1 - Concept

Constellation of nanosat with 2 instruments:

- **NanoCarb**, a miniaturized Fabry-Perot interferometer sensitive to CO₂ and interfering geophysical variables (truncated interferograms)
- **SPEX**, a multi-angle polarimeter for aerosol retrieval to improve prior constraint of scattering particles

2 - Method

Without / With SPEX improved prior constraint of scattering particle parameters

INVERSE RADIATIVE TRANSFER (based on Bayesian Optimal Estimation)

- XCO₂ systematic error
- XCO₂ random error
- XCO₂ vertical sensitivities

NanoCarb truncated interferograms (simulated for 540 error-critical situations)

3 - Results

- XCO₂ systematic and random errors for 540 atmospheric and observational situations
- Comparison of results Without / With SPEX
  - XCO₂ systematic bias [ppm]

  ![Map showing XCO₂ systematic bias with and without SPEX](image)

- Comparison of NanoCarb and CO₂M random errors
Level 2 performance assessment of NanoCarb miniaturized GHG sensor proposed in the Space CARbon Observatory (SCARBO) project

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• Conclusions
The SCARBO project

Constellation of nano-satellites that carry 2 instruments:

- **NanoCarb**, a miniaturized Fabry-Perot interferometer developed by UGA/IPAG, ONERA
- **SPEX**, a multi-angle polarimeter for aerosol retrieval developed by SRON

Objective of SCARBO = Proof of the NanoCarb concept

- Prototype version of NanoCarb
- Airborne campaign to demonstrate the prototype ability to detect strong CO₂ sources
- **L2 performance assessment of SCARBO** (NanoCarb+SPEX) space design following [Buchwitz et al, 2013] approach for CarbonSat (this work)

http://scarbo-h2020.eu/
The NanoCarb instrument combines 4 arrays of static Fabry-Perot interferometers that sample the interferogram at Optical Path Differences (OPDs) that are the most sensitive to geophysical variables (see above). A 128x128 pixel snapshot of the overpassed scene is captured for all OPDs by an imager.

[Gousset et al, 2019]: NanoCarb part 2: Performance assessment for total column CO₂ monitoring from a nano-satellite
SCARBO L2 performance assessment: general approach

**STEP 1**  
**FORWARD MODELLING**  
Level 1: Truncated interferograms

**STEP 2**  
**INVERSE MODELLING**  
(WITHOUT / WITH SPEX)  
Level 2:  
$XCO_2$  
Systematic & random errors  
Averaging kernels

**STEP 3**  
**L2 ERROR PARAMETERIZATION**

**STEP 0**  
540  
ATM & OBS SITUATIONS  
ALB • SZA • CTH • COD • AOD

ATMOSPHERIC INVERSION

Level 4:  
Continental / Local $CO_2$ fluxes

Please see Friedemann Reum,  
Session 6, 5th June, 14:45 (UTC)
We define a set of 540 situations with the scattering error critical atmospheric and observational parameters included in the following table. We perform SCARBO L2 performance assessment for these 540 situations.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Notation</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albedo</td>
<td>ALB</td>
<td>Soil, Vegetation, Desert (ASTER spectral library)</td>
</tr>
<tr>
<td>Solar Zenith Angle</td>
<td>SZA</td>
<td>0°, 25°, 50°, 70°</td>
</tr>
<tr>
<td>Cirrus Top Height</td>
<td>CTH</td>
<td>8, 10, 12 km</td>
</tr>
<tr>
<td>Cirrus Optical Depth</td>
<td>COD</td>
<td>0, 0.05, 0.15, 0.30, 0.40</td>
</tr>
<tr>
<td>Aerosol Optical Depth</td>
<td>AOD</td>
<td>0.08, 0.12, 0.22</td>
</tr>
</tbody>
</table>

Aerosol + cirrus profile

(Height of 8, 10 or 12 km)
**STEP 1: Forward modelling**

Radiance spectra are computed for each situation and viewing angle with 4A/OP radiative transfer code, using GEISA spectroscopic database, and coupled to LIDORT model for scattering.

