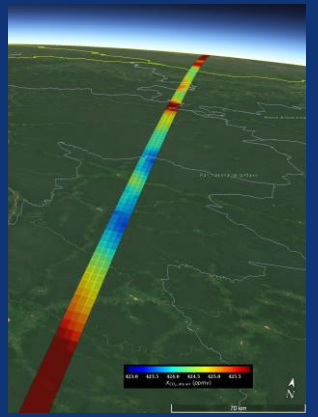

The MicroCarb CO2 mission: Imminent launch!

IWGGMS-21 June 9th 2025

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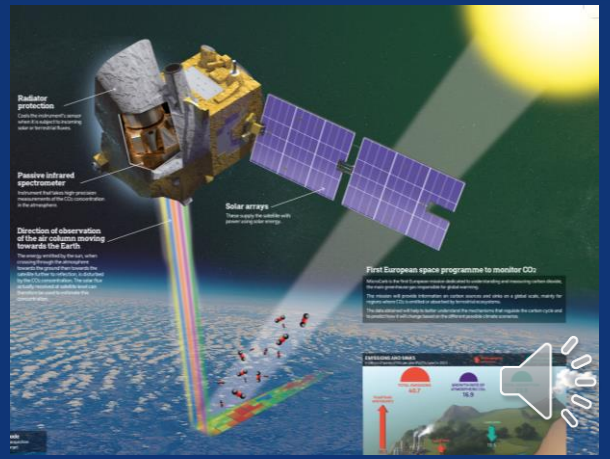
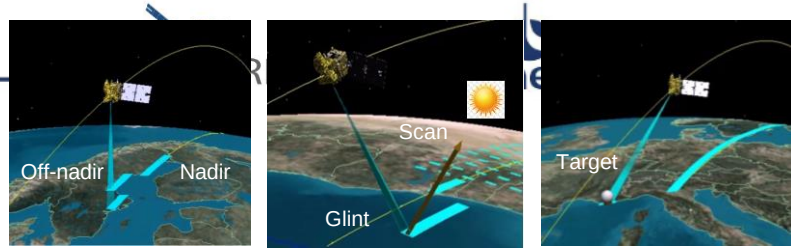
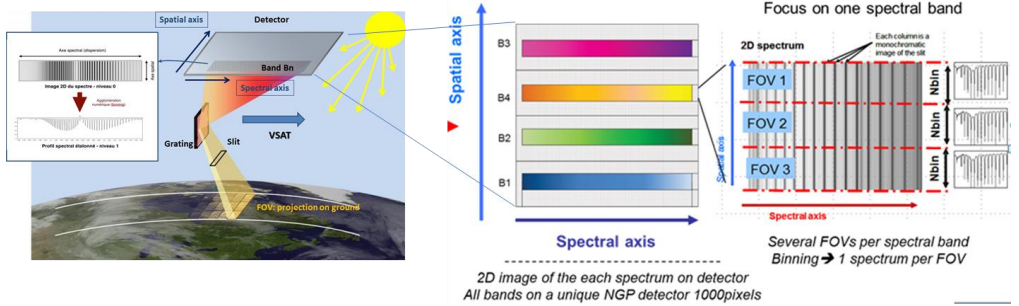


