

This discussion paper is/has been under review for the journal Atmospheric Measurement Techniques (AMT). Please refer to the corresponding final paper in AMT if available.

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

The impact of spectral resolution on satellite retrieval accuracy of CO₂ and CH₄

A. Galli^{1,2}, S. Guerlet³, A. Butz⁴, I. Aben¹, H. Suto⁵, A. Kuze⁵, N. M. Deutscher^{6,7}, J. Notholt⁶, D. Wunch⁸, P. O. Wennberg⁸, D. W. T. Griffith⁷, O. Hasekamp¹, and J. Landgraf¹

¹SRON Netherlands Institute for Space Research, 3584 CA Utrecht, the Netherlands

²Physics Institute, University of Bern, 3012 Bern, Switzerland

³Laboratoire de Météorologie Dynamique, 75252 Paris, France

⁴Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, 76344 Leopoldshafen, Germany

⁵Japan Aerospace Exploration Agency, Tsukuba, Ibaraki 305-8505, Japan

⁶Institute of Environmental Physics, University of Bremen, 28334 Bremen, Germany

⁷Centre for Atmospheric Chemistry, University of Wollongong, Wollongong, NSW 2522, Australia

⁸Department of Earth Science and Engineering, California Institute of Technology, Pasadena, CA 91125, USA

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Received: 15 November 2013 – Accepted: 28 November 2013 – Published: 4 December 2013

Correspondence to: A. Galli (andre.galli@space.unibe.ch)

Published by Copernicus Publications on behalf of the European Geosciences Union.

AMTD

6, 10399–10441, 2013

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

The Fourier-transform spectrometer on board the Japanese GOSAT satellite offers an excellent opportunity to study the impact of instrument resolution on retrieval accuracy of CO₂ and CH₄. This is relevant to further improve retrieval accuracy and to optimize the cost-benefit ratio of future satellite missions for the remote sensing of greenhouse gases. To address this question, we degrade GOSAT measurements with a spectral resolution of $\approx 0.24 \text{ cm}^{-1}$ step-by-step to a resolution of 1.5 cm^{-1} . We examine the results by comparing relative differences at various resolutions, by referring the results to reference values from the Total Carbon Column Observing Network (TCCON), and by calculating and inverting synthetic spectra for which the true CO₂ and CH₄ columns are known. The main impacts of degrading the spectral resolution turn out to be consistent for the first two approaches; pure forward model errors identified with simulated measurements are much smaller.

For GOSAT spectra, the most notable effect on CO₂ retrieval accuracy is the increase of the standard deviation of retrieval errors from 0.7 % to 1.0 % when the spectral resolution is reduced by a factor of six. The retrieval biases against atmospheric water abundance and airmass become stronger with decreasing resolution. The error scatter increase for CH₄ columns is less pronounced. The selective degradation of single spectral windows demonstrates that the retrieval accuracy of CO₂ and CH₄ is dominated by the spectral range where the absorption lines of the target molecule are located. For both GOSAT and synthetic measurements, retrieval accuracy decreases with lower spectral resolution, suggesting increasing interference errors.

1 Introduction

Carbon dioxide (CO₂) and methane (CH₄) are the two most important anthropogenic greenhouse gases. Remote sensing of these gases with satellites allows us to globally monitor their atmospheric abundance. Both trace gases have to be retrieved with high

AMTD

6, 10399–10441, 2013

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



degraded. Section 3.3 summarizes the results for the European dataset, and Sect. 3.4 summarizes the results from synthetic retrievals. Section 4 will conclude the paper with recommendations for future satellite missions.

2 Data selection and retrieval method

2.1 Retrieval algorithm

To retrieve CO₂ and CH₄ from the GOSAT spectra, we used version 1.9 of the RemoTeC algorithm. The first version of the algorithm was described by Butz et al. (2011) in the context of GOSAT measurements and by Butz et al. (2010) in the context of synthetic spectra. The algorithm is based on the efficient radiative transfer model developed by Hasekamp and Butz (2008). From the measured radiances in one or several spectral windows, the algorithm simultaneously retrieves 12-layer profiles of CO₂ and CH₄ column densities along with other absorber species (water), surface albedo, spectral shifts, intensity offsets, and three effective aerosol parameters to describe the scattering properties of the atmosphere. The latter are the mean height of the scattering layer h_{aer} , the size parameter of the power-law distribution α_{aer} , and the total column number density of aerosols. Scattering particles are parametrized as spherical particles with a fixed refractive index ($1.400i \times 0.003$), and their size distribution follows a power law, $n(r) \sim r^{-\alpha_{\text{aer}}}$, with r the particle radius. In the forward model, the aerosols exist in a single scattering layer with a Gaussian height distribution around the central height h_{aer} . Molecular absorption lines of O₂ and CO₂ are modelled by a spectroscopic model that includes line mixing as well as collision-induced-absorption by O₂ (Tran and Hartmann, 2008; Lamouroux et al., 2010). Absorption by CH₄ and the interfering absorber H₂O is modelled by Voigt line-shape models based on HITRAN 2008 (Rothman et al., 2009). Since 2010, the RemoTeC algorithm has been improved in several ways. The version used for this study is described by Guerlet et al. (2013).

