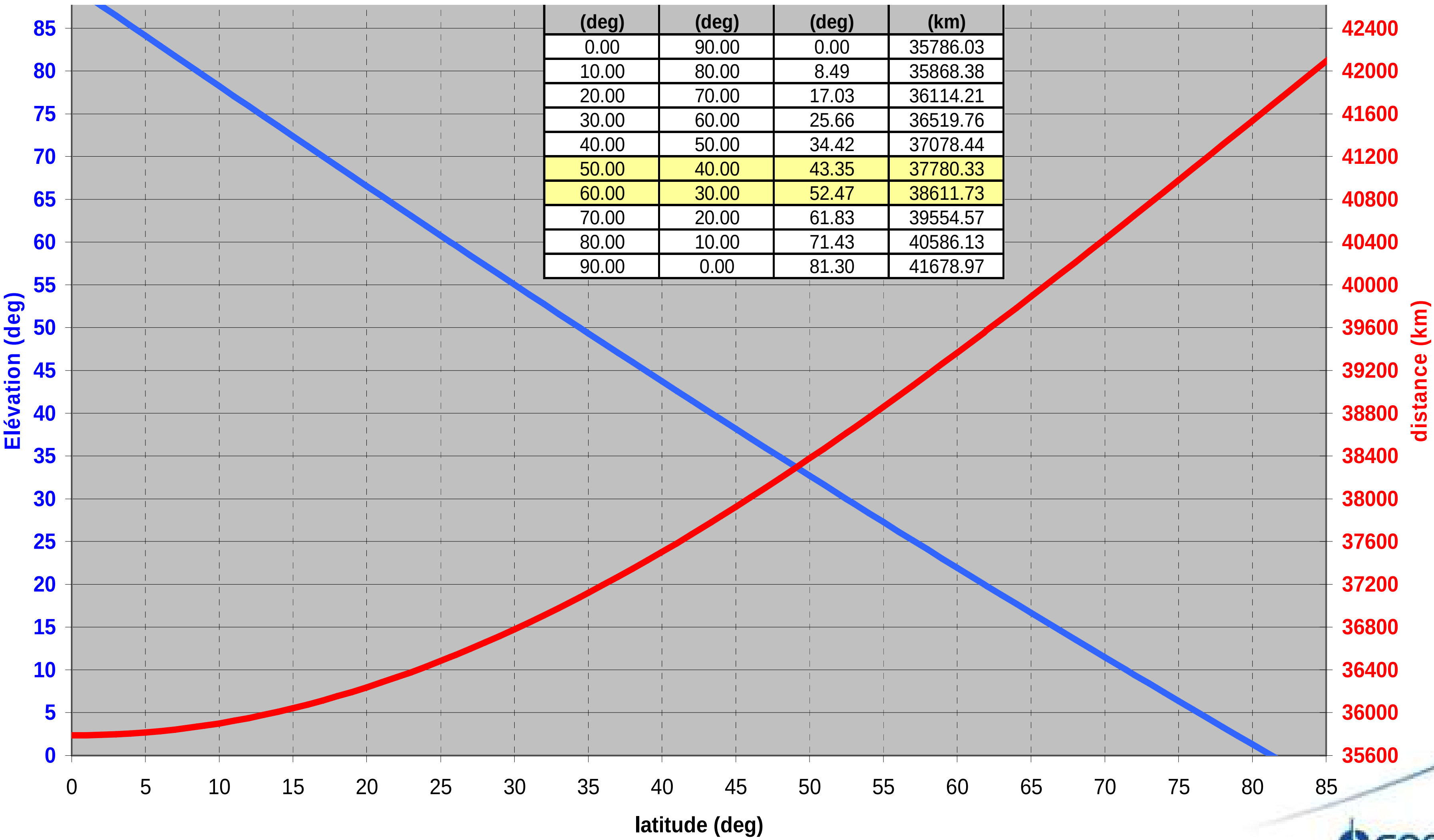
- Drawbacks :
  - ➢ Revisit, i.e. temporal resolution
  - ➢ Limited communications

Geostationnary Satellite (1/2)



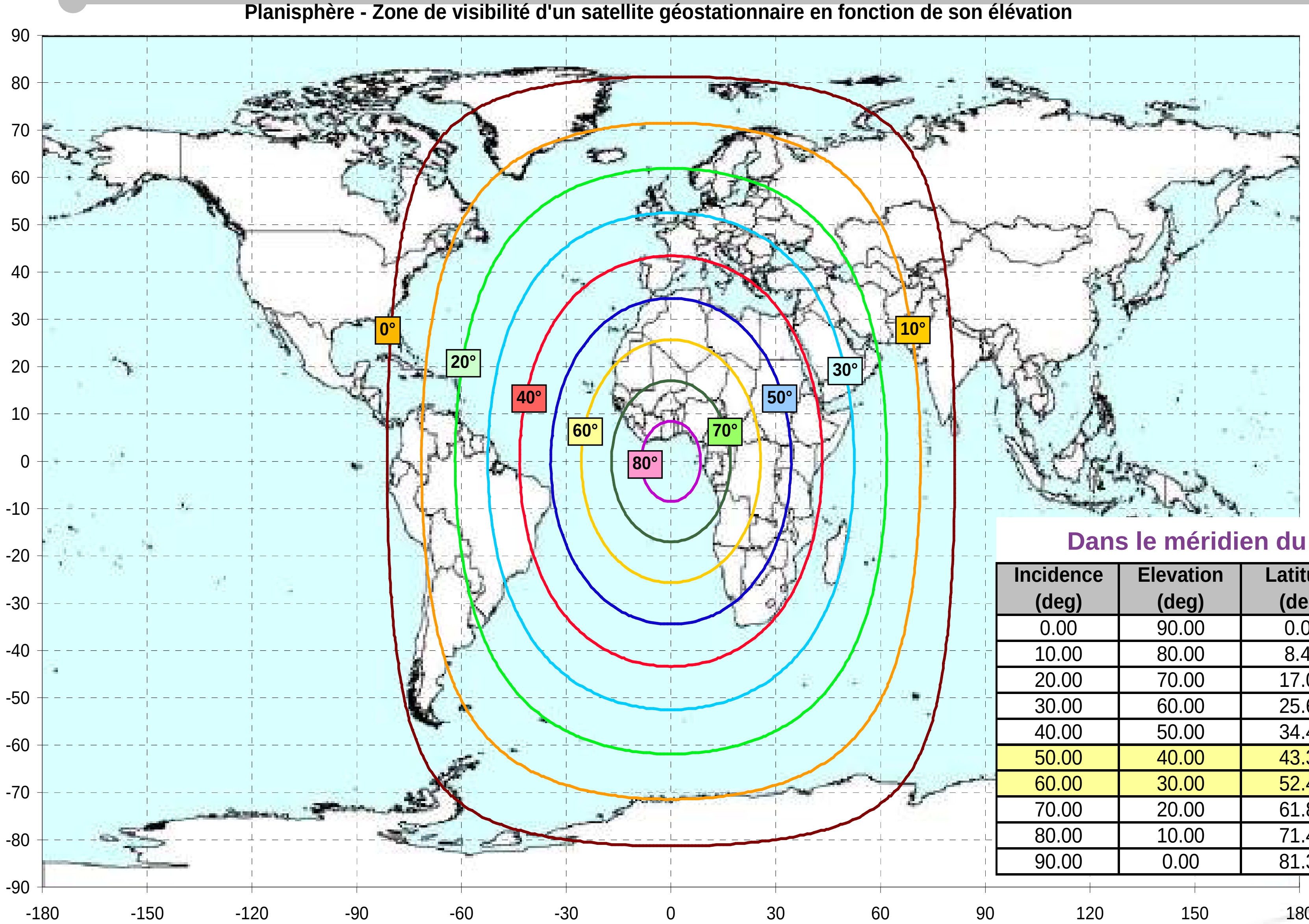
Geostationnary Satellite (2/2)

Elevation and distance depending on latitude (satellite and point at the same longitude)



(deg)	(deg)	(deg)	(km)
0.00	90.00	0.00	35786.03
10.00	80.00	8.49	35868.38
20.00	70.00	17.03	36114.21
30.00	60.00	25.66	36519.76
40.00	50.00	34.42	37078.44
50.00	40.00	43.35	37780.33
60.00	30.00	52.47	38611.73
70.00	20.00	61.83	39554.57
80.00	10.00	71.43	40586.13
90.00	0.00	81.30	41678.97

Visibility area of geostationnary satellite depending on elevation angle



Dans le méridien du satellite

Incidence (deg)	Elevation (deg)	Latitude (deg)	Distance (km)
0.00	90.00	0.00	35786.03
10.00	80.00	8.49	35868.38
20.00	70.00	17.03	36114.21
30.00	60.00	25.66	36519.76
40.00	50.00	34.42	37078.44
50.00	40.00	43.35	37780.33
60.00	30.00	52.47	38611.73
70.00	20.00	61.83	39554.57
80.00	10.00	71.43	40586.13
90.00	0.00	81.30	41678.97

GEO Orbits

Examples : Weather Forecast Satellites (MSG, MTG, NOAA satellites) , Korean instrument GOCI (Ocean color)

- Advantages :
  - ✓ Revisit
  - ✓ Persistance
  - ✓ Permanent satellite-ground communications
- Drawbacks :
  - ➢ Geometrical Observation Conditions (distance, incidence) and no variability
  - ➢ Geographical Coverage limited to the geostationary disk
  - ➢ Expensive launching

Orbit Parameters choice impacts

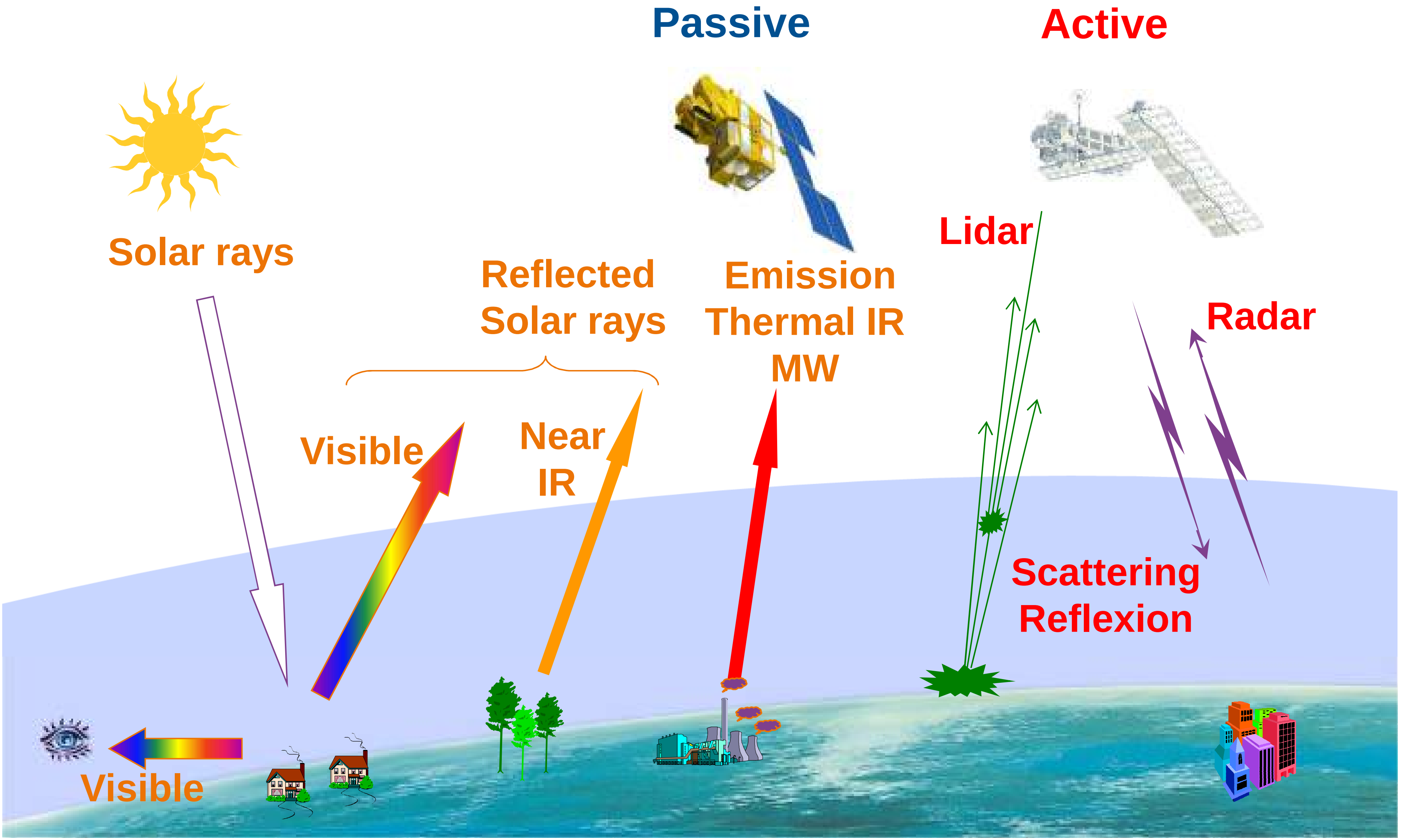
❑ Observation conditions :

- Distance,
- Sun illumination conditions,
- View angle,
- Instrument velocity / Scene

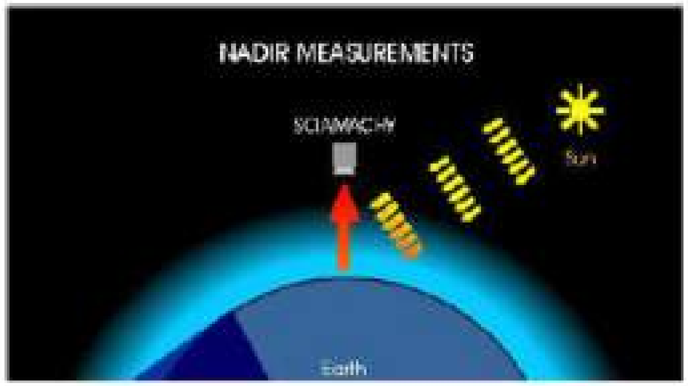
❑ Operational capacity :

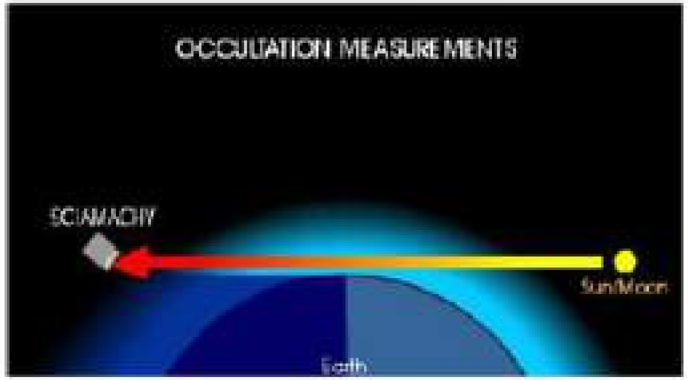
- Geographical coverage,
- Revisit,
- Reactiviy,
- Latency

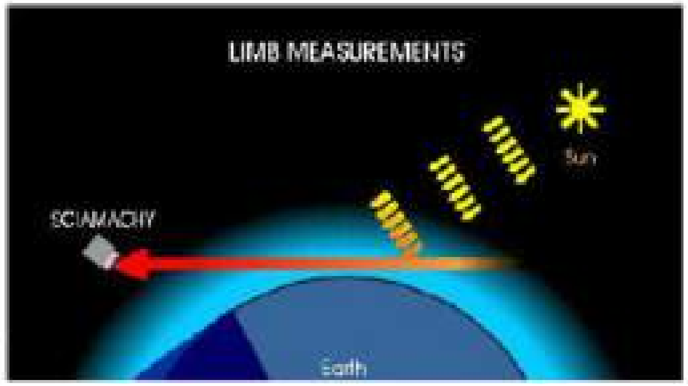
Physics of remote sensing



Satellite observation geometries





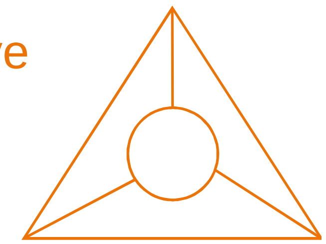


- Nadir :
  - Backscattered solar or artificial radiation (for active instruments) and/or emission measurements (also nighttime)
  - Good spatial coverage and resolution
  - Low vertical resolution
- Solar occultation :
  - Direct solar absorption
  - High vertical resolution
  - Low spatial resolution ; low spatial coverage
- Limb :
  - Scattered light at the limb (UV-Vis)
  - Limb emission (IR) ⇒ also nighttime
  - High vertical resolution Low spatial resolution; high spatial coverage

Introduction : Sensors Typology

- Functional Classification:

Imagers	most object geometry representative
Spectrometers Sounders	spectral radiances measurement
Radiometers	precise radiance measurement
Altimeters	distance



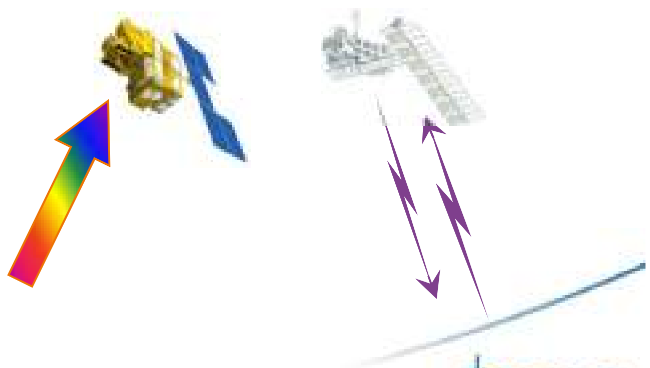
- Wavelength Classification:

γ , X, UV, visible, infrared, sub-millimetric, radiofrequency.

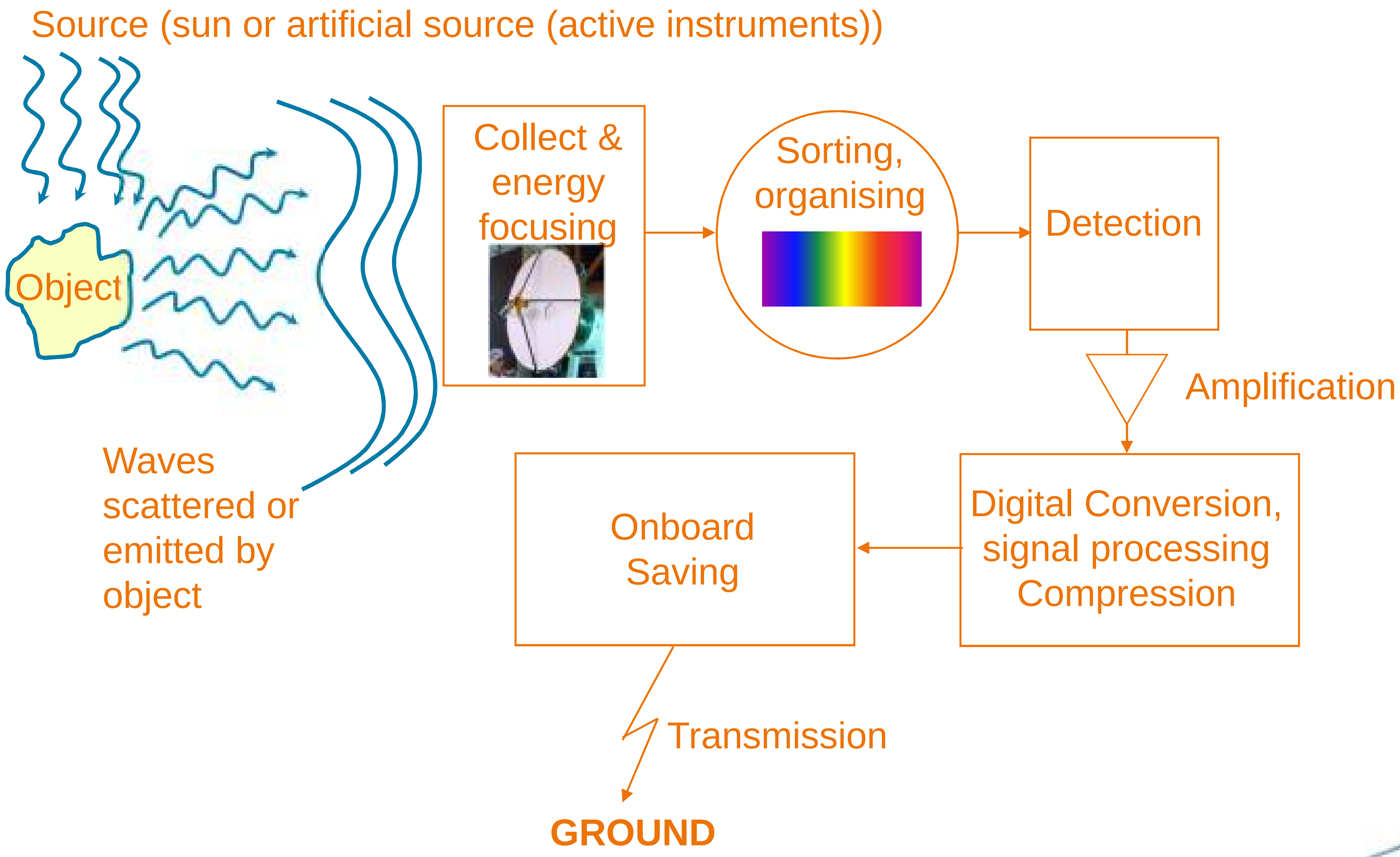
- Passive & Active Classification:

Passives : imagers, radiometers, spectrometers.