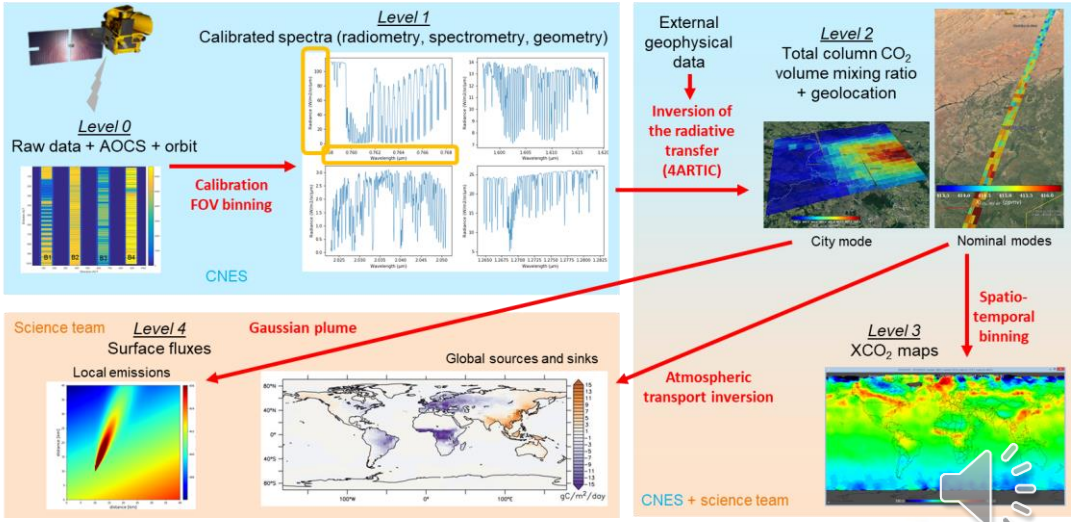
The MicroCarb CO2 mission at a glance

- **Objectives**
  - Natural CO_2 fluxes at regional scale
  - Demonstrator for CO_2 anthropogenic emissions (city mode)
- **Main product: CO_2 column integrated concentration**
  - Rqmt for random error < 0.5 ppm (G) , < 1.5ppm (T)
  - Rqmt for regional bias < 0.1 ppm (G), < 0.2 ppm (T)
- **Orbit**
  - Polar sun-synchronous, alt 649 km, LTDN 10h30
  - Cycle 25 days, sub-cycle 7 days, ± 200km ACT mirror

  ➔ Any target can be observed once a week
- **Observations modes**
  - Science: Nadir, scan, glint, city
  - Calibration: Shutter, Lamp, Sun, Moon, Limb
  - Validation: Fixed-Target, Off-nadir target
- **Instrument**
  - Compact instrument (80 kg, 60W) on micro-satellite (180kg)
  - Passive SWIR grating spectrometer
    - CO_2 1.61 µm & 2.05 µm + O_2 0.76 µm & 1.27 µm
    - High resolving power 25000, high SNR
    - 3 ACT footprints 4.5x9 km²
  - Embedded imager (red band, 140m) for cloud and geolocation
- **XCO2 retrieval : 4ARTIC**
  - Full physics, optimal estimation







Outline

- **Project**
- **Performances**
- **Algorithms**
- **Cal/Val**

A long history

- **Early 2000s: First thoughts (CARBOSAT)**
- **2009: Start of phase 0 (MiniCarb)**
- **2011: Start of phase A (MicroCarb)**
  - With a more compact instrument
- **Early 2014: ~2 years break, waiting for a program**

- **2015: COP21 in Paris ➔ Decision of MicroCarb**
- **End 2015: Start of phase B**
  - But on a smaller satellite and therefore more compact instrument
  - Launch planned in 2020!
- **Early 2017: Start of phase C**
- **Early 2019: Start of phase D**
- **2020: new break due to covid and to detector remanence effect**

- **End 2022: new break due to failure of Vega-C VV22**

- **But at last…**

System is ready!

SPACE SEGMENT

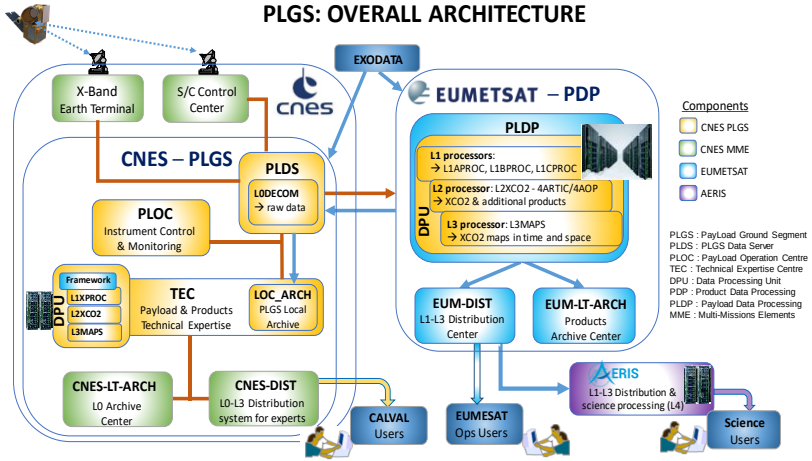
2022: Instrument AIT

2023: Satellite AIT

2024: storage in Toulouse

VEGA-C (VV27) launch
25/07/2025 23h03 (UTC-3)

GROUND SEGMENT

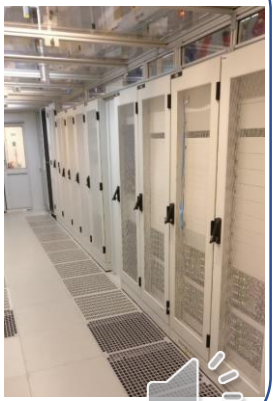


Ground Segment (PLGS)

- Complete delivery July 2025

Data Processing Unit (DPU)

- ATBDs written and implemented by CNES
- Online processing hosted by EUMETSAT
- All HW ready
- Ready for regular ATBD upgrades



Organization

In the context of the 2015 COP21 climate conference, France decided the MicroCarb project
French government ANR funding + European contributions: UK, UE

