Atmos. Meas. Tech. Discuss.,
doi:10.5194/amt-2019-414-AC2, 2020

Atmospheric Measurement Techniques
Discussions

Interactive comment on “Towards space-borne monitoring of localized CO_2 emissions: an instrument concept and first performance assessment” *by* Johan Strandgren et al.

Johan Strandgren et al.

johan.strandgren@dlr.de

Received and published: 6 April 2020

First of all we would like to thank the reviewer for taking the time to read and review our manuscript. The comments raised by the reviewer certainly helped to improve the manuscript and to clarify several aspects. The referee comments are listed below along with the corresponding reply from the authors (in italic font style) as well as possible changes in the manuscript (in blue italic font style).

General comments

1) Plume mapping vs emission quantification - I understand that the quantification of CO2 emissions is the core goal of the proposed system (e.g. “the goal is to reliably estimate the CO2 emissions from localized sources" p1 L7). However, the entire analysis in this manuscript is focused on XCO2 retrieval, without any discussion of the subsequent CO2 flux calculation. Here, I wonder whether the latter drives any observational requirement affecting the instrument/mission configuration. For example, does the CO2 flux estimation interpose any requirement on either revisit or overpass time? On the other hand, the analysis of results in Figs.9-10 is highly based on whether or not XCO2 plumes can be visually detected from the retrieval results. But can those “detected plumes" be used to infer CO2 fluxes within the expected accuracy? I reckon that propagating measurement errors all the way to CO2 fluxes is probably beyond the scope of this study, but some overall discussion of the potential and limitations of the proposed mission/instrument for CO2 emission quantification is certainly missing.

The two aspects of plume detection and flux quantification and how they shall be addressed in the present paper is a valid point. As implied above, the long-term goal of the instrument concept is indeed the ability to independently derive CO_2 fluxes from point sources with an emission rate down to 1 $MtCO_2$/yr. The goal of the present study is, however, to present an instrument concept and demonstrate that it can resolve/detect CO_2 plumes from such point sources at all, assuming a realistic instrument design, and thus has the potential of independent flux quantification. A quantitative evaluation of how accurately the corresponding CO_2 fluxes can be determined from such satellite observations under various conditions is the task of a follow-up study currently being prepared. It is correct that this follow-up study is too comprehensive to include in the present paper. To clarify the two aspects and the goal of the present paper, the related part in the abstract has been rewritten and now reads: “In this paper, we present the concept and first performance assessment of a *compact space-borne imaging spectrometer with a spatial resolution of 50×50 m^2 that could contribute to the "monitoring, verification and reporting" (MVR) of CO_2 emissions worldwide. CO_2 emissions from medium-sized power plants (1–10 MtCO_2 yr^{-1}), currently not targeted by other space-borne missions, represent a significant part of the global CO_2 emission budget. In this paper we show that the proposed instrument concept is able to resolve emission plumes from such localized sources as a first step towards corresponding CO_2 flux estimates"*

Nevertheless, the we agree that some overall discussion of the potential and limitations of the proposed instrument concept for CO_2 flux quantification could be added. A new paragraph has been added to the conclusions section: "Given the results from this first performance assessment, the proposed instrument concept demonstrates a clear potential for the independent quantification of CO_2 emissions from medium-sized power plants (1–10 MtCO_2 yr^{-1}), which are currently not targeted by other planned space-borne CO_2 monitoring missions. On the local scale (Indianapolis), we have constrained the present analysis to one day in July using a rather simplistic Gaussian dispersion model that assumes constant atmospheric stability and (unidirectional) horizontal wind speed. Is might be that the ability to resolve the CO_2 emission plumes becomes more, perhaps even too, challenging under certain more realistic conditions. Nevertheless, these first results are certainly promising and encourage further studies." This is followed by the discussion on further limitation in terms of spatial coverage, arising from the high spatial resolution and forward motion compensation.