Actives : lidar, radar, altimeter



Typical Instrument System Chain



Instrument additional functions (examples)

- System to steer the optical axis

(and thus change the direction it is looking at)

To increase revisit frequency

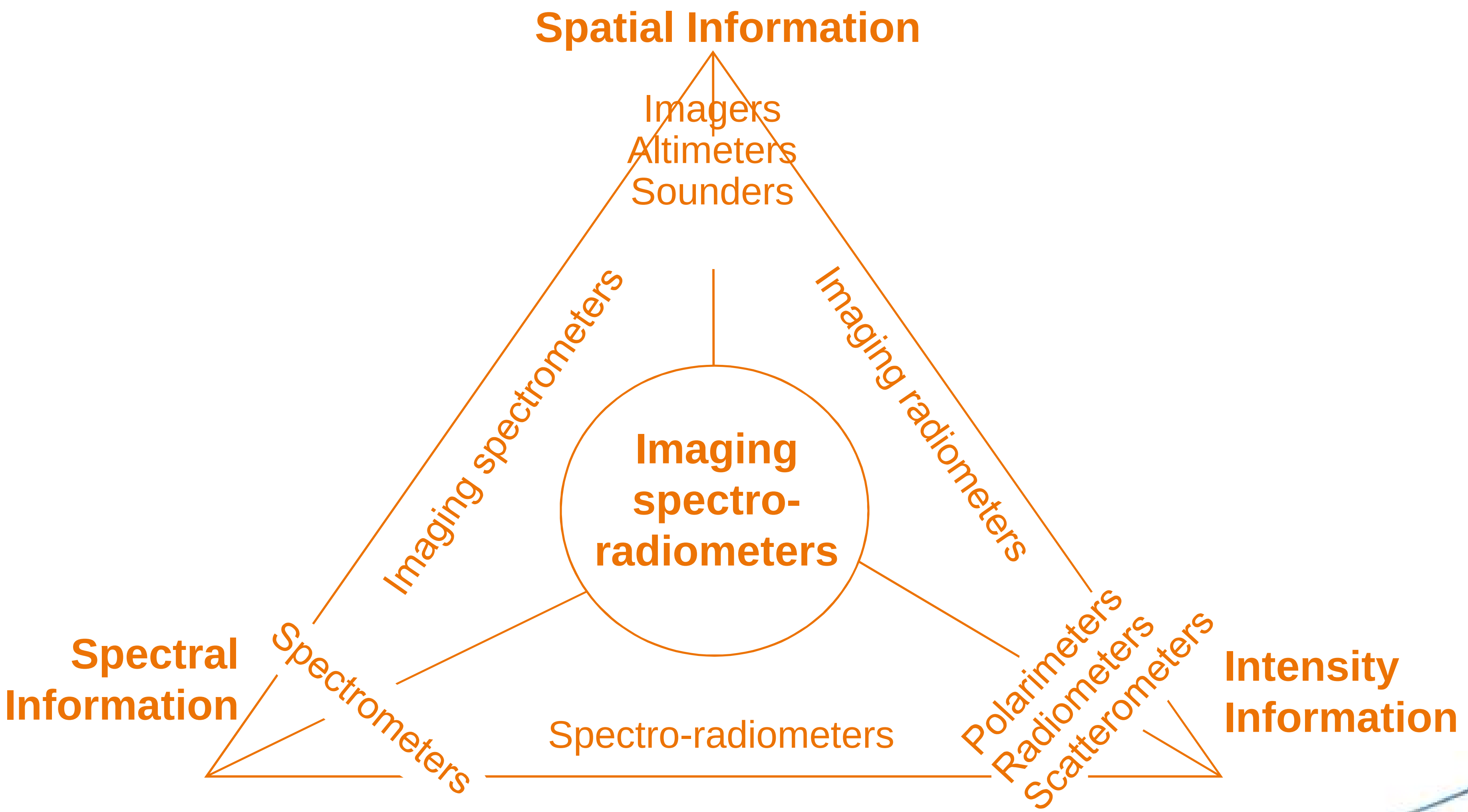
- Radiometric calibration (blackbodies, sun diffuser…)

Needed for all IR instruments

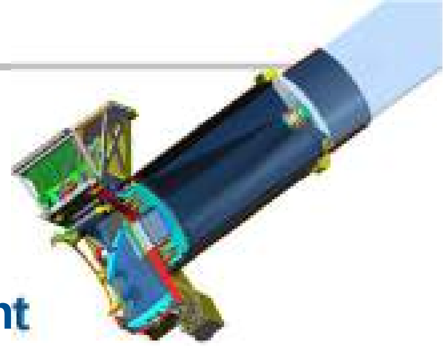
- System to cool detectors with passive or active method
- Other verification and measurement systems

e.g. system for checking and measuring the optical path difference in an interferometer

Sensing Techniques



Fundamentals : Design Drivers



- ✦ **Spatial resolution**
  - » **Size of the smallest observable surface element**
- ✦ **Field of view (FOV)**
  - » **Size of the instantaneously observable area**
- ✦ **Spectral resolution**
  - » **Discrimination of wavelength smallest difference**
- ✦ **Radiometric budget**
  - » **Link budget and signal to noise ratio (SNR)**
- ✦ **MTF**
  - » **The Modulation Transfer Function reveals image contrast**

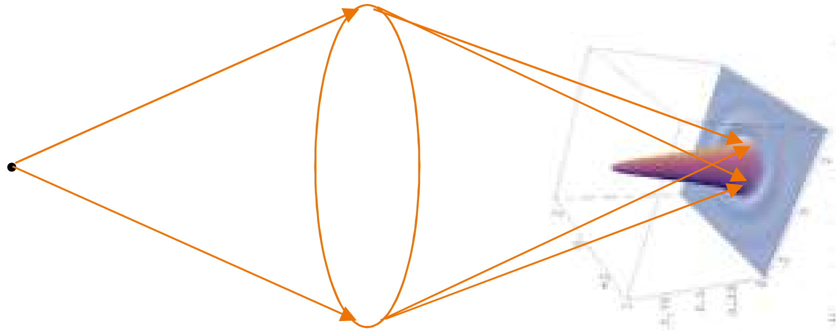
USTH Design Drivers : Spatial Resolution for identification and interpretation

cnes

Design Drivers : MTF

Optics limit:

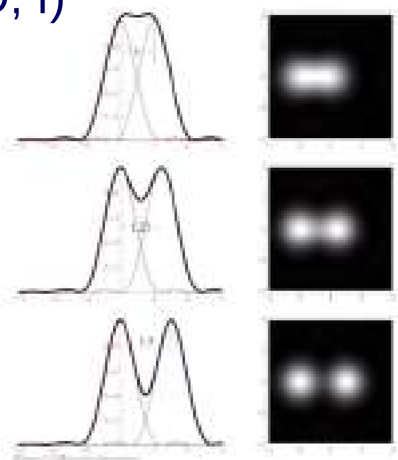
Diffraction Response of optics (Ø, f) to a point-shaped object:



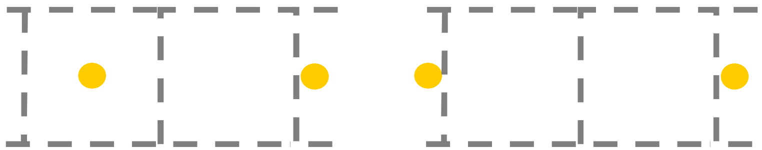
(Ø, f)

Two objects **in focal plane** may be resolved if the distance between them:

$$r \geq 1.22 \frac{\lambda f}{\Phi}$$



Detector Limit:



non-separated separated

Design Drivers : FOV & Spatial Resolution vs Sensor

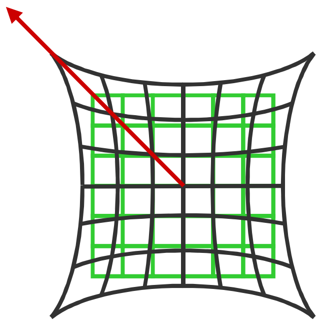
- The detector (of width L) contains N detectors (of width a).

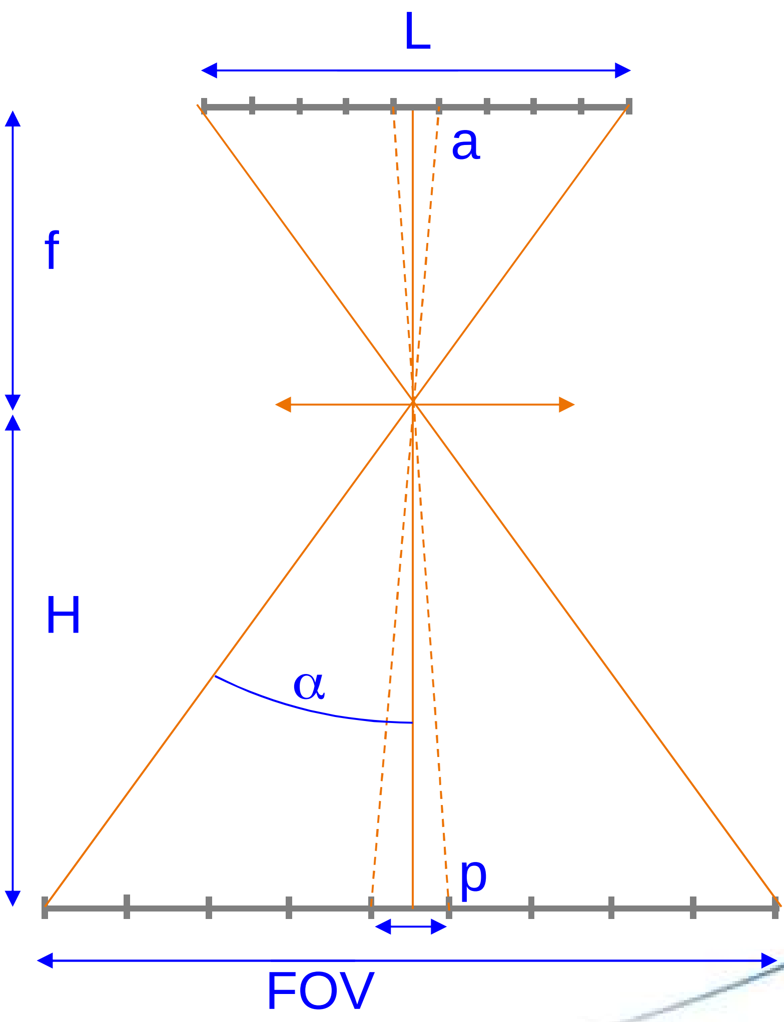
$$\frac{f}{L} = \frac{H}{FOV}$$

– With no distortion, ground sampling p is regular:

$$\frac{f}{a} = \frac{H}{p}$$

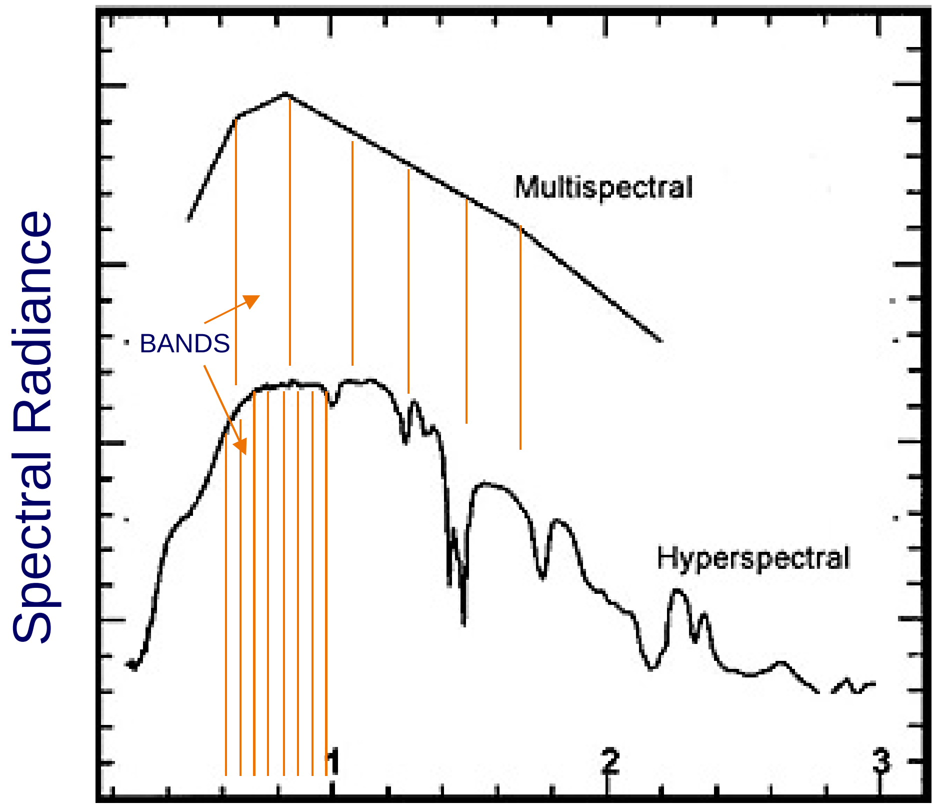
Typical distortion :





Design Drivers : Spectral Resolution

Spectral resolution adjusted against observation requirement



Multispectral Bandwidth : Typically 100nm

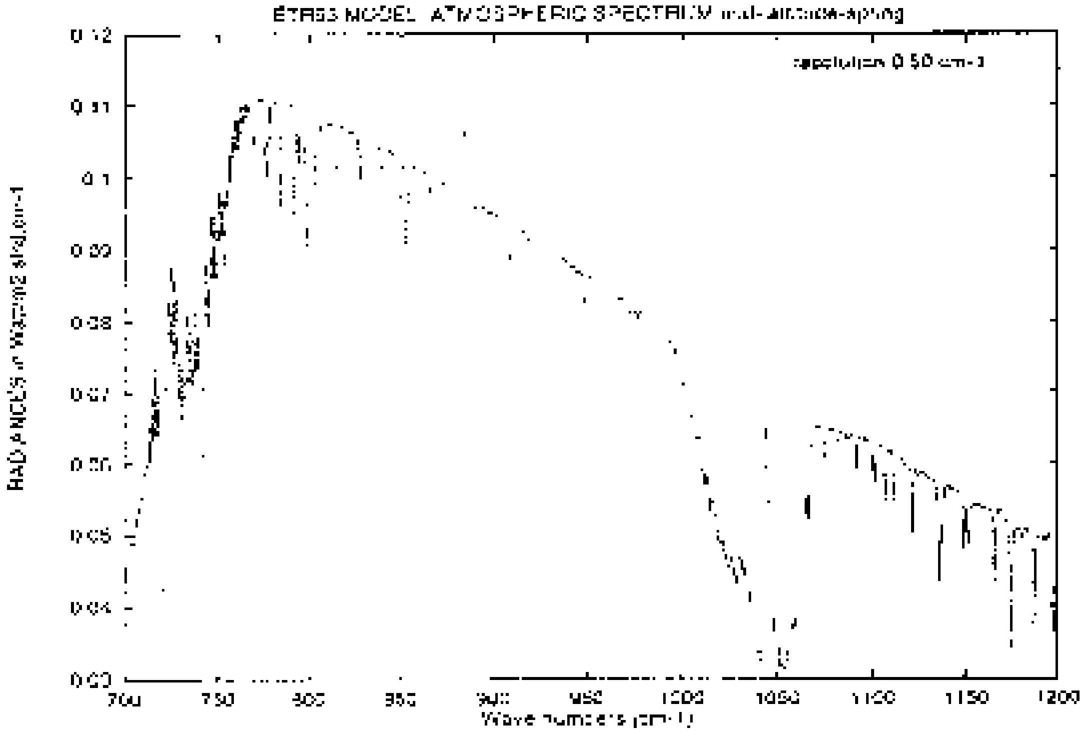
Hyperspectral Bandwidth : Typically 10 nm

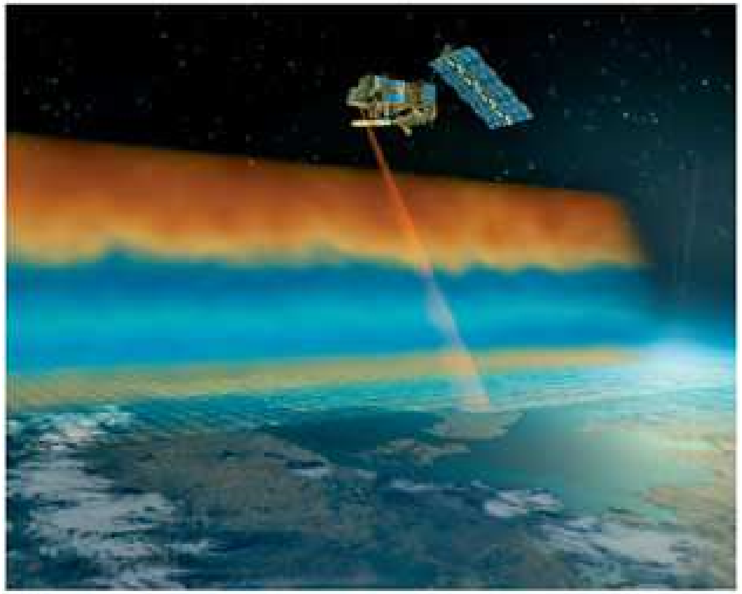
Wavelength in µm

Passive Sensors: Spectrometers

Key parameter: Spectral resolution

- **Resolution: 6 nm at 10µm ($0.5\ cm^{-1}$)**





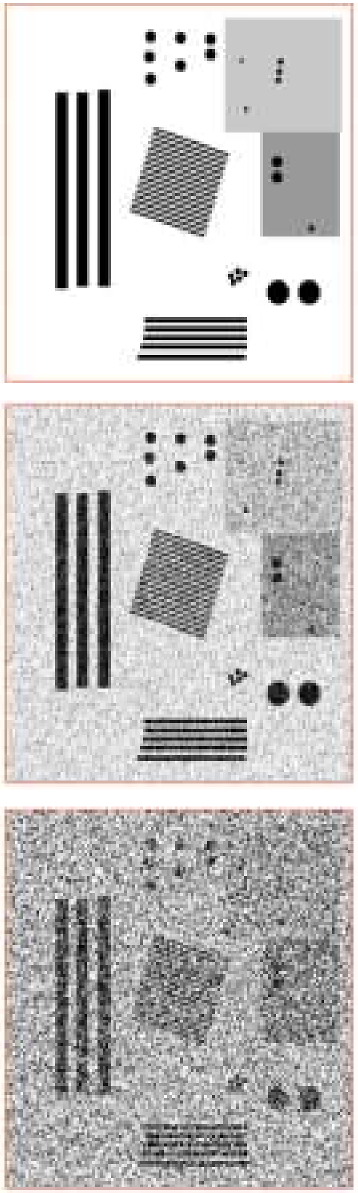
Design Drivers : Radiometric budget & SNR

$$S = \int L(\lambda) \cdot \pi \frac{a^2}{4 \cdot N^2} \cdot T_{opt}(\lambda) \cdot R(\lambda) \cdot t_{int} \cdot d\lambda$$

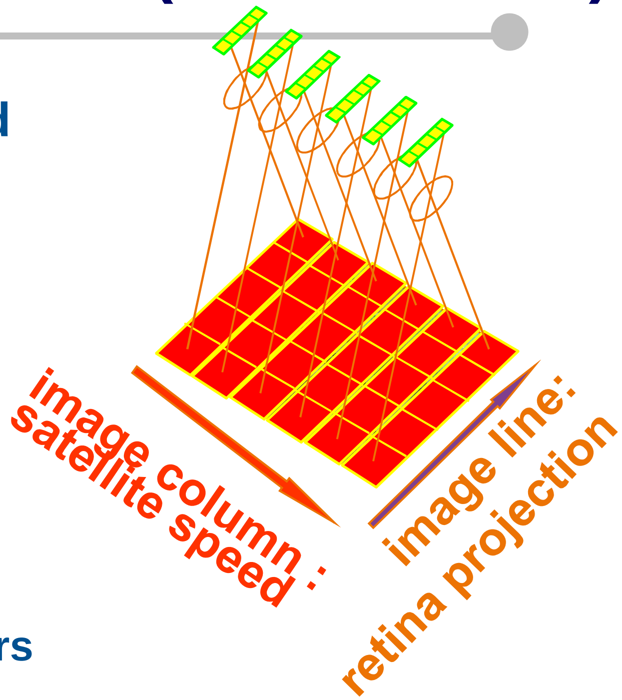
- S: Instrument output signal
- $L(\lambda)$: Scene radiance
- N: Optical aperture (focal length/diameter)
- a: Detector size
- $T_{opt}(\lambda)$: Optical transmission
- $R(\lambda)$: Detector spectral sensitivity
- t_{int}: Integration time

Noise is generated by shot noise, detector and electronics
SNR depends on scene radiance

Typically : Signal / Noise > 100

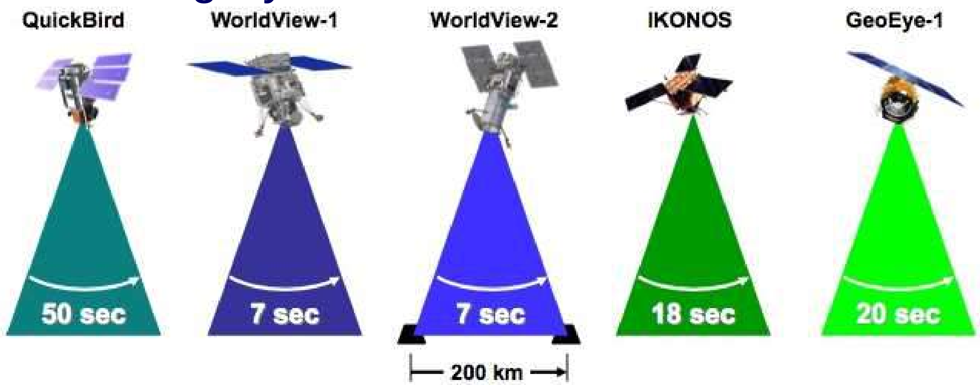


Imaging methods Push-broom systems (line detectors)



- Lines are simultaneously acquired by aligned detectors
- Columns are acquired from satellite motion
- Advantages:
  - » Simple, flexible
  - » Geometrical quality
- Drawbacks:
  - » focal plane complexity
  - » radiometric equalisation problems bw detectors
- Highly used on LEO satellites

Satellite agility:



