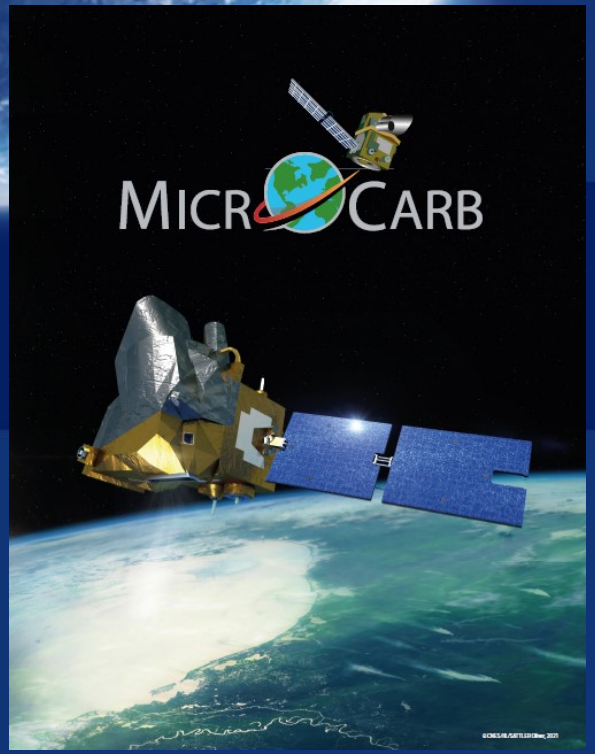


The MicroCarb CO2 mission : status and technical insight

IWGGMS-18 July 12-14 2022

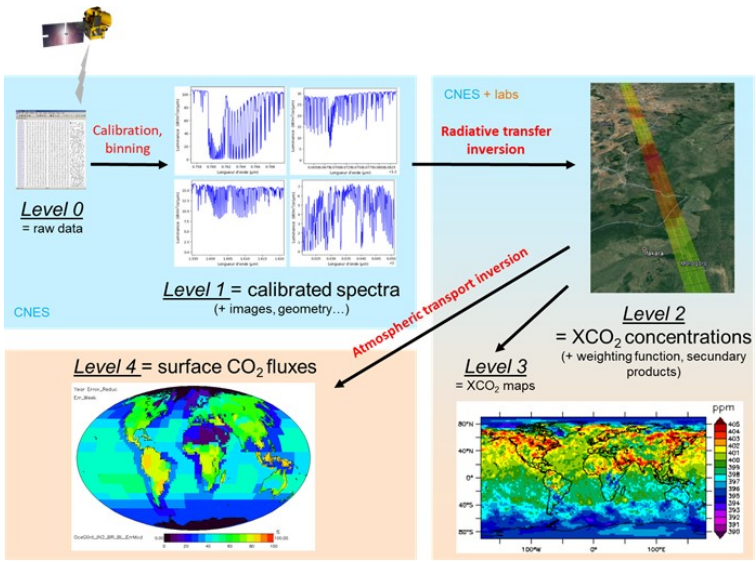
Denis JOUGLET (denis.jouglet@cnes.fr)

Philippe LANDIECH - François-Marie BREON

Mission overview

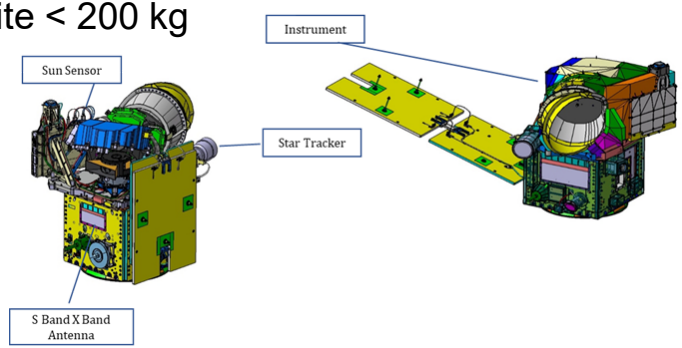
Measurement of CO_2 concentration

- Passive grating spectrometer in 4 VNIR and SWIR bands
- Sampling mission, on ground resolution:
  - 3 simultaneous samples ACT 4.5 x 9 km (@nadir) along orbit
  - Exploratory city mode: imaging 2x2 km² over area 40x40 km²
- Accuracy (XCO2)
  - Bias < 0,1 ppm (goal), < 0.2 ppm (target)
  - Random < 0,5 ppm (G) , < 1,5ppm (T)
- Performances similar to OCO with a more compact (/3) instrument



