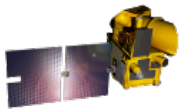


THE MICROCARB L1 & L2 PRODUCTS

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2 - Laboratoire des Sciences du Climat et de l'Environnement – France

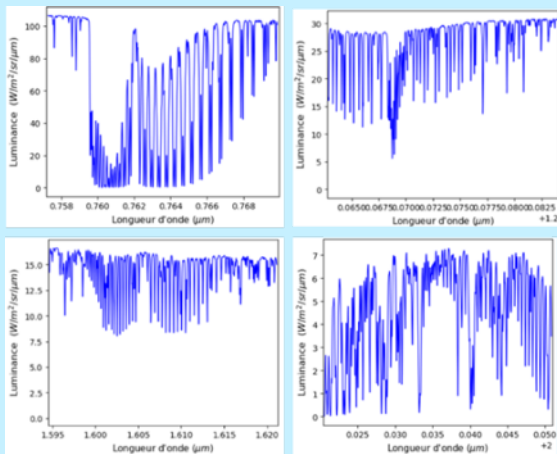


THE MICROCARB PRODUCTS

1	0.758	0.760	0.762	0.764	0.766	0.768
2	0.770	0.772	0.774	0.776	0.778	0.780
3	0.782	0.784	0.786	0.788	0.790	0.792
4	0.794	0.796	0.798	0.800	0.802	0.804
5	0.806	0.808	0.810	0.812	0.814	0.816
6	0.818	0.820	0.822	0.824	0.826	0.828
7	0.830	0.832	0.834	0.836	0.838	0.840
8	0.842	0.844	0.846	0.848	0.850	0.852
9	0.854	0.856	0.858	0.860	0.862	0.864
10	0.866	0.868	0.870	0.872	0.874	0.876
11	0.878	0.880	0.882	0.884	0.886	0.888
12	0.890	0.892	0.894	0.896	0.898	0.900
13	0.902	0.904	0.906	0.908	0.910	0.912
14	0.914	0.916	0.918	0.920	0.922	0.924
15	0.926	0.928	0.930	0.932	0.934	0.936
16	0.938	0.940	0.942	0.944	0.946	0.948
17	0.950	0.952	0.954	0.956	0.958	0.960
18	0.962	0.964	0.966	0.968	0.970	0.972
19	0.974	0.976	0.978	0.980	0.982	0.984
20	0.986	0.988	0.990	0.992	0.994	0.996
21	0.998	1.000	1.002	1.004	1.006	1.008
22	1.010	1.012	1.014	1.016	1.018	1.020
23	1.022	1.024	1.026	1.028	1.030	1.032
24	1.034	1.036	1.038	1.040	1.042	1.044
25	1.046	1.048	1.050	1.052	1.054	1.056
26	1.058	1.060	1.062	1.064	1.066	1.068
27	1.070	1.072	1.074	1.076	1.078	1.080
28	1.082	1.084	1.086	1.088	1.090	1.092
29	1.094	1.096	1.098	1.100	1.102	1.104
30	1.106	1.108	1.110	1.112	1.114	1.116
31	1.118	1.120	1.122	1.124	1.126	1.128
32	1.130	1.132	1.134	1.136	1.138	1.140
33	1.142	1.144	1.146	1.148	1.150	1.152
34	1.154	1.156	1.158	1.160	1.162	1.164
35	1.166	1.168	1.170	1.172	1.174	1.176
36	1.178	1.180	1.182	1.184	1.186	1.188
37	1.190	1.192	1.194	1.196	1.198	1.200
38	1.202	1.204	1.206	1.208	1.210	1.212
39	1.214	1.216	1.218	1.220	1.222	1.224
40	1.226	1.228	1.230	1.232	1.234	1.236
41	1.238	1.240	1.242	1.244	1.246	1.248
42	1.250	1.252	1.254	1.256	1.258	1.260
43	1.262	1.264	1.266	1.268	1.270	1.272
44	1.274	1.276	1.278	1.280	1.282	1.284
45	1.286	1.288	1.290	1.292	1.294	1.296
46	1.298	1.300	1.302	1.304	1.306	1.308
47	1.310	1.312	1.314	1.316	1.318	1.320
48	1.322	1.324	1.326	1.328	1.330	1.332
49	1.334	1.336	1.338	1.340	1.342	1.344
50	1.346	1.348	1.350	1.352	1.354	1.356
51	1.358	1.360	1.362	1.364	1.366	1.368
52	1.370	1.372	1.374	1.376	1.378	1.380
53	1.382	1.384	1.386	1.388	1.390	1.392
54	1.394	1.396	1.398	1.400	1.402	1.404
55	1.406	1.408	1.410	1.412	1.414	1.416
56	1.418	1.420	1.422	1.424	1.426	1.428
57	1.430	1.432	1.434	1.436	1.438	1.440
58	1.442	1.444	1.446	1.448	1.450	1.452
59	1.454	1.456	1.458	1.460	1.462	1.464
60	1.466	1.468	1.470	1.472	1.474	1.476
61	1.478	1.480	1.482	1.484	1.486	1.488
62	1.490	1.492	1.494	1.496	1.498	1.500
63	1.502	1.504	1.506	1.508	1.510	1.512
64	1.514	1.516	1.518	1.520	1.522	1.524
65	1.526	1.528	1.530	1.532	1.534	1.536
66	1.538	1.540	1.542	1.544	1.546	1.548
67	1.550	1.552	1.554	1.556	1.558	1.560
68	1.562	1.564	1.566	1.568	1.570	1.572
69	1.574	1.576	1.578	1.580	1.582	1.584
70	1.586	1.588	1.590	1.592	1.594	1.596
71	1.598	1.600	1.602	1.604	1.606	1.608
72	1.610	1.612	1.614	1.616	1.618	1.620
73	1.622	1.624	1.626	1.628	1.630	1.632
74	1.634	1.636	1.638	1.640	1.642	1.644
75	1.646	1.648	1.650	1.652	1.654	1.656
76	1.658	1.660	1.662	1.664	1.666	1.668
77	1.670	1.672	1.674	1.676	1.678	1.680
78	1.682	1.684	1.686	1.688	1.690	1.692
79	1.694	1.696	1.698	1.700	1.702	1.704
80	1.706	1.708	1.710	1.712	1.714	1.716
81	1.718	1.720	1.722	1.724	1.726	1.728
82	1.730	1.732	1.734	1.736	1.738	1.740
83	1.742	1.744	1.746	1.748	1.750	1.752
84	1.754	1.756	1.758	1.760	1.762	1.764
85	1.766	1.768	1.770	1.772	1.774	1.776
86	1.778	1.780	1.782	1.784	1.786	1.788
87	1.790	1.792	1.794	1.796	1.798	1.800
88	1.802	1.804	1.806	1.808	1.810	1.812
89	1.814	1.816	1.818	1.820	1.822	1.824
90	1.826	1.828	1.830	1.832	1.834	1.836
91	1.838	1.840	1.842	1.844	1.846	1.848
92	1.850	1.852	1.854	1.856	1.858	1.860
93	1.862	1.864	1.866	1.868	1.870	1.872
94	1.874	1.876	1.878	1.880	1.882	1.884
95	1.886	1.888	1.890	1.892	1.894	1.896
96	1.898	1.900	1.902	1.904	1.906	1.908
97	1.910	1.912	1.914	1.916	1.918	1.920
98	1.922	1.924	1.926	1.928	1.930	1.932
99	1.934	1.936	1.938	1.940	1.942	1.944
100	1.946	1.948	1.950	1.952	1.954	1.956