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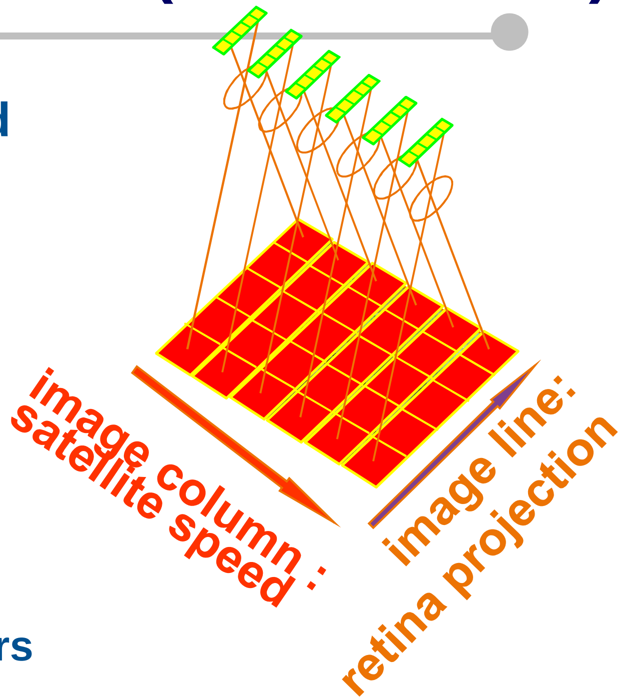

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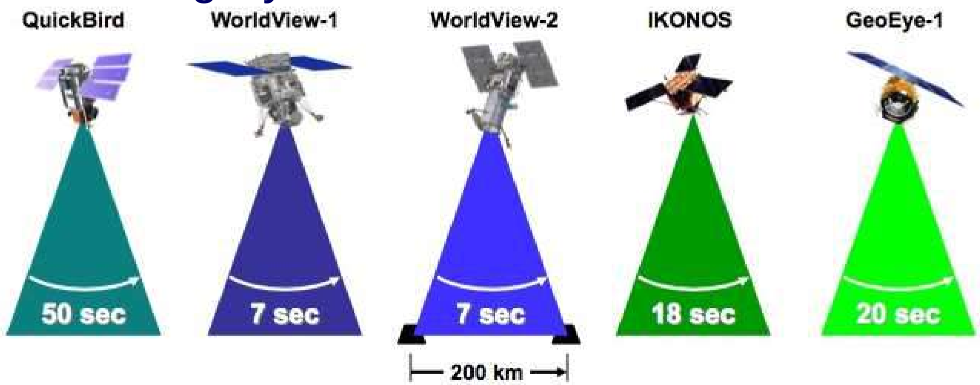
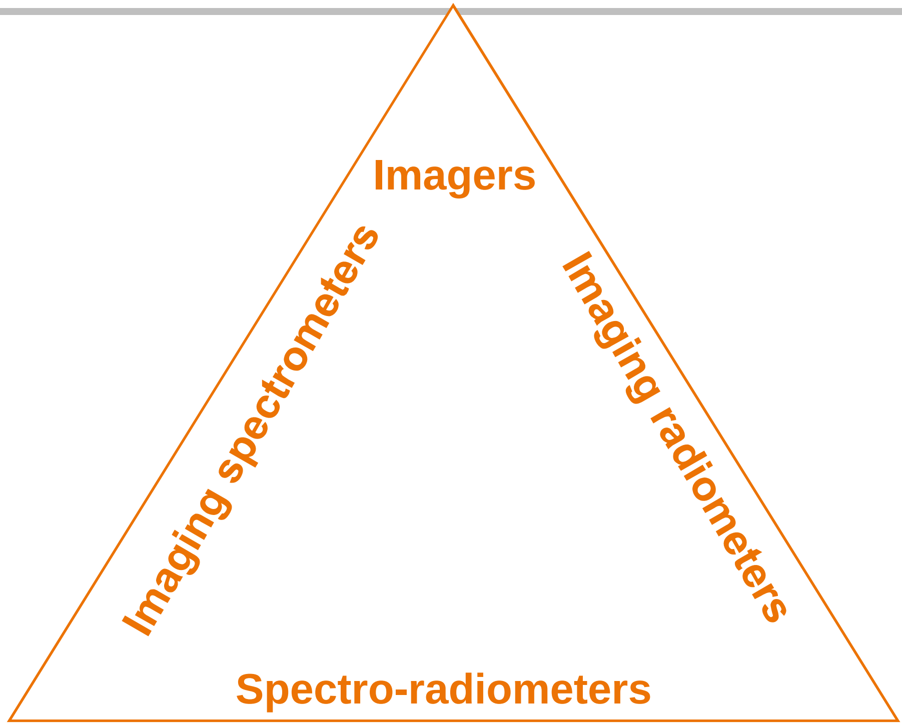


Passive Sensors



	Imagery	Radiometry	Spectrometry
Pixel size	**Small**	**Large**	Large
Focal length	**Large**	-	-
Integration time	Reduced	**High**	High
Aperture size	**Large**	**Large**	-
Spectral resolution	-	Medium	**Fine**

Passive Sensors:

Imagers

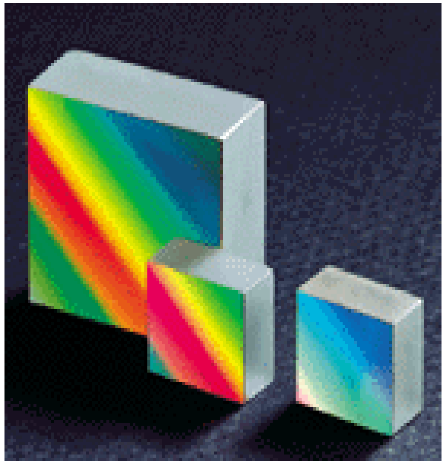
Imaging radiometers

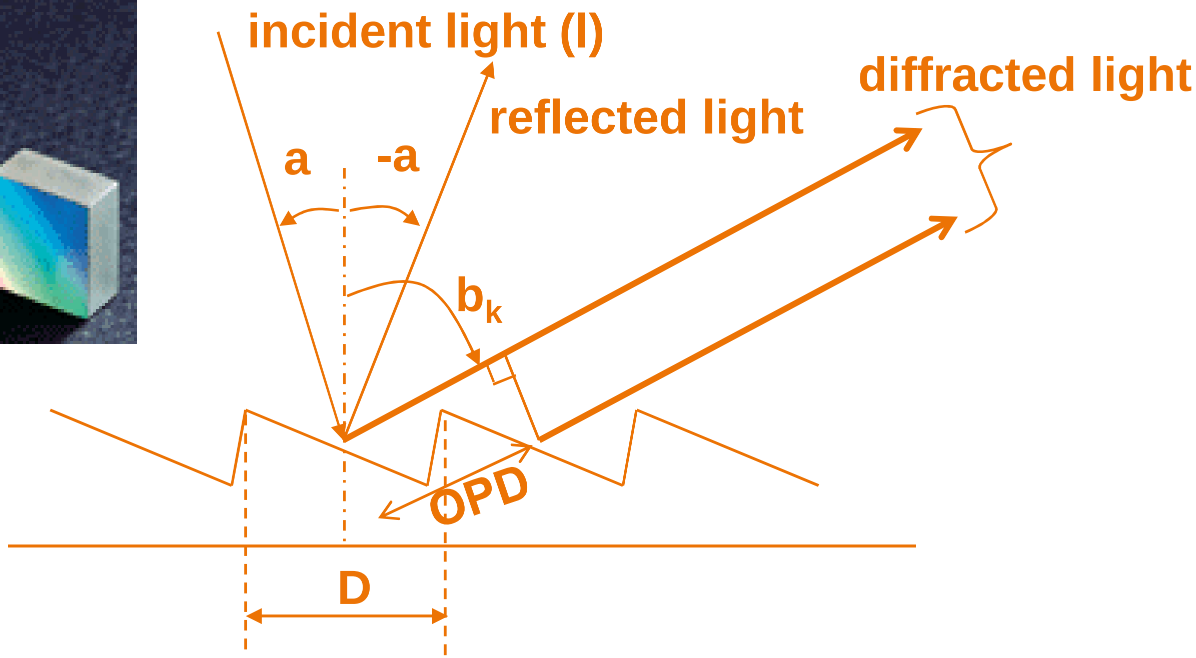
Imaging spectrometers

Spectro-radiometers

	Imagery	Radiometry	Spectrometry
Pixel size	**Small**	**Large**	Large
Focal length	**Large**	-	-
Integration time	Reduced	**High**	High
Aperture size	**Large**	**Large**	-
Spectral resolution	-	Medium	**Fine**

Passive Sensors: Hyperspectral imaging - Diffraction Grating

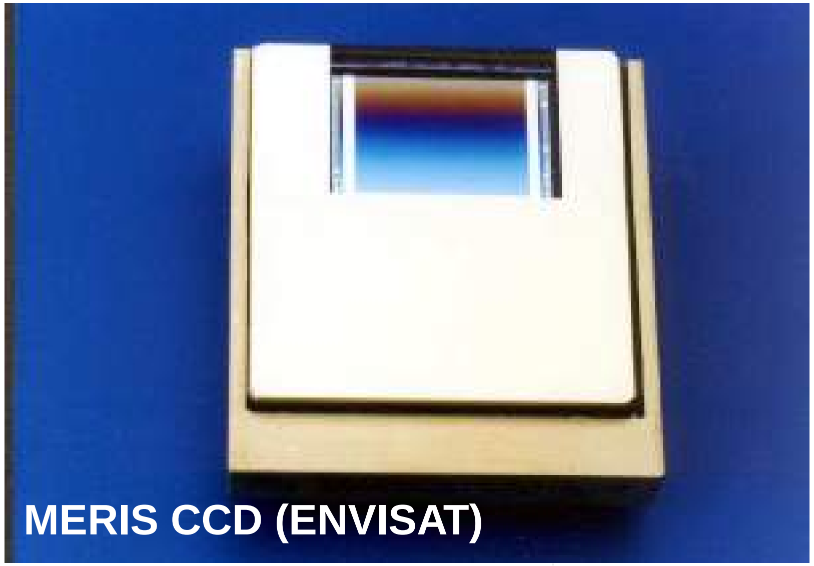


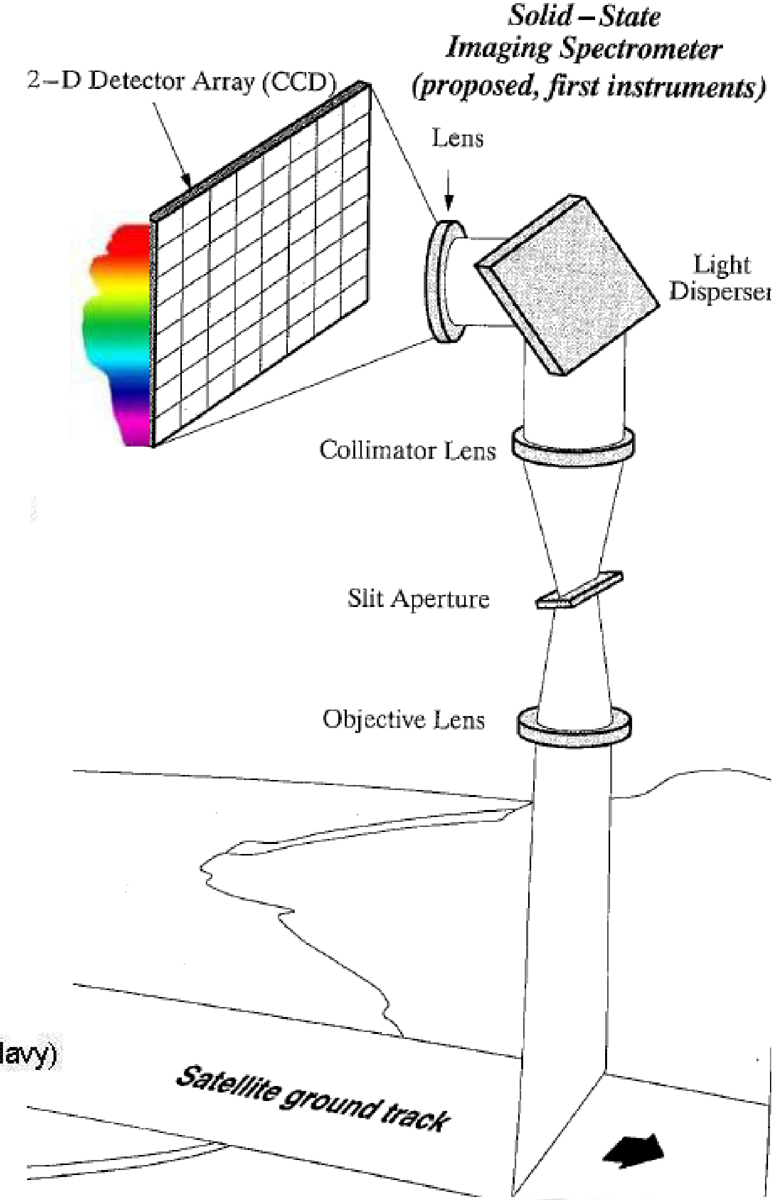


coherent interferences → $k.I = D.(\sin a + \sin b_k)$

Passive Sensors: Hyperspectral imaging

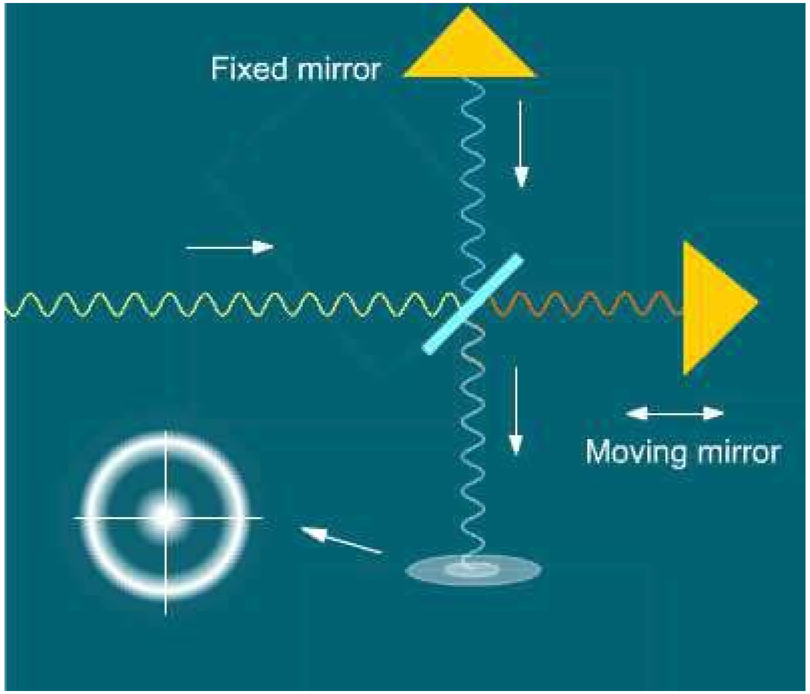
Measuring spectrum at each pixel





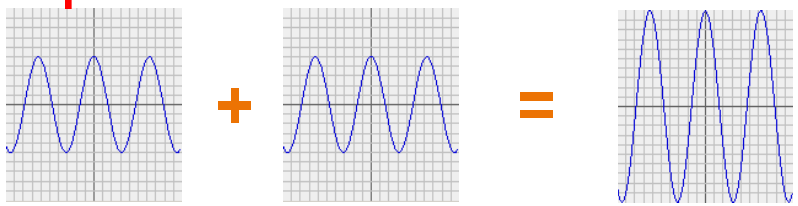
(NEMO Project Office, United States Navy)

Passive Sensors: Spectrometers - Fourier transform interferometers

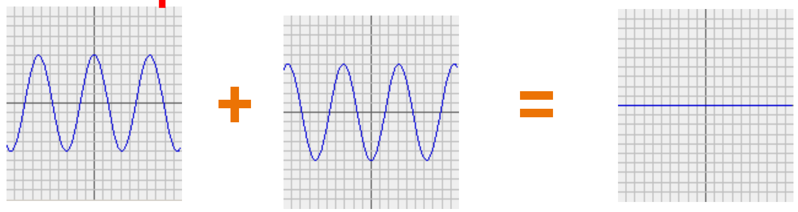


Spectral resolution depends solely on the travel of the moving mirror (L):

In phase:



Out of phase:



Advantages:
Infrared observation
High spectral Res
Wide spectral range

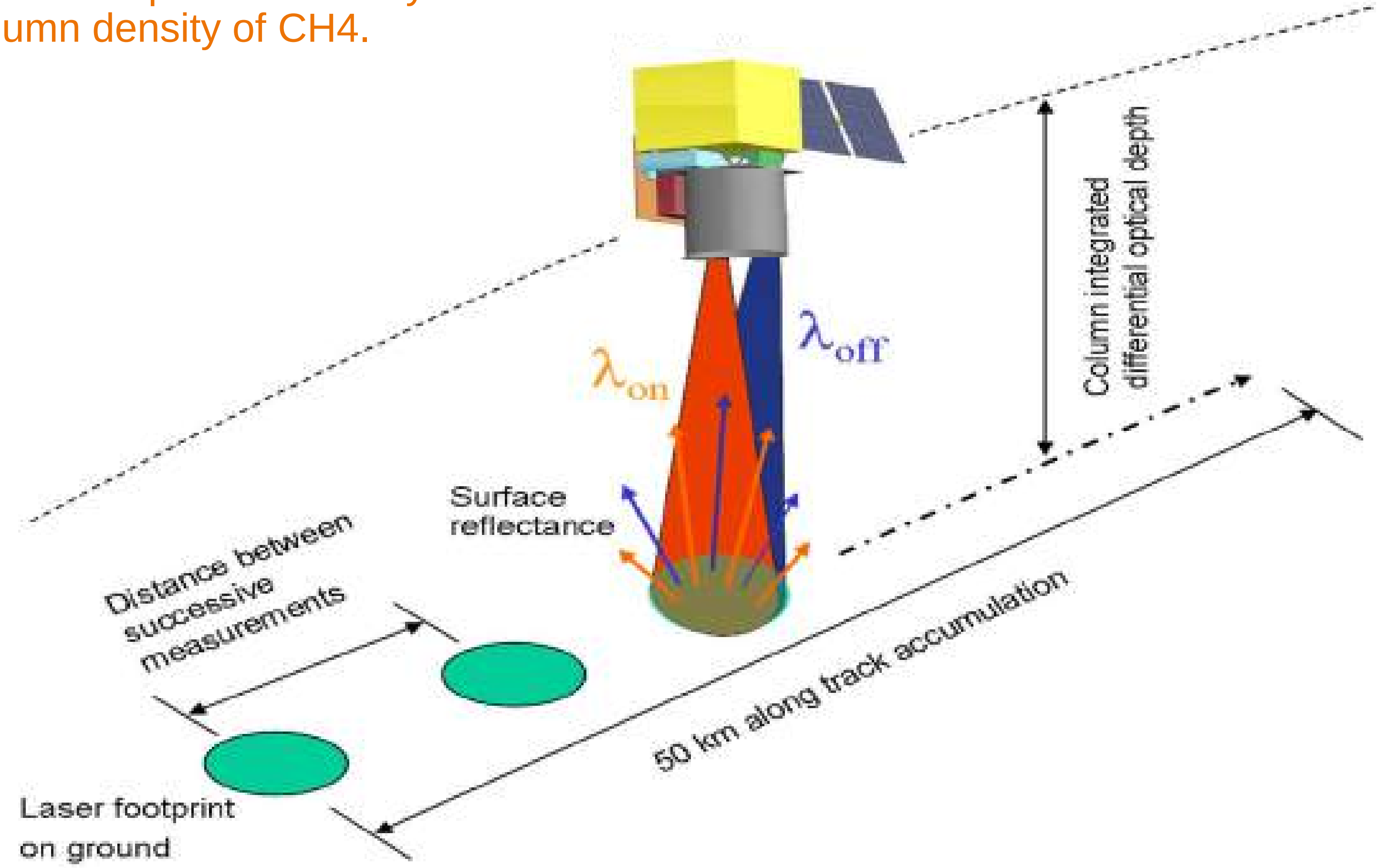
Disadvantages:
Non simultaneous acquisition
Moving mechanical parts
Microvibrations Sensitivity

IPDA Lidars

IPDA : Integrated Path Difference Absorption

CH_4 measurement using the IPDA principle:

The differential absorption between the on- and the offline pulse is directly related to the column density of CH4.



