Atmos. Meas. Tech. Discuss., 6, C4505–C4519, 2014
www.atmos-meas-tech-discuss.net/6/C4505/2014/

Atmospheric Measurement Techniques Discussions

AMTD

6, C4505–C4519, 2014

Interactive Comment

Interactive comment on "The impact of spectral resolution on satellite retrieval accuracy of CO_2 and CH_4" *by* A. Galli et al.

A. Galli et al.

andre.galli@space.unibe.ch

Received and published: 26 February 2014

We thank the two referees for their constructive comments. We answer them point by point below, the referees' comments appear in italics. Changes and additions in the revised manuscript with respect to the first submission are typeset as bold in this document and in the manuscript (added as separate pdf file).

Anonymous Referee 1

The paper "The impact of spectral resolution on satellite retrieval accuracy of CO2 and CH4" of Galli et al., submitted for publication in AMT, is addressing an important scientific aspect most notably relevant for future greenhouse gas observing satellites. It investigates to what extent greenhouse gas retrieval accuracy depends on the spec-

tral resolution of the measured radiances. High spectral resolution typically means high costs. Therefore, it is important to know to what extent high spectral resolution is needed. However, spectral resolution is not the only parameter, which determines the accuracy, and potential accuracy loss by lowering spectral resolution may be compensated by optimizing other parameters such parameters which increase the signal-to-noise performance of the instrument. These related aspects are also discussed in this paper at least to some extent. Overall, the manuscript addresses an important scientific aspect not yet discussed in detail in the scientific literature so far and it is well written. I therefore recommend publication after the mostly minor comments listed below have been considered by the authors.

1) *Abstract, page 10401, line 12: Sentence with "turn out to be consistent for the first two approaches": It is not clear from reading only the abstract, which two approaches are meant here.*

We changed the text to: "**The main impacts of degrading the spectral resolution are reproduced for all approaches based on GOSAT measurements;**"

2) *Abstract, page 10401, last sentence: The statement "For both GOSAT and synthetic measurements, retrieval accuracy decreases with lower spectral resolution, suggesting increasing interference errors" may be misleading. To avoid misunderstandings I suggest to add "for a given signal-to-noise performance" or equivalent to clarify that not only spectral resolution is relevant in this context. This remark is also valid for the Conclusions section (e.g., page 10420, line 21 following).*

Done.

3) *Introduction, page 10402, line 4 following: High signal-to-noise performance is also a competing requirement and I suggest to add this information here.*

The sentence now reads as: "**However, good spatial coverage, high spatial resolution, and high signal-to-noise performance are competing requirements for**

AMTD
6, C4505–C4519, 2014

satellite observations, which results in very expensive and complex instrument concepts.”

4) *Introduction, page 10402, line 13 following: OCO-2 and TanSat will not measure CH4. Earth Explorer 8 will very likely be launched a few years after 2018 and Sentinel-5 will not be optimized for CO2. I recommend to modify the corresponding statements to consider this.*

Done.

5) *Section 2.1, page 10406, line 11 following: Sentence ”We therefore verified that the retrieval accuracy did not notably change when the same retrievals were selected for every resolution at a given TCCON station.” Unclear. Please explain what exactly has been verified? Please provide more details on the results obtained.*

The two sentences now read: “The drawback of filtering the data in this manner is that the number of data points varies for runs at different spectral resolution. **We therefore added a filter method for which the same retrievals were selected for every resolution at a given TCCON station (see Section 3.1).**”

6) *Section 2.2, page 10408, around line 13: Sentence “The systematic errors of the retrieval always exceed this precision”. Is this really true (always?)? It seems to be a too simple summary of the detailed results shown later. I recommend to replace this sentence by “In this manuscript we focus on systematic errors as this error source is known to be the most relevant for the targeted application areas (e.g., Basu et al., 2013, and references given therein)” or equivalent.*

The sentences now read as: “**The systematic errors, assessed with TCCON measurements and simulations, usually exceeded the precision. In this manuscript we focus on systematic errors as this error source is the most relevant for the targeted application areas (e.g., Basu et al. (2013), and references given therein).**”

7) *Section 3.1, page 10411, line 28: “weighted by the scatter at each station”. Are the*

weights the scatter or the inverse of the scatter (or something else)?