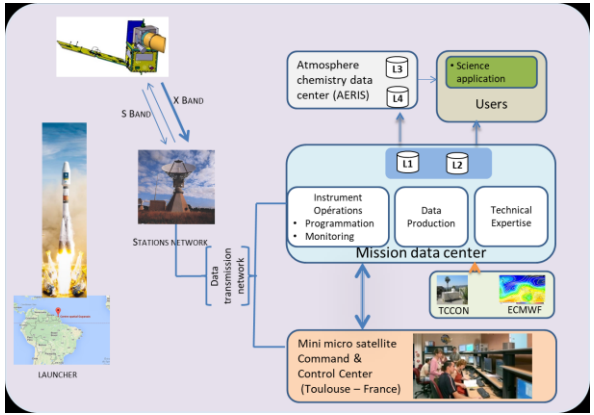
Compatibility with a microsatellite

- Use of Myriade classic platform, Satellite < 200 kg
- 80 kg-60W instrument

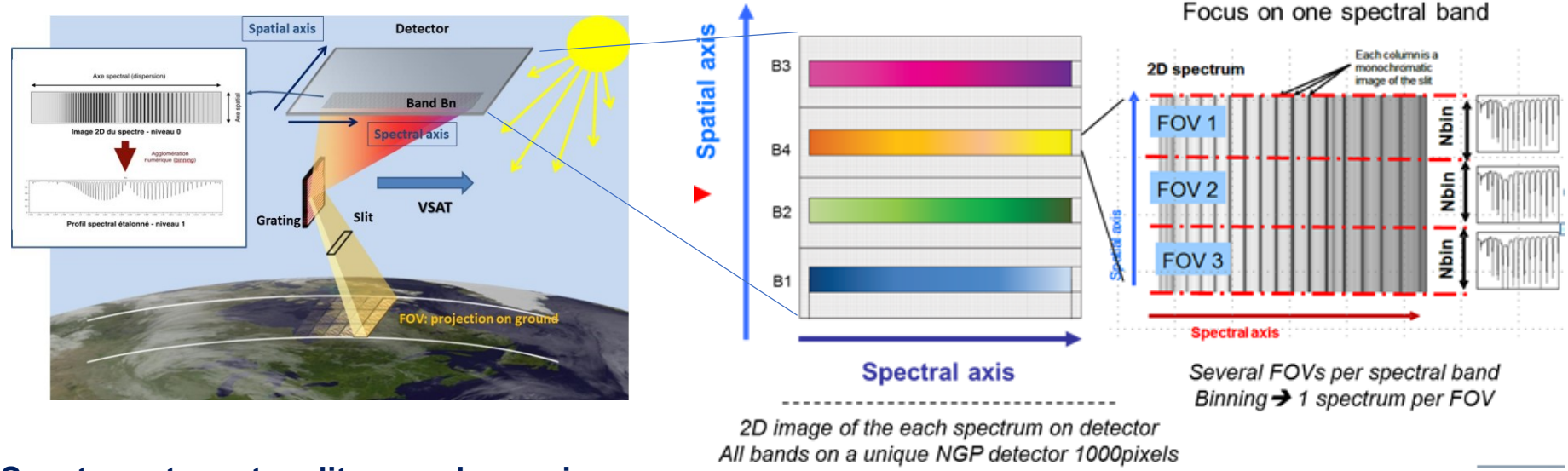


Operations

- SSO, 650 km, 22h30
- Launch date: End 2023
- Life duration: 5 years



Instrument overview



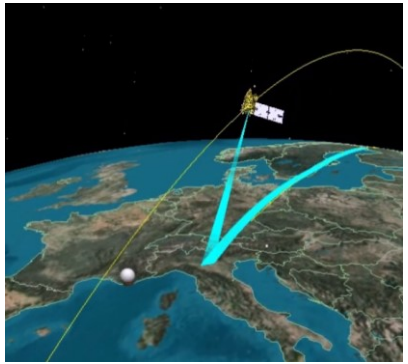
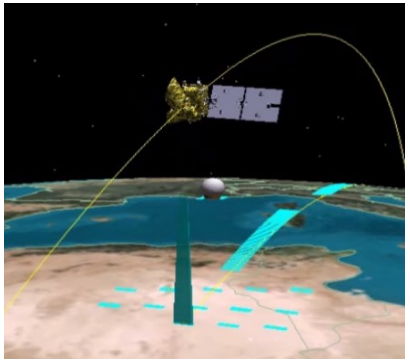
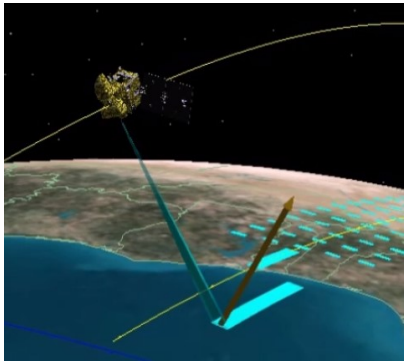
- Spectrometer entry slit groundsweeping during integration time (1,4s)
- Signal split through pupil into 4 bands
- 4 bands signal recomposed on the detector
- All pixels data sent to ground: no on board binning
- Embedded imager

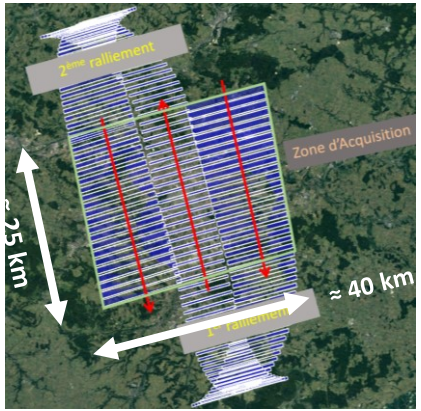
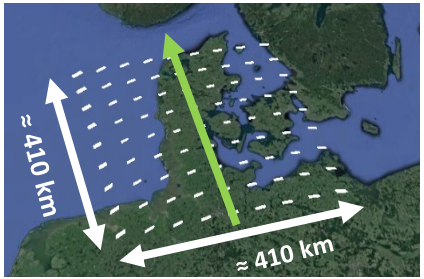
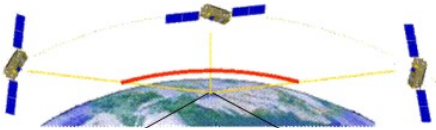
Spectral Performances	B1 (O_2)	B4 (O_2)	B2 (CO_2)	B3 (CO_2)
Central Wavelength (nm)	763.5	1273.4	1607.9	2037.1
Bandwidth (nm)	10.5	17.6	22.1	28,1
Mean Spectral resolution (λ/Δλ)	25 500	25 900	25 800	25 900
SNR @ Lmean (per channel)	285	378	344	177

Operating modes

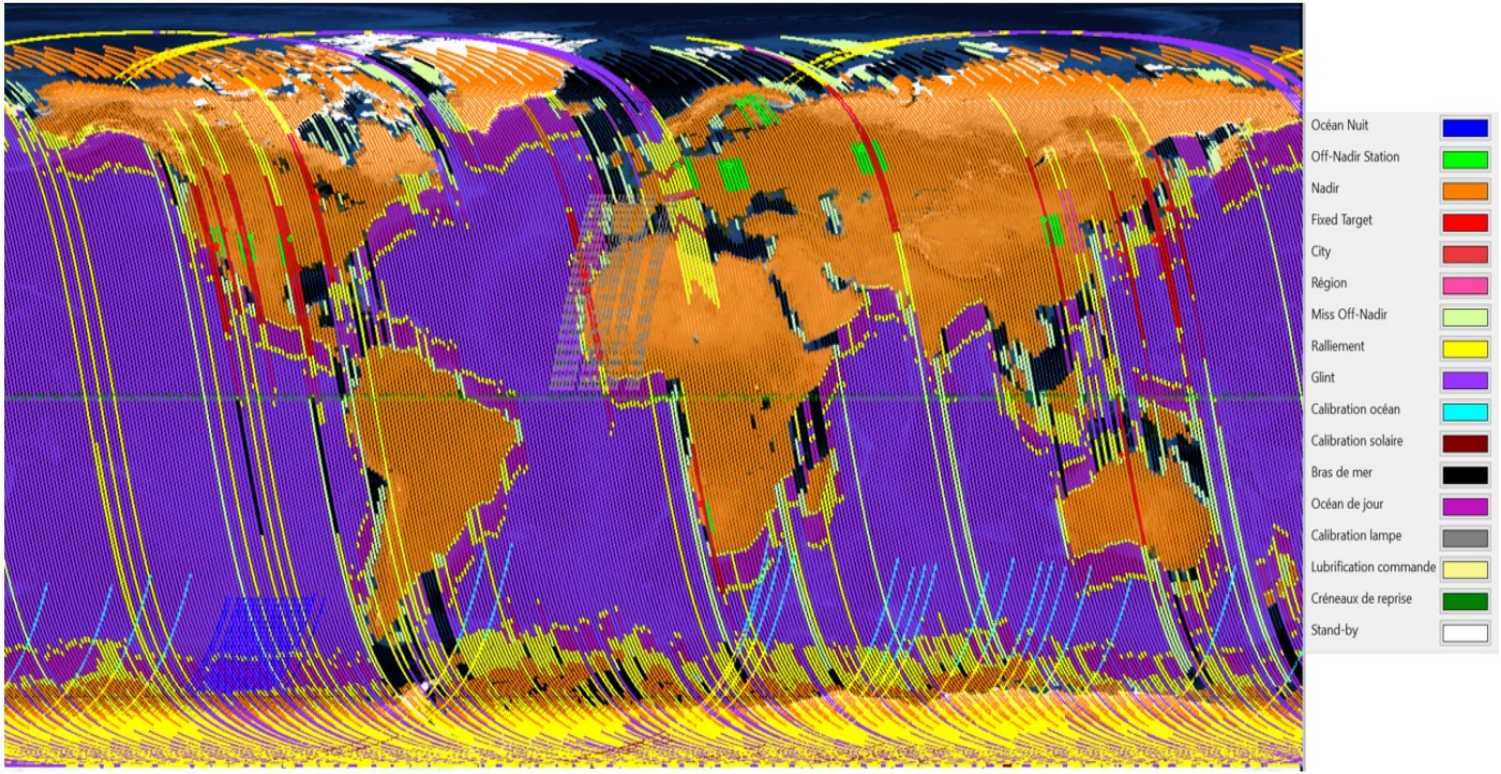
Pointing and Calibration System (PCS): 1-axis scanning capability in the ACT direction of ±35° and calibration lamps

- Science nominal modes
  - Nadir (lands)
  - Scan (lands to decorrelate footprints)
  - Glint (ocean)
  - Offnadir target
- Probatory modes
  - City
  - Region
- Calibration modes
  - Target (L2 validation)
  - Calibration : sun, lamp, shutter, cold space, moon, ground laser…
  - Limb for 1.27µm airglow