Summary

Remote Sensing systems performance (accuracy, resolution, geographical coverage, revisit …) depends on instrument design and observation conditions :

- Orbit parameters (sun illumination, satellite velocity, altitude…)
- Satellite pointing (view angle, pointing stability, …)

Trade-off between single measurement quality and revisit

Rencontres du Vietnam

Atmospheric Remote Sensing and Molecular Spectroscopy

Satellite Measurements : Microcarb

Thanks to François Buisson, Didier Pradines, Carole Deniel
Centre National d'Etudes Spatiales, Toulouse, FRANCE

Vietnam School of Earth Observation, ICISE, Quy Nhon 2018

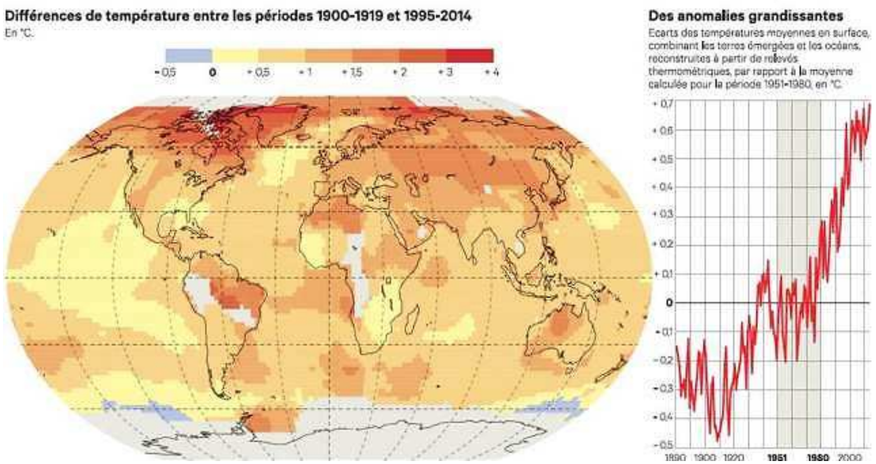
OUTLINE

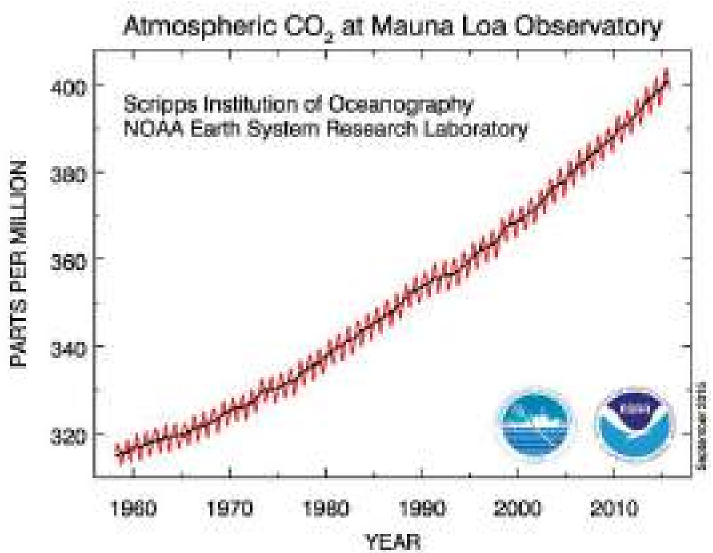
- Basics of atmospheric remote sensing from space
  - Orbit types
  - Instrument types
- Illustration with two CNES missions
  - MICROCARB : CO2 measurement with spectrometer
  - MERLIN : CH4 measurement with Lidar
- Copernicus Atmosphere Monitoring Services

Mission rationale

GHG as an actor of the climate change

- Correlation between Increase of the atmospheric concentration of greenhouse gases and climate change has been established (see IPCC, 2013: Summary for Policymakers. In: Climate Change 2013)
- CO_2 is the GHG with the highest contribution.
  - Mean temperature at earth surface increased by 0.9°C between 1901 and 2012
  - CO_2 atmospheric contents increased by 250 ± 10 GtC, i.e 118 ppm in concentration between 1750 and 2013. It has reached 400 ppm in 2015





Natural sinks mitigate climate change

2000-2012 averages

8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

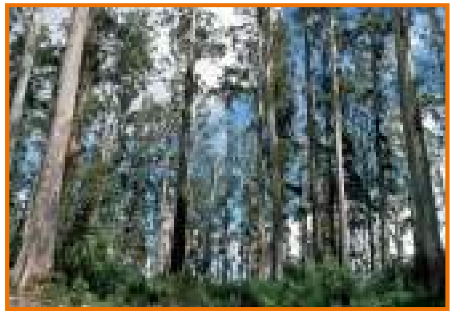
4.3±0.1 PgC/yr

46%

2.6±0.8 PgC/yr

28%

Calculated as the residual
of all other flux components



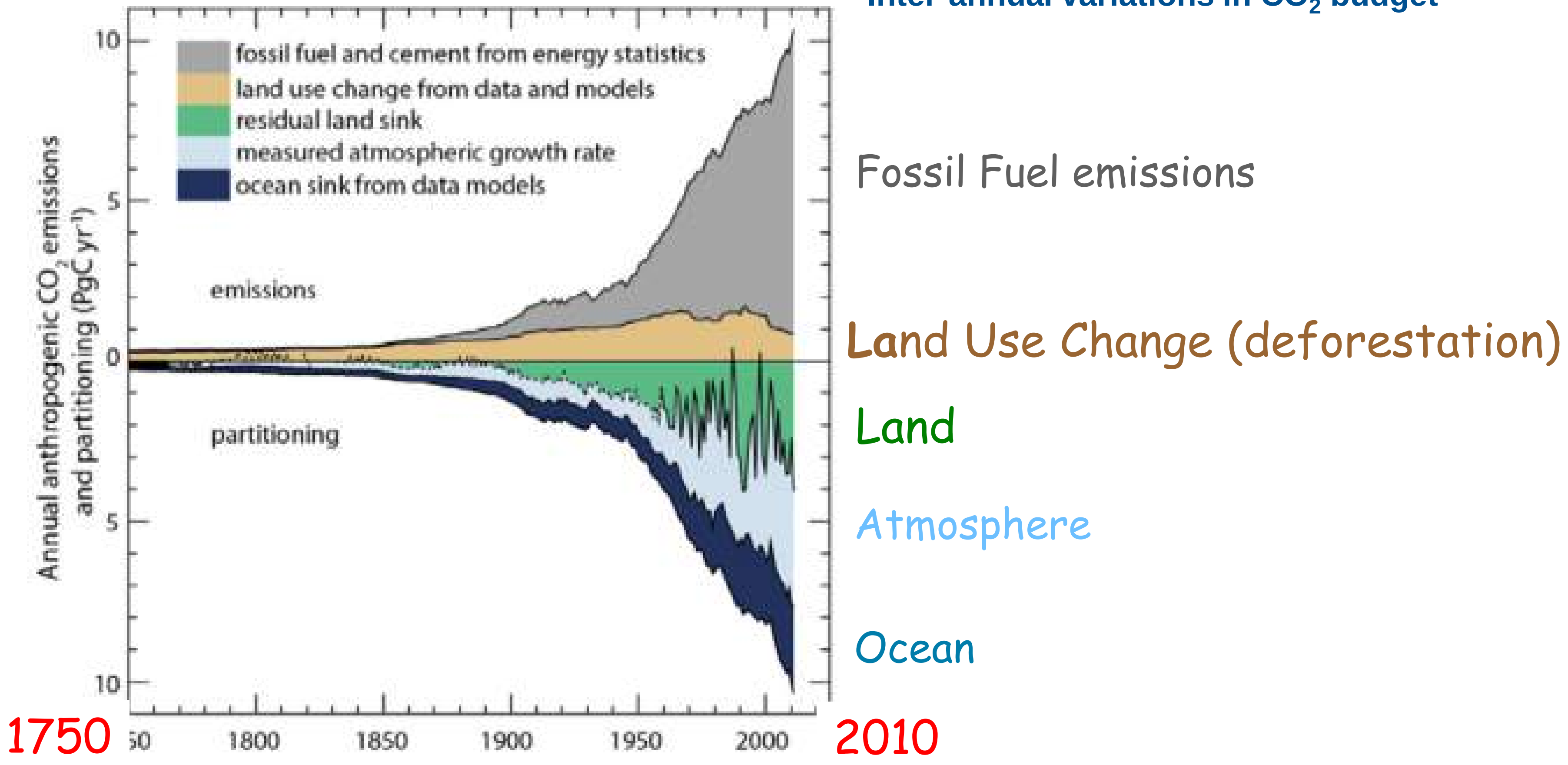
26%

2.5±0.5 PgC/yr

Only ≈half of emitted CO_2 stays in the atmosphere

MICROCARB: Scientific objectives
CO_2 Budget : The Challenge

Inter-annual variations in CO_2 budget

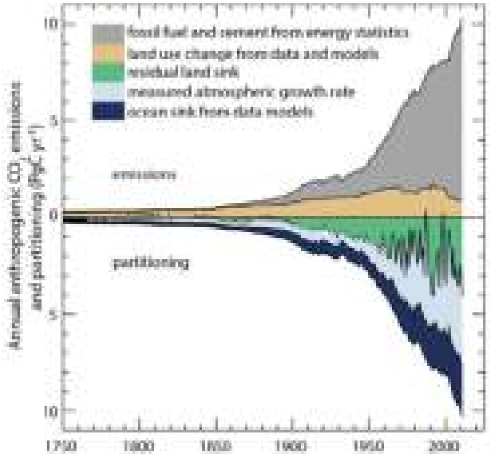


The land sink is highly variable on an annual basis
Strong correlation with El Niño events
Driven by weather anomalies; not yet properly understood.

MICROCARB objectives : Highly Accurate CO_2 observations

With accurate XCO_2 measurements globally, MicroCarb aims to make significant progress in answering the following specific questions:

- Where are the main carbon sources and sinks ?
- What are the processes that control these fluxes ?
- What is the contribution of land use change to the net land flux?
- How does the Carbon cycle react to large climate perturbations such as El Niño/La Niña events?
- How will the carbon cycle react to climate change?
- + *Test at highest space resolution for cities emissions estimation*

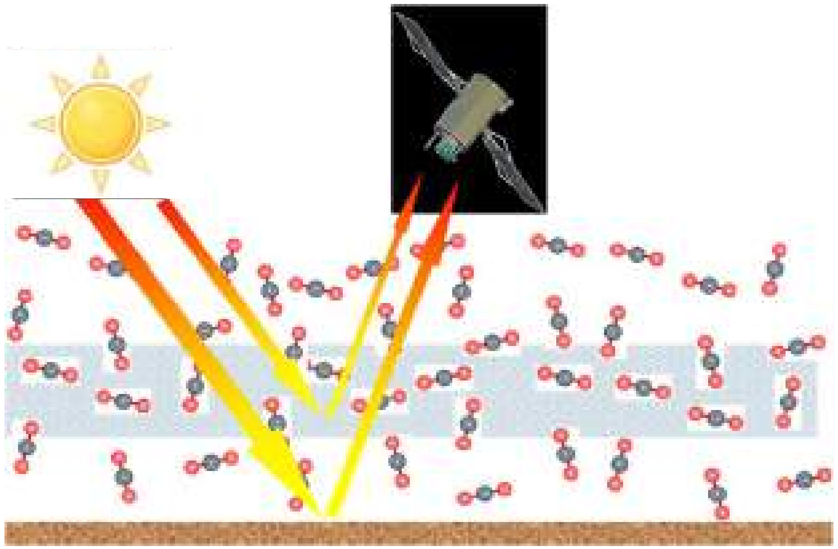


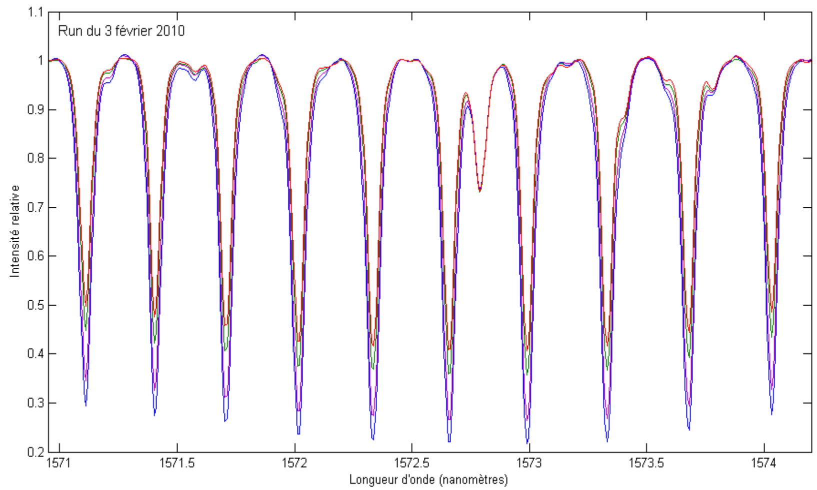
Accurate measurements are required and are difficult to make:

- Precision < 1 ppm & Bias < 0,1 ppm
- XCO2 spatial gradients are small (< 10 ppm)
- Regional biases flaw the flux computation

Principe de mesure de MicroCarb

- On ne peut pas mesurer directement des flux de CO_2 par télédétection
- Principe de MicroCarb : mesurer, dans le proche infrarouge, la lumière solaire réfléchie par la surface terrestre qui présente des raies d'absorption par le CO2 atmosphérique





Exemple de spectre de raies d'absorption du CO_2

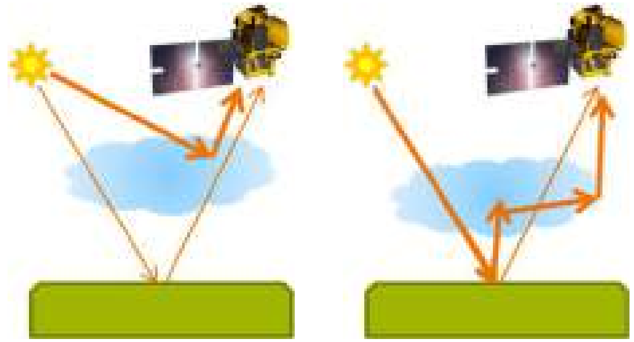
- Au 1er ordre, plus la concentration en CO2 est grande, plus les raies sont profondes

➔ Chaque mesure MicroCarb permet d'obtenir une concentration (locale) de CO2 (XCO2)

Les difficultés de la mesure du CO_2 depuis l’espace

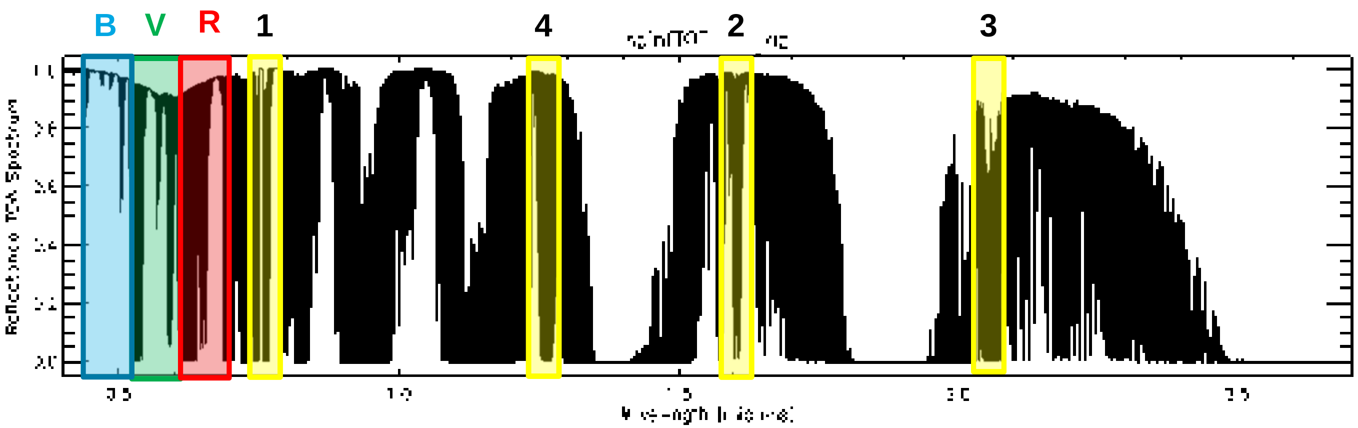
- Le CO_2 est un gaz très stable, ses variations relatives sont très faibles : sur des concentrations actuelles de l’ordre de 400 ppm, le besoin de précision est de 1 ppm (0,25% !)
  ➔ Il faut donc limiter au maximum les bruits et biais de mesure
- Il y a beaucoup de perturbateurs à la mesure, par exemple la diffusion par les aérosols

On « voit » moins de gaz absorbant, on sous-estime sa concentration



On « voit » plus de gaz absorbant, on sur-estime sa concentration

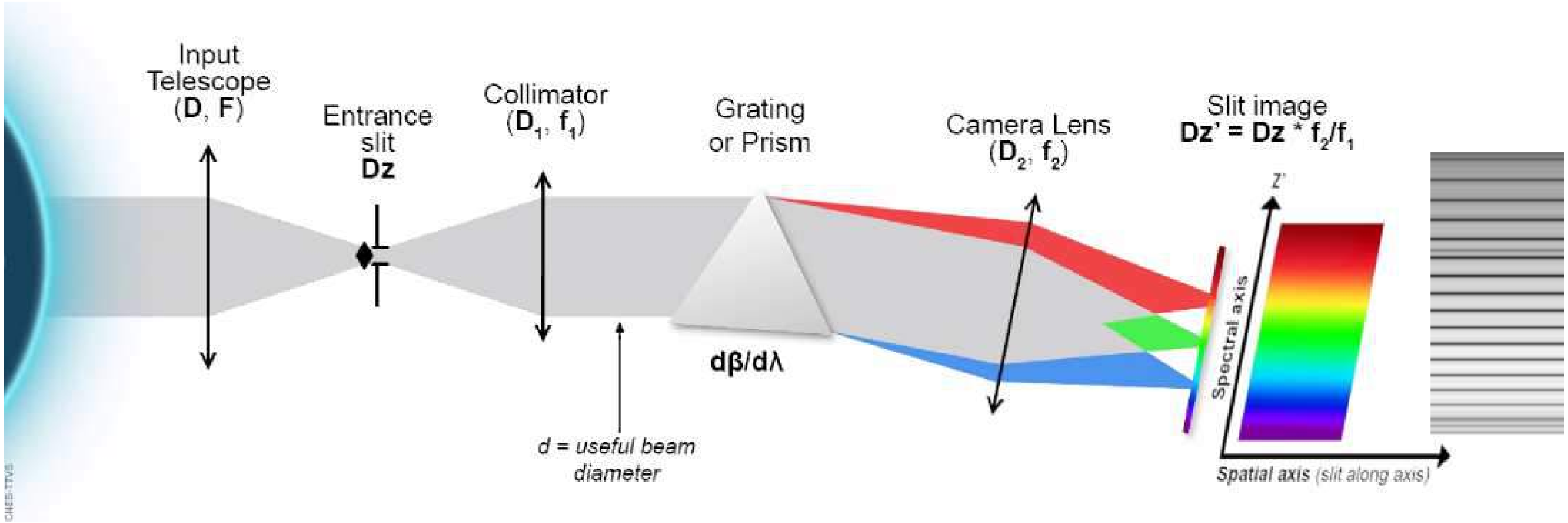
- Le CO_2 présente relativement peu d’absorptions (contrairement à H_2O)

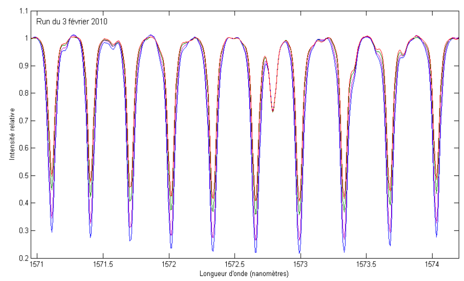


Transmission de l’atmosphère dans le domaine visible et proche IR

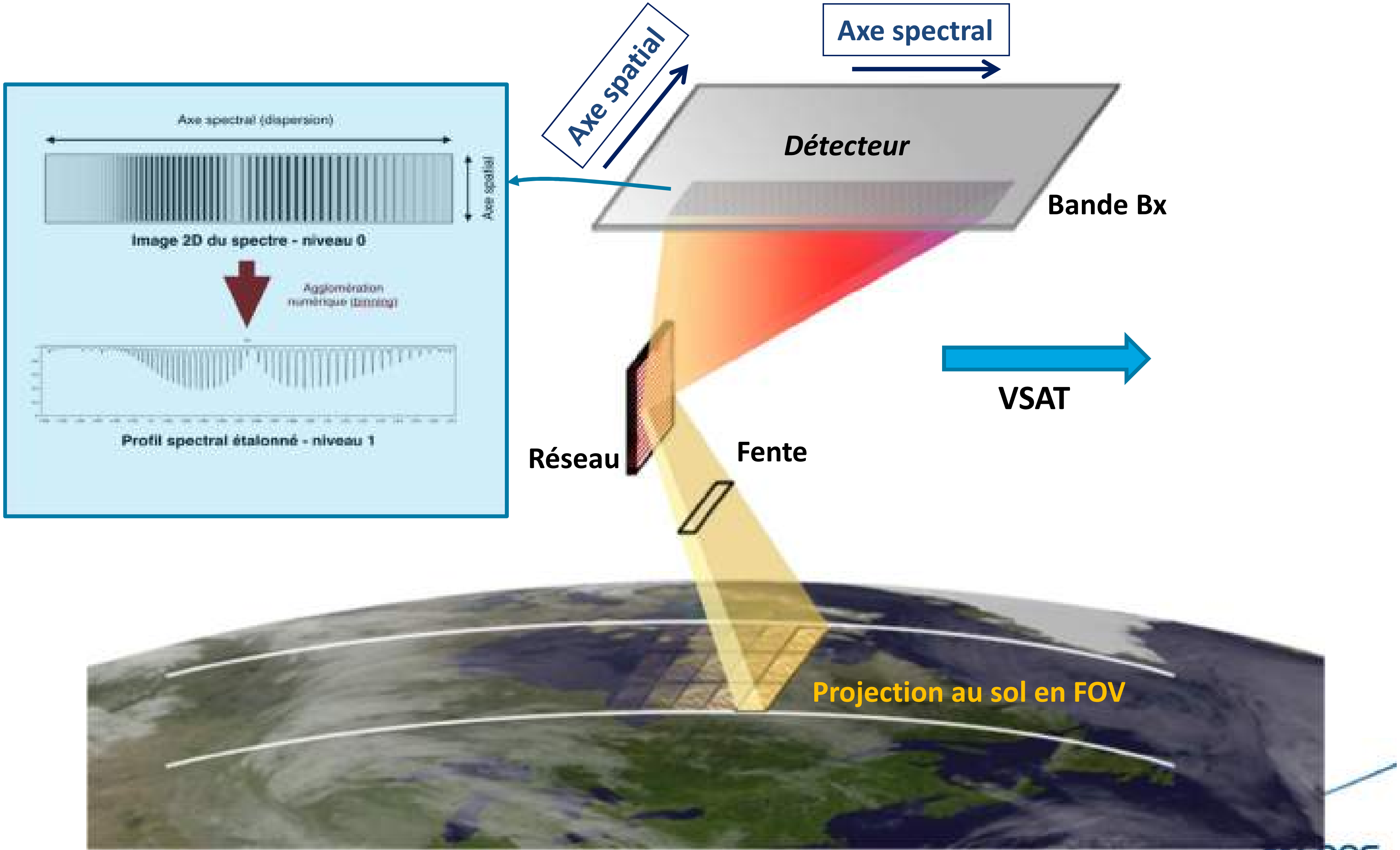
Principe de l'instrument de mesure

- Principe général de fonctionnement d'un spectromètre comme MicroCarb :