Mission Science Group

PI François Marie BREON

LSCE, LA, LMD, LATMOS, MONARIS, GSMA, LIPhy, cea, cnrs, THE UNIVERSITY of EDINBURGH, UNIVERSITY OF LEICESTER, NPL National Physical Laboratory

CO2M representatives

cnes

- System design and development
- Satellite design an development
- Instrument specification
- 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

Copernicus Europe's eyes on Earth — Atmosphere Monitoring Service

Outline

- Project
- Performances
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Instrument TVAC calibration main results

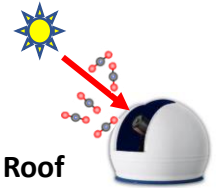
- Held fall 2022, then data exploitation
- Main status : the major requirements (SNR and spectral resolution) are compliant
- But still some non-compliances or unknowns

Performances	Item	Performance status
Radiometry	SNR	OK
	Dark	Larger than expected (FOD), slightly polluted by RTS
	Spurious pixels	Number OK but threshold still under discussion
	Non linearity	Unaccurate characterization, OGSE recalibrated by NPL
	Flat field	Characterized, still working on HF and BF maps
	Absolute Gain	Solar port unsuccessful characterization
	Remanence	OK (a bit better than expected) with FOD
	Straylight	Out of band straylight OK Characterized Rowland Ghosts as expected Unaccurate scattering characterization Unexpected inter-band straylight
	Polarization	OK (<0.5%)
Spectrometry	Dispersion law	~OK but slight unexpected evolution
	Spectral resolution	OK (25,000)
	ISRF shape	Broadening by crosstalk
	ISRF knowledge	Disturbed by crosstalk, new measurements on spare detector
	Keystone	OK (<2 pixels)
	Smile	OK (<0.1 pixel)
Geometry	Line of sight alignment	An easy to manage slight misalignment
	Imager / sounder & inter-band coregistration	OK
	FOV spread Function	OK (but also polluted by crosstalk)

- On-going works
- Overall consistency of the radiometric chain
- Deliver a complete ground parameter data set
- Finalize processing of L1 and L2 from solar test