Nadir	Scan + offnadir target	Glint
		

City	Region	Fixed-Target
		Target Mode observes surface zenith angles between ±75° 

Mission planning



Example of a mission plan (1 cycle = 368 orbits = 25 days)

The dedicated satellite and the scanning mirror give a large flexibility in planning

The target and cities will easily configurable, and benefit from weather forecast

Organization

In the context of the COP21 climate conference, France decided to kick-off the MicroCarb project in 2016
French government ANR funding + European contributions: UK, UE

cnes

System design and development
Satellite design an development
Instrument specification
Data processing definition
Mission performances
Calibration and validation
Operations

Instrument development qualification and calibration

AIRBUS DEFENCE & SPACE

Satellite Assembly integration and Test

ThalesAlenia Space

UK SPACE AGENCY

EUMETSAT

esa European Space Agency

Data production, archiving and dissemination

Launch service

Mission Advisory Group
+ MAG members exchanges with CO2M

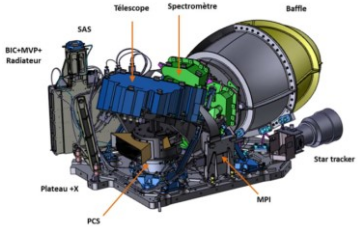
Main Progresses

Significant progress since last IWGGMS-17 !!!

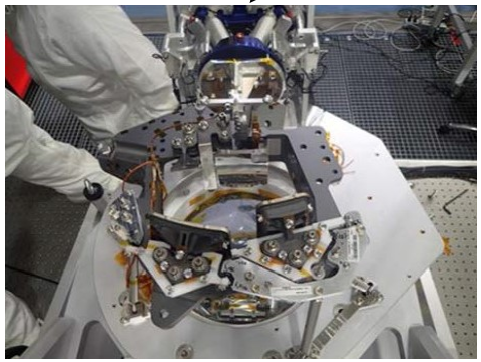
- **NGP detector complete characterization, flight detector final selection**
- **Then spectrometer & telescope characterizations in ambiant conditions with ground SWIR detector**
- **Instrument complete assembly**
- **Mechanical tests underway**
- **Late summer 2022 : crucial TVAC 45 days test, including direct sun pointing**
- **Instrument delivery expected by end September this year, then 10 months of satellite AIT**
- **Discussions underway for an auxiliary position on a VEGA-C flight end of 2023 / beginning of 2024**

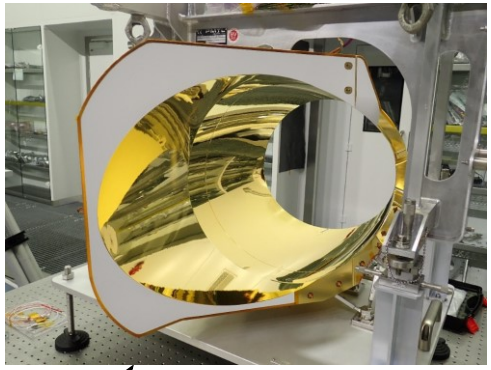
Instrument AIT Activities

- Integration considering very compact instrument successfully performed
- Instrument final alignement in between telescope, spectrometer and detector achieved
- EMC and mechanical tests on-going, before TVAC



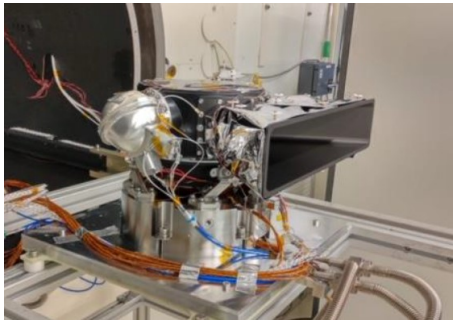
Spectro



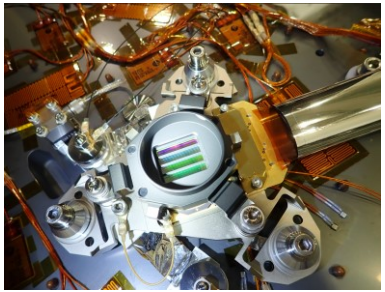


Baffle
Therm.