The text now reads: “The latter is the standard deviation of the six biases, weighted by **the inverse of** the scatter at each station.”

8) *Section 3.1, page 10413, line 16: Please replace “;” by “,” after Guerlet et al., (2013).*

Done.

9) *Section 3.4, page 10417, line 26 following: It is a bit strange that COT is reduced by a factor of 10 because this means that first realistic scenarios have been selected and then these scenarios are artificially modified, which means that the finally used scenarios are not realistic anymore!?*

See our answer 33).

10) *Conclusion, page 10421, line 12: “The two spectral degradation approaches”: Please make this section “stand alone” and explain which two approaches are meant here.*

The section now reads: “**For a given resolution of the degraded spectrum, the convolution approach with an oversampling ratio of 2.5 and the truncation approach with an oversampling ratio of 1.0 yield a similar increase in scatter and decrease of correlation. The particular shape of the ILS and the oversampling ratio are thus of minor relevance compared to the retrieval errors introduced by a reduced spectral resolution.**”

11) *Conclusion, page 10422, last sentence: “to collect more spectra in a given . . . pixel”. Unclear.*

If the same pixel (a 10x10 km footprint for instance) can be covered N times during the same time period (e.g, one month), then the average of the N spectra can be evaluated, which will reduce random errors by a factor of 1/sqrt(N). We formulate this idea as follows: “The impact of random detector noise on retrievals with lower spectral res-

AMTD
6, C4505–C4519, 2014

olution will also be smaller than presented in this paper if the loss in spectral resolution can be traded against additional **measurements of the same area over a given time period.**"

12) *Table 6, page 10432: Please add one column and list the parameter range mentioned in the caption.*

Done.

13) *Figure 7, page 10439: The color bar numbers are hard to read. Please enlarge.*

Done.

14) *Figure 8, page 10440: I recommend to add vertical lines (or equivalent) as otherwise it is difficult to figure out when one year ends and the following one begins.*

Done.

15) *Figure 9: This figure indicates that for "high enough SNR", spectral resolution doesn't matter. Notable accuracy differences only occur for "lower" SNRs. This highlights the importance of the SNR and that spectral resolution is not the only aspect that matters in the context of this study. This needs to be clearly stated in this manuscript to avoid misunderstandings (therefore my corresponding SNR related comments given above).*

In an ideal world of noise-free measurements, spectral resolution may not matter. In the real world, however, reaching SNRs around 1000 (the region between the two columns on the left in Fig. 9) with a space-borne spectrometer is very ambitious. We would not like to go so far as to conclude that for high enough SNR, spectral resolution does not matter. In the conclusions, we state that: "Our study confirms that lowering the spectral resolution of satellite observations decreases retrieval accuracy to a certain extent **for a given signal-to-noise ratio**." (also see Answer 2).

Anonymous Referee 2

Galli et al. 2013 discuss the effect of different spectral resolutions on the accuracy of CO2 and CH4 measurements. They employ two different sets of spectra measured from space by GOSAT. The first set includes measurements collocated to TCCON sites, whereas the second set incorporates measurements over Europe and North-Africa to encompass a greater range of geophysical scenarios. The study is completed by analysing the effect of spectral resolution and different signal to noise ratios (SNR) on the retrieval, which need to be considered together to assess future satellite instrumentation. The investigations discussed in the manuscript are well in the scope of Atmospheric Measurement Techniques. It addresses scientific questions which have to be answered every time a new earth observation mission is prepared and their methodology is sound. The broad range of geophysical scenarios used in all three sets of measurements allows to draw valuable general statistical conclusions. Special interest has been given to study the effect of individual physical parameters like dependencies on water and albedo, the effect of degradation of spectral resolution of individual windows as well as the mitigation of diminished spectral resolution by an increased SNR. The work is fit for publication in AMT with minor comments to be addressed. However, the authors might increase the impact of their work. In its current state, the manuscript is very descriptive. The authors went to great lengths to disentangle the observed dependencies (using single window degradation and synthetic spectra), but the explanation of increased error remains somewhat speculative (spectroscopic errors, mainly for CH4). Some additional elaborating on causes of the observed changes to facilitate a deeper understanding may greatly increase the impact of the work.