MicroCarb TVAC atmospheric observations

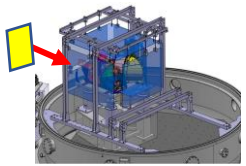
Solar test setup during TVAC



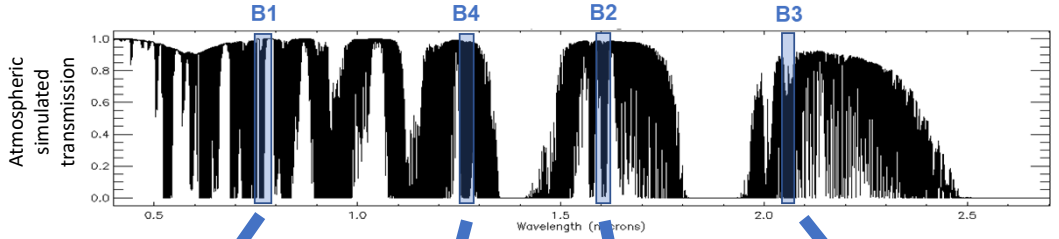
Roof heliostat telescope

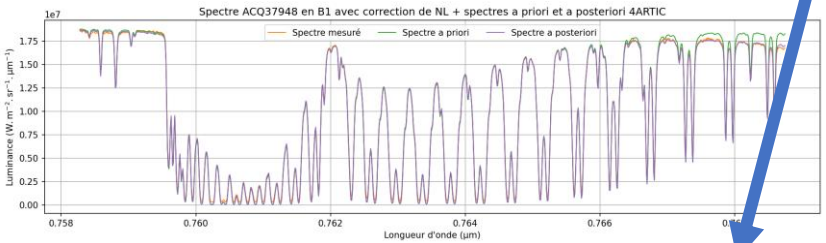
70m optical fiber

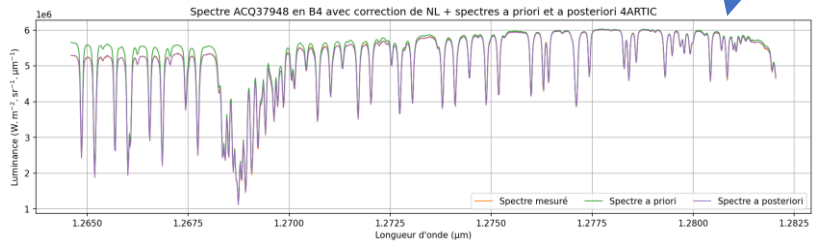
OGSE

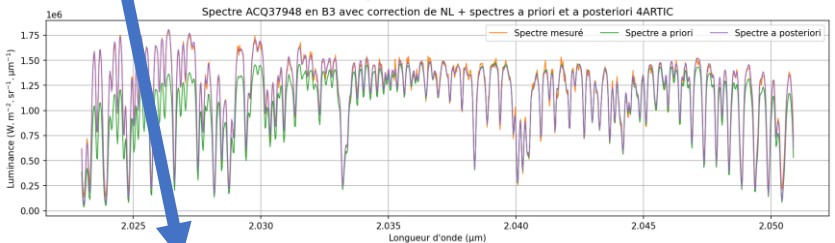


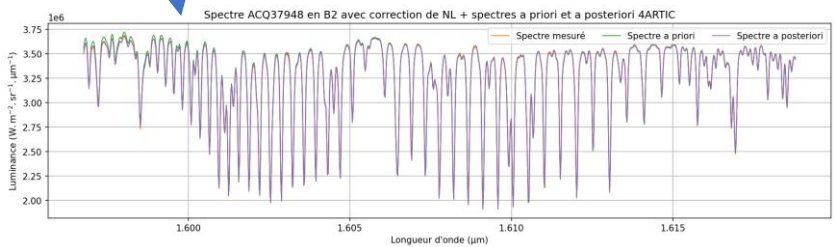
TVAC chamber











Level 1
- Good general shape
- Some residuals affecting continuum and line bottom
- Partly related to unstabilized detector during TVAC

Level 2
- Nominal observations: 2.5ppm bias
- Scene-variable observations (ex : under tunable aperture): a few ppm bias

Outline

- Project
- Performances
- Algorithms
- Cal/Val

4ARTIC (L1 ➔ L2 retrieval tool) in a nutshell

4ARTIC is a « full physics » retrieval tool

Forward Model : 4AOP (F)

- Spectroscopy from GEISA + non-Voigt line models, line-mixing, CIA
- Pre-computed optical depths in LUT (« atlases »)
- Scattering by (V)LIDORT + LSI acceleration
- Pre-computed scattering parameters (« datscat »)
- Computes spectra and jacobians

Estimated variables in the State Vector (X)

- CO_2 19 vertical layers or scaling factor
- H_2O 19 vertical layers or scaling factor
- Psurf ➔ Constant number of pressure levels = YES or NO
- Albedo parametrized by 2nd order polynomial per band
- 1 aerosol layer parametrization
  - AOD(λ0)
  - Zaero (Mean altitude of a Gaussian vertical profile)
  - Kaero Angström coefficient : $AOD(\sigma) = AOD(\lambda 0)(\lambda/\lambda 0)^k$
- Under testing : 1 cirrus layer (COD(λ0))
- Under testing : B1 fluorescence amplitude
- B4 airglow amplitude and temperature
- Instrumental parameters if necessary : offset, gain, spectral shift

Unestimated auxiliary parameters (B)

- Temperature profile
- Geometry (SZA, VZA, VAA, SAA)
- Aerosols and cirrus parametrization (Sherlock model)
  - Single Scattering Albedo (SSA=0.98 or given by CAMS)
  - Henyey-Greenstein phase function (g=0.8 or given by CAMS)

Priors (x_a) = first guess

- CO2 : CAMS operational forecast or LSCE climatology
- Psurf, H2O, T, cirrus : ECMWF operational analysis or LWDA
- AOD for several λ, vertical profiles and types : CAMS operational forecast
- DEM : CopernicusDEM
- Surface albedo : spectrum continuum or from S2 MAIA L3
- SIF : 0 or TROPOSIF climatology
- Airglow : LATMOS climatology

Retrieval based on optimal estimation from Rodgers [2000]

- Iterative fitting of measured spectrum (Y_{mes}) by 4AOP spectrum
- All parameters estimated at the same time
- Minimization of a cost function made of measurement and prior

$$\Phi(x) = \underbrace{(y - F(x))^T S_\varepsilon^{-1} (y - F(x))}_{\text{Attache à la mesure}} + \underbrace{(x_a - x)^T S_a^{-1} (x_a - x)}_{\text{Attache à l'a priori}}$$

(y_{mesure}, y_{calc})

- Levenberg-Marquardt iterative optimisation scheme

$$x_{i+1} = x_i + (S_a^{-1} + K_i^T S_\varepsilon^{-1} K_i)^{-1} [\underbrace{K_i^T S_\varepsilon^{-1} (y - F(x_i))}_{\text{Attache à la mesure}} - \underbrace{S_a^{-1} (x_i - x_a)}_{\text{Attache à l'a priori}}]$$

x_a est l'ébauche (= a priori dans MicroCarb)

Jacobian matrix — Noise covariance matrix — State vector a priori covariance matrix

- Stop criteria
  - Crit 1 : stabilisation of chi (residuals)
  - Crit 2 : stabilisation of state vector
  - Crit 3 : absolute chi value (informative only)
  - Crit 4 : strong divergence of cost function
- Control of physical sense of VDE
  - Thresholding or reset to prior