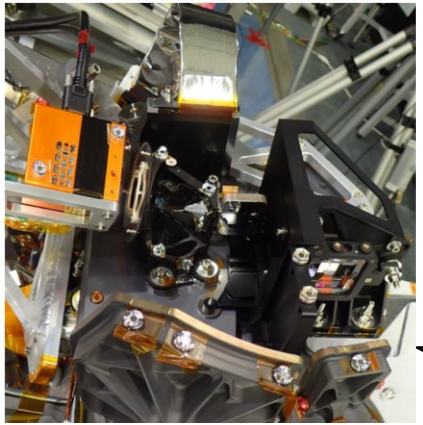
PCS



Coupling



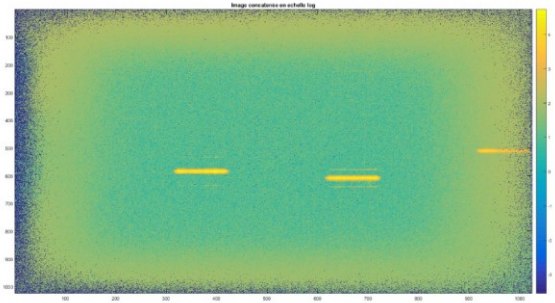
NGP detector
and filters



Telescope

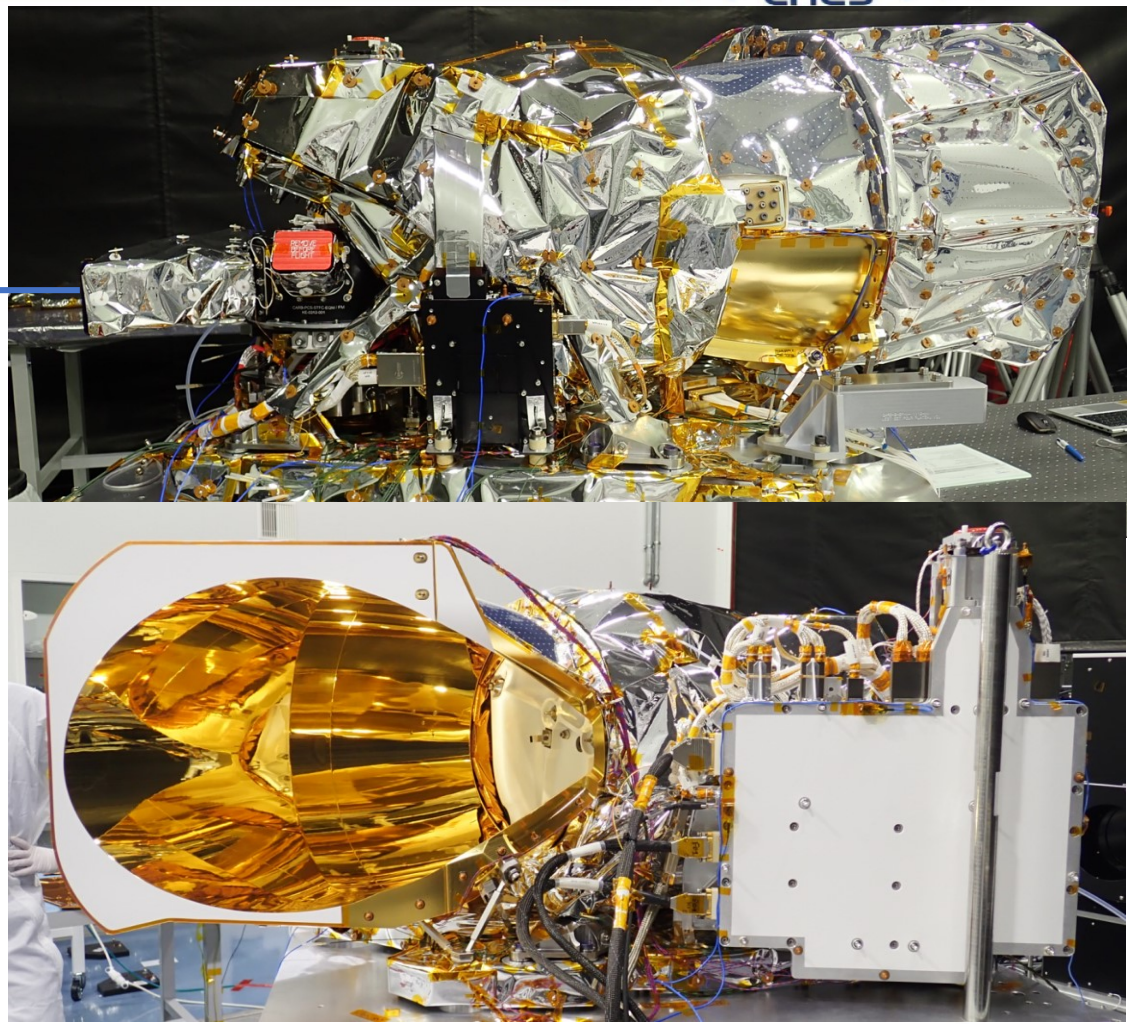
© ADS

Overall instrument status



First measurements with flight detector at ambient temperature (while 150 K in flight nominal detector temperature):
instrument facing 3 lasers at 3 different wavelengths, moved to scan the 13.5 km across track dimension

Earth view



© ADS

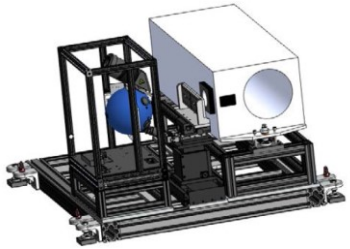
Instrument overall figures

Mass	80kg
Power	60W
Volume	600 x 500 x 1100 mm^3

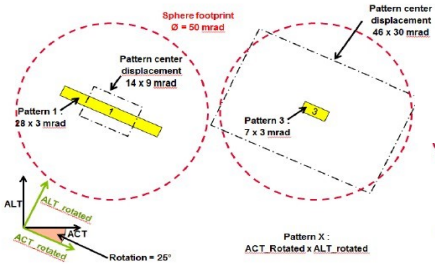
TVAC Ground Calibration by Airbus

- **OGSE (Optical Sources)**
  - Lasers and white lamps
  - Collimator
  - Field patterns

Integrating large sphere



Small sphere + Collimator



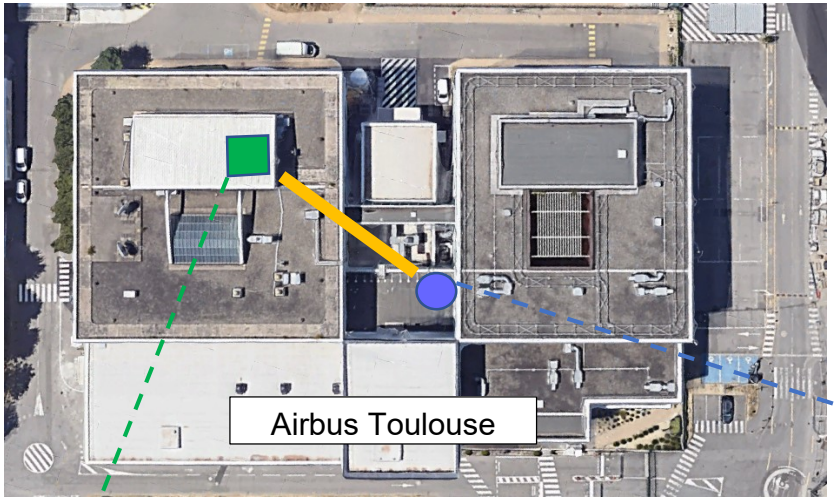
Field plane patterns

- **Main performances characterisation**

Performances	Item	Facility
Radiometry	Absolute Gain	Lamp + integrating sphere, laser + photodiode
	Flat field	Internal lamp
	Non linearity	Lamp + integrating sphere
	Dark	Dark screen at different temperatures
	Remanence	Lamp + integrating sphere, internal lamp with calibration mecanism
	Straylight	Laser + field pattern
	Polarization	Variable direction polarizer (only glint viewing)
Spectrometry	Dispersion law	Accordable laser + lambdameter
	ISRF shape	Accordable laser + lambdameter, field patterns
	Keystone	Lamp
	Smile	Laser
Geometry	Line of sight alignment	Theodolites
	Imager – sounder – bands registration	Field patterns
	FOV spread Function	Field patterns

- **Additional tests requested by CNES**
  - Gaz Cell for absorption lines (only for CO2, and characterized only at 1.6µm)
  - Solar test

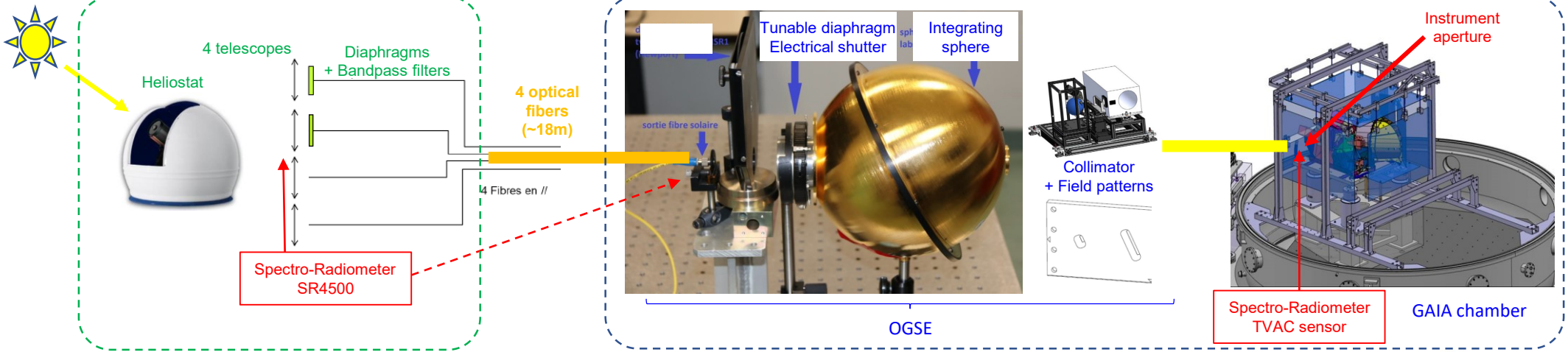
Solar Test Setup



- Airbus setup based on telescope + optical fiber ≠ OCO setup (mirrors)
- Spectro-Radiometer sensors will enable the setup characterization
- We will insert the solar measurement (2 separate days) in between instrumental characterisations

Roof

Clean room



Assets of the ground solar test

Remember the challenge to reach the mission performances! In particular scene-related biases

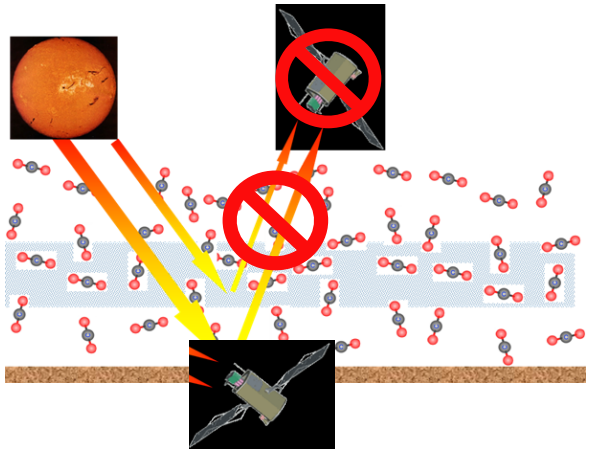
- **Single opportunity for real atmospheric scenes before launch**
  - Enable to characterise L1 (atmospheric spectra) and L2 performances before launch
  - Laser, lamps and even gas cell (only 1.6µm) are not atmospheric like

  ➔ Will see unexpected effects?