Level 0
= raw data

Calibration,
binning

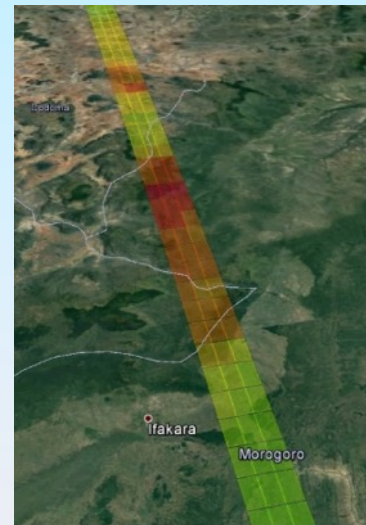


Level 1 = calibrated spectra
(+ images, geometry...)

CNES

CNES + labs

Radiative transfer
inversion

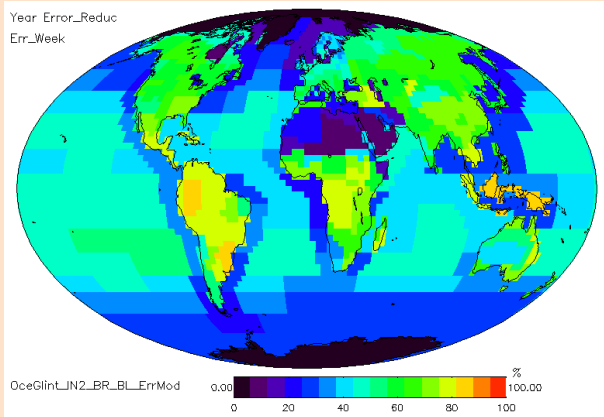


Level 2
= XCO₂ concentrations
(+ weighting function, secondary products)