Current works on L2 algorithm assessment

We have a complete set of performance estimation for 4ARTIC
- Synthetic spectra to master the truth
- Other satellite spectra
- Ground spectra (easier case) but uncalibrated

➔ The 4ARTIC performance is high but not state of the art, still needs some progress (aerosols, continuum fitting)
➔ Diagnostic tools are implemented (convergence, state vector elements, spetral residuals)

4ARTIC on MicroCarb synthetic spectra

= Orbital simulator on realistic scenes, with noise
- **Acceptable number of iterations (mean ~5)**
- **Almost no retrieval error**
- **Airglow is manageable**
- **B1B2B3B4 std ~ 1.5ppm**
- **B2B3B4 is better ! std ~ 1.2ppm**

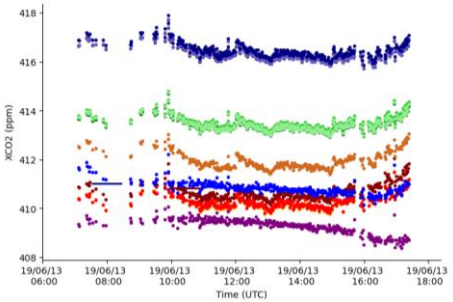
➔ **New 1.27µm is promising**

Experience	median	EqStdev
Spectrum with airglow, no airglow in retrieval	16.668	8.591
Spectrum with airglow, airglow in retrieval	0.033	0.017
Spectrum with airglow without B1, airglow in retrieval	0.268	0.070
Spectrum without noise, no aerosols in retrieval	-0.102	1.804
Spectrum with noise, no aerosols in retrieval	-0.525	2.325
Spectrum with noise without B1, no aerosols in retrieval	0.115	1.253
Spectrum with noise, with aerosols in retrieval	-0.467	1.533
Spectrum with noise without B1, with aerosols in retrieval	-0.309	1.171

4ARTIC on EM27/SUN spectra

- Calibration by 4ARTIC
- Psurf read from PTU
- No debiasing

➔ **Very close to AirCore @ 1.58µm**
➔ **But a 6ppm error @ 1.61 µm, likely related to continuum fitting and solar lines**



AirCore006
AirCore008
PROFFAST2ter band with 4ARTIC
MicroCarb band with 4ARTIC
PROFFAST1 band with 4ARTIC
PROFFAST1ter band with 4ARTIC
PROFFAST2 band with 4ARTIC
PROFFAST2bis band with 4ARTIC
PROFFAST1 plus PROFFAST2 bands with 4ARTIC
PROFFAST1 plus PROFFAST2bis bands with 4ARTIC
PROFFAST1ter plus PROFFAST2ter bands with 4ARTIC
PROFFAST large band with 4ARTIC
PROFFAST v2.3
PROFFAST raw v2.3

4ARTIC on OCO-2 spectra

- Nadir mode, averaging in +/-20km & +/-30min around each TCCON
- No SIF, no cirrus in state vector

➔ **Same order of magnitude as ACOS raw**
➔ **We have to improve our aerosol parametrisation**

XCO2 difference	Number of overpasses	count	mean	std
4ARTIC-TCCON	122	122	0,495	2,102
rawACOS-TCCON		122	-0,222	1,207
4ARTIC-rawACOS		122	-0,717	2,18