- **Very high knowledge of scene and instrument**
  - Complete instrument characterisation performed at the same time in TVAC
  - Large number of data, on slowly varying scene ➔ very low noise
  - Very weak perturbation of XCO2 by atmospheric scattering
  - No uncertainty on surface reflectance
  - Simultaneous atmospheric measurements (EM27, balloons and others)

  ➔ **No flight equivalent**

- The single path (DOWN) gives absorption lines that are only slightly different from the flight range (DOWNUP)



Main expectations from the solar test

- **Independent verification of some critical instrumental performances**
  - Ex: Non-linearity, ISRF (uniform and non uniform scenes), remanence, straylight
  - Some of them are much easier to detect on XCO2 than at detector level (cumulative effect of all pixels)

  ➔ Impact at level 1 and level 2

  ➔ Complementary with the Airbus characterizations (not replacing)

- **Test and improvement of the L2 algorithm**
  - Spectroscopy validation
  - Variation of P, T, H2O, SZA
  - Additional to the 4ARTIC tests with OCO-2 L1 data (not exactly the same bands and resolution, + B4)

➔ **In both cases we look for impacts > 0.1 ppm (scene-related bias)**

- **Reference measurement for ground / flight traceability and cal/val preparation**
  - Ex: solar line shape evolution at L1 = ISRF evolution

  ➔ 1st step of cal/val

- **Test of the L1 and L2 processing chains on real MicroCarb data**
  - Adapted version without geometry

- **MicroCarb XCO2 traceability to the International System**
  - Same procedure as TCCON with in situ vertical profiling

- **Team building and external communication**

Parallel measurements in the solar test

- **Needs for parallel measurements**
  - Mainly: the XCO2 truth the day long
  - The CO2 profile (for RT codes, for inversion)
  - The P,T,U profile (for RT codes, for inversion)
  - The high resolution entrance spectrum
  - The actual state of the sky (by classical camera)
  - The entrance photometry + AOD

- **Baseline : MAGIC campaign experiments**
- **Any other relevant instrument is welcome!**

Satellite measurements (if possible)

Photometry and AOD measurements

Ground and XCO2 measurements

+ TCCON SPECTROMETER?

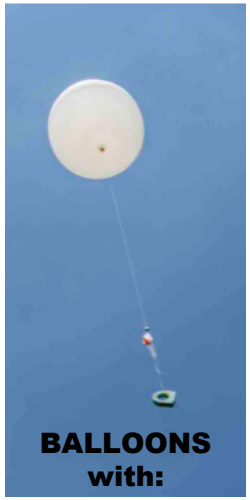


Figure 9 : Echantillonneur atmosphérique AirCore (photo : Alexandre Ollier)

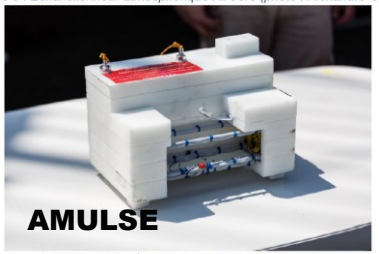
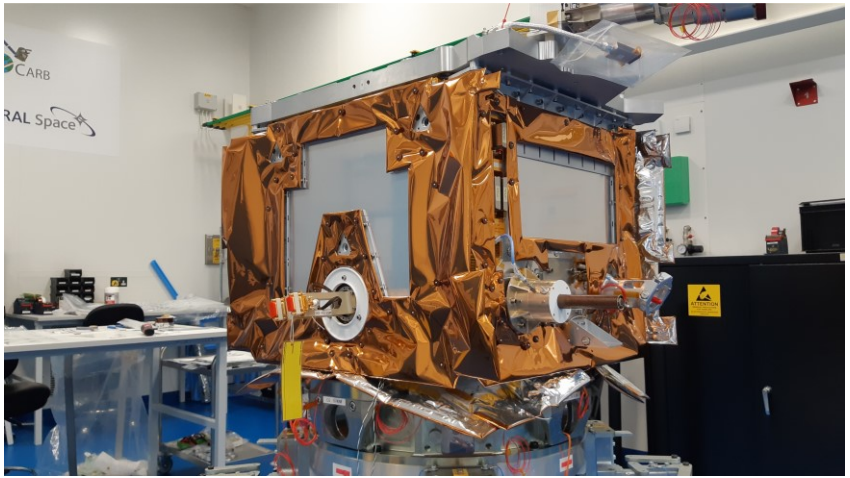


Figure 11 :Spectromètre Amulse (Photo : Alexandre Ollier)

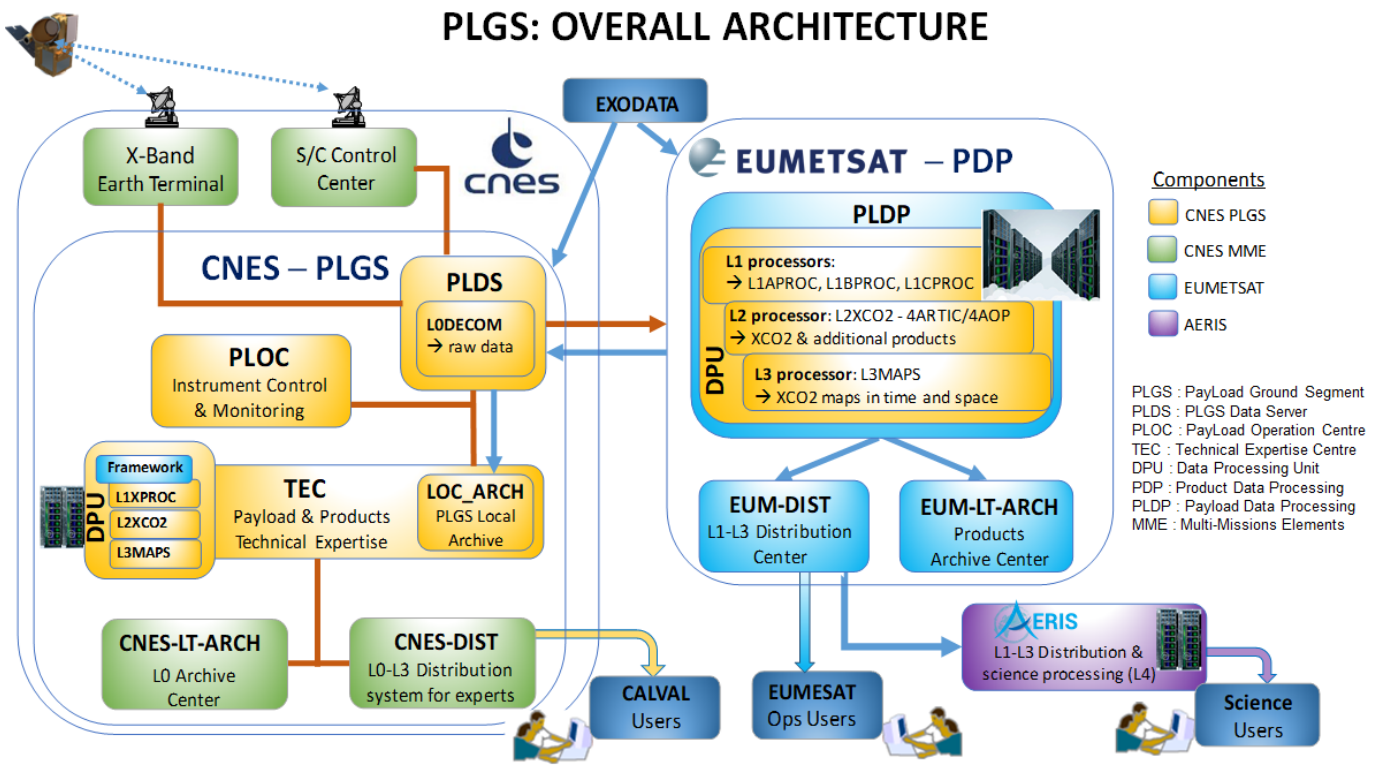
In situ measurements

PF-Sat activities including AIT by TAS-UK

- All PF equipment now delivered
- PF integration almost complete, to be finalized this summer
- Including extensive board to ground system tests taking advantage of the Myriade experience
- Satellite mechanical compatibility checked wrt VEGA-C launcher environments in all positions