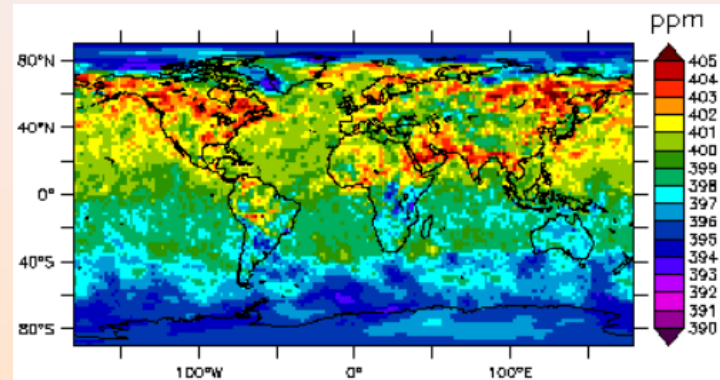
Atmospheric transport inversion

Level 3
= XCO₂ maps

Level 4 = surface CO₂ fluxes

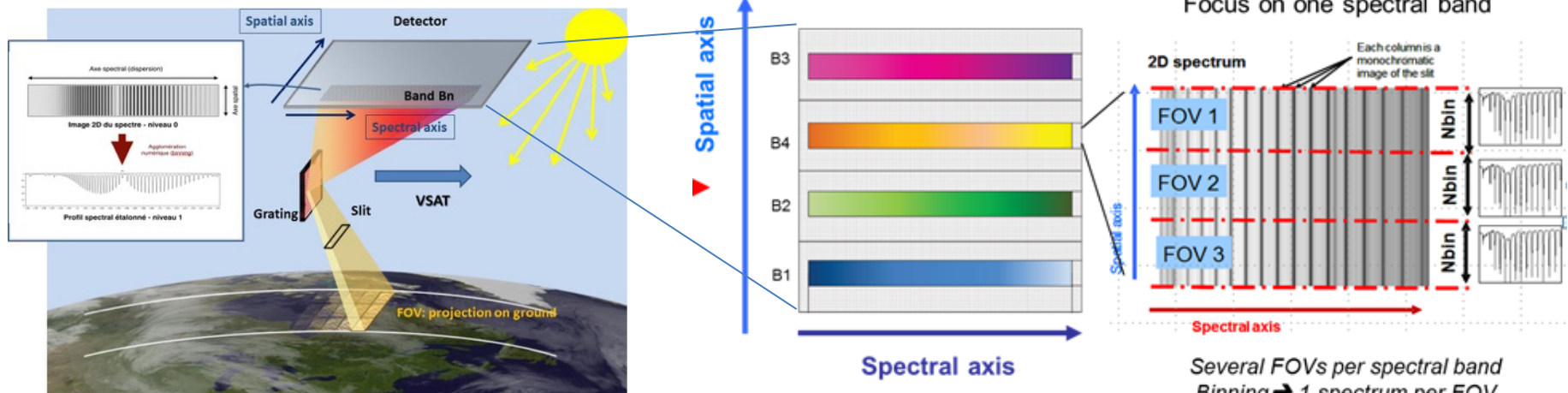


Labs

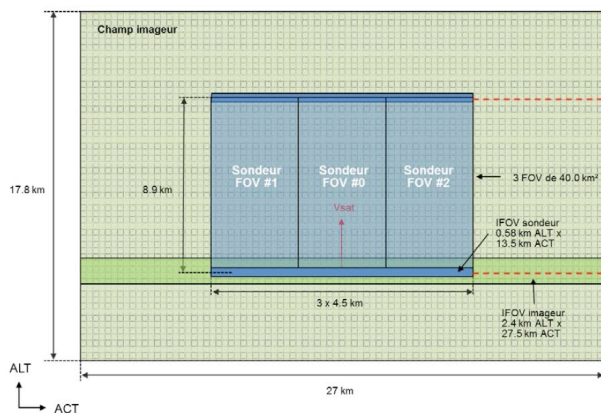


THE MICROCARB INSTRUMENT

- Instantaneous slit projection : 0.64 km x 13.5km, split in 3 IFOV ACT
- Temporal integration of 1.3s : 3 footprints (FOV) of 4.5 km * 9 km ~40 km²
- 4 spectral bands : 0.76 μm O₂, 1.61 μm CO₂, 2.03 CO₂ & new 1.27 μm O₂
- Only 1 telescope, 1 spectrometer, 1 grating, 1 detector



2D image of the each spectrum on detector
All bands on a unique NGP detector 1000pixels



- Embedded imager
 - ◆ Includes the spectrometer FOV
 - ◆ Resolution 110m x 140m
 - ◆ 1 spectral band 550 – 700 nm
 - ◆ Useful for cloud detection and geolocation

L1A SPECTROMETER PRODUCTS (1/2)

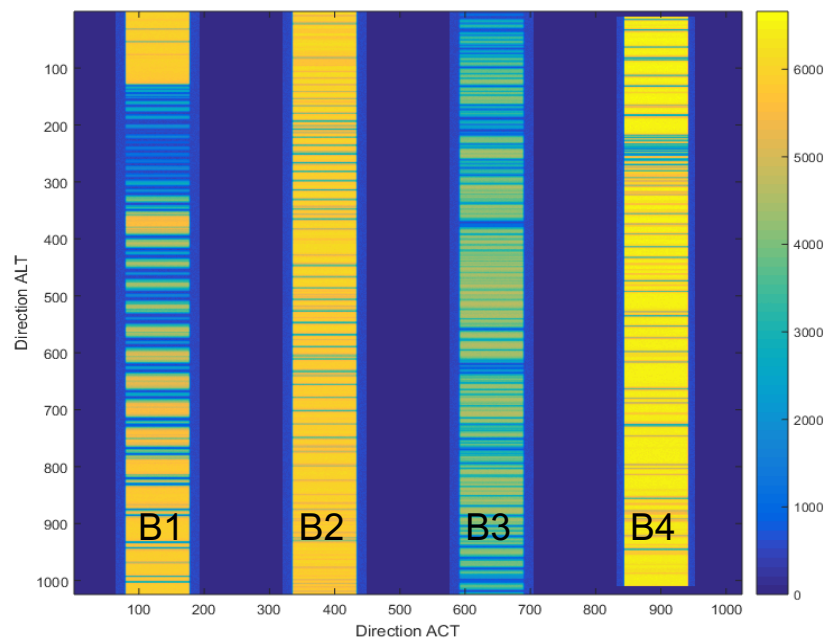
Calibrated data at detector level (pixels)

- All L0 matrix pixels are downloaded
- L1A neither delivered nor archived (too large)

