

We are grateful to the referee for this detailed feedback and comments. Our answers are included within the referee's text in red.

Review of “Synthetic mapping of XCO₂ retrieval performance from shortwave infrared measurements: impact of spectral resolution, signal-to-noise ratio and spectral band selection” by Dogniaux and Crevoisier, amt-2023-233

The present manuscript presents a simulation study of the impact of spectral resolution, spectral band selection and signal-to-noise (SNR) ratio on XCO₂ retrieval performance for space borne passive spectrometers in the shortwave infrared, with a focus on the CO₂M, MicroCarb and NanoCarb sensors. A large part of aforementioned parameter space is explored synthetically by simulating top-of-atmosphere radiances with the 5AI radiative transfer model and then operating an optimal estimation based inversion on the synthetic measurements to discuss XCO₂ retrieval performance with respect to random errors, vertical sensitivity and information content among others. The paper addresses relevant questions within the scope of AMT and presents new data that warrant publication. The language is fluent, the authors give credit to related work and substantial conclusions are reached. However, I believe that the manuscript could be improved by addressing some methodological questions which should strengthen the interpretation of the results.

General comments:

G1: Recent studies have shown that coarse-resolution SWIR instruments tend to be affected by strong trace gas biases induced by surface albedo features (e.g. for XCO₂ or XCH₄). I feel that this is not sufficiently addressed in your discussion of retrieval performance as a function of spectral resolution and SNR (section 4.1), in the discussion of information entanglement (section 4.2.3) and your observations regarding XCO₂ precision as a function of Degrees of Freedom for Signal (DoFS): In your synthetic study it may be true that precision can be easily “bought” at the expense of spectral resolution by increasing SNR. However, in the real world, for resolving powers below ~1000 I would expect that this stops being true. It would probably go beyond the scope of this paper to include a more realistic albedo model in your framework, but it sure would be interesting. You should at least discuss this more in-depth throughout the manuscript (e.g. near Figure 3, etc.).

We agree with the referee, only albedo models that are assumed to be perfectly known are considered here, thus underestimating the impact of albedo spectral-dependence misknowledge on CO₂ (and GHG in general) enhancement retrieval for low resolving power instruments. These effects have for example been discussed by Ayasse et al. (2018). This could indeed be incorporated in the study by either studying the retrieval sensitivity to realistic albedo spectral features or by inflating the Se matrix appropriately to reflect forward model misknowledge. However, as the referee noted, this would go beyond the scope of the paper which – at this stage – focuses on SNR-based performance results only.

Besides, this remark could also be generalized to all resolving power, for which we assume, for example, that spectroscopic parameters are perfectly known, as well as aerosol optical properties.

In the revised manuscript (1) we better precise the scope of the study regarding what is included in the performance; (2) we elaborate better on how the Se matrix is constructed and

the implications of these choices; and (3) we include additional discussion elements dedicated to the limits of this study regarding the precision of low-SNR observing concepts.

Lines 106-108	In this work, we perform a systematic survey that synthetically explores the impact of spectral resolution, signal-to-noise ratio (SNR) and spectral band selection, three design parameters for SWIR CO₂ observing satellite concepts , on X_{CO_2} retrieval performance (SNR-related precision, degrees of freedom and smoothing error, excluding accuracy)
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Lines 328-346	with σ_e , the noise model for a given spectral sample, and L , the radiance for a given spectral sample. Here, the S_e matrix only includes measurement noise, so the uncertainty (or precision) results obtained from the \hat{S} matrix will only be related to measurement noise. In practice smoothing errors from CO₂ and non-CO₂ state vector parameters add up to the uncertainty (Connor et al., 2008). Finally, uncertainty evaluated on real data is typically larger than the uncertainty obtained from Optimal Estimation calculations, as model-related errors (misknowledge of albedo spectral dependence, spectroscopy errors, etc.) are also encompassed in such evaluations. For example, at low resolving powers, the complexity of spectral dependence in surface reflectance can lead to significant errors (e.g. for methane, Ayasse et al., 2018) that will not be accounted for here or, at high resolving power, real-data uncertainties are evaluated to be twice as large as theoretical uncertainty for OCO-2 (Eldering et al., 2017).
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G2: The fact that turning the aerosol fit off produces strong albedo correlations for NanoCarb indicates to me that you might be overfitting and/or need to adjust the retrieval scheme for NanoCarb. Perhaps the aerosol parameters are simply within the null space. If we think of NanoCarb as a low resolving power spectrometer, it seems physically very plausible that aerosol and albedo parameter fits would strongly impact each other. Please double check the retrieval and discuss this observed behavior. Which retrieval setting is recommended for NanoCarb? How do the retrieved values and standard deviations of XCO₂ and albedo change when you turn the aerosol fit off and on?

This point raised by the referee about NanoCarb null space is interesting. Following this idea, we performed a Singular Vector Decomposition (SVD) of the NanoCarb Jacobian matrix with its columns scaled for state vector perturbations equal to a priori uncertainty. We have: $y = Kx = UAV^T x$, with the columns of V giving a basis for the row space. Figure R1.1 shows the obtained singular value distribution with noise level for all four NanoCarb bands. There are 28 singular vectors (numbered from 0 to 27) as the state vector for NanoCarb is 28-variables long.