Data distribution scheme



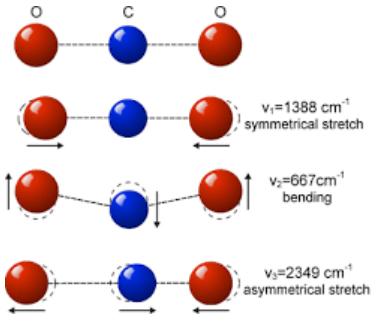
Data policy:

During CALVAL, data distribution limited to Mission Advisory Group (MAG), potentially augmented through a call to be organized

Then along 5 year mission, free data access through AERIS portal for scientists + directly from EUMETSAT for Metoffices, as Copernicus-CO2M precursor

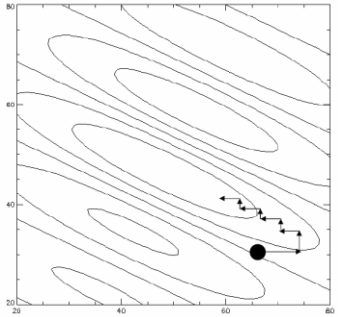
Regular L1-L2 reprocessing campaigns to be organized according to MAG advices

Current works on L2 algorithm

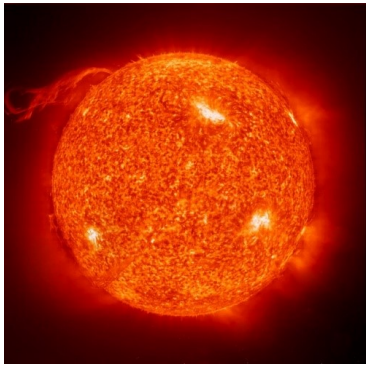


Spectroscopy (LMD, LiPhy)
Lines and continuum,
measurements and modelisation
Mondelain et al. 2019
Tran et al. 2020

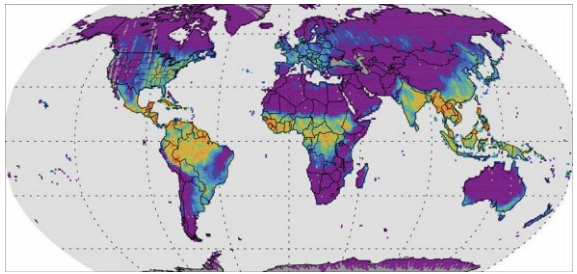
Aerosols and clouds (CNES with LOA)
Optical properties
Vertical and spectral parametrization



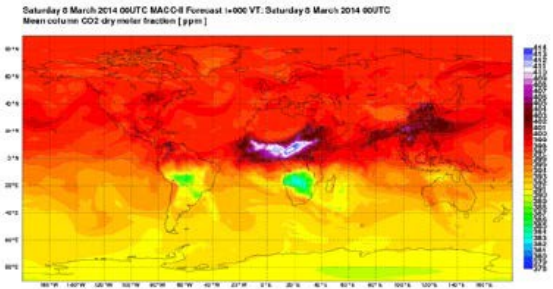
Optimal Estimation
(CNES, ACRI, LSCE)



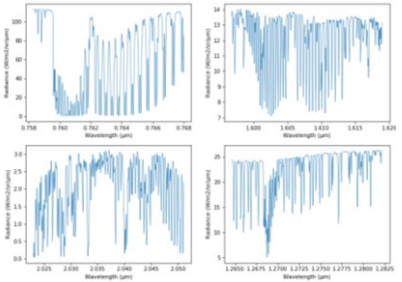
Solar Spectrum (LATMOS)
Lines and continuum
Meftah et al., 2022, in prep



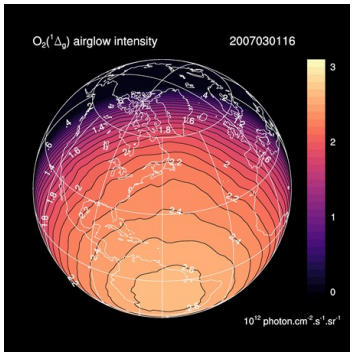
SIF (CNES, LMD, RT solution + UoL)
And implementation in 4ARTIC



ECMWF and CAMS models
use for prior



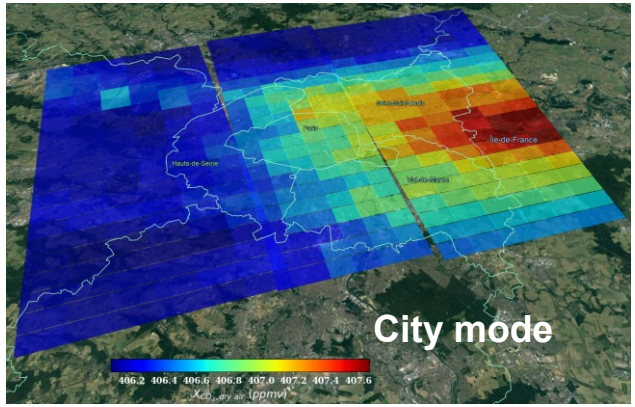
RT acceleration
(CNES, LMD, NOVELTIS)
LSI, atlases
Sic et al., 2022, in prep

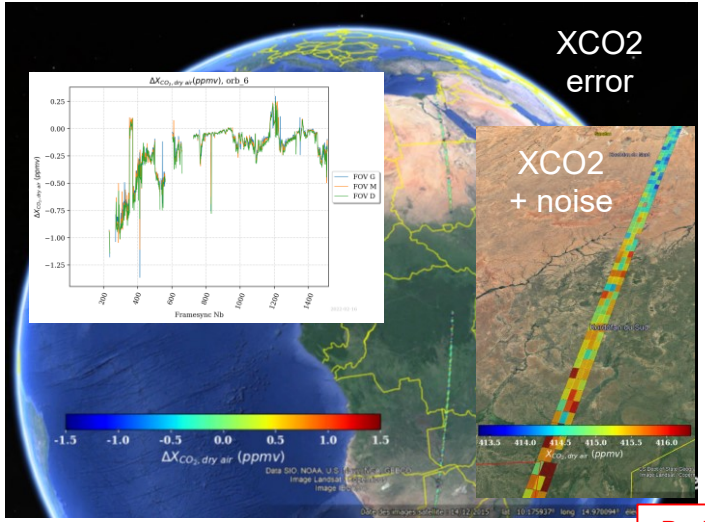


1.27 µm airglow (LATMOS)
From obs and from models
Bertaux et al. AMT 2020

Synthetic data processing

- **Very useful for performances estimation including spatial pattern**
  - The truth is perfectly known, but only with predictible defects
  - Random error is compliant with spec
  - Raw regional biais is not compliant with spec
    - The single L1 budget is only 0.68ppm
    - Processings (ISRF, polarisation) still under improvement
    - Aerosol and spectroscopy errors are dominant but will be improved.
    - Cal/val and bias correction not included
  - Has demonstrated the usefulness of the B4 band in retrievals with aerosols