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Total columns of CO₂ and CH₄ in units of molecules cm⁻² were the prime targets of the retrieval. After the retrieval converged, they were calculated as the sum of the retrieved absorber profile. When volume mixing ratios XCO₂ and XCH₄ were required (for comparison to TCCON values), the total columns were divided by the total dry airmass. The latter was not retrieved from the measurements; it was taken from values provided by the European Centre for Medium–Range Weather Forecasts (ECMWF). In this paper, we will always use volume mixing ratios to quantify retrieval accuracy.

GOSAT measurements with a cloud coverage larger than 5% in the outer field-of-view were a priori rejected. This information is provided by the separate Cloud and Aerosol Imager on board the GOSAT satellite. Apart from clouds, also low albedo or high scattering optical thickness can introduce systematic retrieval errors. To achieve a better retrieval accuracy, it is therefore necessary to filter the converged retrievals as well. Most inversions of GOSAT spectra converge to yield a result (80% in the case of Europe from 2009 to 2011) but roughly half of these results should be excluded from further analysis because they are likely to exhibit large errors. Guerlet et al. (2013) experimented with different filters to selectively reject retrievals based on the retrieved parameters. In the present study, we adopted their most stringent a posteriori filter to quantify retrieval accuracy. The information required for this filter is supplied by the retrieval algorithm. No further model input or observations with different instruments (that may or may not be available for other satellite missions) is required. The filter operates independently for each spectral resolution. It reads:

- a. $\chi^2/\text{DFS} < 2 \times \text{Median}(\chi^2/\text{DFS})$
- b. DFS of target species > 1.0
- c. number of iterations < 11
- d. $\sigma_{\text{CO}_2} < 0.3\%$, $\sigma_{\text{CH}_4} < 0.5\%$
- e. $\tau_{\text{aer}} < 0.25$

f. $3.0 < \alpha_{\text{aer}} < 4.7$

g. $\tau_{\text{aer}} h_{\text{aer}} / \alpha_{\text{aer}} < 300 \text{ m}$

h. $-1 \times 10^{-9} < \text{intensity offset at O}_2 \text{ A band} < 7 \times 10^{-9}$

The filter makes use of fit residuals (χ^2 normalized by degrees of freedom), degrees of freedom for signal (DFS), number of iterations, relative precision of retrieved absorbers (σ_{CO_2} and σ_{CH_4}) derived from covariance matrix, retrieved aerosol optical thickness, retrieved aerosol load (τ_{aer} is the retrieved optical density at the O₂ A band, α_{aer} is the aerosol size parameter), and retrieved intensity offset. In case of a lowered resolution, the cut-off values for the precision (criterion d) are scaled by the worse average precision. 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 verified that the retrieval accuracy did not notably change when the same retrievals were selected for every resolution at a given TCCON station.

GOSAT spectra affected by cirrus optical thickness (COT) larger than about 0.02 can be rejected a priori with the approach presented by Guerlet et al. (2013). For synthetic scenarios, the input COT was therefore reduced accordingly (see Sect. 3.4).

2.2 GOSAT spectra and spectral degradation approaches

Table 1 summarises the four spectral windows covered by GOSAT observations that are used by our retrieval algorithm. The spectral ranges will be kept fixed throughout the study.