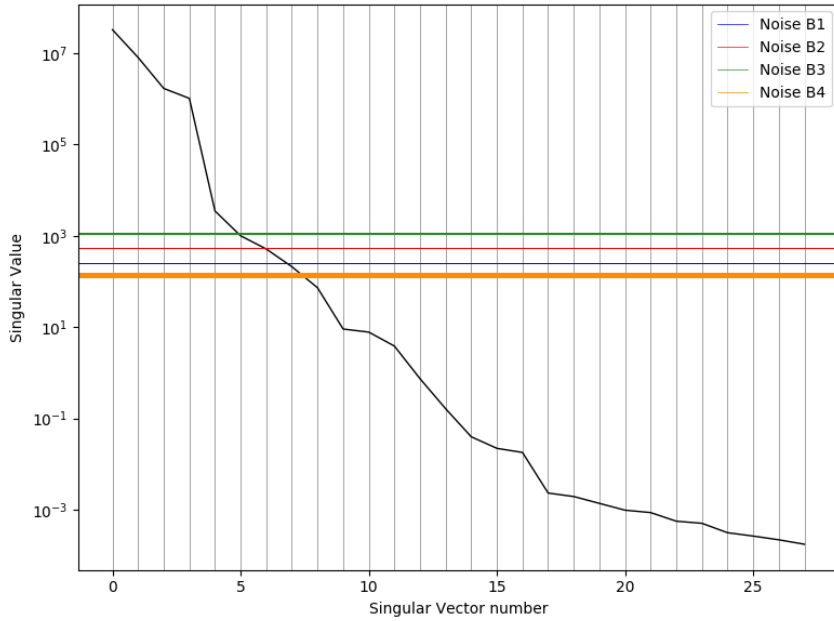
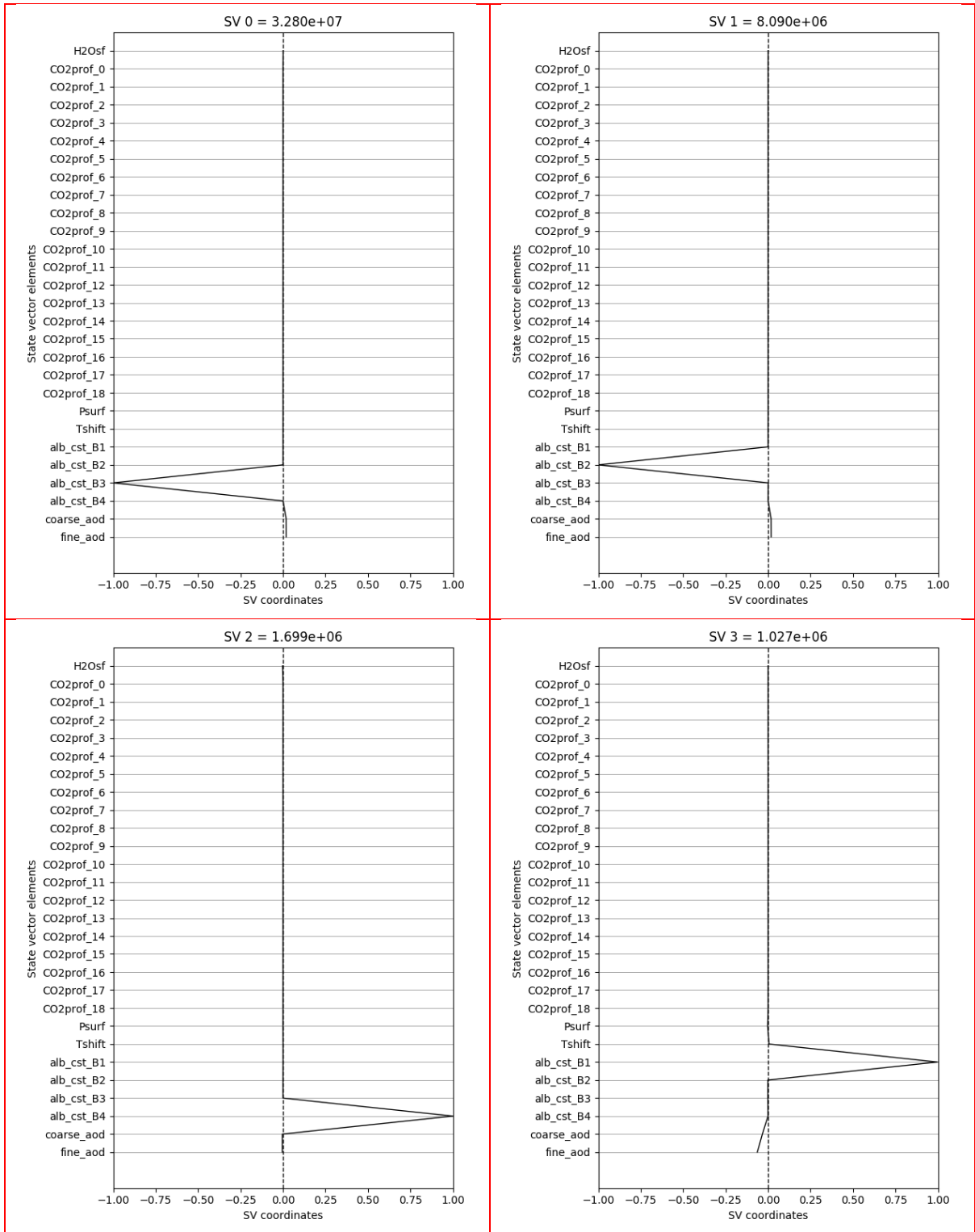


Figure R1.1. Singular value distribution for NanoCarb Jacobian matrix scaled for perturbations equal to a priori uncertainty, for the VEG 50° observational situation. Colored lines show the noise level for all four NanoCarb bands.

While we can numerically compute a row space basis with 28 dimensions, the analysis of the singular value distribution against noise levels shows that a maximum of 8 singular vectors are actually significant (singular vector numbers from 0 to 7 in Fig. R1.1). The remaining 20 vectors are related to singular values lower than the noise level and thus constitute a basis for the null space of NanoCarb Jacobian matrix. First, Figure R1.2 shows significant singular vectors of the row space basis.



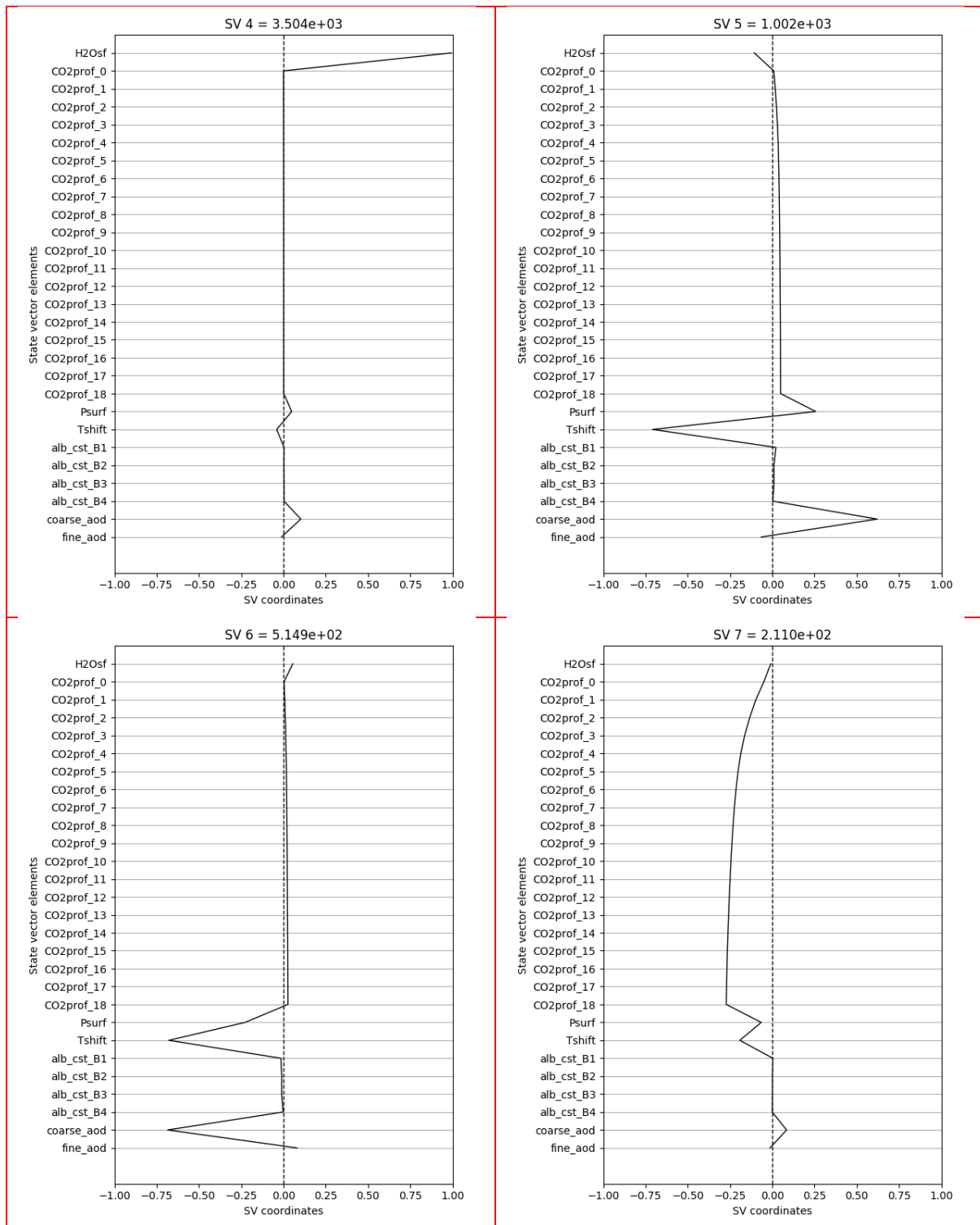


Figure R1.2. The seven first significant singular vectors of NanoCarb row space, for the VEG 50° observational situation.