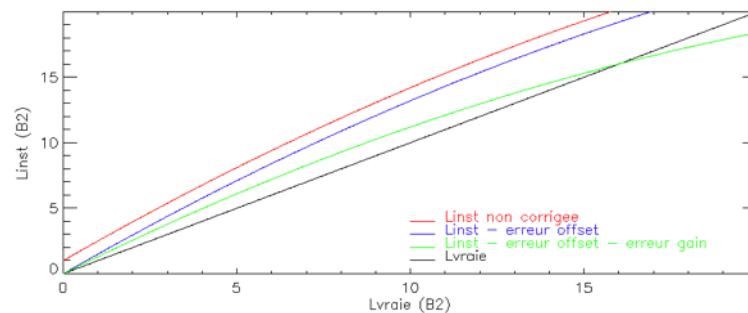
- Radiometric calibration:

$$L1A = A * g_{ij} * f_{NL}(L0 - dark)$$

- ◆ Dark removal
(daily measurements of the shutter)
- ◆ Non-linearity correction f_{NL}
(from ground characterization)
- ◆ Relative gains g_{ij} correction
(from monthly lamp measurements)
- ◆ Absolute gain A
(from monthly solar acquisitions)
- ◆ 2D correction for straylight
- ◆ 2D spike detection



Spectral bands at detector level



Radiometric curve for each pixel

L1A SPECTROMETER PRODUCTS (2/2)

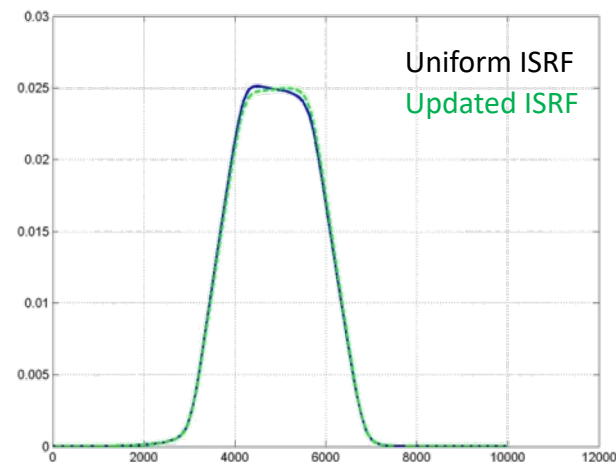
- Spectral calibration:

- ◆ Dispersion law

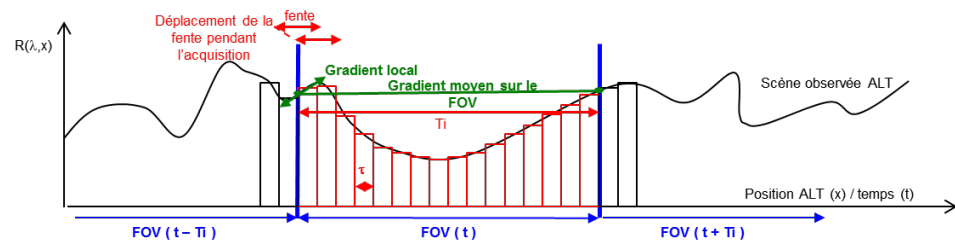
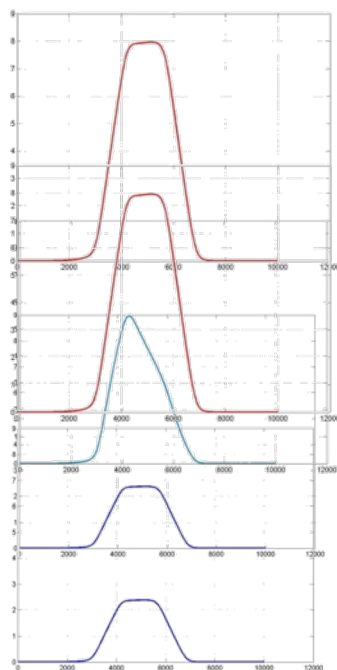
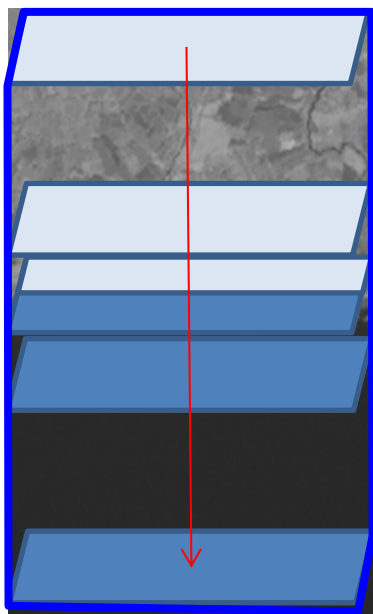
(from monthly solar acquisition and correction for Satellite Doppler)

- ◆ ISRF at pixel level

➔ Combination of ground characterization with the information on ALT non-uniformity from intermediate readings (14 readings of the detector during integration time for a few continuum channels)