The conclusions section has also in general been revised in order to make clear that the goal of this paper is to demonstrate that the target CO_2 plumes can at all be detected, and that the aspect of flux estimation will be addressed in a follow-up study. The first and last paragraphs of the conclusions section now read: "To follow the progress on reducing anthropogenic CO_2 emissions worldwide, independent monitoring systems are of key importance. In this paper, we present the concept of

a compact space-borne imaging spectrometer with a high spatial spatial resolution of 50×50 m^2, targeting the monitoring of localized CO_2 emissions. We further demonstrate how the instrument concept could resolve CO_2 emission plumes from localized point sources like medium-sized power plants, thus having the potential to contribute to the independent large-scale verification of reported CO_2 emissions at facility level. . . . With the successful demonstration in this paper, i.e. that CO_2 emission plumes from medium-sized power plants can be resolved from space with a compact, yet realistic, instrument design, the next step will be to analyse the ability to quantify the corresponding CO_2 emission rates from the two-dimensional fields of synthetically retrieved XCO_2 enhancements. This follow-up study will be conducted for different seasons (with varying surface albedo and solar zenith angles), meteorological conditions and emission source strengths using large eddy, rather than Gaussian, modelling of the CO_2 plume dispersion. Although the effect of aerosols has partly been assessed on the global scale in this study, information on the properties and distribution of aerosols should be included also in the local scale simulations in order to better understand the instrument's ability to resolve and quantify localized CO_2 emissions under more realistic conditions. Such an in-depth aerosol analysis is, however, the task of further future studies."

After the above mentioned follow-up study, when the proposed instrument's abilities in terms of CO_2 flux quantification are better understood, observational requirements like revisit, overpass time, reasonable number of satellites etc. can be further analysed and defined. For now, no such observational requirements have been clearly defined.

2) Cloud screening - I understand that the retrieval can account for aerosol and cirrus, but I miss a discussion on how optically-thicker clouds would be detected and screened out from the processing. Just avoiding cloudy sites in the mission acquisition plan doesn't seem to be enough. As far as I know, either the O2 A-band or the combination of information from two SWIR channels is used for cloud detection in

other CO2 monitoring missions (e.g. OCO-2). What would be the approach here?

It is correct that we will have to be able to identify and screen scenes with thicker clouds and aerosol layers from the data acquired with a single spectral window. The approach we plan is to retrieve XCO_2 *independently from the two* CO_2 *absorption bands centred near 2010 nm and 2060 nm, respectively, assuming a non-scattering atmosphere. Given accurate spectroscopic data, any differences in the* XCO_2 *retrieved from the two bands will be due to scattering particles as a result of the different optical depths of the two* CO_2 *bands. Hence, scenes with significant scattering can be identified and screened out. We have added the following piece of text in Sect. 4.2 of the manuscript: "Although layers of aerosol and cirrus can be partly accounted for in the retrieval, scenes with thicker clouds and aerosol layers will have to be identified and filtered out in the data processing chain. Such a cloud filter could exploit the different optical depths of the two* CO_2 *bands in the SWIR-2 window by retrieving* XCO_2 *from the two* CO_2 *bands independently (assuming a non-scattering atmosphere) and filter for discrepancies."*

3) Spectral albedo variations - the authors discuss the effect of surface albedo on their retrieval using simulations based on Sentinel-2 surface reflectance data, but if I understand correctly a constant reflectance value is assumed for the entire fitting window. However, I think the impact of different spectral signatures within the fitting window should also be tested. This could be especially relevant for retrievals over urban environments, which are not only characterized by highly heterogeneous surfaces, but also by the presence of artificial materials with strong absorption features in the SWIR. See for example Ayasse et al. (https://doi.org/10.1016/j.rse.2018.06.018) or Cusworth et al. (https://doi.org/10.5194/amt-2019-414) for analysis of the impact of surface reflectance on methane retrievals for 10-nm sampling instruments. It might be the case that the decoupling between CH4 and surface reflectance is less challenging for the much higher spectral sampling of the proposed instrument, but I think a test

of this effect would be important nonetheless. The authors could perhaps link their Sentinel-2 background image with the ECOSTRESS spectral library, SPECCHIO (https://specchio.ch/) and/or any other spectral library containing impervious/urban materials (e.g. http://www.met.reading.ac.uk/micromet/LUMA/SLUM.html).

It is correct that we assume a constant reflectance for the entire window. We believe that the decoupling between CO_2 *and surface reflectance indeed will be less challenging with the higher spectral resolution of 1.29 nm assumed for the spectrometer proposed here. Cusworth et al. (2019) show how the retrieval artefacts due to surface reflectance inhomogeneity decrease when the AMPS sensor is assumed, an atmospheric sensor dedicated for* CH_4 *retrievals with a spectral resolution of 1 nm (i.e. similar to the spectral resolution assumed in this study).*