Interestingly, but unsurprisingly, we find that the first four vector are each overall related to the albedo value of one particular band (with very small non-zero contributions of aerosol parameters). Non-zero contributions of CO2 concentration, water vapor, temperature shift, surface pressure and coarse and fine optical depths are present in the following four vectors. As we can see, coarse mode aerosol shows significant contributions to the 6th and 7th singular

vectors, and fine mode aerosol small contributions to all singular vectors shown in Fig. R1.2. Interestingly, looking into less-significant singular vectors, we find that the 10th vector (numbered 9 in Fig. R1.1) shows a significant contribution from fine mode aerosols (see Fig. R1.3). Consequently, we conclude that while both coarse and fine mode do not completely lie in NanoCarb null space, fine mode is indeed considerably lying into it. This analysis is consistent with DOFS values obtained for aerosol parameters as show in Fig 6 of the main text.

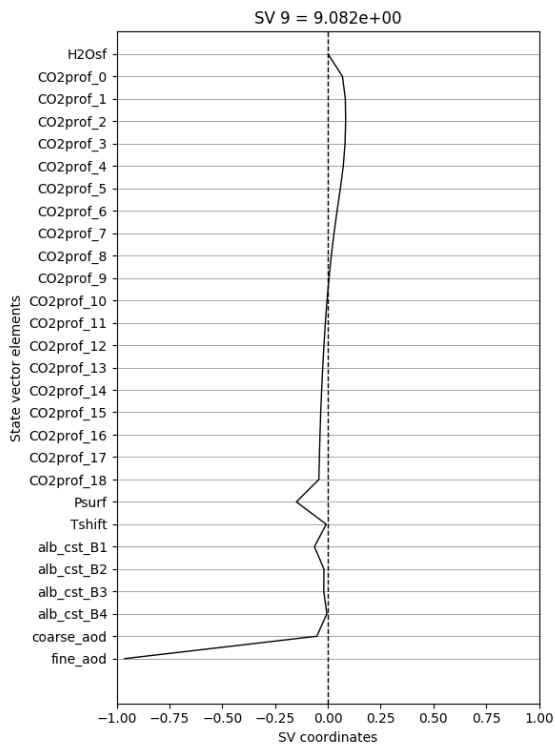


Figure R1.3. The 9th singular vector of the row space basis (associated to a singular value lower than noise level) obtained through SVD decomposition of NanoCarb Jacobian matrix.

Indeed, as seen in the first four singular vectors, we have small non-zero contributions of aerosol parameters in these vectors, thus showing entanglement of albedo and aerosol parameters. This can also be seen in the covariance matrices shown in Fig. 10 of the main text.

NanoCarb is a compact novel observing concept which performance, merits and drawbacks, especially compared to “classic” spectra-observing instruments, are still under examination. This work builds upon the NanoCarb performance assessment performed in Dogniaux et al, 2022. The definition of the appropriate state vector for NanoCarb is thus still in consideration. As one of the goals of this study is to compare NanoCarb performance against “classic” spectra-observing concepts, we decided to include aerosol parameters in the state vector for NanoCarb in order to ensure a comparison as-fair-as-possible. Indeed, we agree with the referee that it would certainly make sense not to include these geophysical parameters in the state vector considering how little information appears to be, as it would make sense for low resolving power cases in the CVAR experiment (see question G3 below).

As the main goal of this work is to assess the impact of instrument design and characteristics on XCO₂ retrieval performance, we chose to use an as-similar-as-possible state vector throughout all cases of CVAR and for exactly-defined concepts (including NanoCarb) in order to ensure an as-fair-as-possible comparison. We propose to better precise the goal of our state vector composition with respect to the goals of this study in the revised manuscript.

Lines 321-325	We include in the state vector all the main geophysical variables necessary to model SWIR spaceborne measurements. Those are listed in Table 4, along with their a priori values and uncertainties. This selection of state vector parameters is used for all exactly-defined concepts (with a small exception on albedo slope for NanoCarb) and CVAR experiment cases because the goal of this study is to explore the impact of design parameters on performance. Using a similar estimation scheme across all resolving power helps us achieve this goal. However, we do realise that, in practice, less geophysical elements are fitted for low resolving power observations (Cusworth et al., 2021).
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Besides, as suggested by the referee, messages on NanoCarb could also be expanded regarding recommending a relevant state vector composition for NanoCarb.

Lines 730-732	... as well as non-zero yet rather low DOF values for H ₂ O profile scaling factor, temperature global shift and coarse mode aerosol optical depth (0.93, 0.36 and 0.55, respectively). Given how little some of these DOF values are, we also conclude that the state vector used to process NanoCarb measurement should be adjusted to only include the most essential geophysical variables. For example, aerosol optical depths could be removed.
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As we only compute \hat{S} for our performance calculation (explained at the beginning of Sect. 4.1.1), there is no retrieved value available for XCO₂ and albedo in our scheme. However, we can indeed examine how their standard deviations change when the aerosol fit is turned on and off. These results are given for the VEG 50° observational situation in Table R1.1.

	Std deviations with aerosol fitting	Std deviations without aerosol fitting
XCO ₂	5.572 ppm (0.600 ppm)	5.566 ppm (0.600 ppm)
Albedo B1	6.83x10⁻² (6.80x10 ⁻³)	4.87x10⁻³ (5.33x10 ⁻⁴)
Albedo B2	2.20x10⁻² (2.18x10 ⁻³)	3.94x10⁻⁴ (3.87x10 ⁻⁵)
Albedo B3	2.31x10⁻² (2.28x10 ⁻³)	3.52x10⁻⁴ (3.46x10 ⁻⁵)
Albedo B4	5.42x10⁻³ (5.33x10 ⁻⁴)	9.32x10⁻⁴ (9.42x10 ⁻⁵)

Table R1.1. A posteriori standard deviations obtained with and without fitting aerosols, for single-pixel retrieval (in bold) and combined results for different viewing angles (in parenthesis), for the VEG 50° observational situation.

As could be expected, we find lower posterior standard deviations for albedo parameters when turning off the fitting of aerosol parameters. XCO₂ posterior standard deviation decreases as well, but very little. In conclusion, aerosol parameters and albedo parameters do

impact each other. We can also see that while fitting the optical depth of two aerosol layers may indeed be a stretch for NanoCarb, given the current state vector design, this choice has nonetheless very little impact on reported XCO2 standard deviation values.

G3: How does the above observation extend to the CVAR experiment? Do you fit aerosol parameters across the spectral-resolution space that you cover?

We do fit aerosol across the spectral-resolution space that is covered in the study. Figure R1.4 shows how standard deviations of XCO2 and albedo related parameters (for the observational situation VEG 50°) evolve when turning on and off aerosol fitting.