The instrument line shapes (ILS) of the GOSAT spectra and of the two different degradation approaches are illustrated in Fig. 1. An example of a GOSAT spectrum (SWIR1a window from 6170 to 6277.5 cm⁻¹) at original (black line) and at 1.5 cm⁻¹ resolution (red line) is shown in Fig. 2. The first approach consisted of convolving the GOSAT spectra with a Gaussian instrumental line shape of a FWHM broader than the original FWHM. The effective FWHM of the resulting ILS was then considered the

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



spectral resolution of the degraded spectrum. The broader the FWHM of the convolution compared to the GOSAT ILS, the closer the new line shape resembles a Gaussian shape (see red line in Fig. 1). The retrieval is not limited to any specific line shape, since the forward model spectrum is subjected to the same convolution before it is compared to the degraded input spectrum. As an independent degradation approach, we truncated the original interferograms with a five times smaller optical path distance than the default. This is mathematically equivalent to convolving the spectrogram with a sinc ILS (see dashed blue line in Fig. 1). The effective FWHM of the truncation approach amounts to 1.2 cm^{-1} . For the convolution approach, the oversampling ratio was 2.5 for all windows, for the original GOSAT spectra and the truncation approach it was 1.0. Varying the oversampling ratio between 1.0 and 3.0 for the convolution approach did not notably affect the retrieval accuracy beside shifting the global bias (by 0.2 % at most).

The two approaches reflect different instrument concepts. Convolution with a Gaussian emulates the instrument properties of a grating spectrometer as employed for OCO, Sentinel-5, and CarbonSat, whereas the truncated interferogram provides the spectral reflectance from a Fourier transform spectrometer. The second approach also allowed us to verify that the decrease in retrieval accuracy is driven by the spectral resolution and does not depend on the degradation method. After this verification, the first approach was chosen as default method for the rest of the study.

The measurement noise of the degraded spectra were deduced from the measurement noise of the original GOSAT measurement. No extra noise was added to the degraded spectra. The measurement uncertainty of each spectral point is needed at all resolutions to invert the spectra. For GOSAT spectra, the SNR is 300, defined under conditions of a diffusive reflectivity of 30 % at a solar zenith angle (SZA) of 30° (Kuze et al., 2009). The measurement uncertainty of the spectrum is derived from this SNR assuming a shot-noise limited instrument model. The SNR of the degraded spectra is scaled from the original spectra by interpreting the convolution as a running average over the spectrum. This implies the same optical throughput of the instrument per pixel

independent of the sampling. Since the absolute uncertainty of the original spectrum is almost constant against wavenumber, quadratic error propagation leads to

$$\sigma_{\text{deg}} = \sigma \sqrt{\frac{\text{FWHM}}{\text{FWHM}_{\text{deg}}}} \quad (1)$$

for the measurement uncertainty of the degraded spectrum. This ensures that the square sum of fit residuals as well as the precision of the retrieved CO₂ and CH₄ columns do not vary by more than a factor of two for all spectral resolutions. For the spectra generated from the truncated interferogram, the measurement error was estimated from GOSAT level-1 processing. From the measurement uncertainties, the typical relative precision of retrieved columns calculated to $\sigma_{\text{CO}_2} = 0.2\%$ and $\sigma_{\text{CH}_4} = 0.4\%$ for GOSAT resolution. For the lowest spectral resolution of 1.5 cm⁻¹, the precision decreased to $\sigma_{\text{CO}_2} = 0.3\%$ and $\sigma_{\text{CH}_4} = 0.6\%$. These values were only relevant for the a posteriori filter criteria. The systematic errors of the retrieval always exceed this precision. To assess the latter, we relied on TCCON measurements and simulations for which the true CO₂ and CH₄ columns were known.

2.3 Selection of datasets

We prepared and evaluated three datasets for this study.

1. All GOSAT observations between April 2009 and May 2011 that are collocated (within 5° × 5° and two hours) with ground-based observations of the TCCON network.
2. The same 25 months, but for all of Europe and Northern Africa without TCCON reference values. This comprises roughly 12 000 GOSAT observations. We chose these regions for their high variability in solar zenith angle and albedo (including partly snow covered scenes and desert).

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the ground albedo (Guerlet et al., 2013). Second, the statistics necessary for correlation studies and to assess inter-station biases are limited because only six TCCON stations offer a reasonably large amount of collocated TCCON and GOSAT observations since the start of GOSAT in 2009. Third, any definition of collocation is somewhat arbitrary (as discussed by Guerlet et al., 2013). Therefore, we also introduced datasets 2 and 3 and studied the relative changes of retrieved CO₂ and CH₄ for the whole European continent (offering many more data points) and the retrieval accuracy without spectroscopic errors for the case of synthetic data.

3 Results

This section provides the results for the different datasets defined in Sect. 2.3. We first present the comparison of GOSAT retrieval results and TCCON reference values for different spectral resolution (Sect. 3.1). This step also serves to verify that our results agree with previous work on GOSAT retrievals. We then proceed with two further approaches, degrading only single spectral windows (Sect. 3.2) and using a wider observation range without TCCON reference values (Sect. 3.3). Section 3.4 on synthetic spectra completes the results section.