Following the reviewer's suggestion, we have analysed the spectral reflectance in the SWIR spectral range in more detail using the SLUM (Spectral Library of Impervious Urban Materials) dataset. This dataset has a spectral resolution of approx. 2.5 nm for the spectral range analysed here. Figure 1 below shows spectral reflectances for various urban materials belonging to different sub-categories like asphalt, stone, cement, metal, granite etc. While significant features in the spectral reflectance are evident between 1800 to 2400 nm for several urban materials, the spectral range of the spectrometer proposed in this study (1982–2092 nm, marked black in the attached figure) exhibit little variability. In many cases the assumption of a constant albedo is valid, and for the other cases the reflectance is sufficiently smooth to be fitted using a second order polynomial during the retrieval. In the 2200–2400 nm spectral region, stronger reflectance features are seen, supporting the conclusion by Ayasse et al. (2018), i.e. that surface reflectance features in the 2200–2400 nm region can cause errors in the CH_4 *retrieval. Hence, we argue that the challenges in decoupling* CH_4 *and surface reflectance at 2200–2400 nm cannot be directly compared to the ability to decouple* CO_2 *and surface reflectance at 1982–2092 nm, even at the same spectral* *resolution.*

That being said, we acknowledge that the albedo heterogeneity at urban scale and at such high spatial resolution will be an important aspect to consider in future studies, especially when scattering by aerosols is considered.

Specific and technical comments

p6, L1 SNR already defined (p4, L5)

Revised.

Table 1 - specs for swath (1000 across-track pixels?), MTF/PSF and uniformity (smile/keystone) would also be useful

We have added information about the assumed 50 km swath width. We do, however, argue that information about MTF/PSF and uniformity (smile/keystone) would be too detailed at this point. This information would be more relevant in future studies, when the preliminary design assumed here has been further consolidated or even realized.

p9, L1, FMC: does this mean that there is a variation of the view zenith angle from +20 to -20 degrees in the along track direction of the image? how is this handled by the retrieval? Please, comment.

Our FMC approach means that the satellite will operate in a normal push-broom configuration but the ground speed will be reduced by a factor 5. Thus, considering a whole target tile of approx. 50 km along-track length, the viewing zenith angle (VZA) will be approx. +20 degrees for the first across-track row of ground-pixels in the tile. The VZA will then continuously decrease to 0 degrees at the center of the tile. This

is followed by a continuous decrease down to approx. -20 degrees at the end of the tile. Measuring the whole tile takes about 70 seconds. The range of VZA for a single ground-pixel is, however, very small, since each ground-pixel is only observed for 70 ms (5 times longer than without FMC). For the study, each tile consists of 1000 ground-pixels in the along-track direction, meaning that if the VZA ranges over 40 degrees for the entire tile, each ground-pixel will have a VZA range on the order of $40/1000 = 0.04$ *degrees (assuming that the FMC was perfectly linear in VZA). The information about the VZA for each ground-pixel is used in the retrieval in order to accurately calculate the corresponding light path. The tile is assembled from all individual ground-pixels after the retrieval. Hence, the range of VZA should not be a problem.*

p10, 3rd paragraph, forward simulation set-up:

- Since CH4 and H2O are included in the retrieval state vector for SWIR-1, shouldn't they be varied in the forward simulations as well?

  In our global trial ensemble, the abundance of CO_2*,* CH_4 *and* H_2O *varies between the scenes. Hence, these greenhouse gas concentrations are all varied in the forward simulations, not only* CO_2*.*

- Should the surface BRDF be considered in the forward simulations in order to evaluate errors from the Lambertian assumption in the retrieval? Not trivial to implement, but probably relevant esp. In the case of urban environments

  As noted above, retrievals are performed for individual ground-pixels under well-defined viewing geometry given the viewing zenith (VZA) and solar zenith angles (SZA) and the relative azimuth. If there is no scattering in the atmosphere, there should not be any BRDF effect on the retrievals since the retrievals estimate an "albedo" parameter. This "albedo" parameter is just the ground reflectivity for the

> *given combination of SZA and VZA - be it a particular value of a non-Lambertian or a Lambertian BRDF. If there is atmospheric scattering, the BRDF plays a role since the scattered light-beams might hit and exit the surface under different angles than the direct light-beam (SZA, VZA). For most parts of this study, we neglect scattering i.e. BRDF effects are by definition neglected as well. Even for the parts of the study that include scattering, we are in a regime of thin particle loads (AOD(NIR) mostly smaller than 0.5). While there might be a BRDF error contribution, we believe that is small compared to the other scattering induced errors (Fig. 6). But, the reviewer is right that we did not include BRDF effects in our study and the reviewer is also correct that this is not trivial. Since the BRDF effects are not decisive, we propose to postpone such an assessment. For clarification purposes, the following sentence has been added to the section with scattering simulations in the manuscript: "Note that errors arising from the Lambertian albedo assumption (BRDF (Bidirectional Reflectance Distribution Function) effects) are neglected in the scattering simulations."*

p16, L21 Sen2Core → Sen2Cor

Revised.

p20, L1: "can nevertheless be clearly separated from the background" - OK, but is this still enough for a useful estimation of the emitted flux?