General comments

16) *Aerosol size parameter is among the studied parameters, but this one is specific parameter of the RemoTeC algorithm and not generally applied in other retrievals. Since it shows one of the greatest impacts when degrading the spectral resolution, the results may only indicative for other algorithms employing different schemes to deal with aerosols. The authors may want to include a sentence to make the reader aware of*

this, although this is also speculative on the part of the reviewer.

The referee addresses a general problem to what extent the performance analysis of one particular retrieval algorithm can be used to assess a certain measurement concept. The employed RemoTeC algorithm is based on the full phyiscs approach, which is used also by several other algorithms. The retrieval of effective aerosol properties is common to all these algorithms and we are convinced that the conclusions are valid for this type of algorithms. To clarify this we updated the text in Section 3.1 according to: "The retrieved aerosol size parameter strongly correlates with water and airmass of a retrieval scenario at any resolution. A dependency on those parameters will also lead to a dependency on α_{aer}. This is the reason why aerosol size is being used to a posteriori filter the data (Guerlet et al. 2013). **This effect may be restricted to algorithms that retrieve scatterers with a few effective parameters and thus should not be interpreted as general consequence of a lowered spectral resolution.**" However, a comparison of several existing retrieval approach with respect to these findings goes beyond the scope of this study.

17) *For the study of synthetic spectra in Sec. 3.4 / Fig. 9, the authors only describe changes in standard deviation of results but do not give any indication of possible changes in bias. From the following discussion it seems that there is no bias present, but this should be explicitly mentioned or shown with an appropriate figure.*

The bias of synthetic retrievals reacts more sensitively to filter criteria and details of the noise model. Therefore, we did not want to over-interpret the bias results to avoid conclusions that are only valid for the particular setting of our retrieval. In the revised manuscript, we add the following paragraph after introducing Figure 9: "**Contrary to the scatter, the bias of synthetic retrievals also depends on the details of the noise model, i.e., on the functional dependence of SNR with albedo, SZA, and other physical parameters. Under the assumption of a constant SNR for all synthetic observations, a negative XCH4 bias at lower spectral resolution occurs only if noise is added to the spectra. At 1.5 cm-1, the bias reaches -0.3% for**

SNR = 600 and -0.5% for SNR = 300, whereas it remains at +0.1% at 0.25 cm-1 resolution. This behaviour resembles real GOSAT data (see for instance Table 6). The absolute XCO2 bias is smaller than 0.2% for any noise level and spectral resolution."

18) *CO2 shows a peculiar behaviour if one is looking at the results of the data set collocated to TCCON sites: Whereas the expected increase in scatter can be observed while reducing spectral resolution, the bias first shows a strong increase comparing a FWHM of 0.24 cm-1 with 0.5 cm-1, but a subsequent decrease for larger FWHM. This jump in bias can also be observed for CH4 when moving from original ISF to reduced ISF as discussed by the authors on P10412. This is not further discussed, but raises questions of possible errors induced by the convolution, especially because the change in bias is relatively large.*