O2	Aérosols en direct	Aérosols en inverse	A priori aérosols	Moy (ppm)	Std (ppm)	Conclusions
	Profil réalistes	Sans aérosols		0.114	1.732	Dans une situation sans Sherlock - B1+B4 donne des résultats mauvais - B1 seule est pire - B4 seule améliore beaucoup, mais pas assez dans l'absolu ➔ On a donc besoin de la paramétrisation de Sherlock.
Sans B4	Profil réalistes	Sans aérosols		0.116	1.917	
Sans B1	Profil réalistes	Sans aérosols		0.083	0.831	
Sans B14	Profil réalistes	Sans aérosols		-0.159	2.067	
	Profil réalistes	Profil & type Sherlock	Pseudo-vérité	-0.243	0.562	La seule paramétrisation de Sherlock induit un biais régional de 0.6ppm ➔ On a besoin d'améliorer Sherlock
	Profil réalistes	Profil & type Sherlock	Pseudo-vérité + tirage aléatoire	-0.214	1.059	L'incertitude sur les a priori aérosols dégrade les résultats ➔ On a besoin de bons a priori aérosols
Sans B4	Profil réalistes	Profil & type Sherlock	Pseudo-vérité + tirage aléatoire	-0.475	1.611	Dans une situation avec Sherlock et incertitude sur les a priori aérosols - enlever B1 améliore beaucoup les résultats - enlever B4 les dégrade fortement. ➔ Fort intérêt de B4!
Sans B1	Profil réalistes	Profil & type Sherlock	Pseudo-vérité + tirage aléatoire	-0.213	0.414	

- **Very useful for product simulation**

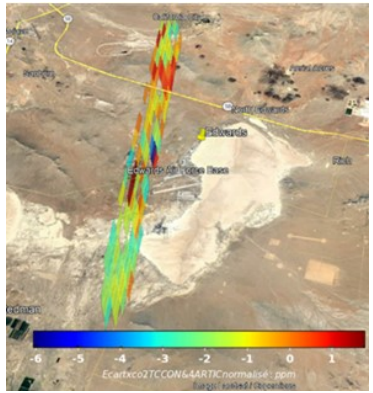
Performance Item	CO2 random error (ppm)		CO2 regional bias
	1sig	Max	1sig
L1 radiometry			
Radiometric noise (SNR)	0.59	1.20	
Absolute gain residual			0.32
Band to band gain residual			0.25
Channel to channel gain residual			0.04
Dark signal residual			0.24
Dark signal channel to channel residual			0.03
Non-linearity residual			0.09
Instrumental polarization residual			0.15
Straylight	0.25	0.25	
Detector persistence	0.19	0.30	0.10
L1 spectrometry			
Spectral shift			0.35
Limited knowledge of the ISRF (uniform scenes)	0.07	0.07	0.32
Limited knowledge of the ISRF (heterogenous sce	0.10	0.10	
L1 geometry			
Limited knowledge of geolocation			
Intra-band misregistration	0.14	0.14	
Inter-band misregistration	0.25	0.25	
Limited knowledge of VZA	0.20	0.20	0.20
Inter band differential VZA	0.15	0.15	0.15
FOV spread function shape			
Limited knowledge of the FOV spread function			
L2 processing			
Limited a priori knowledge of CO2			0.01
Limited knowledge of weather analysis and DEM	0.25	0.5	
Spectroscopy misknowledge			0.30
Impact of aerosols (incl. apriori)			0.70
Limited knowledge of the solar spectrum			
Unscreened clouds	0.20	0.20	0.10
Impact of 1.27 µm airglow	0.22	0.22	
Impact of 0.76 µm vegetation fluorescence			0.03
Impact of 4AOP calculation accuracy			0.20
Approximation of gain matrix formalism (added)			0.30
Mission Requirement (ppm)	**0.5 - 1.5**		**0.1 - 0.2**
Random error budget (ppm)	**0.87**	**1.45**	
Regional bias budget (ppm)			**1.39**

Budget before calval and bias correction

Real data processing

- **Very useful to test 4ARTIC on MicroCarb similar data with real defects. Good preparation to calval. But the truth (TCCON) is not exactly known, and the instrument are a bit different**

- **Retrievals on OCO-2 L1B spectra, w.r.t. TCCON**
  - 43 collocations
  - Results after spatial binning around TCCON (20km)

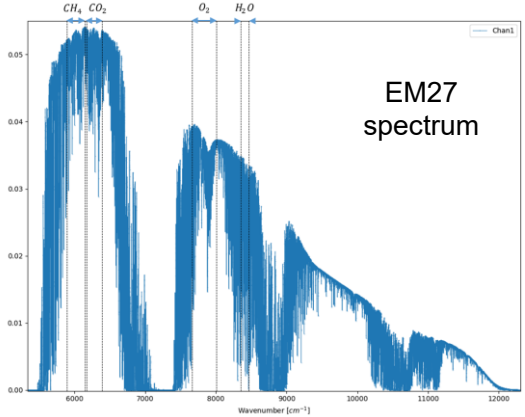


With aerosol parameters					Without aerosol parameters			
	count	mean	std	Total individual spectrums	count	mean	std	Total individual spectrums
Ecart_XCO2_4ARTIC-TCCON	43	0,566	2,02	1307	43	1,41	2,3	1332
Ecart_XCO2_ACOS-TCCON	43	1,19	1,54		43	1,18	1,54	

➔ Close to ACOS raw, still to improve

- **We plan to compare both with in-situ ballon profiles**

- **Retrievals on EM27 spectra, w.r.t PROFFAST**



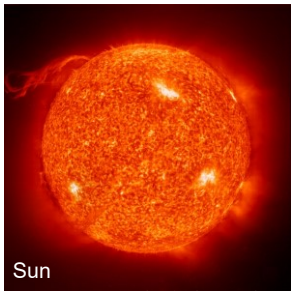
- Result obtained for 1 spectrum 13/06/2021 :
  - 4ARTIC : 412.81 ppm (chi = 13)
  - PROFFAST : 410.59 ppm
- Psurf with 1.27µm biased

Notional Cal/Val Plan (1/2)

Typical expected duration : 1 year

- **Launch ➔ Launch + 6 months**
  - **L1 calibration**
  - **L2 production starting and parameter definition**

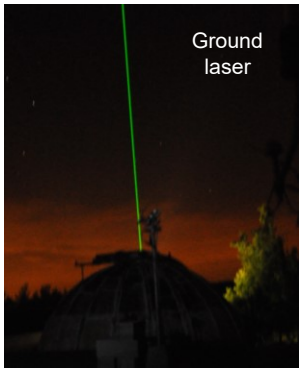
- **Many sources for L1 calibration**



Dispersion law & smile

Dark signal

ISRF shape



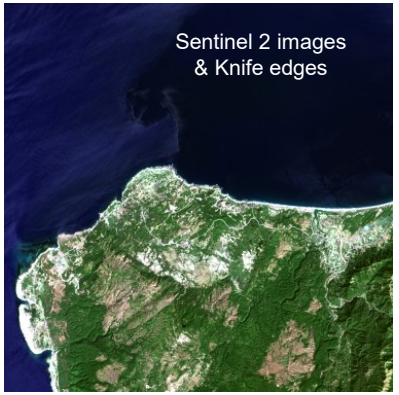
Absolute radiometric gain

Polarization

ISRF on heteregenous scenes

Imager & Band coregistration

Geolocation



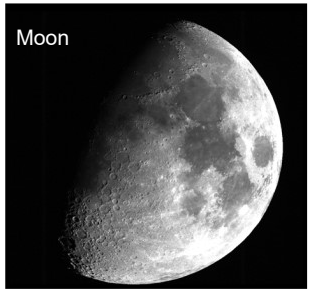
Intra-band relative gains

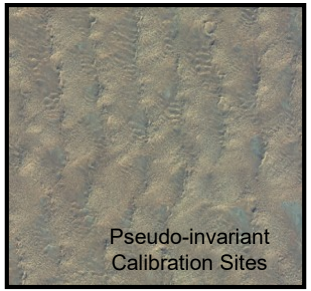
Straylight & lag

Non-linearity

Radiometric noise

ACT relative gains





Internal lamp

Notional Cal/Val Plan (2/2)