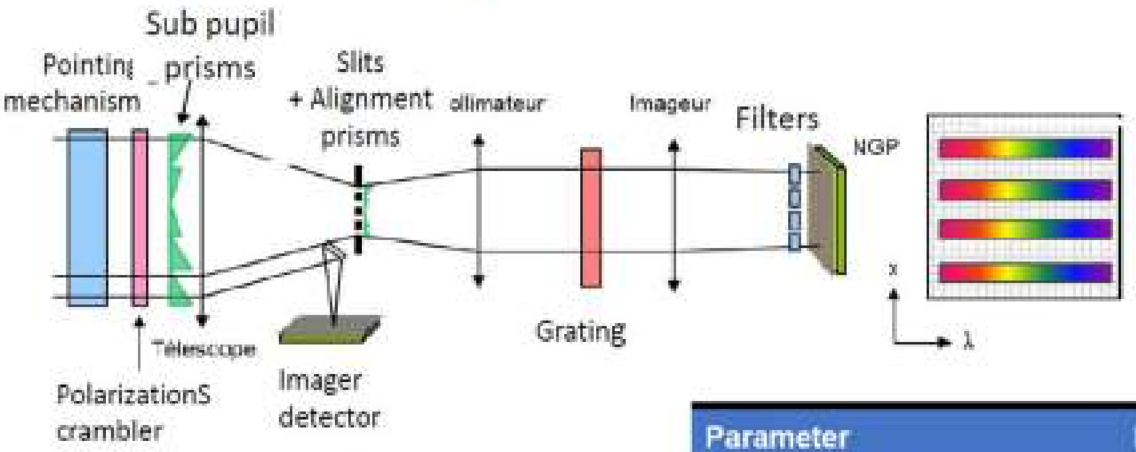


Measurement principle



Microcarb Instrument : High Technology

Instrument Optical design



Unique Spectrometer

Unique detector

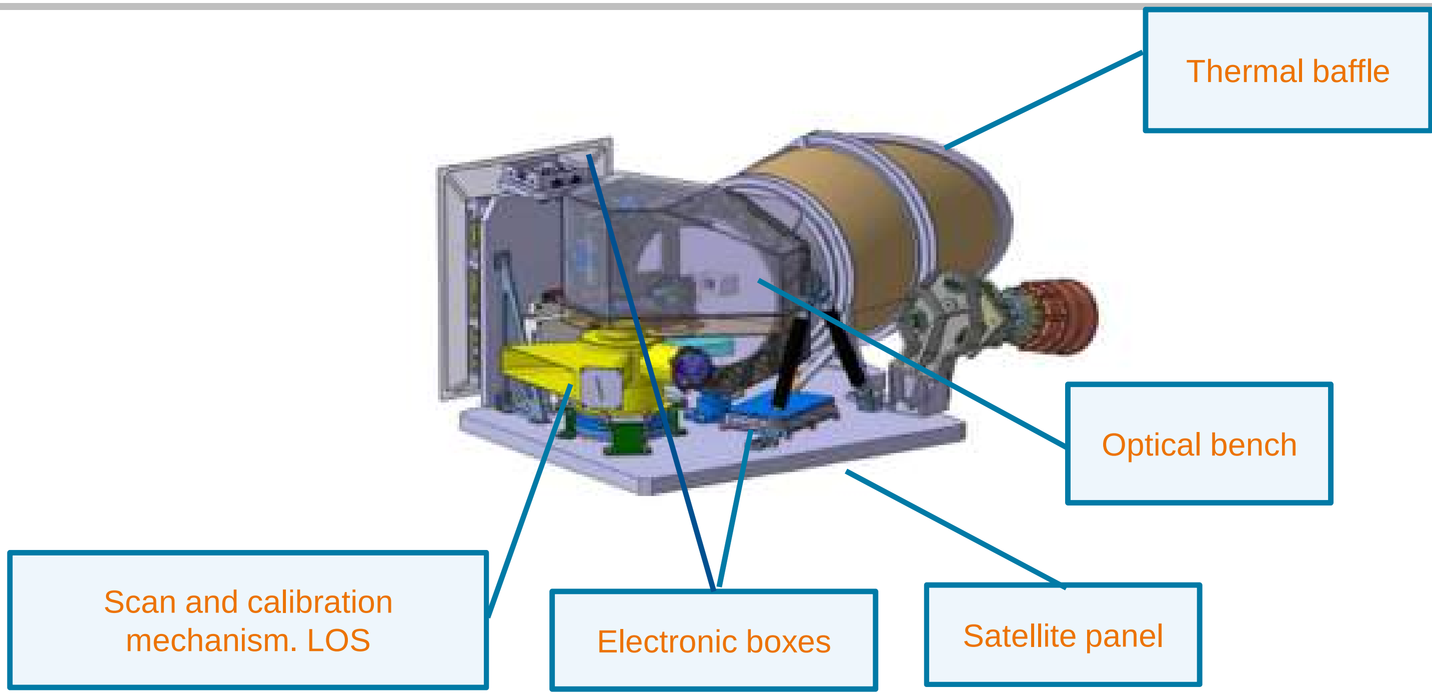
Parameter	B1 (O_2)	B4 (O_2)	B2(CO_2)	B3(CO_2)
Center wavelength (nm)	763	1269	1607	2037
Bandwidth(nm)	10	17	22	27
Mean spectral resolution	24 872	24 996	24 967	24 829
Signal to Noise Ratio per channel (@mean radiance)	285	378	344	177

Imager

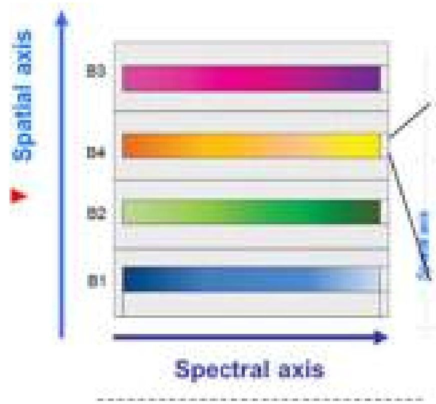
- Detection of sparse clouds

Parameter	Value
Central Wavelength	0.625 µ
FOV	18 x 26 km²
Resolution	140 m

Microcarb Instrument : High Technology



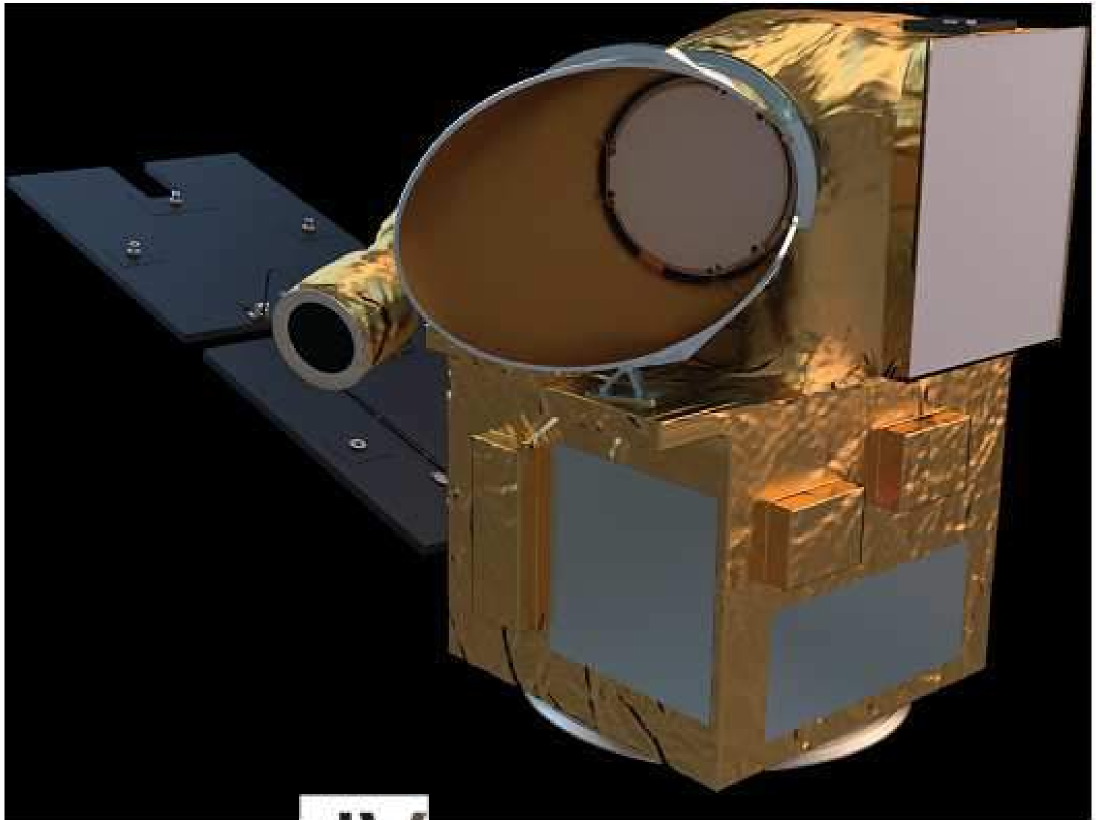
Mass	< 60 kg
Power	< 55 W
Data rate	Toutes les données sont tele mesurées =>débit= 400 Gbits/j
Cooling	Passif : détecteur (150K)
Calibration	Dispositifs de calibration embarqués
Pointing	Mécanisme de scan 1 axe



MicroCarb Satellite

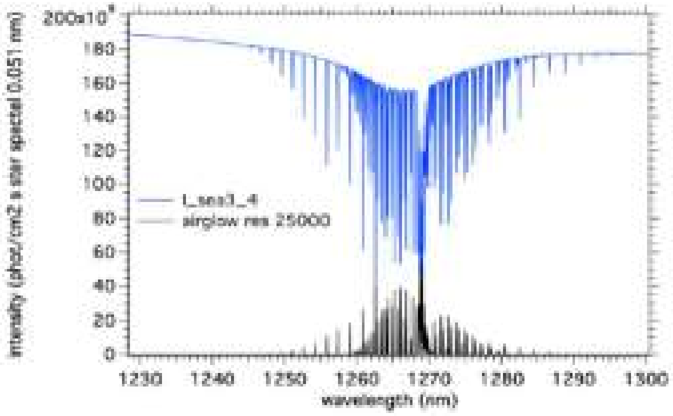
Instrument :
- < 70 kg
- < 50 W

Satellite : 1m (H) x 0,6 m x 0,6 m



Use of 1.27 µ band O2

- Aerosols properties depends on wavelength => interest to have characterization in λ close to CO2 bands
- Band used by TCCON
- A reduction of the uncertainty on X_{CO2} is expected:
  - Better assessment of the spectral impact of aerosols and of $N_{dry\ air}$ at CO_2 wavelengths
  - Reduction of the impact of uncertainty in spectroscopy
- Affected by air glow phenomena in high stratosphere
  - Analysis has demonstrated that air glow could be modeled (Reprobus) and its effects corrected with sufficient accuracy
  - Model was verified with Sciamachy data
  - Airglow will be estimated together with O2 (as an element in 4A RTIC state vector)

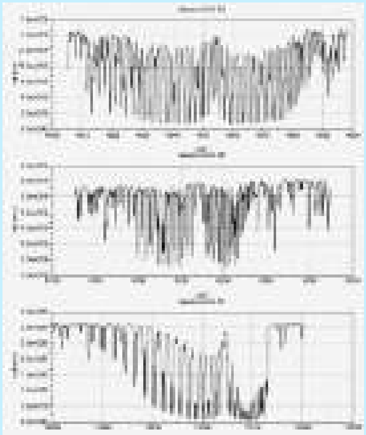


- Work is in progress to improve O2 spectroscopy in this band

De la mesure brute aux concentrations et aux flux

Niveau 0
= télémesure

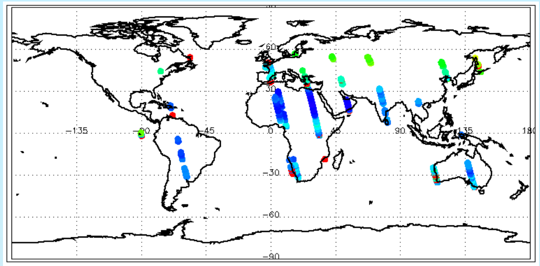
Déspatialisation
+ Etalonnage



Niveau 1 = spectres
(+ données imageur, géométrie…)

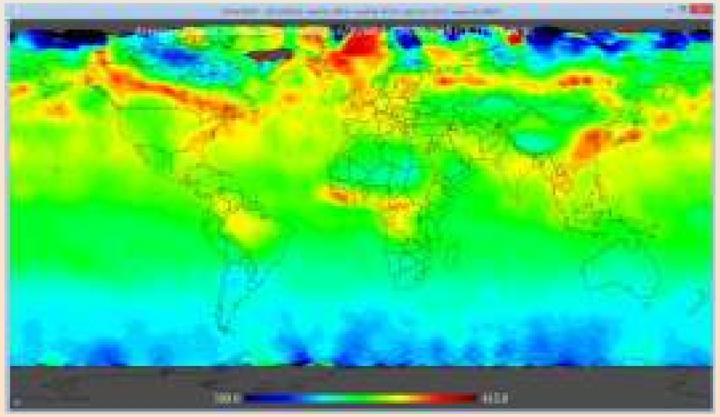
Responsabilité CNES

Modèle de transfert radiatif
(lien entre spectres et géophysique dont CO_2)



Niveau 2
= concentrations CO_2
(+ fonction de poids, données géophysiques)

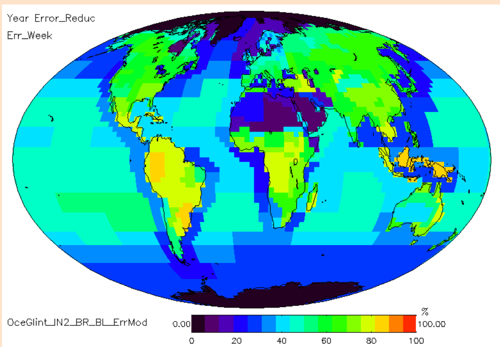
Niveau 3
= cartes XCO_2



Responsabilité CNES + labos

Modèle de transport atmosphérique
(lien entre concentrations, flux et vents)

Niveau 4 = Flux CO_2 surface
(résolution typiquement ≤ 200x200 km, période ≤ semaine)



Responsabilité laboratoires scientifiques

USTH

Rencontres du Vietnam

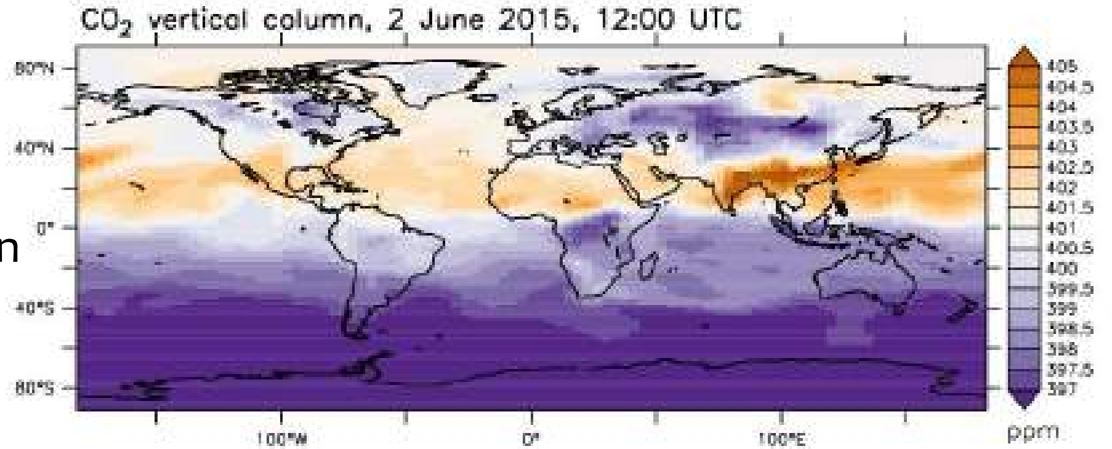
LSCE

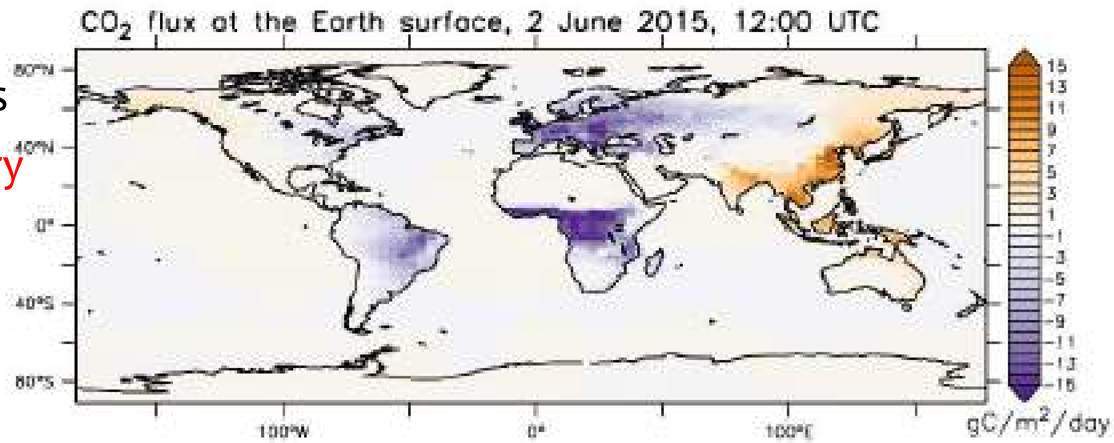
Space variation of CO_2 Concentration and fluxes (from CAMS)

- Fluxes are inferred from gradients of CO2 concentrations.
- Most gradients are primarily driven by meteorology.
- The information about emissions and sinks is subtle

⇒ need of exceptionally accurate measurements – systematic errors < 1.25 ‰ (ESA GHG-CCI, 2014) & very performant transport models.

- Analogy with altimetry.





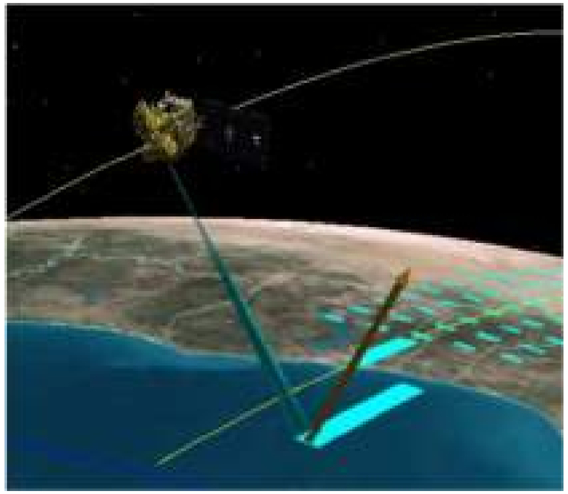
European Commission

Copernicus Europe's eyes on Earth

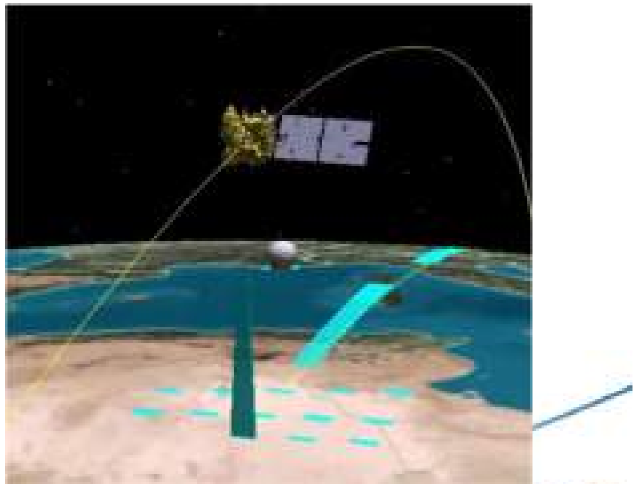
Atmosphere Monitoring Service

cnes

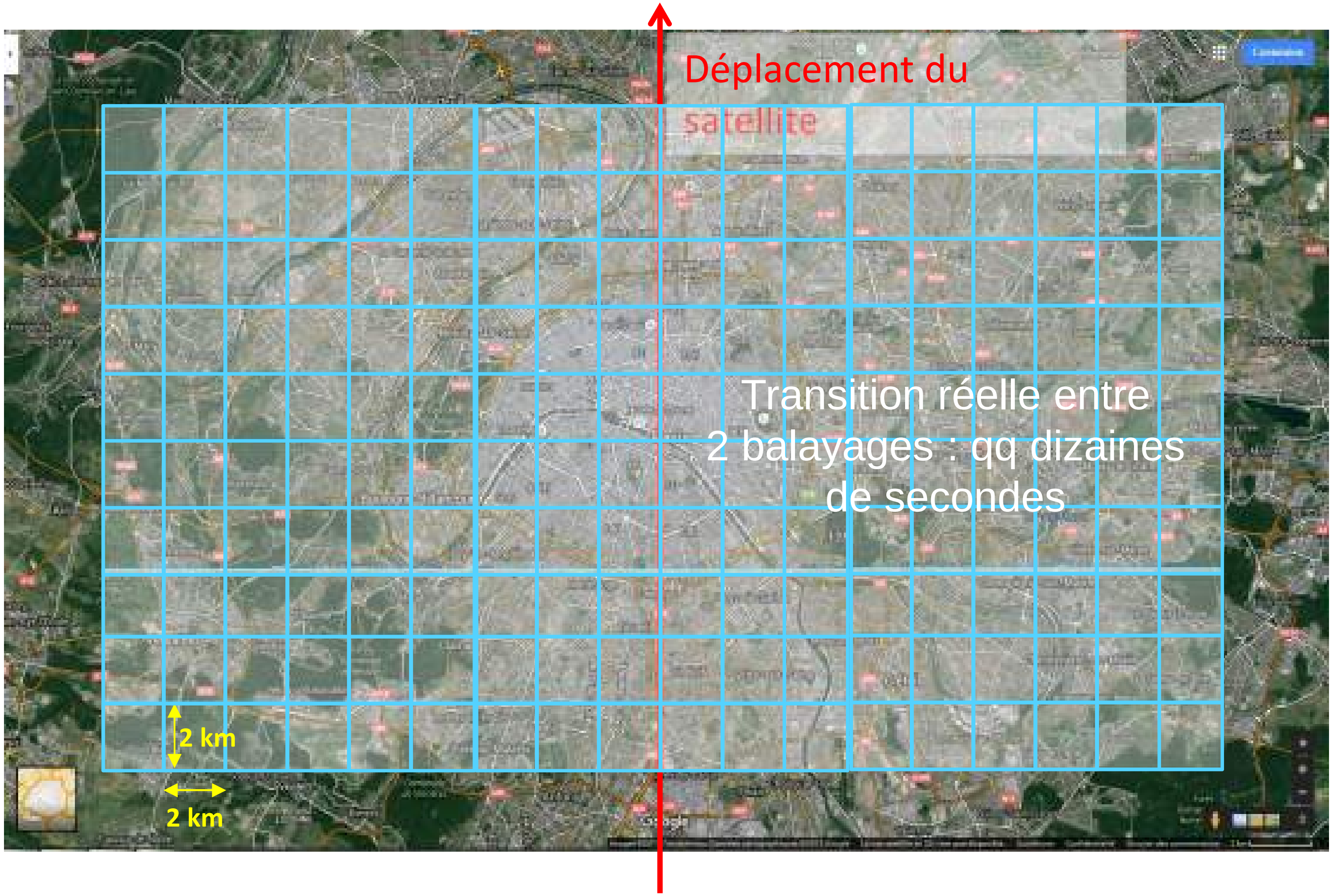
MICROCARB : Operating modes

Nadir	Glint	Target
Over lands	Over oceans	For calibration (TCCON)
		