Bias shifts seem to be more sensitive to the degradation approach and filter criteria than the scatter (see reasoning given in reply to 16 and 17). This makes them hard to interpret in a general manner. For CO2, Table 4 reveals no general trend for lower spectral resolution. First it becomes negative, then it turns positive as the spectral resolution decreases. For CH4, the negative bias shift occurs for any lower resolution at TCCON stations (see Table 5) and all across Europe unless the albedo is very hight (Fig. 7). The negative bias shift is also reproduced with synthetic data, therefore we interpret it as a general consequence of lower spectral resolution. On the other hand, we cannot interpret the CO2 bias in a general manner. The absence of a CO2 shift in synthetic data and in the study by Petri et al. 2012 who relied on TCCON spectra (see comment 28) might indicate that the CO2 bias shifts are specific to GOSAT spectra. But we readily admit that this is speculative. In the second paragraph after Tables 2 to 5 in Section 3.3, we now state: " The bias shift of CH4 is reminiscent of the study by Galli et al. (2012) (...) Nonetheless, substantially degrading the resolution of a spectrum seems to have the general effect of increasing the standard deviation of retrieval errors and of introducing bias shifts on the order of several 0.1%. **Contrary to XCH4, no**

general trend of XCO2 biases with lower spectral resolution can be established."

Minor comments

19) *P10401 L21: please specify "interference errors"*

We now define the meaning of interference errors, and in the section on synthetic retrievals we explain why we primarily attribute the loss of accuracy at lower spectral resolution to interference errors. The text was changed as follows: In Section 1: " Measurements of high spectral resolution are beneficial to reduce errors due to inaccurate spectroscopy and **errors due to interfering retrieval species.**" At the end of Section 2.2: "**The systematic errors, assessed with TCCON measurements and simulations, usually exceeded the precision. In this manuscript we focus on systematic errors as this error source is the most relevant for the targeted application areas (e.g., Basu et al. (2013), and references given therein). Systematic errors can be divided into smoothing errors, model parameter errors (e.g., spectroscopy errors), forward model errors due to the imperfect treatment of scatterers, and interference errors. This distinction follows Sussmann and Borsdorff (2007). They define interference as an error introduced by additional physical quantities that are retrieved together with the target species. The most prominent examples are other molecules, i.e., H2O and CH4 for a CO2 retrieval. In measurements, interference errors of course coexist with other error sources but synthetic measurements allow to disentangle some of them (see Section 3.4).**" In Section 3.4: "The errors that occur in synthetic retrievals originate **from interference errors or** from forward model errors:" "On the other hand, we observed no significant increase of error dependency on physical parameters when we compared synthetic retrievals of the same resolution with and without noise. **A subset of synthetic spectra with very few scatterers (optical thickness below 0.05) shows a similar relative decrease of retrieval accuracy for lower spectral resolution. For XCH4 and SNR = 300, the scatter increases from 0.26% to 0.47% (instead of 0.42% to 0.81%) and the bias shifts by -0.5%. For XCO2 and SNR = 300, the scatter increases from 0.23% to**

AMTD

6, C4505–C4519, 2014

0.44%. This loss of retrieval accuracy must be attributed to interference errors because forward model errors related to scattering are of minor importance for this subset."

20) *P10402 L19-P10403 L2: General specifications of Sentinel 5 are missing here.*

See our answer 4).

21) *P10403 L1-5: The authors should mention that their study can only be indicative for some of the missions due to different wavelength windows (compare e.g. Sentinel 5).*

Done.

22) *P10403 L15: The authors introduce "the first dataset", but do not further elaborate on the other datasets used.*

The paragraph is used to briefly describe TCCON, the three different datasets were mentioned above. We now begin this paragraph with: "**The differences between retrieved greenhouse gas columns from GOSAT spectra and collocated TCCON observations served as our estimate for the absolute accuracy of GOSAT retrievals.**"

23) *P10409 L9: Move definition of collocation to first mentioning*

The entire discussion of collocation criteria is too long to be incorporated into the initial list. Point 1 in the list now reads as: " All GOSAT observations between April 2009 and May 2011 that are collocated **in space and time** (within 5°x5° and two hours) with ground-based observations of the TCCON network."

24) *P10411 L8 Varying number of retrievals for different spectral resolutions: how does this introduce a bias in favour of low resolution?* 25) *P10411 L18 How does the performance at original GOSAT resolution artificially improve because the number of data points drops by 50%? This question also relates to the previous minor comment. This*

AMTD

6, C4505–C4519, 2014

paragraph may need better explanation.