Outline

- Project
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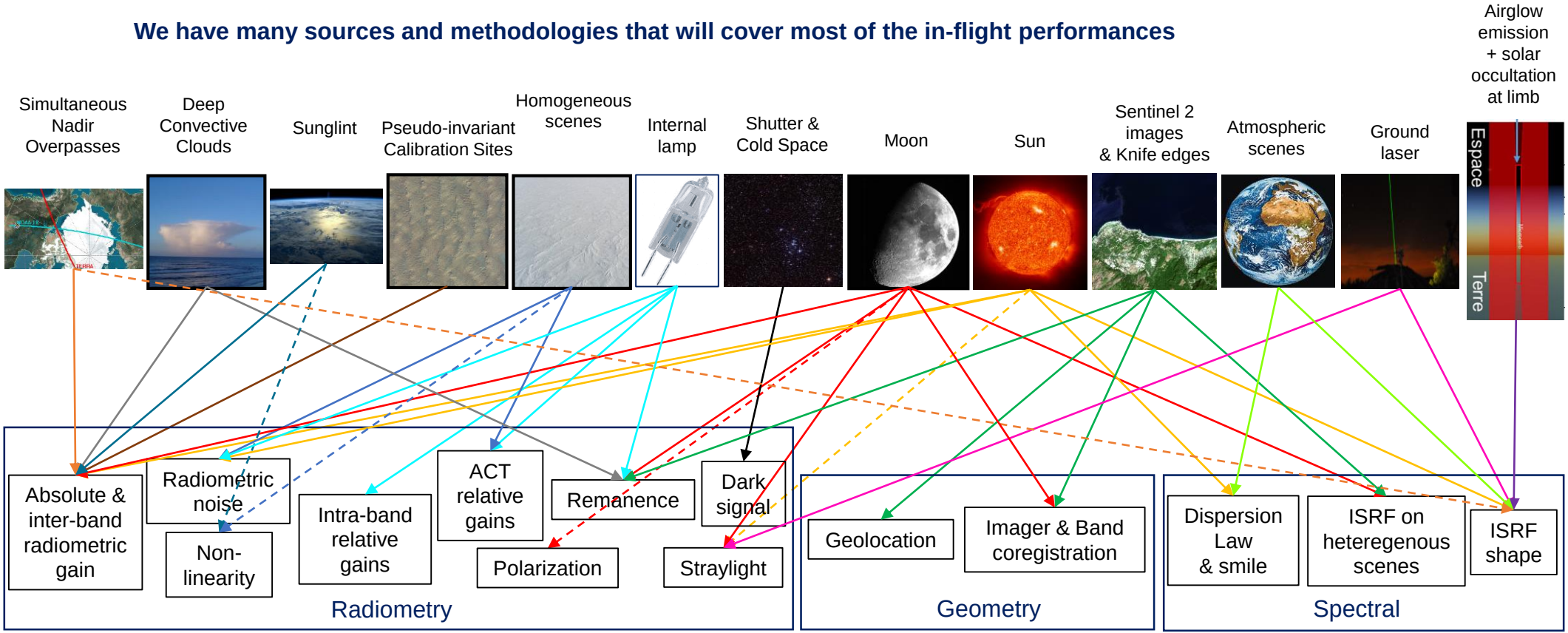
- Algorithms
- Cal/Val

Cal/Val planning

Period	Phase name	Activities	Data
Pre-launch		Performance budget, algorithm finalization, operational qualification	Simulated data + TVAC heliostat
T0 = July 25th 2025			
T0 ➔ T0 + 10 days	**LEOP**		
T0 + 10days ➔ T0 + 60days	**Sat. and instr. in-flight commissioning**	Instrumental decontamination T0 +1day ➔ T0 + 3 weeks Instrument functional tests	
T0 + ~1 month ➔ T0 + 7 months	**Cal/Val phase 1**	Tuning of instrument (Temperature, FOD) L1 & L2 processors started @ TEC L1 calibration, L1 algorithm tuning L2 first tests EUMETSAT first reprocessing @ T0 + 5 months	Acquisitions for Cal/Val Products only at TEC Samples to MAG
T0 + 7 months ➔ T0 + 12 months	**Cal/Val phase 2**	EUMETSAT online processing + 2 reprocessings L2 validation, L2 algorithm tuning L1 calibration consolidation	Acquisitions for Cal/Val and for mission Products of high quality to MAG
> T0 + 12 months	**Routine**	L4 works L1 & L2 validation and algorithm tuning goes on	All products freely downloadable from AERIS & EUMETSAT

Sources for L1 calibration

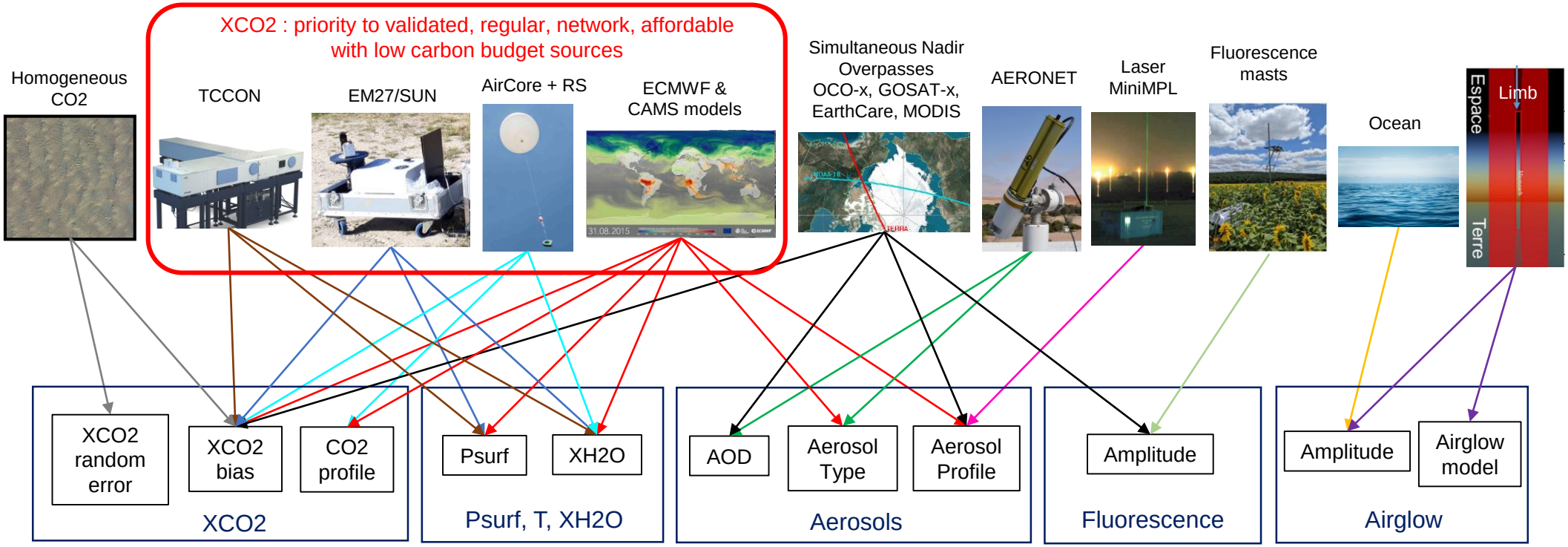
We have many sources and methodologies that will cover most of the in-flight performances



