Towards spaceborne monitoring of localized CO$_2$ emissions: an instrument concept and first performance assessment

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EGU 2020 – Session AS3.15 – Display D3213
Why monitor localized CO2 emissions? How would the proposed instrument concept contribute?

- UN Framework Convention on Climate Change requires every country to report their CO$_2$ emissions
- The Paris climate agreement requires independent verification of the reported emissions
- Power plants are the main source and represent approx. one third of all anthropogenic CO$_2$ emissions
- We propose the concept of an imaging spectrometer optimized for sub-plume resolution ($50 \times 50$ m$^2$) to also resolve emissions from medium-size power plants (1-10 MtCO$_2$ yr$^{-1}$), currently not targeted by other satellite missions
- Such an instrument would be a valuable companion and complement to the fleet of current and planned satellite missions measuring atmospheric CO$_2$ column concentrations
Instrument concept goal: > 1 MtCO$_2$ yr$^{-1}$ (could cover 88% of the power plant CO$_2$ emissions)
- 64% of the emissions from medium-size power plants (1-10 MtCO$_2$ yr$^{-1}$)

Data for 2009 from the CARMA v3.0 dataset

Ummel, 2012; Strandgren et al., 2020, in press
Fine ground resolution key to measure localized CO$_2$ emissions

- Power plant emissions cause large column concentration enhancements in the vicinity of the source.
- But, these enhancements become small when averaging with the background in km-scale ground pixels.
- Point source detection and quantification of medium-size power plant emissions need fine ground resolution.

Wilzewski et al., 2020
**Fine ground resolution key to measure localized CO₂ emissions**

The fine ground resolution does, however, infer challenges for the monitoring of localized CO₂ emissions in terms of:

- Collecting enough photons and reaching a signal-to-noise ratio (SNR) sufficient to resolve the emission plumes
- Constructing a *compact instrument design* required for global monitoring through a constellation of satellite instruments

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Proof of concept and spectral sizing using spectrally degraded GOSAT measurements
**Spectral sizing of proposed instrument concept**

- For a compact instrument design, a single spectral window shall be used.
  - Two alternative spectral windows, SWIR-1 and SWIR-2, are investigated.

- Measured GOSAT spectra (grey thin lines) are convolved to mimic spectra of proposed instrument concept (blue and red bold lines).

- $XCO_2$ is retrieved using the RemoTeC algorithm and the convolved spectra.

- Black thin lines show the spectra used for native GOSAT $XCO_2$ retrievals with RemoTeC.

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**DLR.de • Chart 7**

Wilzewski et al., 2020
Spectral sizing of proposed instrument concept

- Increasing level of spectral degradation is performed in order to determine the appropriate spectral resolution for the proposed instrument.
- XCO₂ retrieved from spectrally degraded GOSAT spectra is compared to reference data from TCCON¹.
- Modifications of the light path due to scattering aerosol are accounted for in retrievals from SWIR-2 spectra. (Light red line shows results for SWIR-2 retrievals when scattering is neglected).
- Due to low sensitivity to aerosol, retrievals from SWIR-1 spectra neglect scattering.
- Black crosses mark the spectral resolution chosen for further analysis.

¹Total Carbon Column Observing Network
Validation with TCCON measurements

- Precision of XCO₂ retrieved from spectrally degraded GOSAT spectra below 1% for both SWIR-1 (3.00 ppm) and SWIR-2 (3.25 ppm) with respect to reference TCCON measurements

- Precision decreases only moderately compared to native GOSAT retrievals (2.40 ppm)
Validation with TCCON measurements

**Conclusion**

- Analysis using spectrally degraded GOSAT measurements shows **similar precision for the two alternative spectral windows SWIR-1 and SWIR-2**.
- However, the **SWIR-2 spectral window is preferred** for the proposed instrument concept, mainly due to three reasons:
  1. Higher sensitivity to *atmospheric aerosol* → scattering can be better accounted for in XCO$_2$ retrieval
  2. **Lower noise errors** → lower instrument SNR is required for the same XCO$_2$ precision
  3. More promising **cloud-filtering possibilities** given the different optical depths of the two CO$_2$ absorption bands
- The preference for the SWIR-2 spectral window with respect to instrument noise errors has also been **confirmed using a realistic numerical instrument noise model**.
Assessing the proposed instrument’s CO₂ monitoring performance through simulations
Step 1: Simulating synthetic measurements