3.1 Retrievals at TCCON stations

Following previous studies on GOSAT retrieval performance (Butz et al., 2011; Morino et al., 2011; Parker et al., 2011; Wunch et al., 2011b; Reuter et al., 2011; Schepers et al., 2012; Oshchepkov et al., 2013; Guerlet et al., 2013) we rely on results obtained at TCCON stations to assess retrieval accuracy in absolute terms. The main drawback for this approach is that only a small fraction of all GOSAT measurements can be used for such an assessment. We therefore check if the results observed at the six TCCON stations (Park Falls, Lamont, Orléans, Białystok, Darwin, and Wollongong)

in this section can be reproduced when we extend the observations beyond TCCON locations (Sect. 3.3).

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 and to give a realistic impression of what the retrieval accuracy at different spectral resolutions looks like. The disadvantage of this comparison is the varying number of included retrievals for differing resolution, which might introduce a statistical bias in favour of the low resolution datasets: 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. Because of the varying size of datasets in Tables 2 and 3, we added Tables 4 and 5. 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. On the other hand, the performance at original GOSAT resolution artificially improved because the number of data points dropped by 50 %.

Tables 2 to 5 list for all six TCCON stations (columns) and for all spectral resolutions (rows) the retrieval performance for XCO₂ or XCH₄. The three numbers in a cell indicate, from top to bottom, the number of converged retrievals inside the filter, the standard deviation of relative retrieval errors compared to TCCON reference values in %, and the median of the relative retrieval error in %. The second number will be referred to as scatter σ , the last number will be referred to as bias b . The last column summarises the performance for all six TCCON stations, indicating total number of retrievals, average scatter $\langle\sigma\rangle$, average bias $\langle b\rangle$, and the inter-station bias σ_b . The latter is the standard deviation of the six biases, weighted by the scatter at each station.

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The main effect of the lower resolution on XCO₂ accuracy is the increase in error scatter. It increases continuously with decreasing spectral resolution by a factor of 1.5 from GOSAT resolution to the 1.5 cm⁻¹ resolution. This holds true for both data selection methods (last columns in Tables 2 and 4). The increase of the XCH₄ error scatter is more modest. For the filter method used by Guerlet et al. (2013), $\langle\sigma\rangle$ increased from 0.85 % to 1.03 % (last column in Table 3), for the reduced number of retrievals (Table 5), $\langle\sigma\rangle$ increased from 0.81 % to 0.97 %. The average retrieval bias of XCO₂ changed in a seemingly random pattern by a few 0.1 % for each step to lower resolution, whereas the inter-station bias σ_b hardly increased from typically 0.2 % to 0.3 %. For XCH₄, the change in mean bias by -0.4 % appeared at all lower resolutions except for the truncation approach (but even here, a negative shift was observed).

The bias shift of CH₄ is reminiscent of the study by Galli et al. (2012) done for the 4190–4340 cm⁻¹ spectral range. They showed that degrading TCCON spectra from a resolution of 0.02 cm⁻¹ to 0.45 cm⁻¹ introduces a CH₄ retrieval bias of 0.5%. The results in Tables 2 and 3 are also consistent with Petri et al. (2012) who compared the measurement accuracy of the TCCON interferometer to a lower resolution interferometer with a FWHM of 0.11 cm⁻¹. They found that reducing the resolution of TCCON spectra introduced an XCH₄ offset of 0.26 %, whereas it was negligible for XCO₂. The authors speculated that this dependence on spectral resolution is caused by inaccurate prior profiles and/or inaccurate spectroscopy of CH₄ or interfering gases. Moreover, Petri et al. (2012) estimated the error scatter of retrieved CO₂ and CH₄ columns from the daily standard deviation of individual measurements. It was larger for the lower-resolution spectrometer than for the TCCON type of instrument. The relative increase amounted to a factor of 1.4 for XCO₂ and a factor of 1.9 for XCH₄. This increase is not identical to our results, since the spectral resolution, the retrieval ranges and the observation geometry (backscattered sunlight in contrast to the direct solar ground-based observations considered by Petri et al., 2012, and Galli et al., 2012) differ. 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 %.