Large CNES heritage from imagery missions (PARASOL, Pleiades, S2)
Adaptations to MicroCarb

Low CNES heritage
On-going specific developments

Sources for L2 validation



- Each location place can be overpassed 4 times per 25 days
- 30 TCCON stations ➔ 150 opportunities every 25 days = 6 per day, 2 per day in clear sky

➔ ~700 TCCON overpasses / year!

Massive statistics are uppermost important

- To disciminate the different bias sources
- To make bias emerge from noise

Status of validation means

- **TCCON**
  - CNES support the Paris station, UKSA the Harwell station
  - Most station PIs individually contacted
  - Request for short timeliness deliver (obj.: 2 weeks, thr.: 4 weeks) during calval
  - Requires processing automation and quick quality check

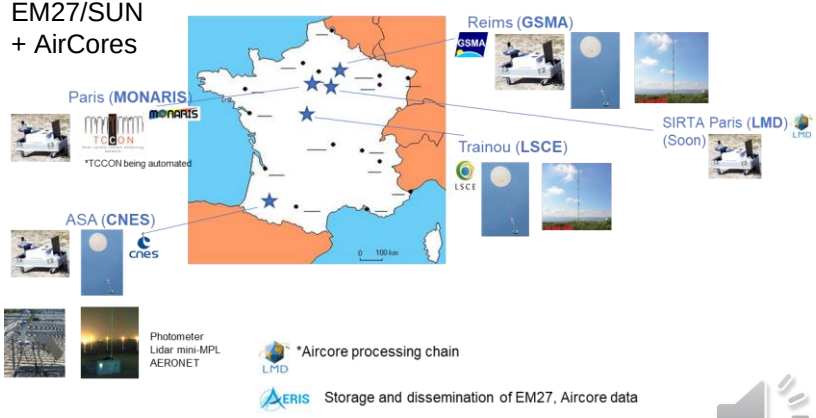
- **EM27/SUN**
  - CNES supports 4 automated EM27/SUN sites in France + 5 EM27/SUN in areas depleted of TCCON
  - Automated processing center in France (AERIS)
  - UKSA supports a network in UK
  - Initiated discussions with some individual PIs in the world

  ➔ Feel free to share your EM27/SUN data!

- **AirCores**
  - CNES supports 3 Aircore site launches in France
  - Operational aircore launches on each MicroCarb Overpass : up to once / week

EM27/SUN
(OBS4CLIM)

EM27/SUN
+ AirCores



Status of validation tools

Our inter-comparison tool is ready

- Was tested for OCO-2 BC
- Local averaging, AK and prior taken into account

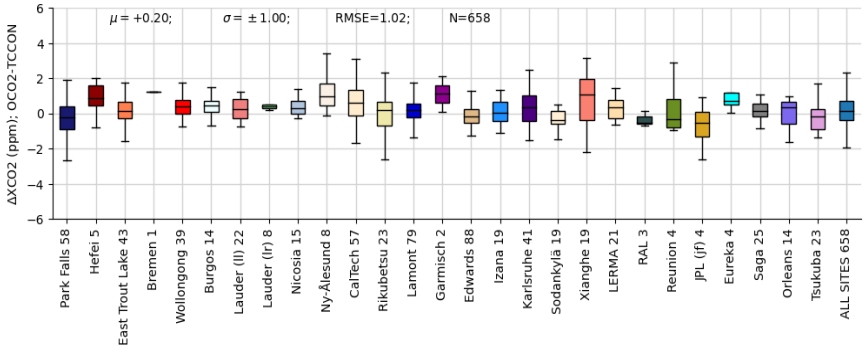
- **OCO-2 XCO2 vs TCCON**
  - Δ = 0.2±1.00 ppm (658 overpasses)

