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Atmospheric Measurement Techniques Discussions
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# *Interactive comment on* "Towards space-borne monitoring of localized $CO_2$ emissions: an instrument concept and first performance assessment" *by* Johan Strandgren et al.

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First of all we would like to thank the reviewer for taking the time to read and review our manuscript. The helpful comments certainly helped to improve the manuscript and to clarify what we want to demonstrate in this first paper. 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).



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## General comments

Detection of an emission plume is not the same as accurate quantification of emissions and the paper including the abstract must make clear what exactly is meant here. Abstract, line 6 following: Sentences: "...the goal is to reliably estimate the CO2 emissions from localized sources down to a source strength of approx. 1 MtCO2/yr," and "Resolving CO2 plumes also from medium-sized power plants (1-10 MtCO2/yr) is of key importance for independent quantification of CO2 emissions from the coalfired power plant sector.". What does "to reliably estimate the CO2 emissions from localized sources" mean? Please clarify already in the abstract. Is 1 MtCO2/yr the expected 1-sigma uncertainty / detection limit ? If yes, this would mean that the 1-sigma uncertainties of the medium-sized power plants are in the range 10 %-100 %. Is this good enough? Or is this just good enough for detection of medium-sized emission sources but not for accurate quantification? In this context: Is it good enough if errors are larger than 4 ppm in 32 % of all cases?

*This is a valid point and we agree with the reviewer that we tend to be one step ahead when discussing the goals of the instrument concept in terms of $CO_2$ flux quantification. The long-term goal of the instrument concept is 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. With the results of that study, we will be able to quantify with what expected accuracy $CO_2$ fluxes can be determined and thus better define what "reliably estimate" means. Before that follow-up study, which is too comprehensive to include in the present paper, we refrain from specifying a goal for the $CO_2$ flux estimation accuracy as it would be too speculative. To make* *this clear we have adapted the corresponding part of the abstract, which 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 $50 \times 50$ 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". Also the last part of the abstract was a bit too bold at this early point and has been changed to: "...i.e. well below the target source strength of 1 $MtCO_2\,yr^{-1}$. This leaves a significant margin for additional error sources like scattering particles and complex meteorology and shows the potential for subsequent $CO_2$ flux estimates with the proposed instrument concept."*

*We have further revised the conclusions section accordingly. The first paragraph now reads: "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 resolution of $50 \times 50$ 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.". Similarly, the last paragraphs has been revised and now reads: "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. It 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."*

*"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."*

*Moreover we have rephrased small parts of the manuscript where the aspect of $CO_2$ flux quantification is too pronounced.*

*The 1 $MtCO_2$/yr is the target source strength that we want to be able to determine emission rates for and does not represent the uncertainty of the emission estimates. How accurate the emission estimates will be for such sources will be addressed in the upcoming study, as explained above. To clarify, the $XCO_2$ errors are only larger than 4 ppm in 32 % of the cases when aerosols and cirrus are included. Accordingly these errors also include systematic errors and should not be understood/treated as statistical errors. We do realize, that the chosen percentiles and presentation of these systematic errors in the manuscript might be confusing and make the reader think that the errors are statistical. This has been revised throughout the manuscript.*

## Specific comments

Page 4, line3: Sentence “With such a dense spatial sampling, . . . ”. This seems to refer to “spatial resolution” mentioned in the sentence before but resolution is not sampling.

*The term “dense spatial sampling" here refers to the large amount of pixels per unit area. To avoid confusion the sentence has been revised and now reads: “With such a high spatial resolution and large amount of ground pixels per unit area, averaging of . . . "*

Page 4, line 6: Sentence “Wilzewski et al. (2019) recently demonstrated . . . " This statement is too strong as the cited paper is still in review.

*The paper by Wilzewski et al. (2019) has now been accepted and published in AMT (https://doi.org/10.5194/amt-13-731-2020). Thus we keep the formulation as it is.*

Page 5, line 9: Is there a reason why “a local equatorial crossing time at 13:00" has been selected?

*13:00 is chosen in order to have 1) the sun high up in the sky leading to a stronger signal and 2) a relatively well developed boundary layer such that the $CO_2$ plumes can be well dispersed vertically. The following sentence has been added to the manuscript: “This orbit is chosen in order to have a well developed boundary layer at overpass together with good radiometric performance (high SNR)."*

Table 1: Please add Adet (detector area) as this is used in several equations. Is the aperture circular so that the aperture area can be computed given the listed diameter? Please add the missing information.





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*This is a good point and since we use pixel area rather than pixel pitch, we have replaced the information about the detector's pixel pitch with the detector's pixel area in Table 1 as well as in the text.*

*The aperture is indeed circular such that the aperture area can be computed using the given diameter. This information has been added in the manuscript.*

Figure 4 (a): The dotted vertical line is at x=0.1 and the label refers to Albedo=0.1 whereas the x-axis annotation lists Albedo times cos(SZA)/PI. If this is not correct then please correct this.

*The dotted vertical line is actually at approx. 0.01 (=0.1·cos(70)/π). The figure and corresponding labels and legends is thus correct as it is.*

Page 9, bottom: Please add a reference for the statement that the SWIR-1 albedo is higher than the SWIR-2 albedo. Is this always the case?