For the collocation criterion used in our study, Guerlet et al. (2013) found (their Table 2, right column) $\langle b \rangle = -0.36\%$ and $\langle \sigma \rangle = 0.65\%$ (2.5 ppm) for 12 TCCON stations between April 2009 and December 2010 for XCO₂. This agrees well with the values in Table 2 of $\langle b \rangle = -0.53\%$ and $\langle \sigma \rangle = 0.65\%$. The small change in bias is due to the TCCON reference values. In October 2012, an improved TCCON data release became available on <http://tccon.ipac.caltech.edu/> (software version GGG2012 instead of GGG2009). In this paper we used these more recent values, whereas the values presented by Guerlet et al. (2013) refer to the older version GGG2009. The only notable difference between old and new TCCON results is a constant shift of XCO₂ by -0.125% . Guerlet et al. (2013) derived an inter-station bias of 0.24 %, defined as standard deviation of the 12 biases weighted by the scatter at each station. In our study, the inter-station bias shows little sensitivity, increasing only from 0.22 % to 0.32 % as spectral resolution decreases.

In contrast to Guerlet et al. (2013); Butz et al. (2011) also compared XCH₄ results of GOSAT retrievals to TCCON values. They used the same six TCCON stations as in this study but their database only extended to summer 2010, and their results were obtained with an older version of the RemoTeC software. Nevertheless, their mean scatter of 0.015 ppm (0.85 % relative error) and mean bias of -0.34% agree well with our study ($\langle \sigma \rangle = 0.85\%$ and $\langle b \rangle = -0.33\%$ according to Table 3). The increase of inter-station bias with lower resolution is statistically significant at a 99.5 % confidence level for both data filtering methods (Tables 3 and 5). For a larger set of twelve TCCON stations, Schepers et al. (2012) found a larger (at GOSAT resolution) inter-station XCH₄ bias of $\sigma_b = 0.24\%$, whereas their $\langle \sigma \rangle = 0.95\%$ and $\langle b \rangle = -0.37\%$ are similar to this study.

The method of spectral degradation (i.e., convolution vs. truncation) did not affect the retrieval performance: the error scatter of CO₂ and CH₄ columns for the truncation method (fourth rows in Tables 4 and 5) fits well to the results for similar resolutions

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(third and fifth rows of same tables). The only change is seen in the global bias. We also examined if the correlation of retrieval errors with light path and atmospheric parameters are comparable if identical retrievals from Park Falls and Lamont are selected. For both CO₂ and CH₄, the dependency of retrievals on water, SZA, and albedo for the truncated interferograms followed exactly the trend set by the convolution retrievals at similar resolutions. This is demonstrated by Fig. 3 for the water dependency. For the rest of this work, we will therefore concentrate on the convolution approach.

To study the dependence of CO₂ and CH₄ retrieval errors on physical parameters, we calculated linear regressions of the retrieval differences (with respect to TCCON reference values) as a function of atmospheric water abundance, airmass, surface albedo at the SWIR1b window, retrieved aerosol optical thickness at the O₂ A band, and aerosol size parameter ($1/\alpha_{\text{aer}}$). The airmass of an observation is related to the SZA and the VZA (viewing zenith angle) via $1/\cos(\text{SZA}) + 1/\cos(\text{VZA})$. 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). Figures 4 and 5 present the results as slope of the linear regressions ($\pm 1\sigma$ -uncertainty) for the four different resolutions available at all six TCCON stations. If the slope is zero within its uncertainty, the retrieval error does not significantly depend on the corresponding parameter. An increase in the slope with decreasing resolution means that accuracy becomes worse as the retrieval errors correlate more strongly with physical parameters. All slopes were evaluated to span the maximum parameter range that can be encountered for GOSAT retrievals passing the a posteriori filter. These ranges are: water – from 0 to 2×10^{23} molecules cm⁻², airmass – from 2.0 to 4.0, albedo – from 0.1 to 0.4, retrieved optical thickness – from 0 to 0.25, inverse of the aerosol size parameter – from 1/4.7 to 1/3.0 (by definition of the a posteriori filter). This way, slopes for different physical parameters can be directly compared to each other. Figures 4 and 5 demonstrate that CH₄ dependencies are generally less sensitive to spectral degradation. The only exception is the water dependency, which

becomes more pronounced for both absorbers. For CO₂, albedo, airmass, and aerosol size parameter also show a stronger dependency as spectral resolution decreases.