Exploratory mode (above Paris)



Démonstrateur d'imagerie du CO2



Mode d'imagerie pour démontrer la faisabilité en vol de suivre les émissions de CO_2 de villes ou de centrales isolées

Summary

- From radiance measurements to CO_2 fluxes : many sophisticated computation and modeling steps
  - From detectors electronic output to spectral radiance : Instrument model and calibration (radiometric and spectroscopic)
  - From spectra to CO_2 concentrations : Molecular spectroscopy and Radiative Transfer
  - From CO_2 concentrations to fluxes : atmospheric transport models

  - At each computation step, it is important to have a characterization of the measurement error (bias or systematic error, random part)

Thanks to François Buisson and Didier Pradines (Microcarb project), Bruno Millet (Merlin Project), François Bermudo (IASI-NG project) and Véronique Mariette (Copernicus CAMS)

MEthane Remote sensing LIdar missioN

Status of MERLIN mission

Carole DENIEL, *CNES, Atmospheric Composition Programm*

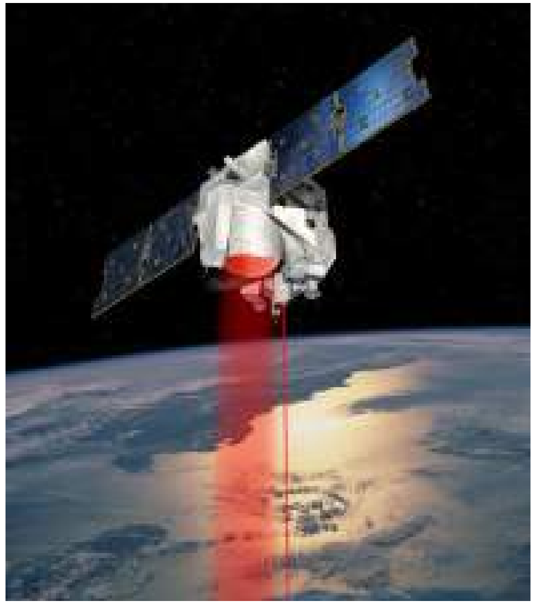
C. Pierangelo[1], B. Millet[1],
G. Ehret[2], M. Alpers[2], A. Friker[2], P. Bousquet[3], C. Crevoisier[4]

1 - Centre National d'Etudes Spatiales (CNES)
2 – Deutsches Zentrum für Luft- und Raumfahrt (DLR)
3 – Laboratoire des Sciences du Climat et de l'Environnement (LSCE)
4 - Laboratoire de Météorologie Dynamique (LMD)

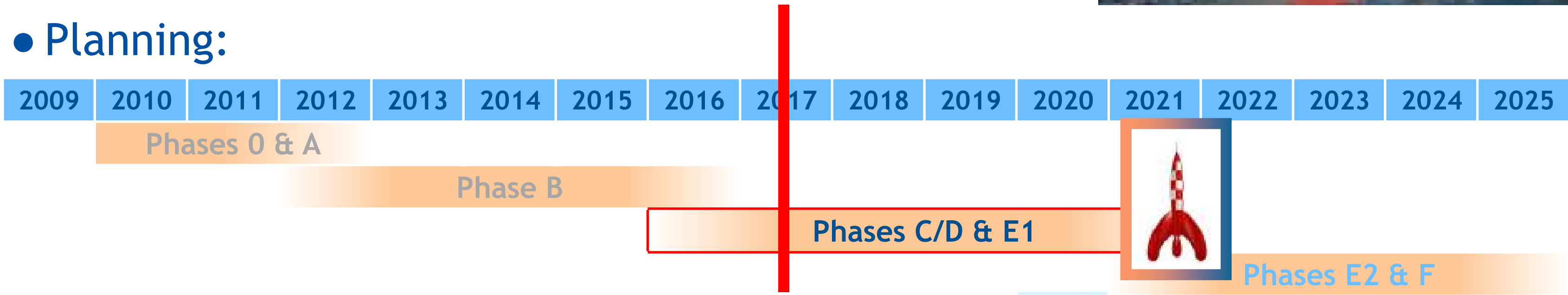
Introduction

- MERLIN is a LIDAR satellite dedicated to the observation of the spatial and temporal gradients of atmospheric methane (CH_4) columns

- MERLIN is a cooperation between France and Germany space agencies:
  - CNES in charge of platform, satellite, system, launcher, and part of ground segments
  - DLR in charge of payload, and part of ground segments



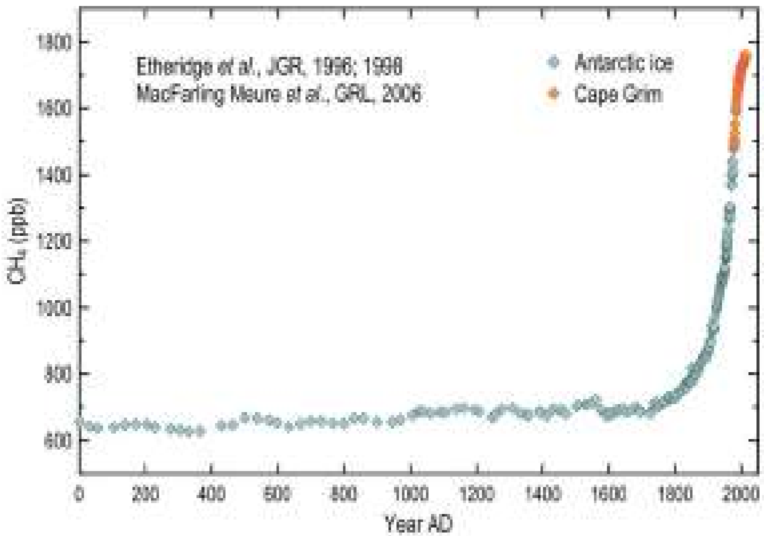
- Planning:



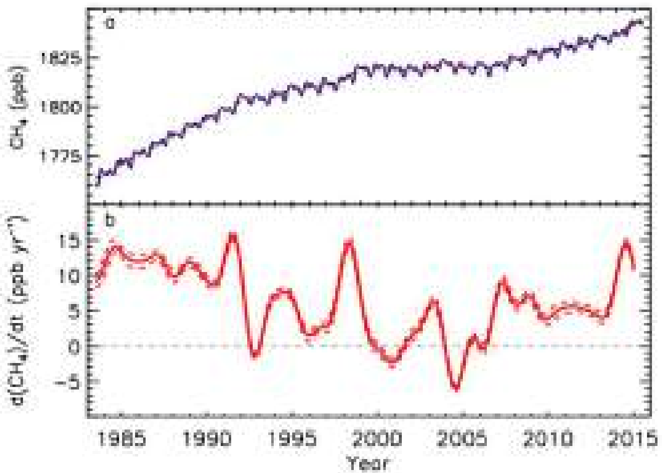
MERLIN shall be the first active mission in space dedicated to GHG

Science: Why methane?

- Atmospheric Increase by 150%, from 722 ppb (1750) to 1840 ppb (2015)
- Responsible for >20% of increase in radiative forcing since 1750:
  - GWP100 = 28 × CO_2
- Contributes to water vapor (H_2O) production in the stratosphere
- Contributes to ozone (O_3) production in the troposphere
- Lifetime of CH_4 is 8-10 years, good target for climate change mitigation
- Present and future CH_4 emissions are highly uncertain
- Recent atmospheric variations are puzzling

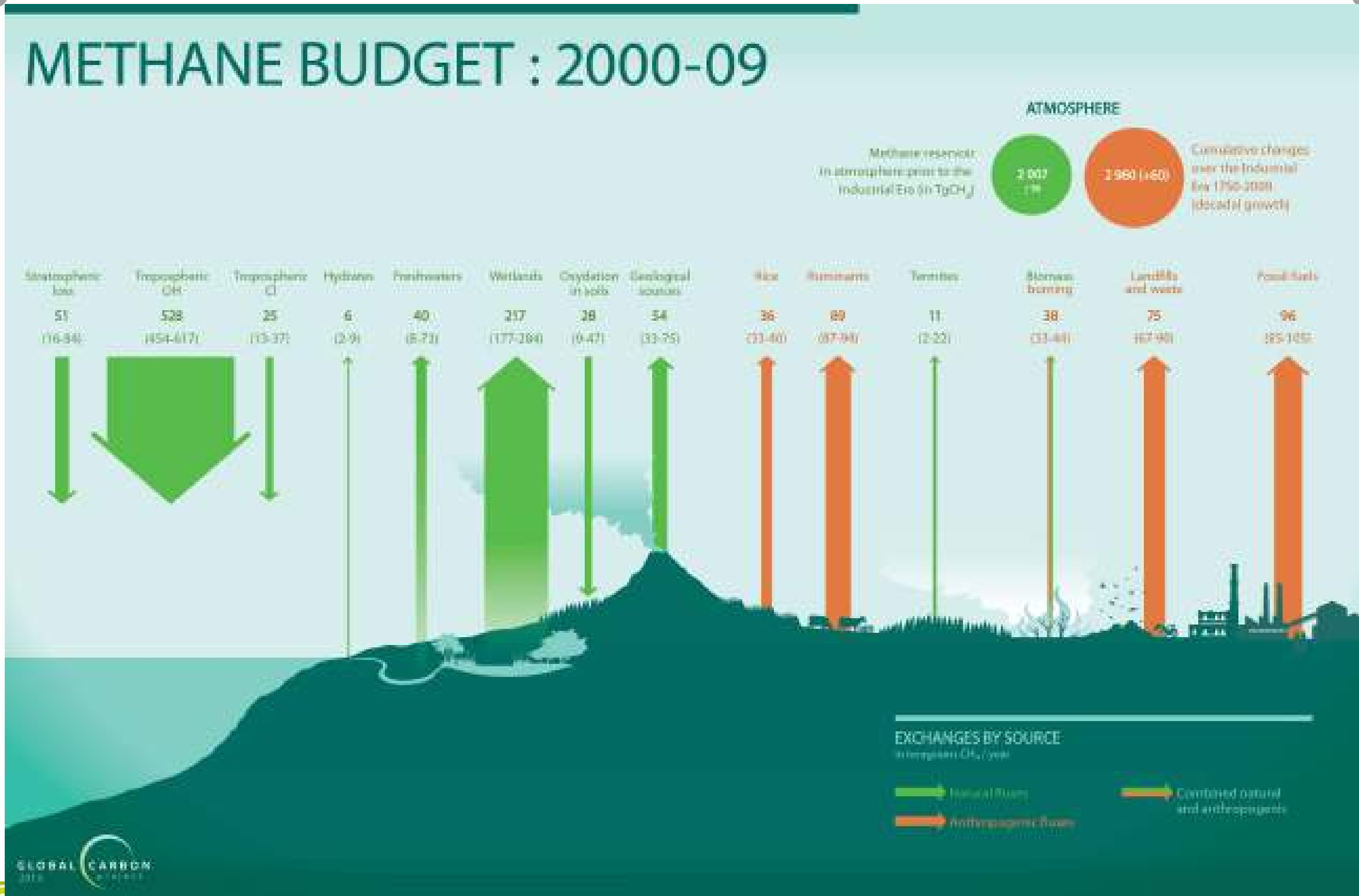


Source: *IPCC AR5*



Source NOAA

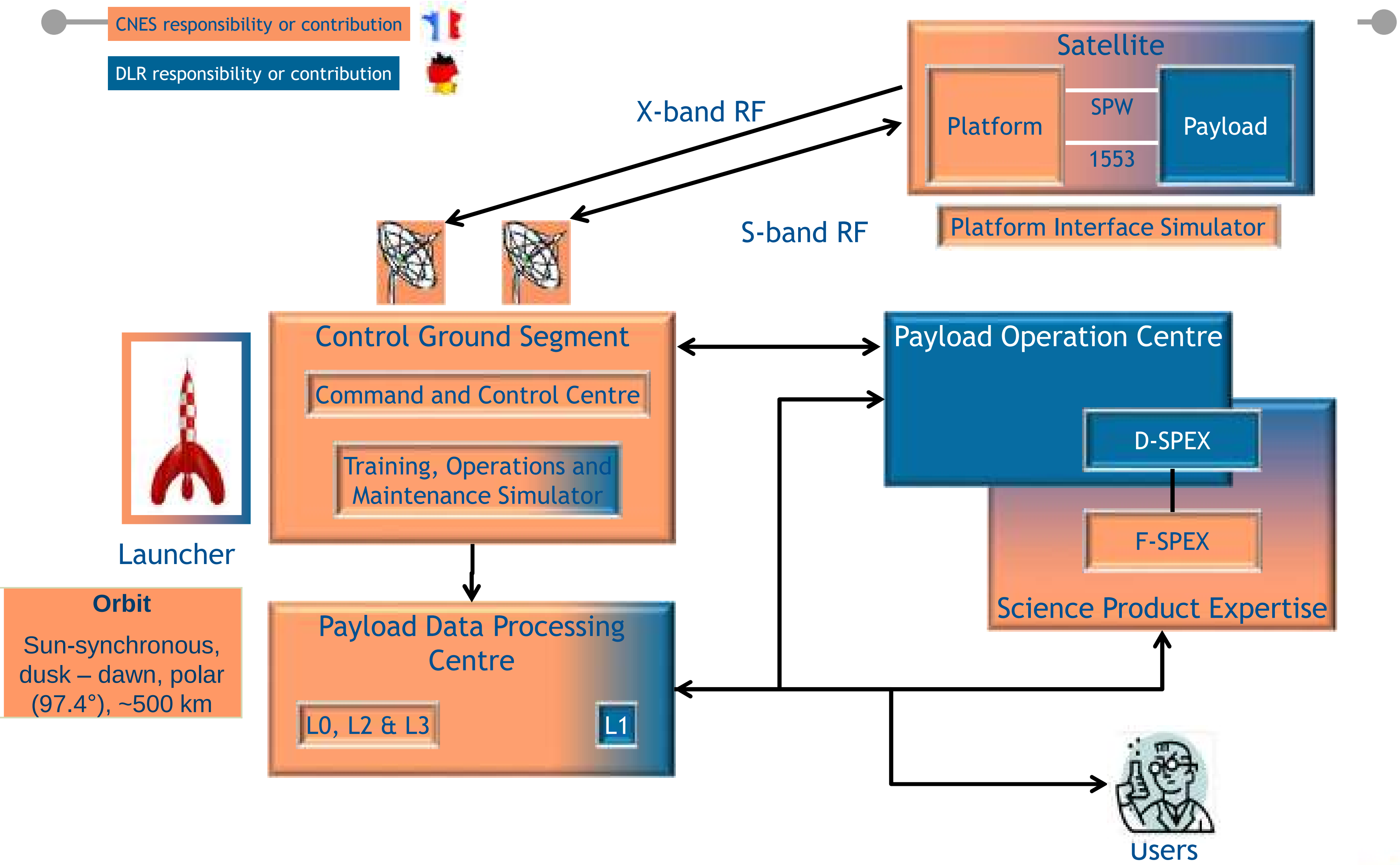
Science: Methane sources and sinks



Science: Methane vs Carbon Dioxide

Item	CO_2	CH_4
Surface mixing ratio	400 ppm	1.860 ppm
Land / ocean fluxes	both	mostly land
Anthropogenic emissions	10 000 Tg	330 Tg
Proportion of anthropogenic emissions	~ 15%	~ 60%
Major anthropogenic emissions/process	Fossil fuel combustion, Land use changes	Fossil fuel production, Livestock, Landfills & waste, Biomass burning, rice
Major natural emissions/process	Respiration	Wetlands, Fresh waters, Earth leaks, Termites, ..
Major sinks/process	Photosynthesis	Atm. Chem., soils
Global Warming Potential	1	28 (100 yr), 74 (20 yr)
Atmospheric Lifetime	Century	Decade

MERLIN System

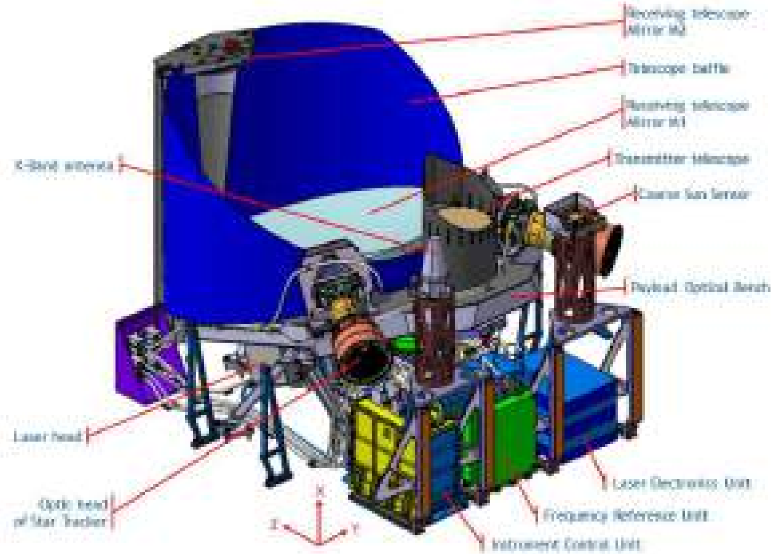


Measurement concept

- Platform: **MYRIADE Evolutions** line of product

Satellite (platform + payload)	
Mass	**430 kg**
Dimensions	**160 cm x 120 cm x 160 cm**
Power	**500 W**

- Payload: **IPDA Laser Instrument:** transmitter based on OPO and Future Laser (FULAS) concept, developed under ESA and DLR contracts



Payload	
Mass	**140 kg**
Power	**150 W**
On-line λon	**1645.552 nm**
Off-line λoff	**1645.846 nm**
Pulse energy	**9 mJ**
Pulse length	**20 ns**
Repetition rate	**20 Hz (double pulse)**
Telescope diameter	**690 mm**

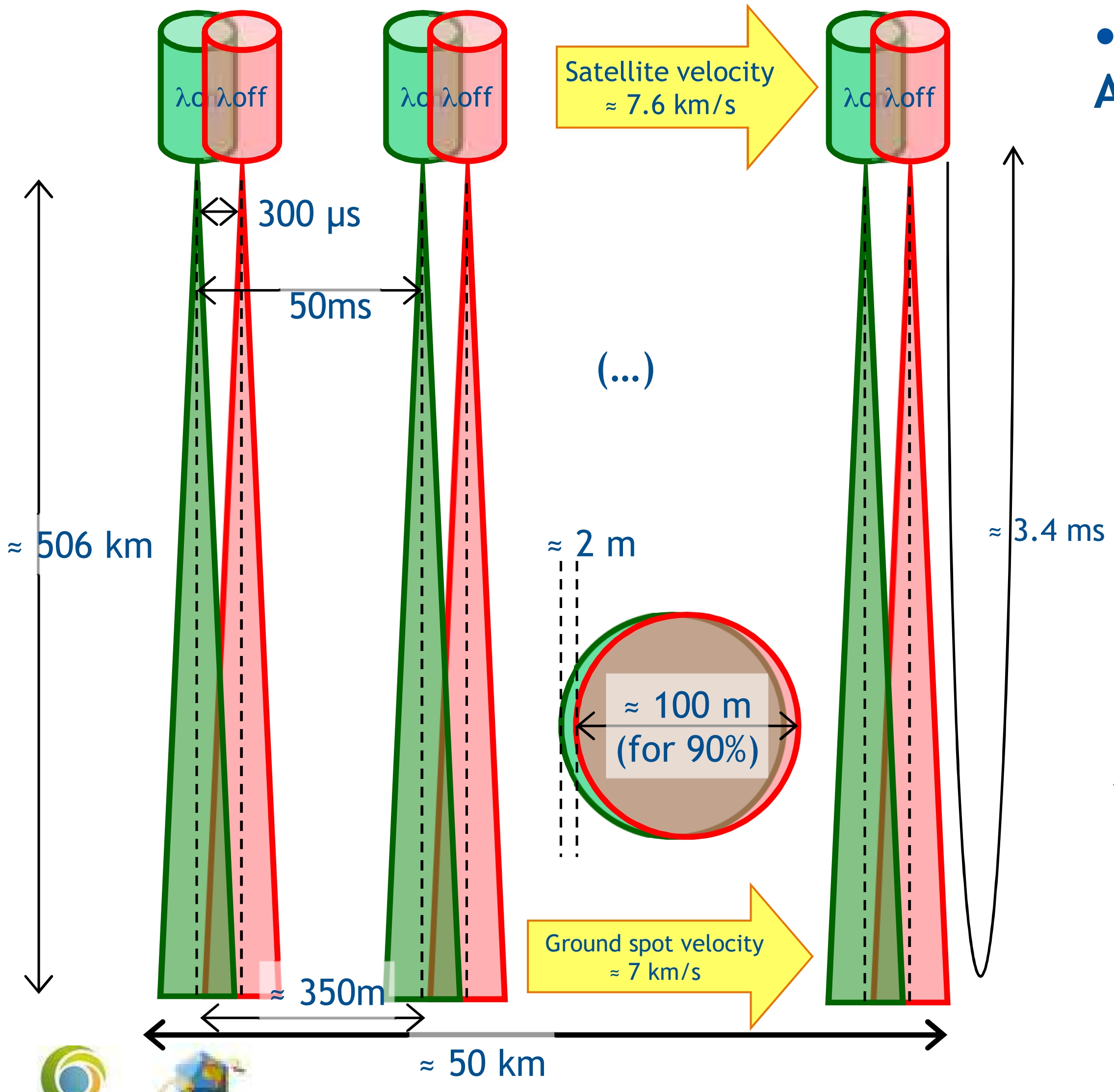
Science objectives

- Methane observing Key regions :
  - Arctic regions (boreal forest, permafrost)
  - Eurasia (anthropogenic emissions)
  - the tropical regions (forest, wetlands).