Integrated difference between uniform and non-uniform ISRF: 2.2%

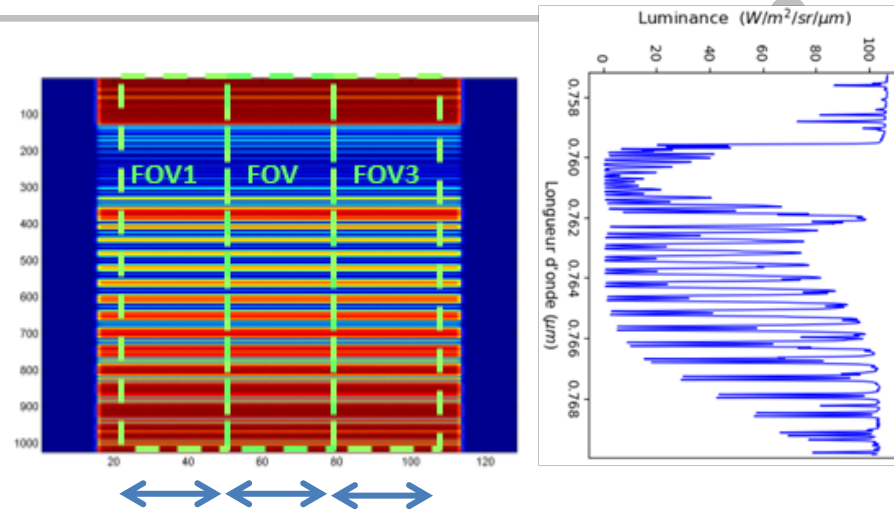


L1B SPECTROMETER PRODUCTS

Calibrated spectra at FOV (after binning)

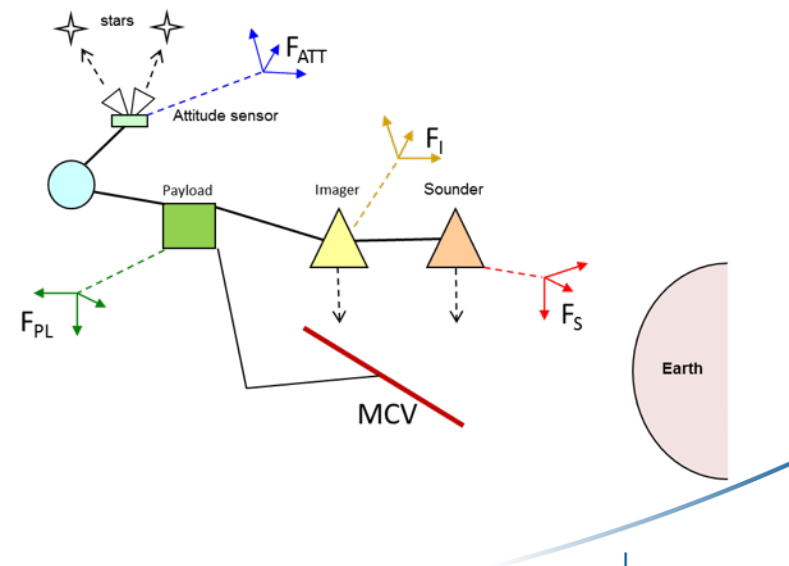
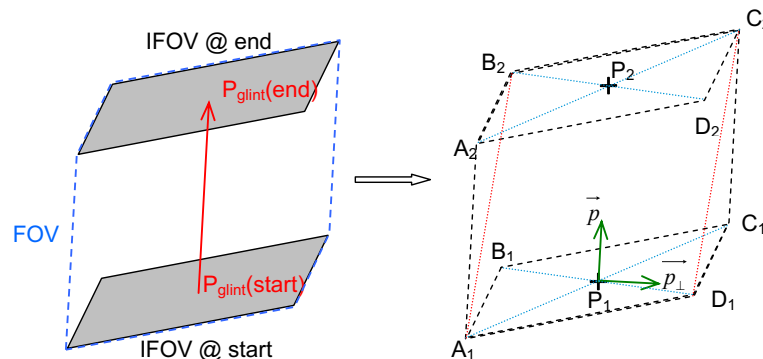
● Binning in 3 FOV

- ◆ Correction for potential smile and keystone
- ◆ Binning of pixels in 3 FOV (29 pixels / FOV)
- ◆ Binning of ISRFs in 3 FOV (29 ISRF / FOV)
- ➔ An updated ISRF is given for each channel of each FOV



● Geometric model of FOV

- ◆ Coordinates of each vertex of each IFOV + center
- ◆ FOV spatial spread function
- ◆ Uses orbitography and attitude



