Radiometric and spectral sizing of future CO$_2$ observing space missions

B. Sierk$^1$, J. Landgraf$^3$, J. aan de Brugh$^3$, J. Caron$^2$, A. Löscher$^1$, Y. Meijer$^2$, A. Butz$^4$, J.-L. Bézy$^1$, R. Meynart$^1$

$^1$ European Space Agency (ESA)  
$^2$ RHEA for ESA  
$^3$ Space Research Organisation of the Netherlands (SRON)  
$^4$ Karlsruhe Institute of Technology (KIT), Germany
The CarbonSat mission

- Candidate mission for ESA’s Earth Explorer program (EE8)
- Phase A/B1 (feasibility and design) with two industrial consortia
- Mission goals
  - biogenic sources and sinks
  - anthropogenic sources (cities and power plants)
- High spatial sampling, wide swath imaging of XCO$_2$ and XCH$_4$
  - 6 km$^2$ (3km ACT x 2 km ALT) spatial samples, 240 km swath width
  - High single sounding precision and accuracy (3 ppm rms / 0.5 ppm bias)
From CarbonSat to Copernicus mission

- The FLEX mission was selected as Earth Explorer 8
- CarbonSat instrument pre-development studies still on-going
- Serves as starting point for future European carbon monitoring system
  - Anthropogenic CO$_2$ emission as primary goal
  - High spatial resolution imaging of point sources (cities, power plants)
  - Global coverage at high temporal sampling
  - High single sounding precision and accuracy (1 ppm rms / 0.5 ppm bias)
Spectral sizing of past and future missions

SNR and spectral resolution trade-off revisited

- CarbonSat was designed for low resolution / high SNR
- OCO-2 and MicroCarb (will) implement high resolution / low SNR

<table>
<thead>
<tr>
<th></th>
<th>CarbonSat</th>
<th>OCO-2</th>
<th>MicroCarb (ICSO 2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>width [nm]</td>
<td>SW1: 1590-1675</td>
<td>SW1: 1594-1619</td>
<td>SW1: 1582-1627</td>
</tr>
<tr>
<td></td>
<td>SW2: 1925-2095</td>
<td>SW2: 2045-2081</td>
<td>SW2: 2004-2061</td>
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High vs Low Resolution

Example: CarbonSat’s SWIR-2 band (2.06 µm)

- Dark vegetation scenario (Albedo 0.05, SZA = 50°)
- $XCO_2$: 396 ppm
High vs Low Resolution

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Example: CarbonSat’s SWIR-2 band (2.06 µm)

- Dark vegetation scenario (Albedo 0.05, SZA = 50°)
- $XCO_2$: 396 ppm + 400 ppm (concentration gradient in power plant plume)
High vs Low Resolution

Example: CarbonSat’s SWIR-2 band (2.06 µm)

- Dark vegetation scenario (Albedo 0.05, SZA = 50°)
- Delta XCO₂ (396 ppm - 400 ppm), low res. and high res.
Example: CarbonSat’s SWIR-2 band (2.06 µm)

- Dark vegetation scenario (Albedo 0.05, SZA = 50°)
- Delta XCO₂ (396 ppm - 400 ppm), low res. and high res. with noise
Impact of systematic errors

- Straylight is a major driver for instrument performance
- Found to be critical for CarbonSat
  - Imaging mode with large radiometric contrast
  - Interpreted as contributor to bias
  - Drives cleanliness, smoothness of optical components

Does the criticality depend on the spectral sizing?
Optimizing spectral sizing

• ESA initiated a scientific support study
• Objective: Investigate the relative impact of various error sources for different spectral sizing points
  • Straylight
  • ISRF distortion
  • Polarisation sensitivity
  • Non-linearity
  • Diffuser features

Approach

1. Simulation of L1b measurements
   • using results of CarbonSat instrument studies (SL kernels, Mueller matrices, non-linearity and speckle measurements)
   • simulating a large ensemble of geophysical scenarios
   • 3-4 spectral sizing configurations (high-low resolution/SNR)

2. Perform Level-2 retrievals for various spectral sizing configurations

3. Compare performance in terms of accuracy and precision
1.) Simulation of a measurement over a contrast scene

- Half of the entrance slit is illuminated with bright scene (Albedo 0.4)
- The other half with dark clear-sky vegetation scene (Albedo 0.05)
- The error-free signal on the focal plane is computed
2.) Simulation of straylight

- The BSDF is derived from straylight simulations for CarbonSat studies
- A simplified straylight kernel is derived from the BSDF
- The straylight-affected signal is computed by 2-dimensional convolution with the kernel
Straylight Simulation Results: Level-0

Relative straylight error across the focal plane (% of local radiance):

Relative straylight error for L1b spectra 5 SSD from the transition:
3.) Generation of L1b data

- The Level-1b radiance spectra are computed by binning across the swath.
- 10 spatial pixels form one ACT spatial sample of 3 km width.
- 80 ACT spatial samples (Field-of-Views).
- Correspond to 240 km swath width.
- Large radiometric errors near the transition dark/bright in the swath center.
4.) Level-2 retrieval for all Level-1b spectra

- RemoTeC algorithm at SRON
- 80 Field-of-Views across the swath (ACT spatial samples)
- Four spectral sizing configurations (instruments)
  - 1 CarbonSat LR and 2 HR configurations
  - OCO-2
- Retrieval of $\text{XCO}_2$ and $\text{XCH}_4$ with and without regularization
Conclusions

- ESA has initiated a study for verification of spectral sizing configurations
  - In preparation for a future carbon monitoring system
  - High spatial sampling, wide swath imaging of emission point sources
- Trade-off revisited in view of systematic instrumental errors
  - wide vs. narrow spectral bandwidth
  - low vs. high spectral resolution
  - high vs. low SNR
- First tests of straylight impact
  - Simulation of L1b data for simple contrast scene
  - Level-2 retrieval (without correction for straylight)
  - Evaluation of bias performance
- Preliminary indication:
  - Low-resolution / high SNR CarbonSat configuration not more sensitive to straylight than high-resolution instruments
Outlook

• **Extensive study will be kicked off in June/July**
  - Space Research Organisation of the Netherlands (SRON)
  - Karlsruhe Institute of Technology (KIT), Germany
  - Institute of Environmental Physics (IUP), Bremen, Germany
  - University of Leicester, UK

• **Simulation of various instrumental error sources**
  - Straylight
  - Polarisation
  - Diffuser speckles
  - Detector non-linearity

• **Large number of geophysical scenarios**
  - Global clear-sky database (~ 10000)
  - Realistic aerosol/cloud scenes (Tropomi orbits, A-train data)

• **Wide range of spectral sizing points for limited subset**

• **Conclusions to be expected by end 2016**

• **Will determine operation point of a future European carbon mission**

• **Suggestions welcome !**