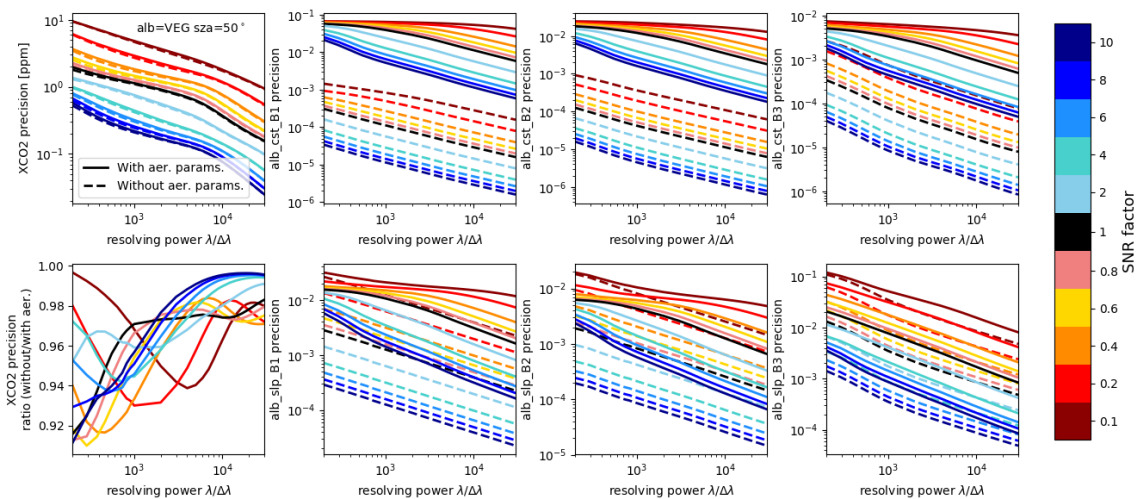


Figure R1.4. XCO2 (top left) and albedo baseline (top center and right) and band-wise slopes (bottom center and right) standard deviations obtained with (full lines) and without (dashed lines) fitting aerosol parameters. For better readability, the bottom left panel shows the ratio between without and with the fitting of aerosol parameters for XCO2 precision.

Similarly to the results obtained with NanoCarb, XCO2 standard deviations reduce by a very little amount (less than 10%) compared to the standard deviations of albedo-related parameters (about an order of magnitude for baseline albedo and from 10% to an order of magnitude for band-wise albedo slope). Thus, results currently presented for CVAR while fitting aerosol parameters are quite representative of what we would obtain without fitting aerosol parameters.

If yes, would it not make sense to turn off the fine mode parameter at some low resolving power (see Fig. 6)?

If we had to operationally process low-resolving power observations ($\lambda/\Delta\lambda < 1000$), it would indeed make sense to turn off fitting fine mode aerosols, and maybe even coarse mode. Usually, these observations can even be processed using a matched filter technique that basically just fits the target atmospheric species (e.g. Guanter et al., 2021). However, as explained before for NanoCarb, the goal is to exhibit the roles of spectral resolution and SNR in XCO2 retrieval performance, thus we seek an as-fair-as-possible comparison across all cases of CVAR and exactly-defined concept.

As detailed for question G2 regarding NanoCarb, we adjusted in the following manner the state vector composition presentation:

Lines 321-325

We include in the state vector all the main geophysical variables necessary to model SWIR spaceborne measurements. Those are listed in Table 4, along with their a priori values and uncertainties. **This selection of state vector parameters is used for all exactly-defined concepts (with a small exception on albedo slope for NanoCarb) and CVAR experiment cases because the goal of this study is to explore the impact of design parameters on performance. Using a similar estimation scheme across all resolving power helps us achieve this goal. However, we do realise that, in practice, less geophysical elements are fitted for low resolving power observations (Cusworth et al., 2021).**

I am surprised that you appear to find sufficient DoFS for the coarse mode parameter even at a resolving power of 200 - how do you explain the very different behavior of the two aerosol retrieval parameters?

In this retrieval scheme, we assume that aerosol optical properties are perfectly known, including the spectral dependence of these optical properties. Figures R1.5 and R.16 show relative radiance sensitivities to aerosol optical depth change for a resolving power of 200 and 10000, respectively.

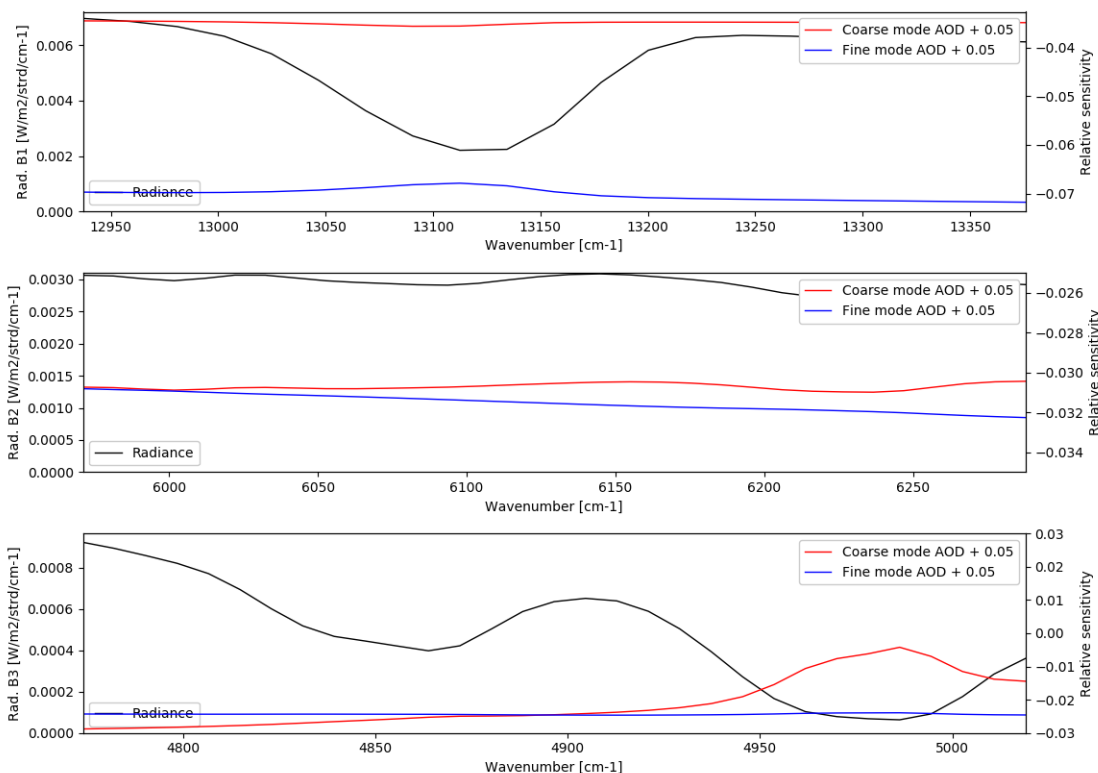


Figure R1.5. Radiance (black, left y-axis) and relative sensitivities to a 0.05 optical depth increase for coarse (red, right y-axis) and fine (blue, right y-axis) modes for all CVAR bands B1, B2 and B3 (top, center and bottom panels, respectively), for the VEG 50° at $\lambda/\Delta\lambda=200$.