See response above regarding revision of abstract and conclusions section in order to clarify the goal of this paper in terms of plume detection vs. flux estimation.

p21 L1 & L18: references to potential synergies with companion instruments - a discussion of the planned strategy for cloud screening would be useful here

A new sentence including reference regarding the synergy between CO_2 and aerosol instruments has been added to the conclusions section: "As an example, a multi-angle polarimeter instrument is planned to fly together with the CO_2 instrument onboard the CO2M mission in order to minimize the systematic XCO_2 errors (ESA, 2019[1])"

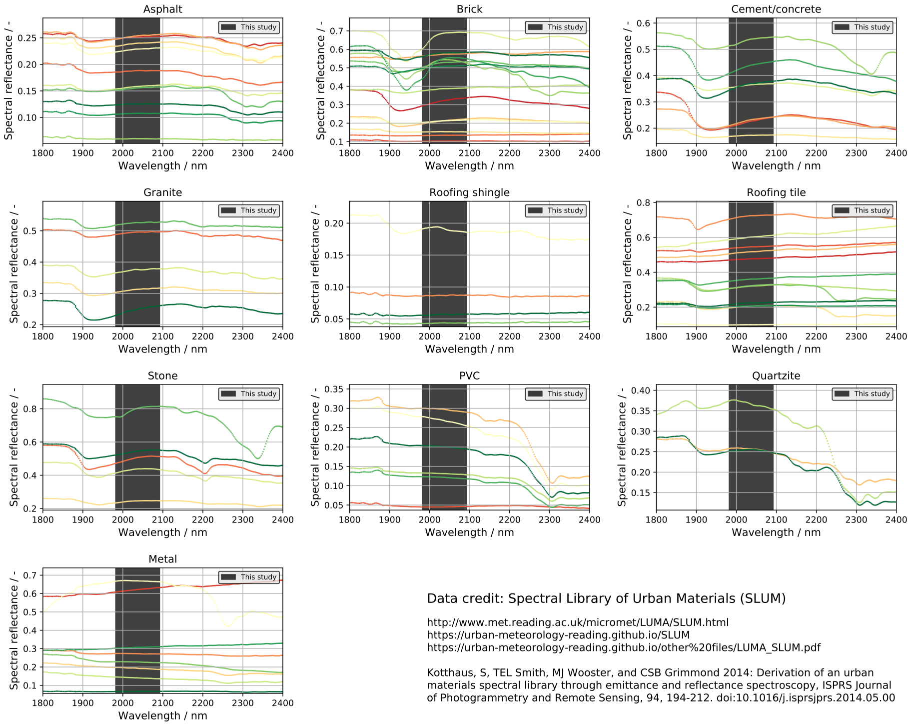
For potential synergies with an active instrument, we are not aware of any suitable reference and we propose to stick to the current reference to a CO_2 lidar (Kiemle et al. 2017).

A discussion about the planned strategy for cloud screening has been added to Sect. 4.2: "Although layers of aerosol and cirrus can be partly accounted for in the retrieval, scenes with thicker clouds and aerosol layers will have to be identified and filtered out in the data processing chain. Such a cloud filter could exploit the different optical depths of the two CO_2 bands in the SWIR-2 window by retrieving XCO_2 from the two CO_2 bands independently (assuming a non-scattering atmosphere) and filter for discrepancies.".

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2019-414, 2020.

---

[1] ESA: Copernicus CO_2 Monitoring Mission Requirements Document, https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v2.0_Issued20190927.pdf, EOP-SM/3088/YM-ym, 2019.



Data credit: Spectral Library of Urban Materials (SLUM)

http://www.met.reading.ac.uk/micromet/LUMA/SLUM.html
https://urban-meteorology-reading.github.io/SLUM
https://urban-meteorology-reading.github.io/other%20files/LUMA_SLUM.pdf

Kotthaus, S, TEL Smith, MJ Wooster, and CSB Grimmond 2014: Derivation of an urban materials spectral library through emittance and reflectance spectroscopy, ISPRS Journal of Photogrammetry and Remote Sensing, 94, 194-212. doi:10.1016/j.isprsjprs.2014.05.00

Fig. 1. Spectral reflectances for various urban materials belonging to different sub-categories (see plot titles) as provided by the SLUM dataset.