The paragraph now reads as follows: “Tables 2 and 3 summarise the results for our nominal filter method (Guerlet et al., 2013) for CO2 and CH4 , respectively. We used the same filter method as Guerlet et al. (2013) to **compare our results to previous work. Because the filter criteria were identical at all spectral resolutions, the number of included retrievals varied with resolution. The number of converged retrievals (in total and also the fraction inside the filter) dropped by up to 25% when the spectra were degraded from GOSAT resolution down to 1.5 cm-1. This decrease is not a necessary consequence of lower spectral resolution since convergence rates depend on the assumed measurement uncertainty. The truncation approach with a FWHM of 1.2 cm-1 implies slightly larger measurement uncertainties. As a result, it yielded convergence rates similar to the original GOSAT retrievals. The varying number of retrievals may pose a problem for interpretation: any filter that reduces the number of considered retrievals based on fit quality (e.g., residuals, precision, or amount of scatterers) excludes predominantly difficult retrievals with a larger error. By using tighter filter criteria, the error scatter of the remaining retrievals can thus be improved at the expense of number of retrievals. To compare the retrieval accuracy derived with two different algorithms or at different spectral resolutions, the number of included retrievals should always be the same. We therefore added Tables 4 and 5 for a more stringent filter. Here, we culled the filtered datasets to those retrievals that pass the criteria for all resolutions. This gives an unbiased impression on the relative performance degradation with spectral resolution.**”

26) *P10411 L20: Tables 2 to 5 list (... moved to the end of the sentence ...) the retrieval performance for XCO2 or XCH4 for all six TCCON stations...*

Done.

27) *P10412 L7: The change in CO2 bias is described as seemingly random. However,*

a pattern is visible: A strong increase in bias after convolving the spectra to FWHM=0.5 cm-1 with subsequent decrease in bias with increasing FWHM. The reason behind this should be discussed, as it directly relates to the core of the manuscript. 28) *P10412 L18: (comment to the previous point) A shift observed by Petri et al for XCH4 may be indicative, but they observed no shift for XCO2 in contrast to this study.*

See our answer 18).

29) *P10414 L4-7 and Figure3: The differences in global bias with applied method to decrease spectral resolution raises the question how the method affects the retrieval. This is also visible for Fig.3. Although the general trend is the same for both, truncated interferograms and convolution, the differences depicted seem to be on the same order as seen in Fig.4. Also the results of the fits should be added for Fig.3.*

The only difference in Fig. 4 between the blue (truncation with 1.2 cm-1) and the green line (convolution with 1.0 cm-1) is the absolute offset, i.e., the bias. This corresponds to the numbers in Table 4: average bias over Park Falls and Lamont: -0.56% for 1.0 cm-1, -0.73% for 1.2 cm-1, and -0.38% for 1.5 cm-1. The description to Fig. 3 now reads as: "**This is demonstrated by Fig. 3 for the water dependency: over the range from 0 to 2x1023 H2O molecules cm-2, the XCO2 retrieval error increases by 1.18% for 1.0 cm-1, 1.10% for 1.2 cm-1, and by 1.54% for 1.5 cm-1 (the results for the convolution approach correspond to the blue curve in Fig. 4).**"

30) *P10414 L28: Only Figure 5 shows CH4. Maybe it would be better to put the last sentence in the paragraph (dealing with CO2) before this one, which would make the numbering of figures coherent.*

The end of the paragraph now reads as: "**Figures 4 and 5 demonstrate that CO2 dependencies are generally more sensitive to spectral degradation than CH4 dependencies. The only exception is the water dependency, which becomes more pronounced for both absorbers.**"

AMTD

6, C4505–C4519, 2014

31) *P10416 L1: The authors speculate that the different effects of degrading different bands on XCO2 may be explained with the fact that only the SWIR 2 band contains information on scattering by cirrus clouds. However, degrading the SWIR 2 band does not have such a strong effect on the retrieval, and basically none for CH4. If SWIR 2 is also used in the CH4 retrieval, an effect due to aerosol scattering should be apparent in the SWIR 1b band as well, which determines CH4. So it seems that the argument is flawed or should be made clearer.*