- MERLIN will provide methane measurements :
  - **not dependent on sunlight** → will allow global coverage, including high latitude during winter
  - small footprint + possibility to get column over dense clouds → observations in tropical regions and other areas that are frequently cloud covered (ex: tropical forest)
  - **Auto-calibrated** → no bias from scattering by aerosol or thin cirrus layers, (which is mandatory for regions with biomass burning, ex: boreal forest)

MERLIN will provide truly global and high accuracy measurements of XCH_4 to estimate CH_4 fluxes at regional to continental scale.

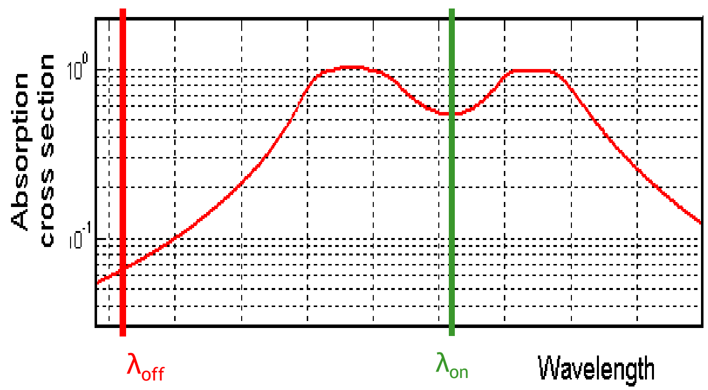
Measurement concept



- **Integrated Path Differential Absorption (IPDA) lidar**

λ_{on}: 1645.552 nm = 6076.988 cm-1

λ_{off}: 1645.846 nm = 6075.903 cm-1



- **acquisition**: all over the orbit, without interruption (20Hz)
- **averaging** of the data along track on 50 km for SNR purpose

Expected performances (1/3)

- MERLIN mission requirements (for a reference value of 1780 ppb):

MERLIN System Requirements:	
Random error:	< 22 ppb (for surface reflectivity 0.1 sr^{-1})
Systematic error:	< 3 ppb
Horizontal sampling accumulation:	50 km
Objectives:	• Seasonal and annual budgets on country scale • Resolves country scale gradients

- random error: high frequency, uncorrelated errors
- systematic error: slowly varying component, (e.g. orbital variations, or scene dependent errors).

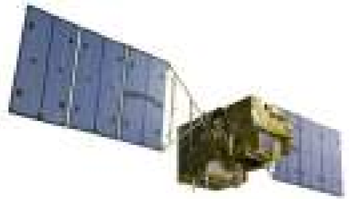
The very low level of systematic error aims at avoiding geographical biases in the XCH4 fields that could lead to uncertainties in fluxes.

Key Instrumentation for MERLIN Validation

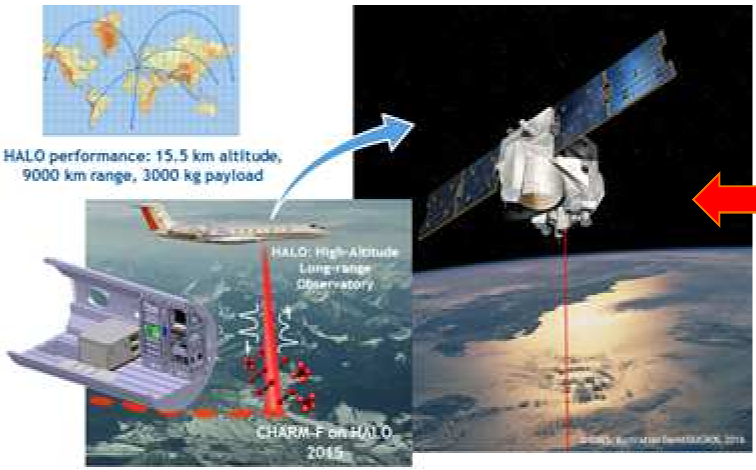
Validation by AirCore sensors on Balloons

- **Profile information** for validation of XCH4 (L2) and DAOD (L1) products

Validation by operational GHG network



Validation by satellites (GOSAT-2, Sentinel 5, IASI)



Validation by CHARM-F on HALO and/or French Falcon

- Correlative measurements of **XCH4 (L2)** and **DAOD (L1)** due to **similar weighting function**
- **CoMET campaign now** in spring 2018
- reservation of German HALO aircraft for **MERLIN validation** in the **2021/22 timeframe**

MERLIN: French Laboratories contribution

#	Topic	GSMA	ILM	LATMOS	LERMA	LISA	LMD	LSCE
1	Science Advisory Group							Co-PI
2	LIDAR Expertise						Prime	
3	Spectroscopy					Prime		
4	Radiative Transfer						Prime	
5	Mission data Simulator						Prime	
6	Ground Processing L0-L2						Prime	
7	Ground Processing L3							Prime
8	Flux Simulator L4							Prime
9	Chemical			Prime				
10	Calibration & Validation						Prime	
11	Secondary Products						Prime	

MERLIN: French detailed Laboratories organisation

Co-PI
Philippe Bousquet
Project manager (TBD)

Science Advisory Group
- **Philippe Bousquet**
- Frédéric Chevallier
- Philippe Ciais
- Fabien Gibert
- Cyril Crevoisier
- Kathy Law
- Patrick Rairoux

LIDAR Expertise
- **Fabien Gibert**
- Dimitri Edouart
- Patrick Rairoux

Spectroscopy
- **Ha Tran**
- Virginie Zeninari
- Raphael Vallon
- Bertrand Parvitte
- Raymond Armante

Radiative Transfer
- **Raymond Armante**
- Thibault Delahaye

Mission data Simulator *(LIDSIM)*
- **Olivier Chomette**
- Thibault Delahaye
- Raymond Armante
- Fabien Gibert
- Dimitri Edouart
- Yoann Tellier (CDD)
- Laurent Crépeau
- Frédéric Nahan (Magellium)
- Catherine Prigent

Ground Processing L0-L2 *(PROLID)*
- **Olivier Chomette**
- Thibault Delahaye
- Raymond Armante
- Fabien Gibert
- Yoann Tellier (CDD)
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- LATMOS (TBD)

GSMA
ILM
LATMOS
LERMA
LISA
LMD
LSCE

MERLIN: Satellite development organisation

Component	Customer	Prime contractor	Responsibility
Bus	CNES	Airbus DS SAS	Platform development based on ISIS & MYREvol product lines Satellite engineering Satellite AIT + Campaign + SIOV
Payload	DLR	Airbus DS GmbH	Payload development based on new technology Payload AIT+…

Component	Requirement book captain
Bus	Bus CNS: CNES PF/PL IRD: CNES
Payload	PL CNS: Airbus DS GmbH

Conclusion and references

DLR and CNES look forward to launch MERLIN satellite to provide the science community with unprecedented all-latitude coverage measurements of methane concentration

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- Chevallier, F., Broquet, G., Pierangelo, C., Crisp, D.: Probabilistic global maps of the CO2 column at daily and monthly scales from sparse satellite measurements, *submitted to JGR Atmosphere*

- And https://cnes.merlin.fr

Thanks for your attention!

MEthane Remote sensing LIdar missioN

Status of MERLIN mission

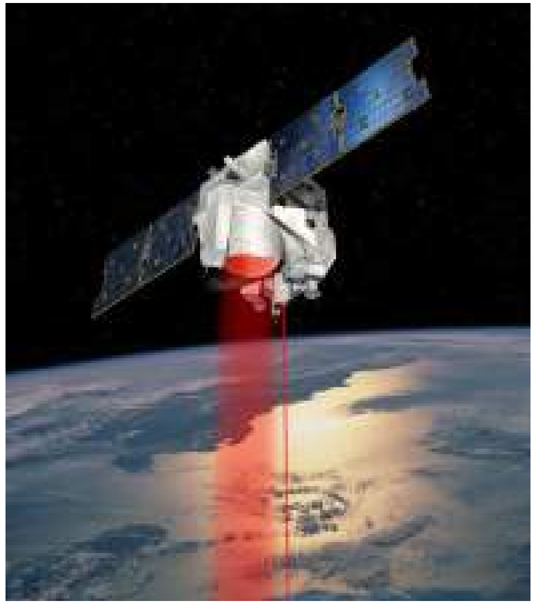
Carole DENIEL, *CNES*, *Atmospheric Composition Programm*

C. Pierangelo[1], B. Millet[1],
G. Ehret[2], M. Alpers[2], A. Friker[2], P. Bousquet[3], C. Crevoisier[4]

1 - Centre National d'Etudes Spatiales (CNES)
2 – Deutsches Zentrum für Luft- und Raumfahrt (DLR)
3 – Laboratoire des Sciences du Climat et de l'Environnement (LSCE)
4 - Laboratoire de Météorologie Dynamique (LMD)

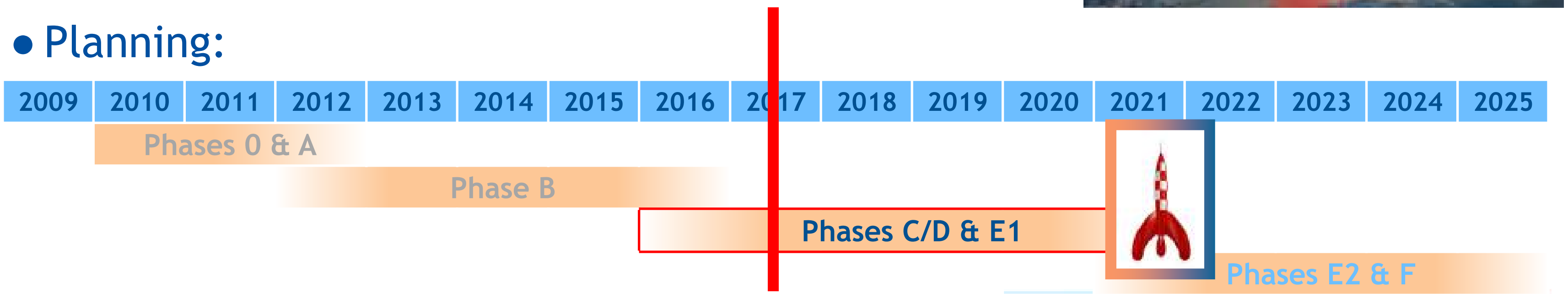
Introduction

- MERLIN is a LIDAR satellite dedicated to the observation of the spatial and temporal gradients of atmospheric methane (CH_4) columns



- MERLIN is a cooperation between France and Germany space agencies:
  - CNES in charge of platform, satellite, system, launcher, and part of ground segments
  - DLR in charge of payload, and part of ground segments

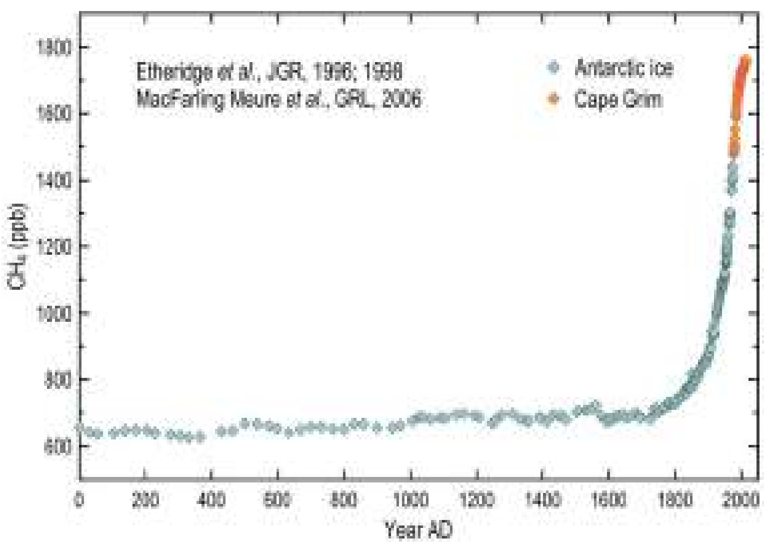
- Planning:



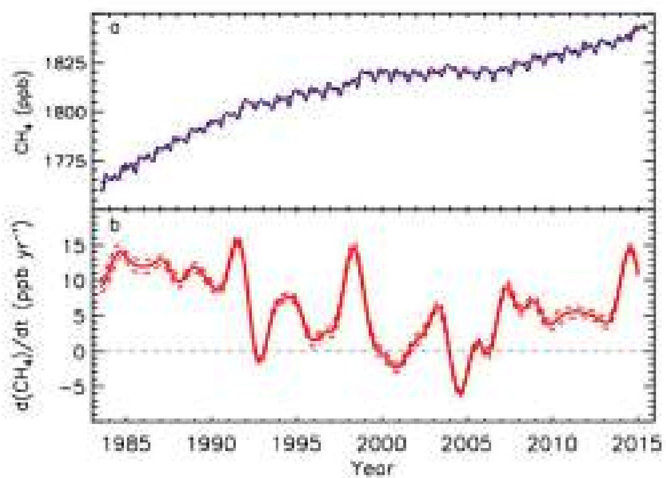
MERLIN shall be the first <u>active</u> mission in space dedicated to GHG

Science: Why methane?

- Atmospheric Increase by 150%, from 722 ppb (1750) to 1840 ppb (2015)
- Responsible for >20% of increase in radiative forcing since 1750:
  - GWP100 = 28 × CO_2
- Contributes to water vapor (H_2O) production in the stratosphere
- Contributes to ozone (O_3) production in the troposphere
- Lifetime of CH_4 is 8-10 years, good target for climate change mitigation
- Present and future CH_4 emissions are highly uncertain
- Recent atmospheric variations are puzzling

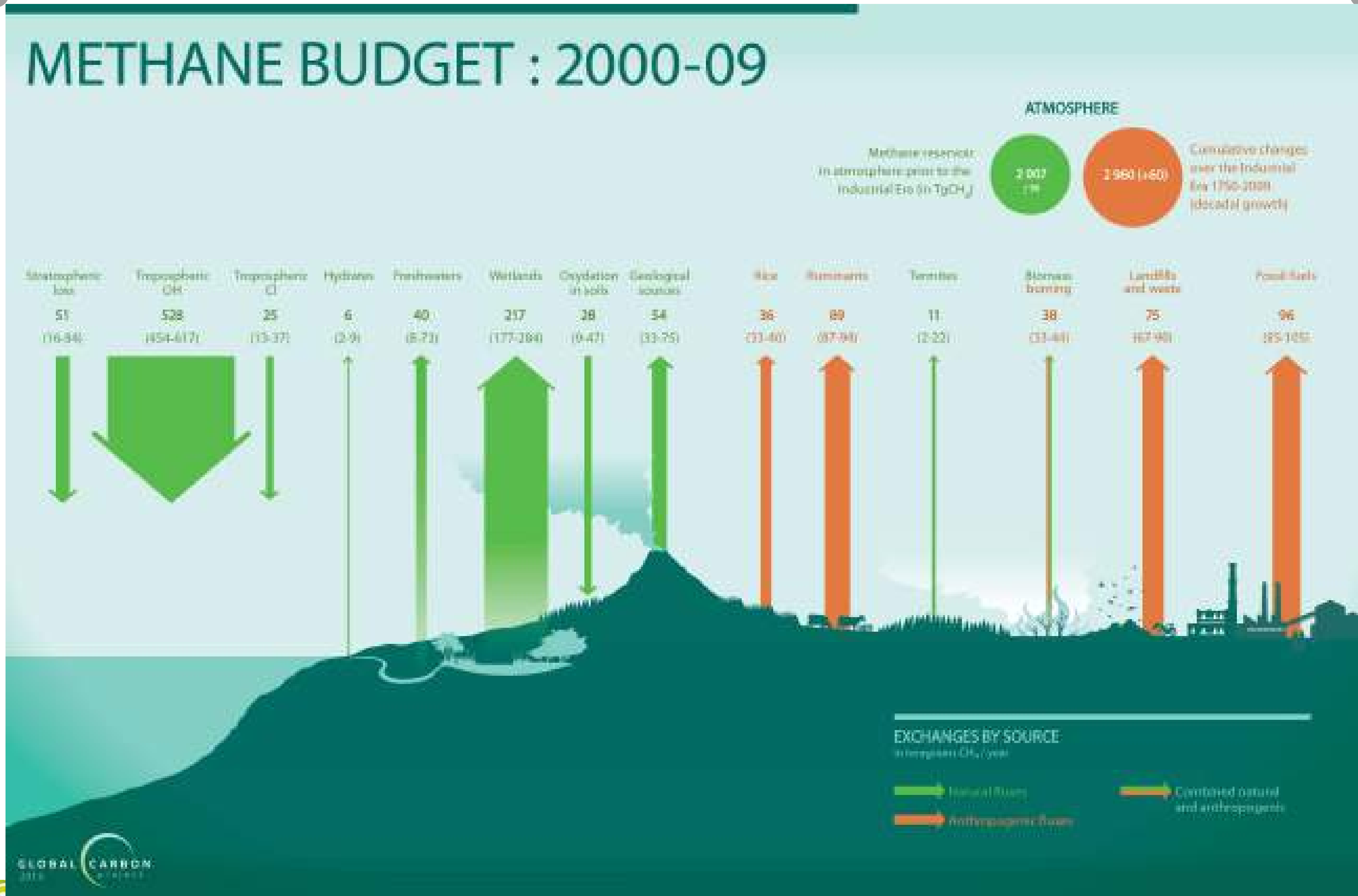


Source: IPCC AR5



Source NOAA

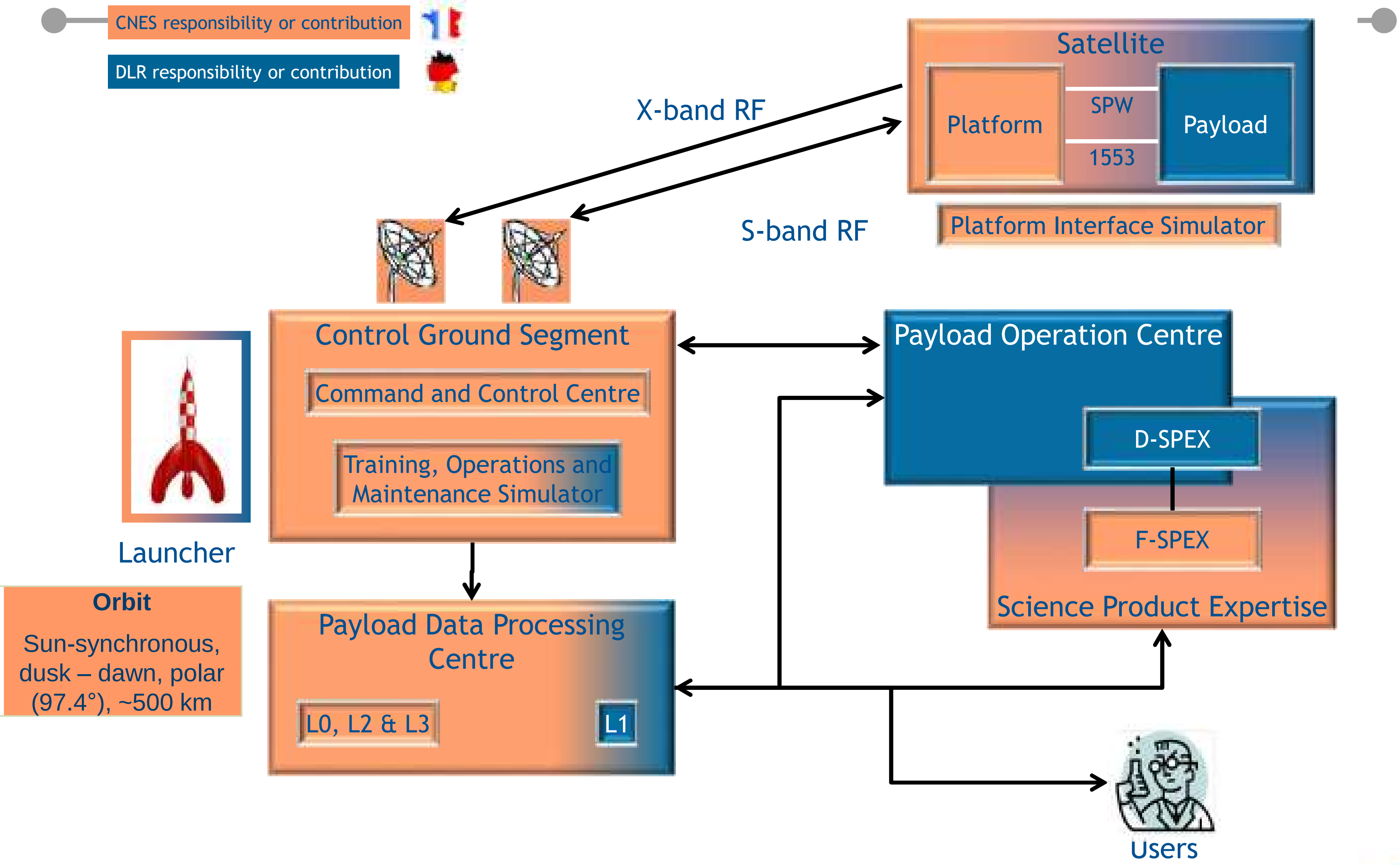
Science: Methane sources and sinks



Science: Methane vs Carbon Dioxide

Item	CO_2	CH_4
Surface mixing ratio	400 ppm	1.860 ppm
Land / ocean fluxes	both	mostly land
Anthropogenic emissions	10 000 Tg	330 Tg
Proportion of anthropogenic emissions	~ 15%	~ 60%
Major anthropogenic emissions/process	Fossil fuel combustion, Land use changes	Fossil fuel production, Livestock, Landfills & waste, Biomass burning, rice
Major natural emissions/process	Respiration	Wetlands, Fresh waters, Earth leaks, Termites, ..
Major sinks/process	Photosynthesis	Atm. Chem., soils
Global Warming Potential	1	28 (100 yr), 74 (20 yr)
Atmospheric Lifetime	Century	Decade