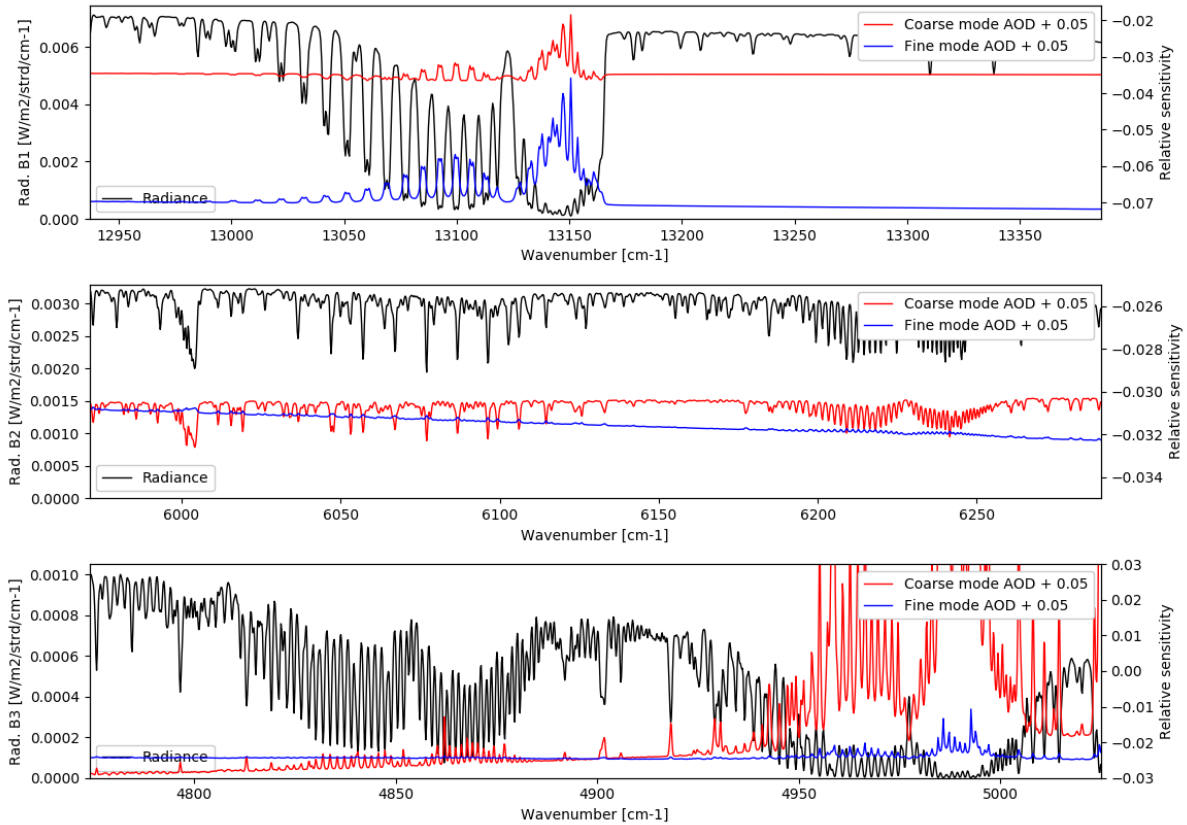


Figure R1.6. Radiance (black, left y-axis) and relative sensitivities to a 0.05 optical depth increase for coarse (red, right y-axis) and fine (blue, right y-axis) modes for all CVAR bands B1, B2 and B3 (top, center and bottom panels, respectively), for the VEG 50° at $\lambda/\Delta\lambda=10000$.

For both resolving power cases, we can notice that coarse mode aerosols produce relative sensitivities with stronger spectral features than fine mode aerosols. The DOFS obtained for coarse mode aerosols at very low resolving power may be explained by these stronger spectral features that bring specific information to the estimation scheme, unlike for fine mode aerosols.

G4: As far as I can tell, the paper currently does not address the accuracy of XCO₂ retrievals as a function of SNR, resolving power and band selection. I believe it would be worthwhile to include this.

Indeed, the scope of this work only includes performance as a posteriori uncertainty given by the \hat{S} matrix (Sect. 4.1.1), and explores smoothing error caused by prior misknowledge of a priori interfering parameters (Sect. 4.2.3 and 4.2.4). Including an actual accuracy assessment would indeed be worthwhile, but would require to extend the scope too much to fit within this publication only, as it would tend towards an actual OSSE. This question could be however be explored in a follow-up study. To manage reader expectations, we propose to better precise the goals of this study and acknowledge this limit in the conclusions, suggesting such a follow-up study on accuracy evaluation.

Lines 106-108	In this work, we perform a systematic survey that synthetically explores the impact of spectral resolution, signal-to-noise ratio (SNR) and spectral band selection, three design parameters for SWIR CO₂ observing satellite concepts , on X_{CO_2} retrieval performance (SNR-related precision, degrees of freedom, vertical sensitivity and smoothing error, excluding accuracy).
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Lines 842-849	Given its scope focused on exploring the impact of concept design parameters on X_{CO_2} retrieval performance, this study could not include all the dimensions of a comprehensive mission performance assessment. For example, the accuracy of X_{CO_2} retrieval has not been studied, and a greater variability of possible atmospheric conditions (different aerosol types, layers, contents, etc., different thermodynamical profiles and CO₂ concentration vertical profiles) could be encompassed, as is usually performed in comprehensive Observing System Simulation Experiment. Besides, this work could not also obviously explore the whole extent of possible design parameters (e.g. band-wise variations of spectral sampling ratios, varying wavelength interval for spectral bands, combination of different instruments, etc.) that impact X_{CO_2} retrieval performance, and its implication for anthropogenic plume imaging. These limitations warrant further studies.
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Minor comments:

M1: In Figure 1, it would be helpful to indicate the FWHM of the band-pass filters of NanoCarb and remind the reader of the FWHM of the NanoCarb bands.

We included these pieces of information in Figure 1 and the FWHM values in the text.

Line 232	... It measures truncated interferograms that are sensitive to four spectral bands, as shown in Fig. 1 right panel, which are associated to narrow-band filters shown in Fig. 1 left panel (follow the arrows). Their FWHMs are 35 cm⁻¹, 24 cm⁻¹, 69 cm⁻¹ and 18 cm⁻¹ for band 1 to 4, respectively. NanoCarb has a two-dimensional field-of-view...
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M2: Section 3.1: Please explain in the text why you confine aerosol particles to the lowermost 4 km of the atmosphere and add details on what kind of aerosol size distributions you used.

This choice is based on Table 2 included in Papayannis et al. (2008) showing that transported desert dust over Europe has a center of mass typically around 3000-3800 m in altitude with layer base altitude values overall comprised between 2000-3000 m and layer top altitude values overall comprised between 4000-5000 m. Papayannis et al. (2008) also show how

variable the layer of transported dust can be and it would definitely be interesting to explore various aerosol content conditions in follow-up studies.

In the revised manuscript, we add the Papayannis et al. (2008) reference and expand on possible further work in the conclusions.

Lines 265-266	... coarse mode aerosols, representative of minerals, are included between 2 and 4 km of altitude (this choice is supported by transported desert dust layers over Europe described by Papayannis et al., 2008).
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Lines 843-846	For example, the accuracy of X_{CO_2} retrieval has not been studied, and a greater variability of possible atmospheric conditions (different aerosol types, layers, contents, etc., different thermodynamical profiles and CO_2 concentration vertical profiles) could be encompassed, as is usually performed in comprehensive Observing System Simulation Experiment.
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Regarding aerosol size distribution, the OPAC library software uses lognormal size distributions. We added this information in the main text.