Typical expected duration : 1 year

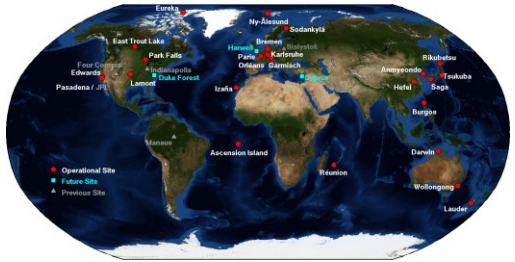
- **Launch + 6 months ➔ Launch + 12 months**
  - **Data delivered to MAG**
  - **L2 validation and bias charaterization (CNES + MAG)**

- **Operational comparisons for massive statistics**
  - **To TCCON network (target and offnadir modes)**
  - **To CAMS CO2 model**
  - **Inter-comparison to other missions**

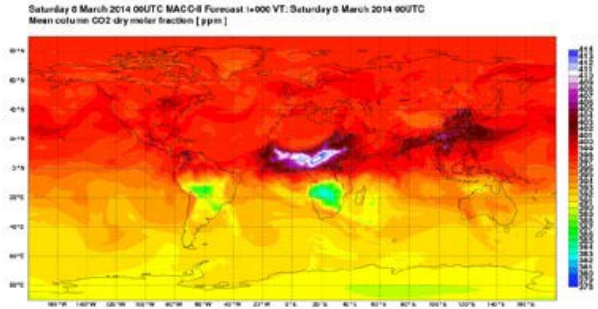
- **Regular measurements**
  - **EM27**
  - **AirCores on ballons**

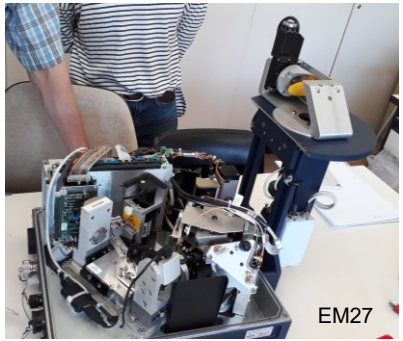
- **Campaigns**
  - **Currently one MAGIC campaign per year**
  - **Instruments:**
  - EM27
  - AirCores on balloons
  - AMULSE on balloons
  - Aircraft (Picarro on Falcon)
  - CHRIS
  - If possible : ICOS and TCCON

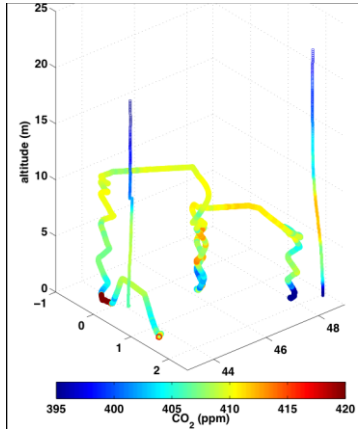
TCCON network



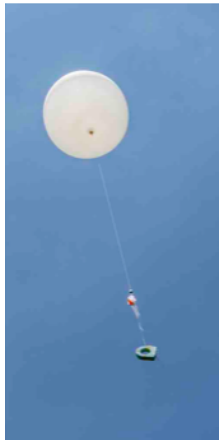
CO2 from CAMS







Results of Falcon and AirCore from MAGIC 2018



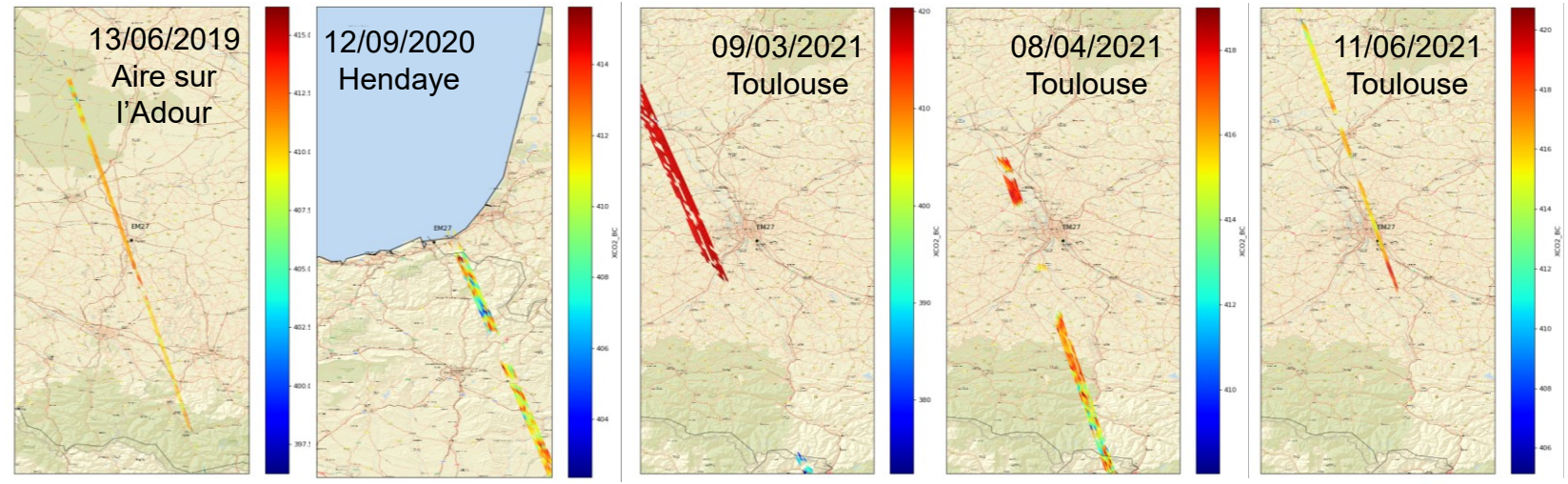
AirCore

OCO-2 vs EM27 (CNES) simultaneous observations

- We have several EM27 in France (and UK), and a dedicated WG in MAGIC framework
- The OCO-2 team regularly sends us the acquisition forecast over France
- This forecast has been used during the MAGIC campaigns and also for regular EM27 observations from CNES Toulouse
- First results show that a few common observations are not enough , we need large statistics!

Date	EM27 (ppm)	OCO2 BC (ppm)	OCO2 raw (ppm)
13/06/2019	409.69	411.21	408.82
12/09/2020	409.18	411.11	411.40
09/03/2021	415.48	417.66	416.94
08/04/2021	415.17	415.29	414.83
11/06/2021	414.83	416.67	414.90

EM27 XCO2 here got from PROFFAST



Conclusion

- Additional partnership are put in place at European level to place MicroCarb in an European frame and contribute to prepare future operational systems (Copernicus)
- Instrument and Platform AIT well engaged, before starting this fall satellite AIT
- Processors benchmarked and extensively tested using synthetic and OCO-2 data and give promising results
- Payload ground segment under development
- L1 and L2 cal/val preparation started
- Launcher main passenger looked for
- MicroCarb heading for a launch end 2023-beginning 2024

Thank you for your attention !