Preliminary instrument design
Orbit, spectral sizing, optical design and detector properties → SNR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Orbit</td>
<td>600 km, sun-synchronous</td>
</tr>
<tr>
<td>Mass / kg</td>
<td>90</td>
</tr>
<tr>
<td>Swath / km</td>
<td>50</td>
</tr>
<tr>
<td>Spatial resolution / m²</td>
<td>50 × 50</td>
</tr>
<tr>
<td>Spectral range / nm</td>
<td>1982–2092</td>
</tr>
<tr>
<td>FWHM (2.5 pix) / nm</td>
<td>1.29</td>
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<tr>
<td>Resolving power / -</td>
<td>1600</td>
</tr>
<tr>
<td>Aperture diameter / cm</td>
<td>15.0</td>
</tr>
<tr>
<td>f-number (f_{num}) / -</td>
<td>2.4</td>
</tr>
<tr>
<td>Optical efficiency (\eta) / -</td>
<td>0.48</td>
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<tr>
<td>Integration time (t_{int}) / ms</td>
<td>70</td>
</tr>
<tr>
<td>Detector pixel area (A_{det}) / \mu m²</td>
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</tr>
<tr>
<td>Quantum efficiency (Q_e) / e⁻ / photon⁻¹</td>
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</tr>
<tr>
<td>Dark current (I_{dc}) / fA pix⁻¹ s⁻¹</td>
<td>1.6</td>
</tr>
<tr>
<td>Readout-noise / e⁻</td>
<td>100</td>
</tr>
<tr>
<td>Quantization noise / e⁻</td>
<td>40</td>
</tr>
</tbody>
</table>
Step 1: Simulating synthetic measurements

- **Preliminary instrument design**
  Orbit, spectral sizing, optical design and detector properties → SNR

- **Realistic urban emission scenario**
  Hestia data for Indianapolis

Strandgren et al., 2020, in press
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- 3D CO₂ concentration field
  Gaussian plume model

Strandgren et al., 2020, in press
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  CarbonTracker model
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  Sentinel-2 data

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Radiative transfer model
- Sun-satellite geometry
- Numerical instrument noise model

Simulated synthetic spectrum

= what the proposed instrument would measure for the given scenario and instrument design

Strandgren et al., 2020, in press
Step 2: Retrieve corresponding XCO$_2$ from the synthetic measurements

- During the retrieval, a set of variables in the state vector (XCO$_2$, H$_2$O, albedo, solar/spectral shift) are fitted.
- The ability to find the true parameters is limited by the instrument’s noise level (SNR).
- Hence, we can evaluate the instrument’s CO$_2$ monitoring capabilities by looking at the retrieved (noisy) XCO$_2$ field.
Step 2: Retrieve corresponding XCO$_2$ from the synthetic measurements

**Upper panels** Retrieved two-dimensional fields of XCO$_2$ enhancements in the vicinity of the four strongest CO$_2$ emitters $E_1$, $E_2$, $E_3$ and $E_4$ within the Hestia Indianapolis dataset. **Lower panels** Corresponding per-pixel (circles) and average (solid lines) along-track XCO$_2$ enhancements within the area 200 to 2200 m downwind and -1000 to 1000 across-wind of the respective emitters. The blue rectangles in the upper panels show the areas from which the corresponding per-pixel and average along-track XCO$_2$ enhancements, depicted in the respective lower panels, are extracted and calculated. The color of the circles follow the color bars in the respective upper panels.
Summary and conclusions

- Systems for the independent verification of reported CO$_2$ emissions are needed

- Emissions from medium-size power plants (1-10 MtCO$_2$ yr$^{-1}$) are responsible for a significant part of anthropogenic CO$_2$ emissions in general and from the power plant sector in particular

- In order to independently monitor such emissions from space we propose an imaging spectrometer with a fine ground resolution of 50 x 50 m$^2$

- Measurements near 2.0 µm (SWIR-2 window) are most promising for this task

- Simulations using a realistic instrument design, emission scenario and surface albedo show that when the instrument is only limited by its own noise, plumes from emitters with a source strength down to 0.3 MtCO$_2$ yr$^{-1}$ can be resolved

  → Significant margin for additional error sources (e.g. aerosols, meteorology)

- The compact instrument design, with a single spectral window, would allow for a constellation of satellites, hence increasing the spatial coverage and temporal resolution
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- Emissions from medium-size power plants (1-10 MtCO\(_2\) yr\(^{-1}\)) are responsible for a significant part of anthropogenic CO\(_2\) emissions in general and from the power plant sector in particular.
- In order to independently monitor such emissions from space, we propose an instrument concept with a fine ground resolution of 50 x 50 m\(^2\).
- Measurements near 2µm (SWIR-2 window) are most promising for this task.
- Simulations using a realistic instrument design, emission scenario, and surface albedo show that the instrument is only limited by its own noise; plumes from emitters with a source strength down to 0.3 MtCO\(_2\) yr\(^{-1}\) can be resolved.
- Significant margin for additional error sources (e.g., aerosols, meteorology).
- The compact instrument design, with a single spectral window, would allow for a constellation of satellites, hence increasing the spatial coverage and temporal resolution.

Outlook

The next steps that we are currently working on include:

- Simulate CO\(_2\) plume dispersion with LES, rather than Gaussian, modeling.
- Include scattering effects by atmospheric aerosol in the radiative transfer simulations also at local/urban scale.
- Quantify the ability to inversely determine the corresponding CO\(_2\) emission rates under various conditions representing for example different emission source strengths, seasons, surface albedo, meteorological conditions etc.
Thank you for your interest!

Please feel free to contact me for any questions
Email: anytime
EGU live chat: 2020/05/06, 08:30-10:15 CEST

Johan.Strandgren@dlr.de

Further details and references can also be found in the following publications:

Wilzewski et al., AMT, 2020
Strandgren et al., AMTD, 2020