Lines 313-314	... aerosol optical properties are taken from the OPAC library, which uses lognormal size distributions (Hess et al., 1998).
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M3: Section 3.1: The albedo values you chose for the SWIR seem pretty high in my opinion. Is this really the value over all ASTER samples?

These three albedo models used here were the same that have been used for the initial NanoCarb L2 performance assessment in Dogniaux et al. (2022). They were built from the ASTER spectral library (by co-authors who contributed to Dogniaux et al., 2022), with the ‘soil’ (SOL) model intended as a minimum albedo case and the ‘desert’ (DES) model intended as a maximum case. Figure R1.7 taken from Dogniaux et al. (2021) shows all vegetation ASTER albedo models (thin grey lines) along SOL, VEG and DES albedo models used here, and with retrieved albedo values for all three OCO-2 bands at different TCCON stations (markers). We can see that the retrieved albedo values for OCO-2 bands satisfyingly match values corresponding to a mixture of SOIL and VEG albedo models, as expected considering where TCCON stations are located on Earth. Thus, we think that these three albedo models are realistic enough for the scope of the performance assessment

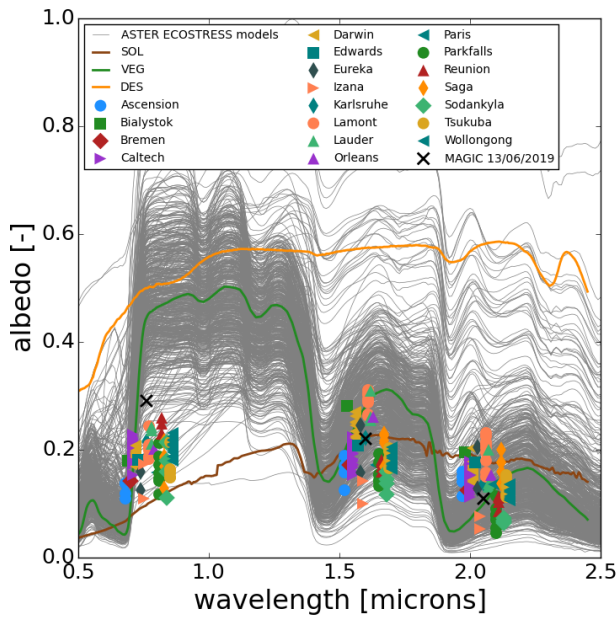


Figure R1.7. Retrieved albedo values for all three OCO-2 bands (markers, distributed over $\pm 0.1 \mu\text{m}$ intervals around actual OCO-2 band locations for readability) for different TCCON stations and OCO-2 target sessions and all ASTER vegetation models (thin grey lines). The models used in this study are shown in colored lines. Figure taken from Dogniaux et al (2021).

M4: Figure S1: It would be useful to magnify the albedo Jacobian for NanoCarb, especially in the context of albedo biases and aerosol retrievals (see above).

We have split Fig. S1 between CO2M and NanoCarb (Fig. S2 in revised Supplements) to provide figures that are easier to read.

M5: Page 7, line 147: add reference for CO2M XCO2 random error value of 0.7 ppm

We have added a reference to Meijer 2020, the CO2M Mission Requirement Document: https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf

Line 179	... aiming to provide an imaging of X_{CO_2} with a random error lower than 0.7 ppm and systematic errors as low as possible (Meijer, 2020).
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M6: Page 9, line 189: add reference for the “latest design of the NanoCarb instrument”

We have added the reference

Lines 227-230	... we use here the latest design of the NanoCarb instrument, currently considered with a $\sim 200 \text{ km}$ swath and a $2.3 \times 2.3 \text{ km}^2$ spatial resolution. The optimal OPD selection accounts for CO2 information entanglements with H2O and aerosols, neglects
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	atmospheric temperature and assumes that albedo is band-wise constant (Gousset et al., 2019).
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M7: Section 2.3: Mention a few more details on NanoCarb so the reader doesn't have to go to other references to find out about the ground sampling distance, swath, etc.

We have added information on swath and spatial resolution in the NanoCarb presentation.

Line 227	As in Dogniaux et al. (2022), we use here the latest design of the NanoCarb instrument, currently considered with a ~200 km swath and a 2.3 x 2.3 km² spatial resolution.
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M8: Section 3.2.2: Why did you use the GEISA 2015 database as opposed to HITRAN (and as opposed to a newer version)?

We chose the GEISA spectroscopic database that has been selected by the French Centre National d'Études Spatiales (CNES) as the reference spectroscopic database for different satellite instruments, including the (thermal) Infrared Atmospheric Sounding Interferometer (IASI) and MicroCarb. Regarding shortwave infrared, Dogniaux et al. (2021) showed that it is possible to obtain fair L2 retrieval results (against TCCON and ACOS columns) from OCO-2 spectra.

Here, GEISA 2015 is used instead of GEISA 2020 because the set of radiative transfer simulations used in this work has been performed while rolling out the newer GEISA 2020 version (Delahaye et al., 2021). We do not expect significant changes for synthetic performance results between both versions.

M9: Section 3.2.2: How about the treatment of the 1.27 μm band and airglow emission? Did you leave it out or did you model it for MicroCarb?

We do not account for Airglow emission in the 1.27 μm band. We added this information in the revised manuscript.

Lines 317-318	Finally, the atmospheric model is discretized in 20 atmospheric layers that bound 19 layers, as done by the ACOS algorithm (O'Dell et al., 2018). Airglow emission which impacts MicroCarb 1.27 μm band (Bertaux et al., 2020) is not included here in 4A/OP simulations.
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M10: Table 4: To which parameter does the following statement refer? "Not included in the state vector for NanoCarb". Please clarify.

This statement refers to 1st order spectral dependence parameter of band-wise albedo models (the band-wise spectral slope of the albedo). It has been left out from the state vector for NanoCarb because its latest design (Gousset et al, 2019) assumed that albedo is band-wise constant, and NanoCarb measurements do not carry information to satisfyingly fit the albedo slope, despite its impacts on retrieved XCO₂ values (not shown). Upcoming developments will explore adjustments to the NanoCarb OPD selection and design to enable the fitting of the spectral dependence of albedo over the wavelengths observed by NanoCarb bands.

In the revised manuscript, Table 4 now includes a reference to Sect 2.3 in this cell, where we extended the text to better explain that the OPD NanoCarb selection was performed assuming constant band-wise albedos.

Lines 328-330	The optimal OPD selection accounts for CO ₂ information entanglements with H ₂ O and aerosols, neglects atmospheric temperature and assumes that albedo is band-wise constant (Gousset et al., 2019).
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Line 347 (Table 4)	Not included in the state vector for NanoCarb case, see Sect. 2.3.
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M11: Page 14, lines 311-313: The XCH₄ biases in Borchardt et al. (2021) are caused by albedo interferences, not by the prior information. Please reword.