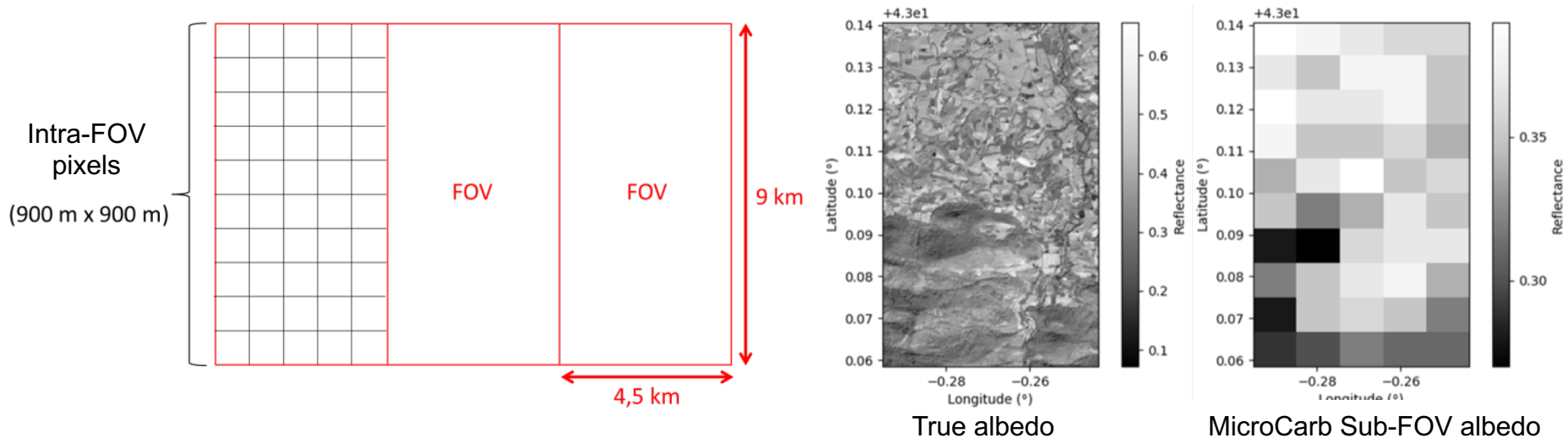
L1C SPECTROMETER PRODUCTS

Calibrated spectra for each FOV including corrections from geophysical data

- L1C processing (experimental) to reach the best L1 performance so as to reduce L2 regional biases
 - ◆ Geolocation refinement by correlation of the imager with Sentinel 2
 - ➔ Increase the quality of surface pressure and albedo priors
 - ◆ Creation of a 4AOP polarized theoretical spectrum
 - » Same priors as L2
 - ◆ Correction of dispersion law by correlation with the theoretical spectrum
 - ➔ Corrects any instrumental spectral defect, rather than in the L2 processor
 - ◆ Correction of residual instrumental polarization with the theoretical spectrum and the Mueller matrix of the instrument projected in the same frame
 - » MicroCarb has a low polarization rate (Glint: 0.2%, Nadir : <1%) thanks to a scrambler
 - » This rate is still high enough to induce regional biases
 - » Most part of the natural polarization is known : Rayleigh, glint ➔ easy to correct
 - ➔ This methodology reduces the L2 ground segment sizing by avoiding polarized computations with iterations

L1C SPECTROMETER PRODUCTS

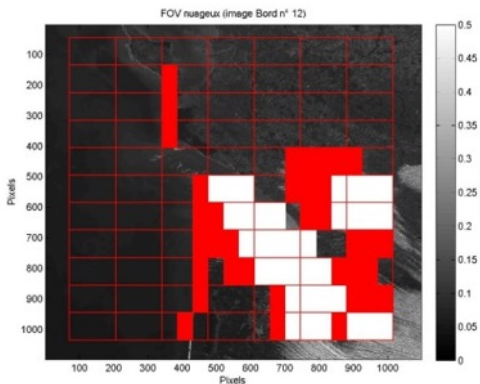
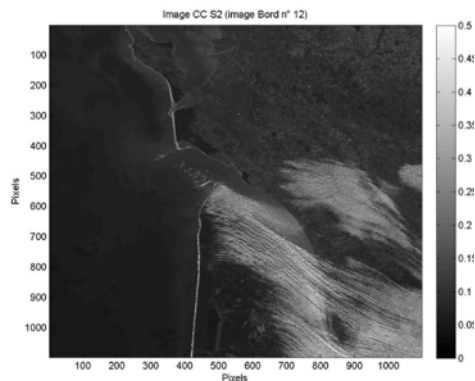
- Computation of Intra-FOV Pixels (PIF)
 - ◆ Using the intermediate readings and the 29 ACT pixels / FOV in ~200 channels (continuum + lines), we can build sub-FOV maps of some geophysical parameters
 - ◆ Albedo in 4 bands (+ imager)
 - ◆ Ice, vegetation (NDVI)
 - ◆ Thick clouds (see next slides)



L1C EMBEDDED CLOUD DETECTION

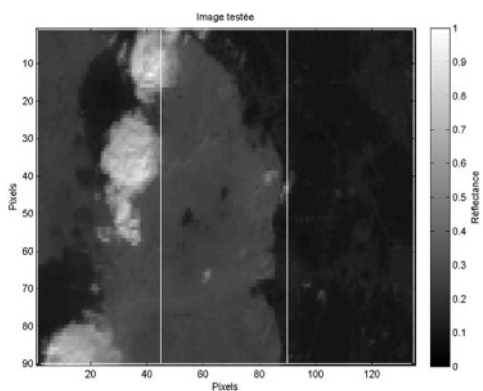
- ◆ 1st filter for thick cloud detection : very rough
 - » Threshold on the radiometry of the imager (mean reflectance of MODIS + margin)

MicroCarb image to analyze

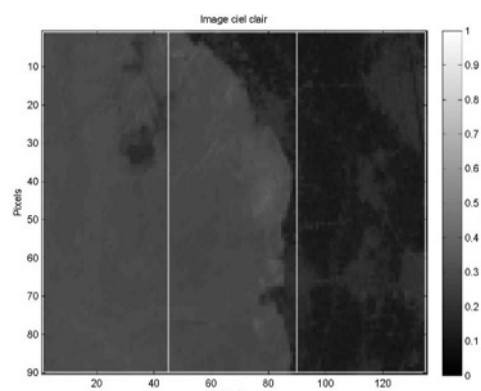


Thresholding

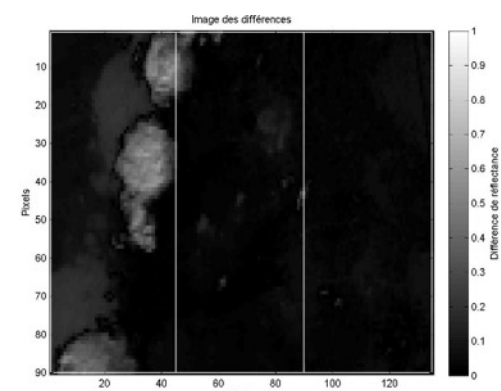
- ◆ 2nd filter for thick cloud detection
 - » Pixel to pixel comparison of the imager with a clear sky S2 image climatology