**Radiance Spectra [W/m² strd cm⁻¹]**

- **O₂ A-Band (0.7 µm)**
- **CO₂ weak (1.6 µm)**
- **CH₄ (1.65 µm)**
- **CO₂ strong (2.0 µm)**

**NanoCarb instrument model v2 (UGA/ONERA)**
- 4 Bands: O₂-A band, CO₂ weak, CH₄, CO₂ strong
- Fabry-Perot interferometer -> Intensities @ 64 different OPD/band
- Same scene observed under 128 different angles

**Intensity of NanoCarb truncated interferogram [e-/frame/pixel]**

Full Spectral Bands
STEP 2: Inverse modelling

We retrieve XCO$_2$ from NanoCarb simulated truncated interferograms used as input to an inverse scheme based on Bayesian Optimal Estimation [Rodgers, 2000] and relying on 4A/OP radiative transfer model + GEISA spectroscopic database.

NanoCarb simulated truncated interferogram (simulated observations)

(INVERSE RADIATIVE TRANSFER (based on Bayesian Optimal Estimation))

RETRIEVAL SETUP DESIGN

XCO$_2$ systematic error

XCO$_2$ random error

XCO$_2$ vertical sensitivities

a priori values and uncertainties

(Without / With SPEX linear error analysis results)
STEP 2: Imager retrieval strategy

As NanoCarb is an imager, a unique scene on the ground is observed under 128 viewing angles along the track of NanoCarb.

In this work, L2 performance assessment is performed along the symmetry axis of NanoCarb imager.

For all the 540 atmospheric and observational situations (slide 6), fixed on the ground, we assume that the 128 observations realized during NanoCarb overpass are available.

We perform one retrieval per observation and average the results to yield a unique retrieval result per situation.
### STEP 2: Retrieval set up: **Without SPEX**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value range</th>
<th>A priori value</th>
<th>A priori uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cirrus Optical Depth (COD)</td>
<td>0.001 – 0.40</td>
<td>0.05</td>
<td>SPEX a priori = 0.5 *</td>
</tr>
<tr>
<td>(retrieved)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerosol Optical Depth (AOD)</td>
<td>0.08 – 0.22</td>
<td>0.12</td>
<td>SPEX a priori = 0.5 *</td>
</tr>
<tr>
<td>(retrieved)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloud Top Height (CTH)</td>
<td>8 – 12 km (not retrieved)</td>
<td>10 km (not retrieved)</td>
<td>-</td>
</tr>
</tbody>
</table>

* SPEX data provided by SRON
We retrieve XCO₂ from NanoCarb truncated interferograms simulated for all the 540 atmospheric and observational situations defined at STEP 0 (slide 6). To identify all these situations in retrieval result plots, we display all the parameters values along 1 dimension, in the 5 stacked panels presented above, sorted in ALB, SZA, CTH, COD and AOD increasing order.
SCARBO L2 performance assessment: **Without SPEX**

**XCO₂ systematic error [ppm]**

- **ALB**
- **SZA**
- **CTH**
- **COD**
- **AOD**

**XCO₂ random error [ppm]**

**Reminder:**
128 NanoCarb observations considered for every situation (see slide 9)

Grey areas denote situations filtered out with the **Without SPEX** filtering criteria:
AOD+COD<0.3

IWGGMS-16 – 2nd June 2020
### STEP 2: Retrieval set up: Without SPEX + With SPEX

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value range</th>
<th>Without SPEX</th>
<th>With SPEX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A priori value</td>
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<td>-</td>
</tr>
<tr>
<td>(not retrieved)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*SPEX data provided by SRON*
SCARBO L2 performance assessment: **Without SPEX + With SPEX**

Grey areas denote situations filtered out with the **Without SPEX** filtering criteria: AOD+COD<0.3