Actually, here, we do not refer to the albedo-related interferences reported in Borchardt et al. 2021, but to the – included – vertical averaging kernel correction that is mentioned page 1270 (right column) of their article’s pdf. Citing here:

“The light passed the air mass above the air- craft once on the downward path to the Earth but transected the air mass below the aircraft on both downward and up- ward paths. Consequently, the retrieval was more sensitive to atmospheric changes below the aircraft than above. This was captured by the averaging kernel which represented the sensitivity of the instrument to changes at a specific altitude layer. In our case, strong local enhancements in atmospheric methane were confined below the aircraft, so we multiplied the total column enhancements by the inverse of the averaging kernel for the air mass underneath the aircraft (kAK) to determine the true enhancement of CH₄ caused by an emission source near the ground.”

This correction is described in Krings et al, 2011, in equations 11 and 12. The point we make here is that, similarly to aircraft-based retrievals, the vertical-sensitivity of satellite-based XCO₂ retrievals must be examined and any non-unity sensitivity must be corrected for.

We revised the sentence to better underline that we refer to artefacts caused by non-unity vertical sensitivity, and how the given references relate to this question.

Line 432	Indeed, any deviation from unity in the vertical sensitivity wrongfully scales differences between the unknown truth and the prior into the retrieved column enhancement, thus calling for a posteriori corrections, as presented by (Krings et al., 2011) and also included by (Borchardt et al., 2021) for aircraft observation processing.
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M12: Figure 8: This is related to G1. Your albedo perturbation is not doing anything to the retrieved XCO₂ under any scenario. I think you should introduce a linear or periodic perturbation and observe the effect. This would be a very interesting experiment!

The albedo perturbation is not effect-less, see Figure R1.8 that provides a Zoom for the albedo part of Figure 8, but these effects are very small indeed.

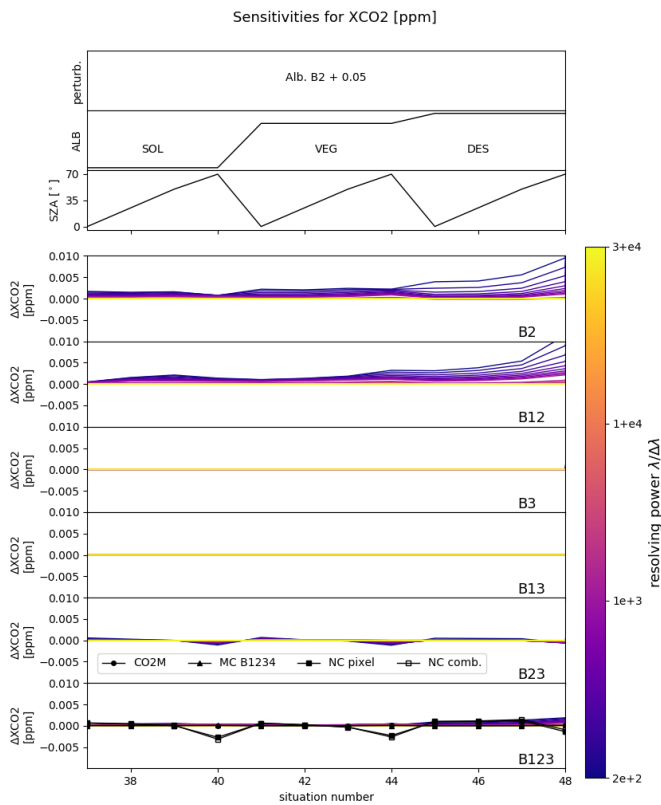


Figure R1.8. Zoomed in the albedo-related section of Figure 8.

We agree that including a linear or periodic perturbation to the albedo would be an interesting experiment. This could be explored in a follow-up study exploring a wide variety of observational situations tending towards the OSSE. Besides, as we cannot fairly explore the effect of albedo spectral dependence with the NanoCarb concept given its design assumptions (see answer to M10), we refrain from addressing this question for the moment.

M13: Figure 3: Maybe add a “disclaimer” to the caption, explaining that NanoCarb is symbolically added at very low resolving power (as in Page 23, lines 503-504).

We added this disclaimer in the revised manuscript for all figures that include NanoCarb markers against spectral resolution. Thank you for this suggestion. (Figures 3, 5 and 6, as well as Figures S4, S5, S10-17)

M14: Page 27, lines 607-608: I am not convinced that this statement is generally true across the resolving power space you explore. Potentially reword.

For reference, the statement lines 607-608 is: “Overall, precision is more easily gained through SNR improvement than through spectral resolution improvements.”

This statement is indeed ambiguous as it does not precise which scale of change is considered here. In the original manuscript, we meant precision gains for the maximum range of change available in the 2-dimensional space (SNR x resolving power) that we explore. Figure R1.9

shows in full lines the Normalized XCO₂ precision improvement for a resolving power (resp. SNR) improvement of 2.2 orders of magnitude (resp. 2.) for all SNR (resp. resolving power) values in red (resp. blue). We note this Normalized XCO₂ precision improvement with G , and have:

$$G = \left(\frac{\sigma_{XCO_2}(x_i)}{\sigma_{XCO_2}(x_j)} \right) / \left(\frac{x_j}{x_i} \right)$$

With σ_{XCO_2} the XCO₂ precision and x , the variable along which we study the improvement, with $x_i < x_j$.

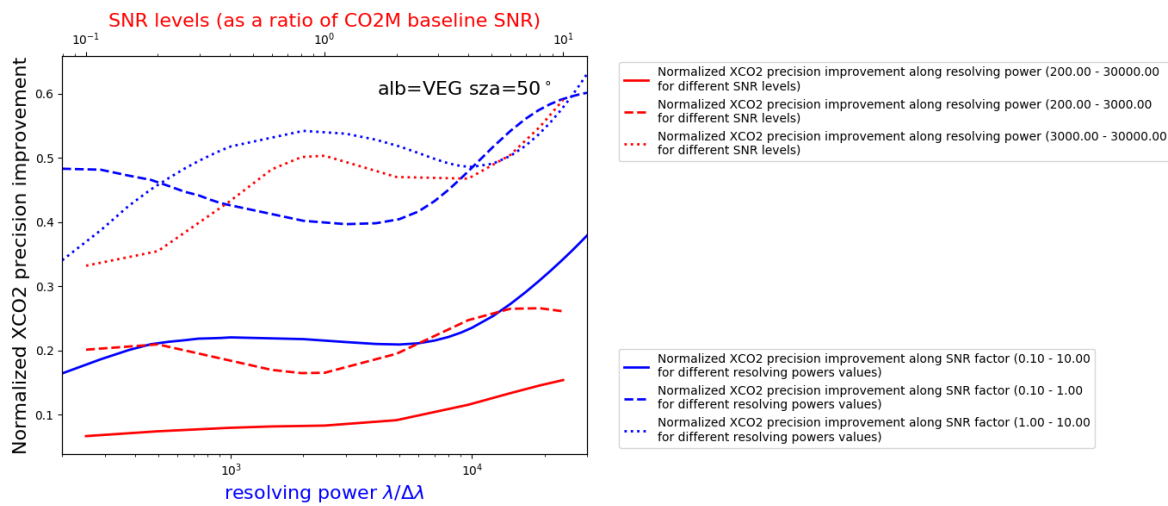


Figure R1.9. Normalized XCO₂ precision improvement (G) for a resolving power (resp. SNR) improvement of different magnitudes (line styles) for all SNR (resp. resolving power) values in red (resp. blue).

We added some precisions in the revised manuscript.