MicroCarb Image to analyze



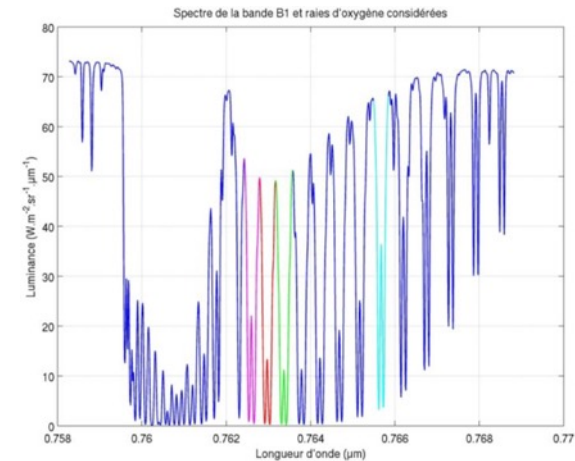
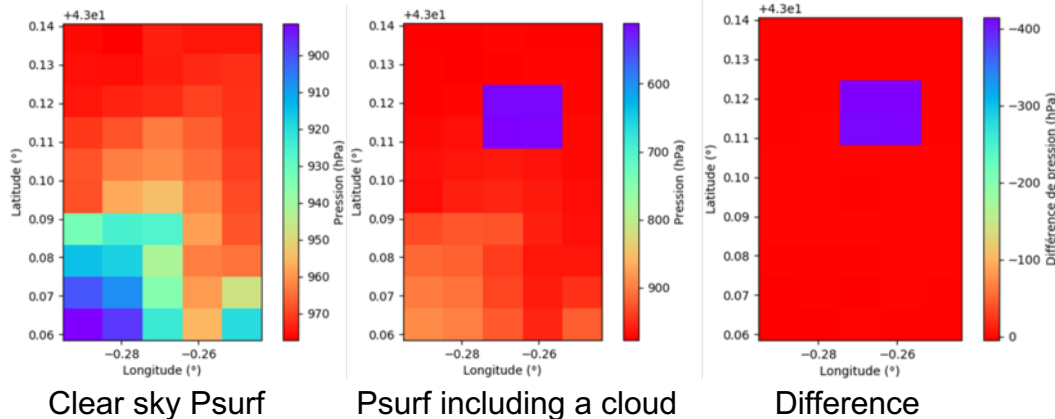
S2 clear sky image



Difference

L1C CLOUD DETECTION : FINAL INDEX

- ◆ Comparison of prior and estimated surface pressure at FOV level (high SNR)
- ◆ Cloud intra-FOV maps. For each PIF:
 - » Estimation of surface pressure from a few O₂ lines @ 0.76 μ m (with Rayleigh but no aerosols)
 - » Computation of prior surface pressure from ECMWF + Digital Elevation Model)
 - » Difference between both enlightes clouds (even with the PIF low SNR)



O₂ absorption lines of multi-reading used for Psurf retrieval

- ◆ Same work may be done with H₂O lines @ 2.04 μ m (under evaluation)
 - » More sensitive close to the surface
- ◆ Albedo intra-FOV maps
 - » Difference between MicroCarb and S2 albedo enlightes clouds

➔ All this information is combined to provide a cloud contamination index

L2 PRE-FILTER

- The beginning of mission will focus on the easiest scenes, and progressively increase the situations
- The filter have to be refined
- Pre-filtering :
 - ◆ Remove SZA > 75°
 - ◆ Remove lower SNRs / seas
 - ◆ Remove highly heterogeneous scenes
 - ◆ Remove thick cloud contaminated scenes
 - ◆ Remove aerosol loaded scenes (AOD>0.3) from CAMS index

L1 -> L2 INVERSION TOOL : 4ARTIC

- Inversion of the radiance spectra to retrieve the geophysical state

$$\begin{array}{c}
 \text{Measured} \\
 \text{spectrum (L1)} \rightarrow y = f(x) + \varepsilon \approx Kx + \varepsilon \text{ with } K = \frac{\partial y}{\partial x} \\
 \leftarrow \text{Geophysical state vector (L2)} \quad \leftarrow \text{Jacobian matrix}
 \end{array}$$

- Based on Rodgers 2000: optimal estimation with gaussian probability functions

$$\begin{array}{c}
 \blacklozenge \text{ Iterations for non-linearity : } x_{i+1} = x_a + \left(S_a^{-1} + K_i^T S_\varepsilon^{-1} K_i \right)^{-1} K_i^T S_\varepsilon^{-1} \left[(y - F(x_i)) + K_i (x_i - x_a) \right] \\
 \leftarrow \text{State vector a priori} \quad \leftarrow \text{Noise covariance} \quad \leftarrow \text{Prior state vector} \\
 \text{covariance matrix} \quad \text{matrix}
 \end{array}$$

- ◆ Gauss-Newton or Levenberg-Marquardt
- ◆ Stop criteria based on slight evolution of chi2 & slight evolution of state vector

- Radiative transfer (K & spectra) computed with 4AOP

- ◆ Pre-computed LUT of cross-sections, spectroscopy from GEISA
- ◆ Diffusion from LIDORT, accelerated with Low-Stream Interpolation (O'Dell 2011)
- ◆ Our RT speed has still to improve (not at the state of the art)
- ➔ Diffusion with SOS under progress