No filtering in the **With SPEX** scenario

Reminder: 128 NanoCarb observations considered for every situation (see slide 9)
In this figure, we assess the impact on XCO₂ random error of the number of available NanoCarb (NC) observations for one satellite overpass of a fixed atmospheric and observational situation on the ground (see slide 9). XCO₂ being a Gaussian random variable, its random error basically decreases with the square root of the number of available observations during averaging.
As the SCARBO project aims to complement the ESA Copernicus CO$_2$M mission by increasing revisit over carbon emission hotspots, their respective products should have similar precisions. We compare CO$_2$M XCO$_2$ random error (thick line) for one nadir observation against NanoCarb (NC) XCO$_2$ random error for various numbers of available NC observations for one situation. SNR values for CO$_2$M are taken from ESA Copernicus CO$_2$ Monitoring Mission Requirements Document (27/09/2019). About 30 available NanoCarb observations for a unique situation are required to yield an averaged XCO$_2$ with a random error comparable to CO$_2$M.
STEP 3: parameterization of L2 performance results

We fit the previously presented XCO₂ errors with a **linear regression** as a function of ALB, SZA, CTH, COD and AOD. Hence, with a synthetic constellation of SCARBO satellites to produce SZA maps, CAMS products to yield realistic values of ALB, CTH, COD and AOD and using the linear parameterizations of L2 performance, we can compute large XCO₂ error maps at low computational cost.

Above are the 8 maps (average values for June 2015) used as input to the linear regression enabling to compute parameterized XCO₂ errors. SZA comes from a simulated SCARBO constellation of 14 nano-satellites, and ALB from ADAM/ECLIPS/MODIS, CTH from ERA5, COD from ERAS5 and AOD from CAMS.
STEP 3: parameterization of L2 performance results

In addition to a MODIS cloud mask, as detailed in STEP 2 (slides 12,14), **AOD+COD filters** must be applied in order to remain in the definition range of the L2 error parameterisations [Buchwitz et al, 2013]:

**Without SPEX scenario:**

- AOD+COD<0.3

**With SPEX scenario:**

- AOD<0.6 and COD<0.6

Number of observations taken into account for June 2015 in the **Without SPEX** and **With SPEX** scenarios.
NanoCarb L2 performance assessment: parameterization example

**Averaged parameterized XCO$_2$ errors for June 2015**

- **XCO$_2$ systematic bias [ppm]**
  - Without SPEX
  - With SPEX

- **XCO$_2$ random error [ppm]**
  - Without SPEX
  - With SPEX

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IWGGMS-16 – 2nd June 2020
Conclusions and further steps

• We performed an **L2 performance assessment of systematic and random XCO₂ errors for the SCARBO (NanoCarb+SPEX) concept**. These results are **parameterized** as a function of Albedo, Solar Zenith Angle, Cloud Top Height, Cirrus Optical Depth and Aerosol Optical Depth, enabling to **efficiently compute large synthetic SCARBO error maps** from CAMS products that can be used for flux inversions.

  Flux estimates and atmospheric inventories from space-based measurements (Session 6)
  Performance of upcoming CO₂ monitoring satellites in the new high-resolution inverse model CTDAS-WRF
  Friedemann Reum, Friday 5th June, 14:45 (UTC)

• Using improved aerosol prior values and constraints provided by the SPEX aerosol instrument has the potential to greatly reduce systematic errors. Random errors remain similar.

• About 30 NanoCarb measurements of an atmospheric situation registered during a unique overpass are necessary to equal an XCO₂ retrieved random error comparable to one CO₂M nadir sounding.

**Further steps:**

• Extend L2 performance assessment to all NanoCarb imager pixels
• Improved assumptions for the Without SPEX / With SPEX scenarios
• Comparative study of sensitivity to interfering geophysical parameters for NanoCarb and usual CO₂M, OCO-2, MicroCarb concepts
This project has received funding from the European Union’s H2020 research and innovation programme under grant agreement No 769032.