We do not entirely understand the referee's counter-argument. Our basic finding is that for a notable impact of spectral degradation, the region of absorption lines of the target species must be affected. For a XCH4 retrieval, the SWIR 2 window is included to obtain scattering information, but there are no CH4 absorption lines in SWIR 2. All we can say (or speculate) from this observation is that retrieving scatterers seems to notably interfere with retrieving greenhouse gases only if the absorption lines of the target species coincide with those of the scatterers.

32) *P10416 L25: The positive bias is indeed the most obvious bias. However, the low amount of coverage over the Sahara raises the question how many retrievals were successful over the desert, given that it is a two year data set. What is the statistical base for this observation?*

16 retrievals below latitude = 33° converged and passed all filters for CO2 and CH4. Nevertheless, the Sahara biases differ significantly from the bias over Europe: $b = +0.5\% \pm 0.1\%$ ($b = -0.4\%$ over Europe) for CH4, $b = +0.7\% \pm 0.1\%$ ($b = +0.2\%$) for CO2. We added these numbers to Section 3.3.

33) *P10417 L27: The restriction of COT to smaller than 0.02 seems reasonable given the filter for real measurements. A problem might be that scenes with a low COT in general will become effectively scenes without cirrus cover. The possibility of introducing a bias might be slim (judging also from the referenced literature), but a check might have been worthwhile.*

AMTD
6, C4505–C4519, 2014

Cirrus usually introduces a negative bias for synthetic retrievals. In the present case, the CO2 bias shifts by -0.1% and the CH4 bias shifts by -0.2% if nominal COT values are assumed instead of reducing them by a factor of 10. The error scatter of course increases (from 0.4% to 0.5% for CO2, from 0.4% to 0.6% for CH4, which is the number also stated by Butz et al. (2012)). The reason for reducing COT was twofold: First, we wanted to compare our results to real GOSAT data where all data with COT > 0.02 were excluded a priori. The second reason was statistics: For nominal COT, the number of retrievals passing all filters at all resolutions and at all noise levels was not sufficient to make a statistically sound statement. In Section 3.4 we now explain: "**A second reason for this reduction was statistics: for nominal synthetic COT, the number of retrievals passing all filters at all resolutions and at all noise levels was not sufficient for a statistically sound statement. Reducing the COT introduced a small bias of +0.1% for XCO2 and +0.2% for XCH4.**"

34) *P10418 L14-....: Discussed and depicted is only the scatter of XCH4 and XCO2 , but not whether or not a bias is introduced. It should be mentioned if the retrieval does not yield any significant bias, or otherwise shown as for the scatter. This important point seems to be implicitly assumed for the following discussion.*

See our answer 17).

35) *P10420 L7: The discussion is valid as long as the only errors present are spectroscopic and calibration errors. Other errors present may be, e.g., radiative transfer induced due to simplified aerosol representation, cirrus, etc. Then the discussion and its conclusion is indeed misleading.*

We have created (Butz et al. 2012) synthetic spectra from radiative transfer with scatterers that is much more complex than the retrieval forward model with its three parameters. We therefore think that the contribution of the forward model error to synthetic retrievals is comparable to the one for real measurements. Also refer to our answer 16).

AMTD

6, C4505–C4519, 2014

36) *P10421 L6: see previous comment on the effect of aerosol scattering.*

See our answer 31).

37) *P10421 L12-15: The paragraph may be moved forward to follow the structure of the manuscript and most results are only discussed for the convolution.*

Done. Also see our answer 10).

Please also note the supplement to this comment:
http://www.atmos-meas-tech-discuss.net/6/C4505/2014/amtd-6-C4505-2014-supplement.pdf

---

Interactive comment on Atmos. Meas. Tech. Discuss., 6, 10399, 2013.