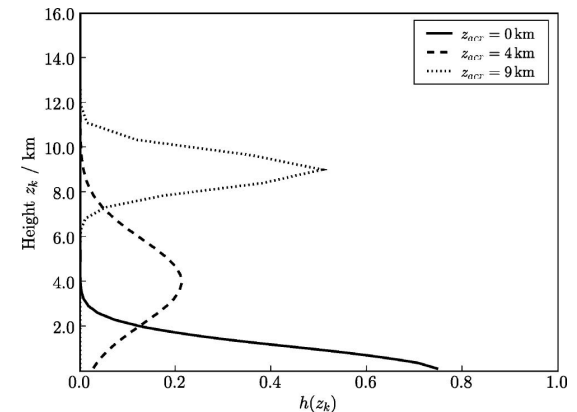
4ARTIC MAIN HYPOTHESIS

● State vector:

- ◆ 19 layers of CO₂ and H₂O + P_{surf} + albedo (& slope) per band, fluorescence, airglow, aerosols
→ These will be delivered as primary or secondary products
- ◆ May include the retrieval of instrumental unknowns (radiometric offset, spectral shift)

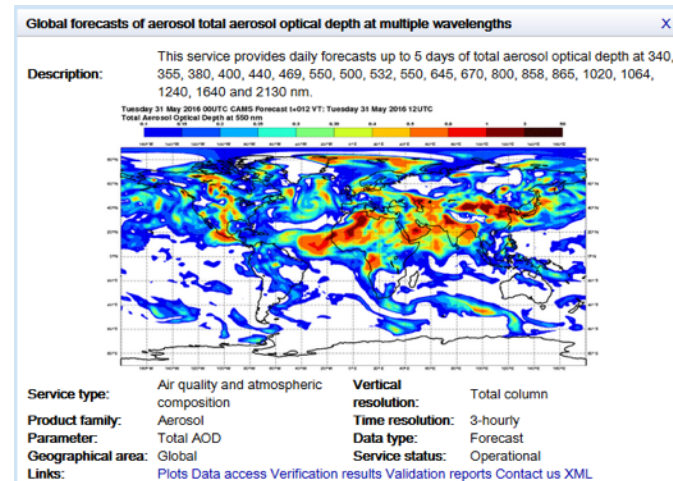
● Aerosol / thin clouds retrieval baseline:

- ◆ 3 parameters retrieved in the state vector [AOD(σ_0), k , z_{aero}]
- ◆ Angström coefficient : $AOD(\sigma) = AOD(\sigma_0)(\sigma/\sigma_0)^k$
- ◆ Gaussian vertical distribution with mean altitude z_{aero} , decreasing width with z_{aero} (Butz et al. 2009)
→ Retrieval eased by the 1.27 μm O₂ band
- ◆ Single Scattering Albedo = 1
- ◆ Henyey-Greenstein phase function with $g=0.8$



● Priors:

- » P_{surf}, H₂O and T profiles from ECMWF
- » Aerosol AOT at different wavelengths, vertical profiles and aerosol main type from CAMS
- » Altimetry from Planet Observer
- » CO₂ from CAMS
- » Albedo from Sentinel 2 L2 synthesis
- » Airglow from LATMOS climatology



INVERSION OF OCO-2 L1B WITH 4ARTIC

4ARTIC is currently tested with the OCO-2 L1B B9

- Most favorable conditions:
 - ◆ Work with TARGET data over TCCON
 - ◆ Clear sky, same prior and a priori covariances as OCO-2, no aerosol retrieval
- Statistics on 2400 spectra (courtesy of Leslie David, LSCE) :

	XCO₂ (ppm)	P_{surf} (hPa)	XH₂O (ppm)
4ARTIC - TCCON	-0.67 +/- 2.03 (0.51%)	1.42 +/- 4.43 (0.45%)	-33.03 +/- 153.27 (6.19%)
ACOS (raw) - TCCON	-2.23 +/- 1.80 (0.45%)	-0.43 +/- 3.23 (0.33%)	112.74 +/- 182.37 (7.37%)

- ◆ Overall biases are low
- ◆ Overall standard deviation of the same order of magnitude as ACOS
- Continued work:
 - ◆ Understanding of residuals
 - ◆ Aerosol loaded scenes
 - ◆ Glint observations
 - ◆ Own priors, application of some L1 processings

CONCLUSIONS

- MicroCarb main innovations :
 - ◆ ISRF knowledge in heterogeneous scenes
 - ◆ L1C with refined geolocation, spectral law and polarization impact
 - ◆ Intra-FOV information (a few channels) gives access to albedo, ice, NDVI, clouds
 - ◆ Cloud detection: based on imager and intra-FOV pixels
 - ◆ 1.27 μm band : better assessment of the aerosols (Angström coefficient), less sensitive to spectroscopy errors, same vertical sensitivity to aerosols as wCO₂ + sCO₂
- A complete chain of processing for L1 & L2 (& L3) is now specified
 - ◆ Most critical parts are prototyped
 - ◆ Testing under going for 4ARTIC, to come for other parts
 - ◆ Ground segment development starts next september
- Format of products : as similar as possible to OCO-2
 - ➔ To ease the use of the MicroCarb data by the community
- A SIF product will also be computed by a pre-processor provided by UoL (Hartmut Boesch & Dongxu Yang)