Line 793-794	Overall, for these large changes of about two orders of magnitude , precision is more sensitive to SNR improvement than to spectral resolution improvements.
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However, as the referee guessed, this statement is not true for all ranges of change. Dashed and dotted lines in Figure R1.9 show Normalized XCO₂ precision improvements for changes of an order of magnitude (or slightly more). It is interesting to note that an order of magnitude of improvement in resolving power shows similar improvement in XCO₂ precision as an order of magnitude of improvement in SNR for the higher end of explored resolving power values (dotted red line) only (to be compared to the dashed red line). This is due to the $\lambda/\Delta\lambda \sim 1000 - 4000$ resolving power range where increasing spectral resolution is less efficient to improve XCO₂ precision compared to elsewhere in the explored, as it can be noted on Figure R1.10, that shows local Normalized XCO₂ precision improvement values.

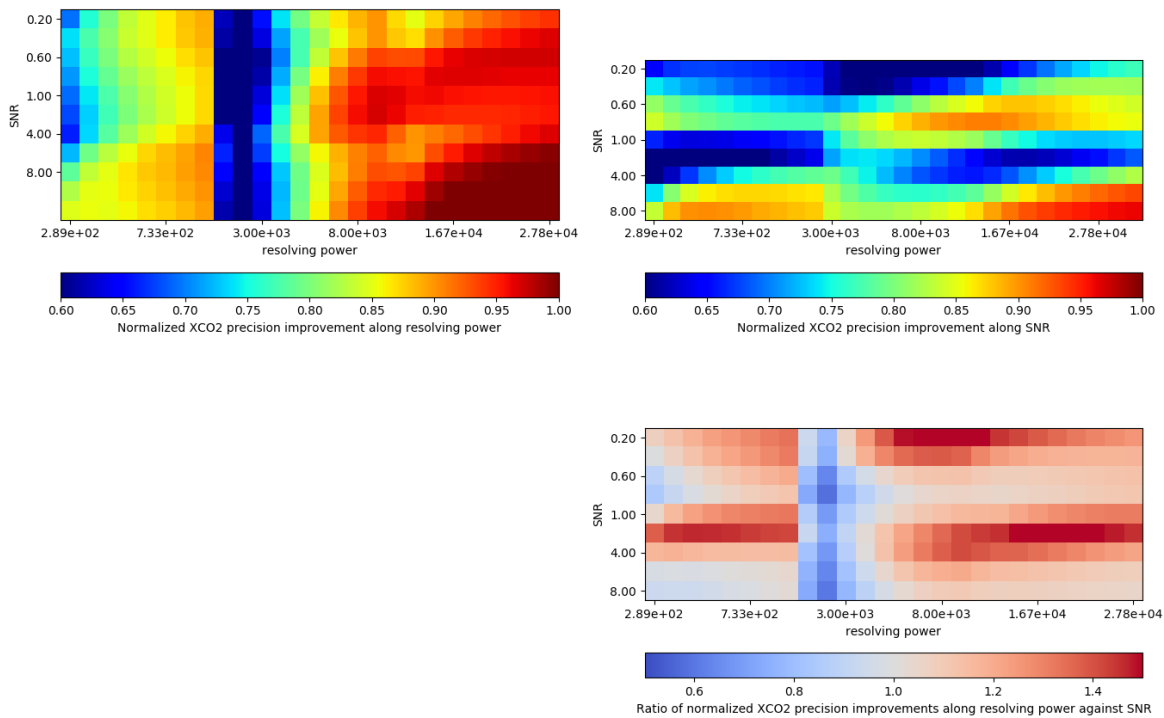


Figure R.10. Local Normalized XCO₂ precision improvement along resolving power (top left) and SNR (top right), and the ratio of these improvements (along resolving power divided by along SNR)

We added some text in the revised manuscript to note this interesting role of the $\lambda/\Delta\lambda \sim 1000 - 4000$ range and added Fig. R1.10 to the Supplements.

Line 392-396	Hence, it appears that X_{CO_2} precision is more sensitive to SNR improvements rather than to resolving power improvements, for large improvements of two orders of magnitude centred on CO ₂ M instrument characteristics. However, as it can be seen in Fig. 3 (and in Supplementary Fig. S3), this conclusion does not hold for smaller local improvements, that generally result in better X_{CO_2} precision gains through resolving power improvements than through SNR improvements (see Supplementary Fig. S3).
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Lines 402-407	it corresponds to the individual spectral lines of CO ₂ becoming clearly visible in spectral band branches, as also commented for Fig. 2. Between these two slope breaks ($\lambda/\Delta\lambda \sim 1000 - 4000$), improvements in resolving power are less efficient in improving X_{CO_2} precision than elsewhere along the resolving power dimension (see Supplementary Fig. S3). This explains why, across the large two order of magnitude improvements in resolving
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	power and SNR explored in this study, SNR has a larger impact on precision than resolving power. This result also underlines the critical importance of resolving new spectral features (the P-R band structure below $\lambda/\Delta\lambda \sim 1000$ or the individual spectral lines above $\lambda/\Delta\lambda \sim 4000$) to gain X_{CO_2} precision efficiently.
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We consequently brought nuance into the conclusions:

Lines 793-795	Overall, for these large changes of about two orders of magnitude, precision is more easily gained through SNR improvement than through spectral resolution improvements. However, we see that small magnitude improvements in resolving power generally yield more X_{CO_2} precision improvements than SNR improvements, especially when CO₂ spectral lines are resolved. The separate
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M15: I find that you could try to summarize your results more concisely in the conclusion: e.g. The SNR-resolving power-space holds very little performance gain for sensors with two SWIR bands, the 2 um CO₂ band carries higher XCO₂ and aerosol DoFS than the 1.6 um band, etc...

We have removed some less essential details from the conclusions (see tracked-changes version of the MS Word document).

Technical comments:

T1: check entire reference list for spelling errors and typesetting issues

We have corrected unresolved LaTeX-related typos not handled by the MS Word Zotero plugin.

T2: Abstract, line 22: perturbing -> perturbing

Corrected, thank you for catching this spelling mistake.

T3: Page 2, line 35: ...carbon cycle compares results... -> ...carbon cycle is based on comparisons of results...

Corrected, thank you.

T4: Page 2, line 44: pioneer -> pioneering

Corrected, thank you.

T5: Page 2, line 59: gather -> are responsible for

Corrected, thank you.

T6: Page 3, line 64: atmospheric schemes -> atmospheric inversion schemes ?

Corrected, thank you.

T7: Page 7, line 165: measure a continuous spectra -> measure continuous spectra

Corrected, thank you.

T8: Page 11, line 246-247: A also enables to compute the ... -> A also enables computation of ...

Corrected, thank you.

T9: Page 11, line 255: layers -> levels

As “levels” is used in the original manuscript and not “layers”, we assume that the referee suggested a change in the other way around, and indeed “layers” is more appropriate than “levels”.

T10: Page 15, line 336: “which sensitivities also correlate” reword

Line 467	This spectral band is indeed sensitive to surface pressure, temperature and aerosols, and can thus bring independent constraint on these geophysical parameters, that show sensitivities that correlate with CO ₂ sensitivity in 1.6 and 2.05 μm bands
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T11: Page 23, line 516: variable Jacobians -> Jacobian variables ?

We refer to both CO₂ and other variables’ partial derivative, so the sentence seems correct as it is. We replace Jacobians to may be ease the understanding:

Line 685	One can indeed notice that CO ₂ and other variables’ partial derivatives are correlated
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