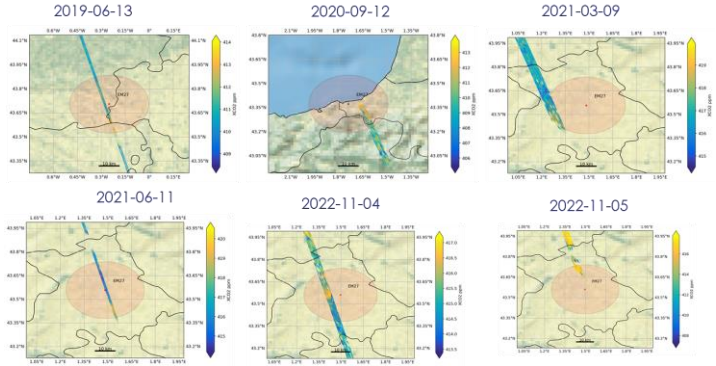
- **OCO-2 XCO2 vs EM27/SUN**
  - Δ = 0.21±0.52 ppm (11 overpasses)
  - Δ = 0.43±0.52 ppm (6 SN092 overpasses)
  - Δ = -0.01±0.41 ppm (7 SN118 overpasses)

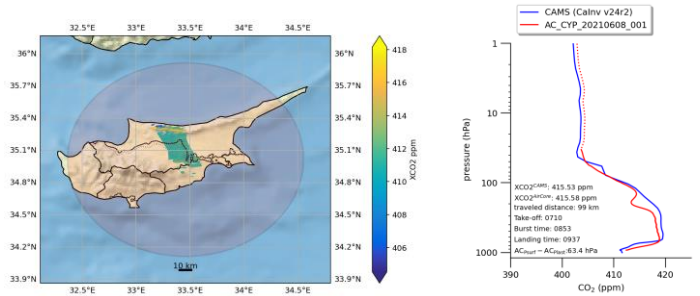
- **OCO-2 XCO2 vs AirCores**
  - Δ = -0.63±1.25 ppm (8 overpasses)

- **OCO-2 XCO2 vs CAMS optimized fluxes**
  - Δ = -0.10±1.30 ppm (1.81e6 overpasses on TCCON sites)

- **OCO-2 AOD755nm vs AERONET**
  - Δ = 0±0.07 ppm (1928 overpasses)







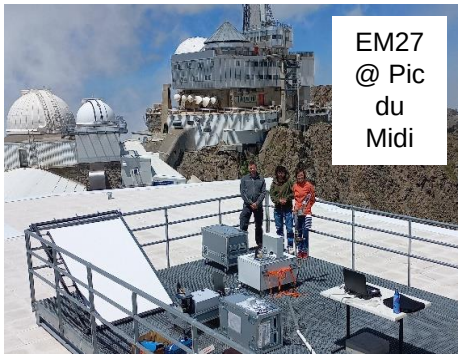
Conclusions

CNES project managing team

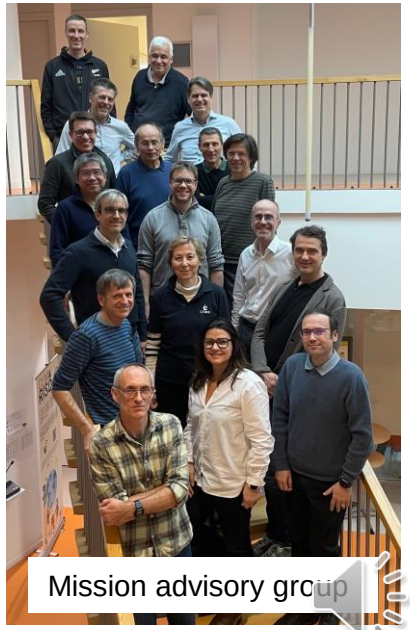
CNES project full team

- **System**
  - Space and Ground segment are ready to fly
  - Launch date : July 25th 2025
  - Data portal opens July 2026
- **Performances**
  - How challenging the requirements are!
  - Mission globally compliant with requirements
  - Some hard points from TVAC to mitigate with TVAC reprocessing and calval
- **L2 algorithms**
  - Demonstration on OCO-2 and EM27/SUN spectra is ready and convincing
  - Improvements still required
- **Cal/Val preparation**
  - Planned duration : 1 year
  - Many activities to manage
  - Means and tools are ready for validation

➔ **We are eager to fly, to discover our flight data and to share results with the community**



EM27 @ Pic du Midi



Mission advisory group