MERLIN System

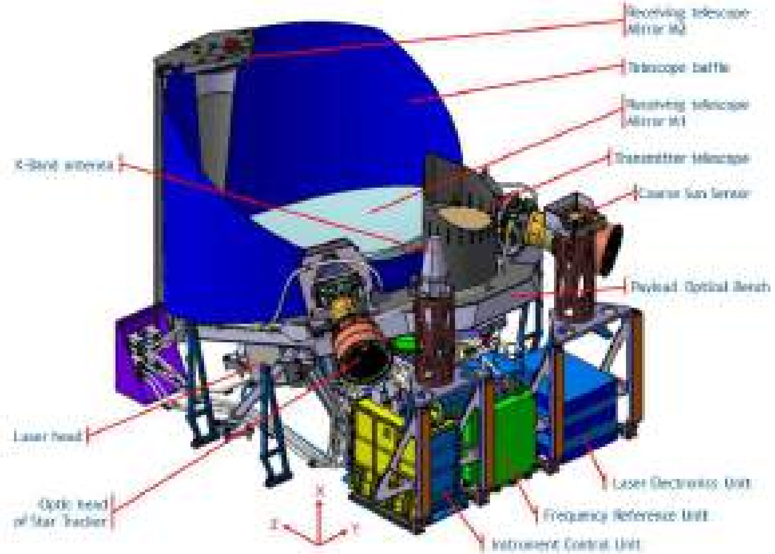


Measurement concept

- Platform: **MYRIADE Evolutions** line of product

Satellite (platform + payload)	
Mass	**430 kg**
Dimensions	**160 cm x 120 cm x 160 cm**
Power	**500 W**

- Payload: **IPDA Laser Instrument:** transmitter based on OPO and Future Laser (FULAS) concept, developed under ESA and DLR contracts



Payload	
Mass	**140 kg**
Power	**150 W**
On-line λon	**1645.552 nm**
Off-line λoff	**1645.846 nm**
Pulse energy	**9 mJ**
Pulse length	**20 ns**
Repetition rate	**20 Hz (double pulse)**
Telescope diameter	**690 mm**

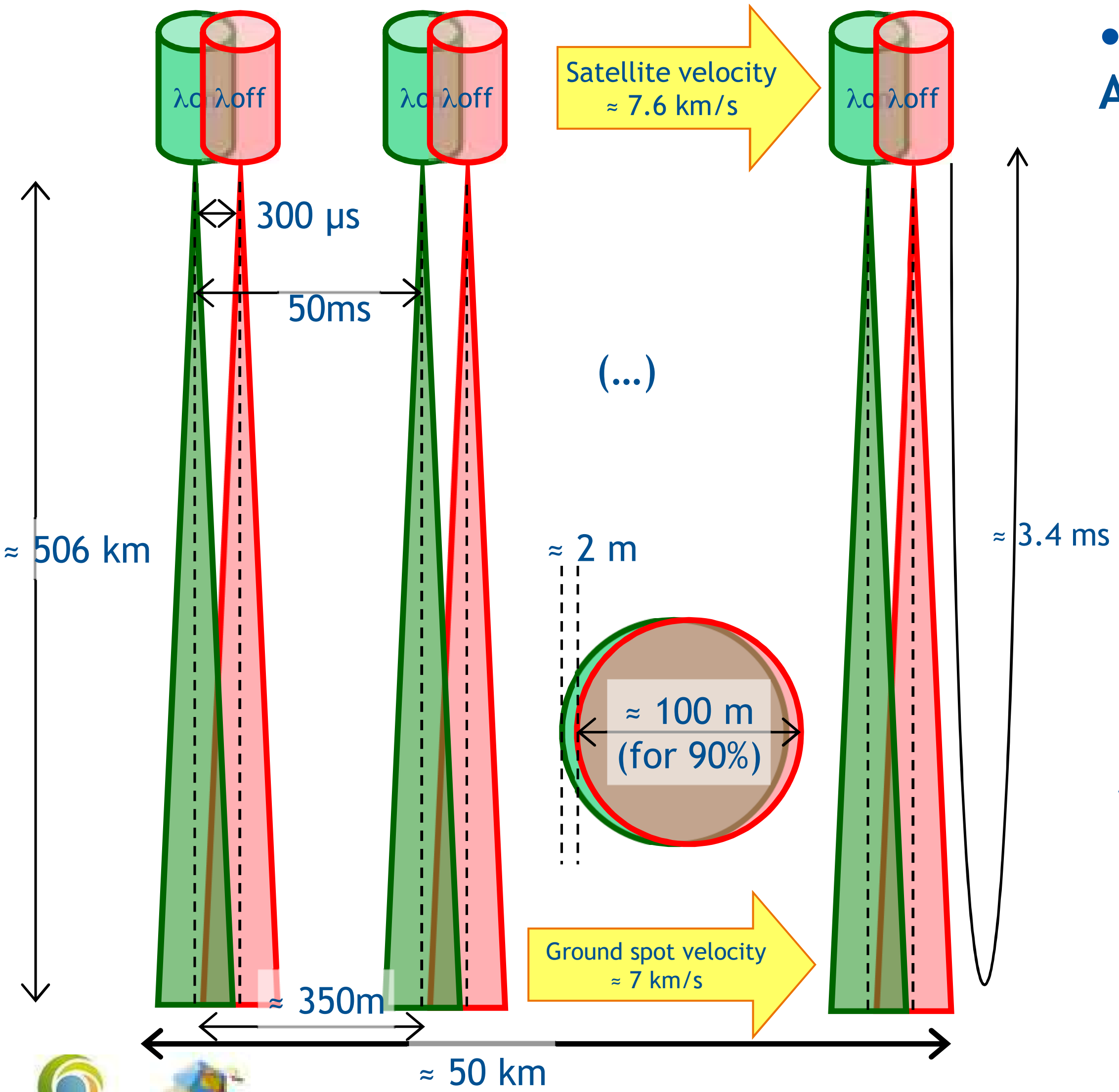
Science objectives

- Methane observing Key regions :
  - Arctic regions (boreal forest, permafrost)
  - Eurasia (anthropogenic emissions)
  - the tropical regions (forest, wetlands).

- MERLIN will provide methane measurements :
  - **not dependent on sunlight** → will allow global coverage, including high latitude during winter
  - small footprint + possibility to get column over dense clouds → observations in tropical regions and other areas that are frequently cloud covered (ex: tropical forest)
  - **Auto-calibrated** → no bias from scattering by aerosol or thin cirrus layers, (which is mandatory for regions with biomass burning, ex: boreal forest)

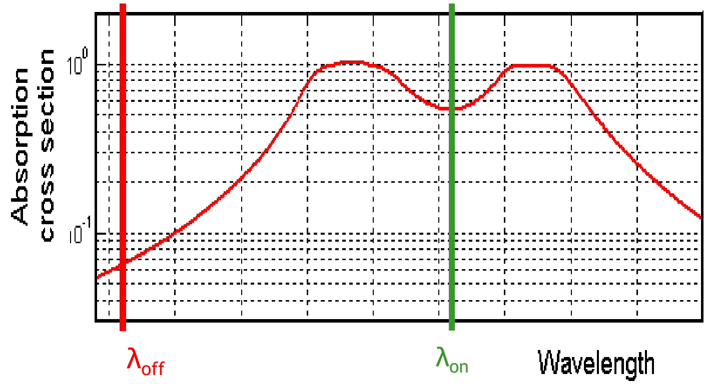
MERLIN will provide truly global and high accuracy measurements of XCH_4 to estimate CH_4 fluxes at regional to continental scale.

Measurement concept



- **Integrated Path Differential Absorption (IPDA) lidar**

λ_{on}: 1645.552 nm = 6076.988 cm-1
λ_{off}: 1645.846 nm = 6075.903 cm-1



- **acquisition**: all over the orbit, without interruption (20Hz)
- **averaging** of the data along track on 50 km for SNR purpose

Expected performances (1/3)

- MERLIN mission requirements (for a reference value of 1780 ppb):

MERLIN System Requirements:	
Random error:	< 22 ppb (for surface reflectivity 0.1 sr^{-1})
Systematic error:	< 3 ppb
Horizontal sampling accumulation:	50 km
Objectives:	• Seasonal and annual budgets on country scale • Resolves country scale gradients

- random error: high frequency, uncorrelated errors
- systematic error: slowly varying component, (e.g. orbital variations, or scene dependent errors).

The very low level of systematic error aims at avoiding geographical biases in the XCH4 fields that could lead to uncertainties in fluxes.

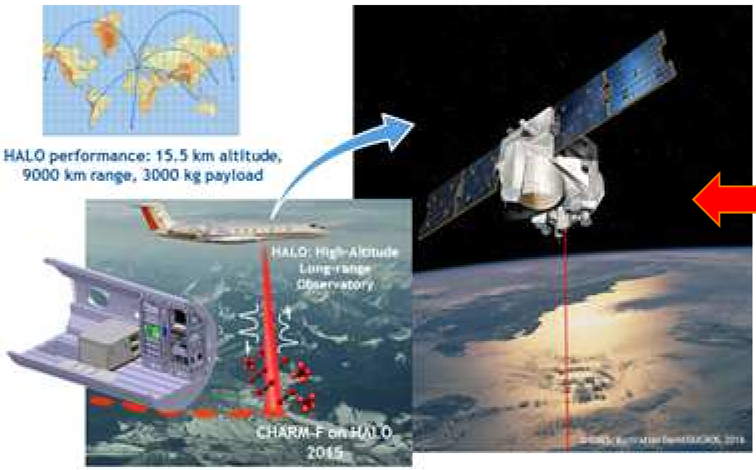
Key Instrumentation for MERLIN Validation

Validation by AirCore sensors on Balloons

- **Profile information** for validation of XCH4 (L2) and DAOD (L1) products

Validation by operational GHG network

Validation by satellites (GOSAT-2, Sentinel 5, IASI)



Validation by CHARM-F on HALO and/or French Falcon

- Correlative measurements of **XCH4 (L2)** and **DAOD (L1)** due to **similar weighting function**
- **CoMET campaign now** in spring 2018
- reservation of German HALO aircraft for **MERLIN validation** in the **2021/22 timeframe**

MERLIN: French Laboratories contribution

#	Topic	GSMA	ILM	LATMOS	LERMA	LISA	LMD	LSCE
1	Science Advisory Group		■	■			■	Co-PI
2	LIDAR Expertise		■				Prime	
3	Spectroscopy	■				Prime	■	
4	Radiative Transfer						Prime	
5	Mission data Simulator				■		Prime	
6	Ground Processing L0-L2						Prime	
7	Ground Processing L3							Prime
8	Flux Simulator L4							Prime
9	Chemical			Prime				■
10	Calibration & Validation		■	■			Prime	■
11	Secondary Products			■			Prime	

MERLIN: French detailed Laboratories organisation

Co-PI
Philippe Bousquet
Project manager (TBD)

Science Advisory Group
- **Philippe Bousquet**
- Frédéric Chevallier
- Philippe Ciais
- Fabien Gibert
- Cyril Crevoisier
- Kathy Law
- Patrick Rairoux

LIDAR Expertise
- **Fabien Gibert**
- Dimitri Edouart
- Patrick Rairoux

Spectroscopy
- **Ha Tran**
- Virginie Zeninari
- Raphael Vallon
- Bertrand Parvitte
- Raymond Armante

Radiative Transfer
- **Raymond Armante**
- Thibault Delahaye

Mission data Simulator *(LIDSIM)*
- **Olivier Chomette**
- Thibault Delahaye
- Raymond Armante
- Fabien Gibert
- Dimitri Edouart
- Yoann Tellier (CDD)
- Laurent Crépeau
- Frédéric Nahan (Magellium)
- Catherine Prigent

Ground Processing L0-L2 *(PROLID)*
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Component	Customer	Prime contractor	Responsibility
Bus	CNES	Airbus DS SAS	Platform development based on ISIS & MYREvol product lines Satellite engineering Satellite AIT + Campaign + SIOV
Payload	DLR	Airbus DS GmbH	Payload development based on new technology Payload AIT+…

AIRBUS DEFENCE & SPACE

Component	Requirement book captain
Bus	Bus CNS: CNES PF/PL IRD: CNES
Payload	PL CNS: Airbus DS GmbH

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Thanks for your attention!

IASI New Generation Development Status

F. Bermudo – CNES

CEOS AC-VC-14 – NOAA - May 2nd - 4th 2018

IASI NG mission

CNES cooperation with EUMETSAT, United Kingdom Space Agency, Swiss Space Office and Norway Space Center

Launch dates : **Sept. 2021 (Metop-SG A1), Sept. 2028 (Metop-SG A2), Sept. 2035 (Metop-SG A3)**

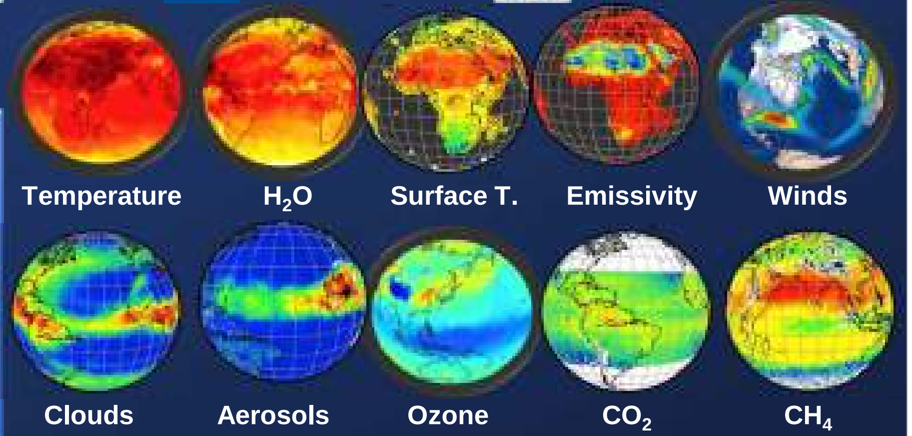
Mission objectives: hyper spectral sounding of the atmosphere in the Thermal Infra Red domain dedicated to

- **Numerical Weather Prediction** => precise humidity and temperature profiles
- **Air Quality Monitoring** => observation/detection of > 20 species
- **Climate** => observation of half of the ECVs of the atmosphere

Instrument on board Metop SG A Satellites :

- First implementation of Mertz Interferometer in Space
- Day & Night, Land & Sea observations
- Sounding Pixels Size 12 km @ Nadir
- Spectral coverage = 3.62 – 15.5 µm
- Spectral resolution 0,25 cm-1 , 16922 channels
- Radiometric noise ~0.1 K

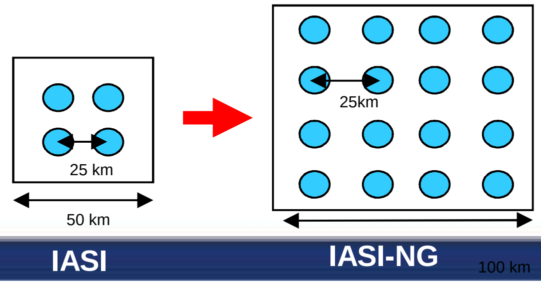
IASI-NG will provide continuity of IASI mission with Spectral and Radiometric performances improved by a factor of 2 .



From IASI to IASI New Generation

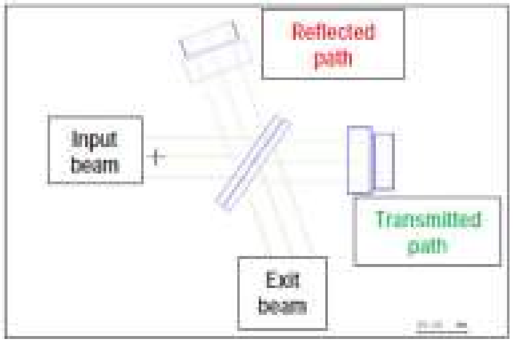
- **IASI-NG will improve the IASI performances by a factor of 2 :**

Main figures	IASI	IASI-NG
Radiometric Resolution (NeDT)		IASI/2
Spectral resolution	0.5 cm^{-1}	IASI/2 (0.25 cm^{-1}@L1C)
Absolute Radiometric Calibration	< 0,5K	IASI/2 (<0,25K@280K)
Spectral bands	3 bands	4 bands
Number of sounder pixels per acquisition	4 pixels	16 pixels
Ground Pixel diameter	12 km	12 km
Ground sampling	25 km	25 km

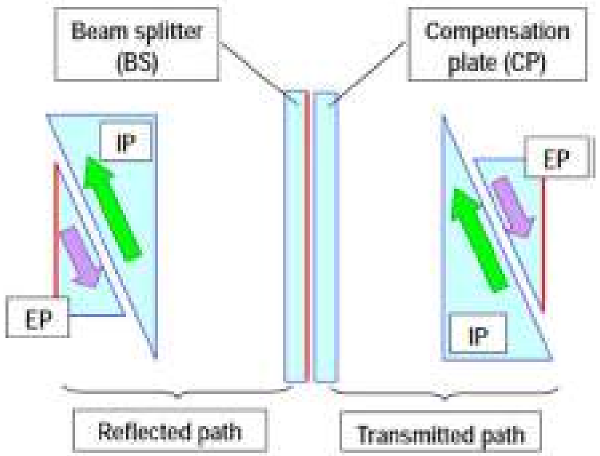


IASI New Generation instrument concept

- IASI NG instrument concept is based on a Mertz interferometer allowing a field compensation (self- apodisation correction)
  - Field compensation is achieved by introducing optics with correct optical index



- A single "dual-swing" mechanism translates two pairs of prisms proportionally and creates simultaneously the OPD change and the self- apodisation compensation.
  - The external face of the external prisms is used as a mirror
  - An appropriate motion ratio allows both OPD generation and field compensation
  - All-KBr design, with very good transmittance over the whole spectral range (3.62 – 15.5 µm)



100 km

IASI-NG Instrument Status

- **EM Instrument activities started with several EM subunits already under integration and tests**

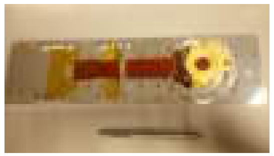
- Focal Plane Cryostat Assembly **:**

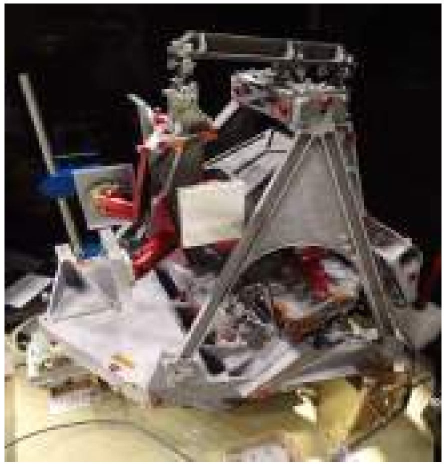
Cryostat integration and TV test performed with stabilized temperatures close to predictions

Focal Plane with EM detectors integration started

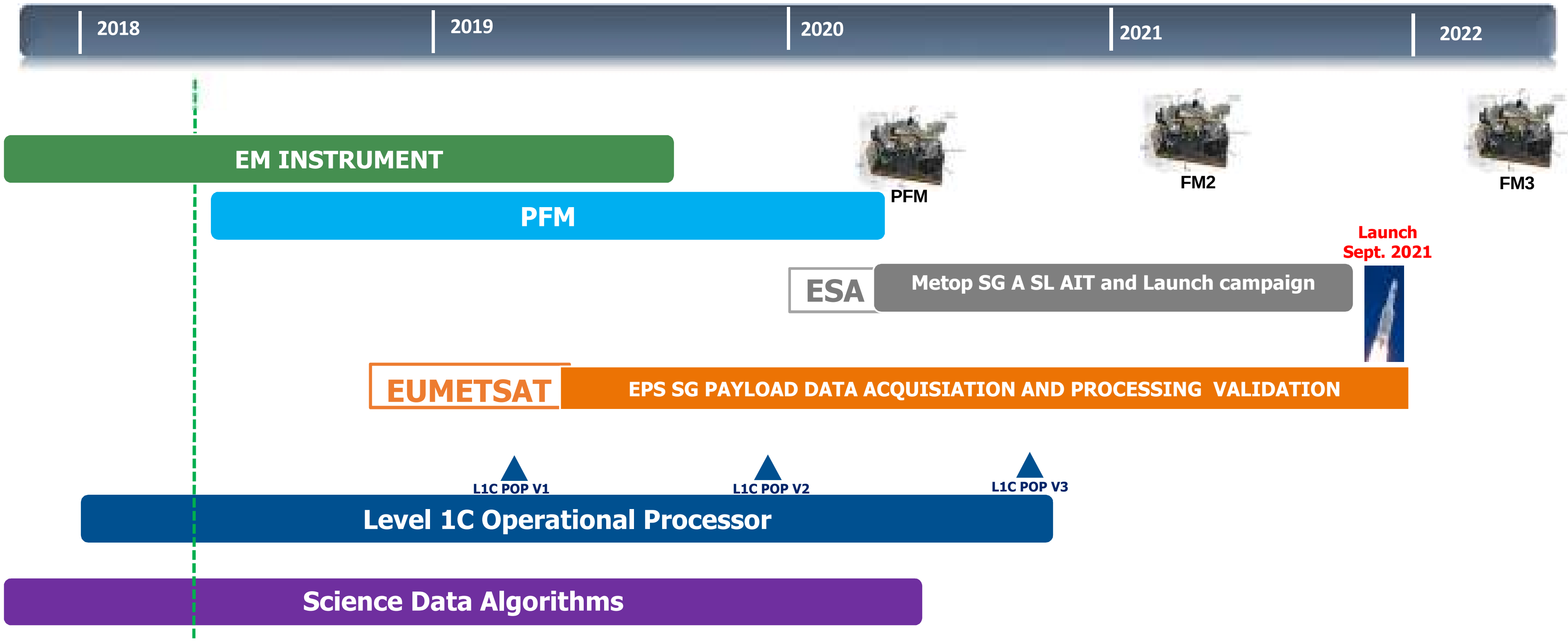
- Interferometer :

Duals Swing Mechanism assembled & aligned and KBr Prisms bonded on their support arm





IASI-NG Program Status




QUESTIONS ?

THANK YOU FOR YOUR ATTENTION