*Although not always the case, it is certainly most often the case. We have added a reference (Fig. 7 in https://doi.org/10.1364/AO.48.003322) where this general pattern is visualized for the global trial ensemble used is this study. Additionally, Fig. 1 below shows surface reflectance/albedo data for SWIR-1 and SWIR-2 (and the difference between the two) inside the Indianapolis domain analysed in this study. The SWIR-2 surface reflectance data are the same data used for the study and the SWIR-1 surface reflectance data are derived from Sentinel-2's band 11 (approx. 1560–1660 nm), which is well aligned with the potential SWIR-1 window assumed in this study. The figure clearly shows that the SWIR-2 reflectance is generally lower than the SWIR-1 reflectance, also at urban scale. In addition to the added reference, the manuscript has also been revised to say that the albedo in SWIR-2 is* ***generally*** *lower than in SWIR-1.*



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*Furthermore the important aspect of higher solar (ir)radiance in SWIR-1, compared to SWIR-2, was missing as an explanation for the consistently higher SNR for SWIR-1. After some further rearrangements, the related paragraph in the paper now reads: "Figure 4a shows the continuum SNR (calculated with Eqs. (1)–(5)) as a function of the scene brightness for the two prospective spectral set-ups SWIR-1 and SWIR-2. The scene brightness describes the conversion from incident solar irradiance to reflected solar radiance and is calculated as the product of the surface albedo and the cosine of the SZA, divided by $\pi$, hence assuming a Lambertian surface. For the reference scene (albedo $= 0.1$, SZA $= 70$), the continuum SNR is approx. 180 and 100 for SWIR-1 and SWIR-2, respectively. The consistently higher SNR for SWIR-1, compared to SWIR-2, is mainly the result of higher solar radiance (see Fig. 3) as well as generally higher surface albedo (see e.g. Fig. 7 in Butz et al. (2009)) in SWIR-1. Looking at the individual contributions from the different instrument noise sources in Fig. 4b, it is clear that the readout noise and signal shot noise are the major contributors, whereas the noise arising from quantization errors, dark current and thermal background radiation has a small or even negligible contribution in comparison. The signal shot noise is, however, smaller than the dark current, read-out noise and quantization noise inside the $CO_2$ absorption bands, where the signal, and hence the signal shot noise, decreases. Note that all noise terms, except for the signal shot noise $\sigma_{SS}$, are constant."*

Section 4.2, Fig.9, Fig.10: Is the retrieval using the true CO2 profile? If not: are the reported errors including the smoothing error? Do Figs. 9(b) and 10(top) only show noise or are there also systematic XCO2 biases? If yes, where are the biases coming from? Is the bias correlated with the emission plume (e.g., due to aerosols)? Please show retrieved minus true also for Fig. 10. I would expect to see an aerosol-related XCO2 bias correlated with the emission plume.

*Yes, the true $CO_2$ profile is used for the retrieval and no smoothing error is included. Figs. 9 and 10 only show the noise. Systematic biases from e.g. aerosols is not analysed at urban scale in this study, but will be investigated in further studies. Since* *there is no bias, we see no added value of including further panels in Fig. 10, showing retrieved minus true $XCO_2$.*

**Technical comments**
Page 12, line 4: Strange sentence: "For the SWIR-2 set-up it is only retrievals over scenes . . . ". Probably "it is" needs to be removed.

*Revised. The sentence now reads: "For the SWIR-2 set-up, only retrievals over scenes that are darker than our reference scene (albedo $= 0.1$, SZA $= 70$) are expected to have instrument noise induced errors larger than approx. 2 ppm."*

Page 12, line 14: Add "nm" after "1.29".

*Revised.*

Page 14, line 2: "Which effect that is dominating . . . ": delete "that".

*Revised.*

Page 14: ". . . the Hestia Project was gridded . . . ". Replace by ". . . the Hestia Project data set was gridded . . . " or equivalent.

*Revised.*

Various places including References: Check CO2 etc and use subscripts where needed, e.g., for CO2 and CH4.

*Several instances without proper use of subscript in the reference list have been re-*

*vised. In the main text, however, no such instance could be found apart from "CO2M" and "CO2MON", which should be written without the use of subscript.*

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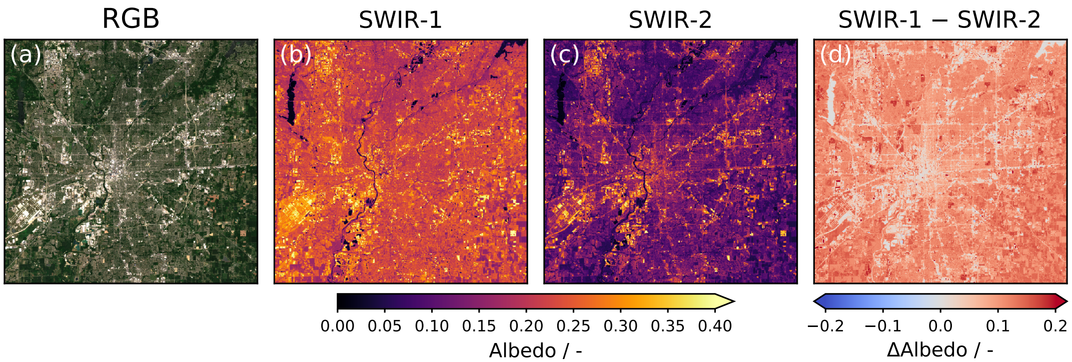


**Fig. 1.** (a) True color RGB for the city of Indianapolis. Corresponding surface reflectance/albedo data in SWIR-1 (b) and SWIR-2 (c) as well as the difference between SWIR-1 and SWIR-2 (d).