3.2 Single window degradation

To determine the spectral windows that are more severely affected by spectroscopic or interference errors, we also degraded single windows. We repeated the retrievals at the six TCCON stations degrading only one of the four retrieval windows to 1.5 cm⁻¹ resolution. The results of this selective degradation are shown in Fig. 6. The upper panel shows the change of error scatter (σ) relative to the retrieval results at GOSAT resolution in all windows. The lower panel shows the absolute change in bias (b). Only those retrievals were used that passed the a posteriori filters for every spectral resolution scenario. The total number of filtered retrievals varied by up to 20 % for different scenarios and absorbers but no clear correlation with retrieval accuracy was visible.

For XCH₄, the picture is simple. Only when the SWIR1b window (6045–6138 cm⁻¹) was degraded, did the negative shift in bias and the increase in scatter occur. In that case also the dependency of retrieval error on water abundance became stronger whereas the dependency remained at the level found for original GOSAT resolution for the three other scenarios. This indicates that the CH₄ and H₂O spectroscopy in the 1.6 μm range might still benefit from improvements. For XCO₂, the bias most markedly increased when the SWIR1a window (6170–6277.5 cm⁻¹) was degraded, whereas the scatter increased to a similar extent when the SWIR1a or the SWIR2 window were degraded.

This reflects the position of CO₂ absorption lines in SWIR1a and SWIR2 and strong CH₄ absorption lines in SWIR1b (Rothman et al., 2009). In contrast, degrading the O₂ A window had a rather small effect on the retrieved columns. Our results imply that a degradation of the SWIR2 window does not affect XCH₄ retrieval accuracy because no CH₄ absorption lines are present. Aerosol parameters were apparently retrieved at a similar accuracy for the SWIR2 degradation scenario as for the non-degraded case,

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



by Schepers et al. (2012) and Guerlet et al. (2013). Our study shows that this bias becomes stronger at lower resolution.

The relative change in XCO_2 and XCH_4 dependencies on physical parameters between GOSAT and 1.5 cm^{-1} resolution follows the results obtained at the six TCCON stations (see Figs. 4 and 5). Degrading the spectral resolution introduced a positive XCO_2 dependency on water and a negative XCO_2 dependency on airmass. Table 6 lists the complete results of XCO_2 and XCH_4 dependencies. XCO_2 results at lower resolution depend on water, airmass, and aerosol size parameter. XCH_4 retrieval differences correlate with water abundance.

The combination of water and airmass dependency results in a seasonal bias of XCO_2 differences. This is demonstrated in Fig. 8. During summer, the water content of the atmosphere is high and the airmass of the observations is lower than in winter. The absence of a strong XCH_4 dependency on airmass probably explains why the seasonal XCH_4 bias is weaker. We fit a harmonic bias with a constant frequency of $\omega = 2\pi/365\text{ days}^{-1}$. The amplitude of this bias calculates to 0.29 % for XCO_2 . The $1-\sigma$ probability interval of the amplitude calculates from F-statistics to 0.18 %. For XCH_4 , the amplitude of the seasonal bias only reaches 0.11 % and is not significant with respect to a $1-\sigma$ confidence level.

3.4 Synthetic spectra

To complete the examination of spectral degradation, we calculated synthetic spectra at GOSAT resolution and degraded them again to 1.5 cm^{-1} resolution. We did this for the 11 036 scenarios of the global ensemble defined by Butz et al. (2012). They cover the entire land surface at an $SZA \leq 70^\circ$ for four days in January, April, July, and October. The synthetic scenarios include a realistic range of aerosol and cirrus optical properties. Since cirrus pre-filtering (see Sect. 2.1) allows us to exclude GOSAT observations with a COT larger than 0.02, we reduced the COT of all scenarios by a factor of ten, such that 97 % have $COT < 0.02$. Restricting retrievals to those scenarios whose

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



COT is smaller than 0.02 in the first place would result in insufficient statistics. In this section, retrieval errors represent the relative deviation of the retrieved column density of CO_2 and CH_4 from the true input column density. Contrary to real measurements, synthetic retrievals are not affected by spectroscopic errors or calibration errors. The errors that occur in synthetic retrievals originate from forward model errors; the treatment of scattering effects for radiative transfer in the retrieval algorithm is much simpler than the one used to simulate the measurement. A second source of errors is the noise. By default, we add Gaussian distributed noise to the calculated input spectrum; the noise amplitude is determined by the noise model. We reproduced GOSAT instrument performance assuming a $\text{SNR} = 300$ at the continuum and holding the absolute measurement uncertainty constant at each spectral entry. In addition, we retrieved the same synthetic spectra with reduced noise ($\text{SNR} = 600$) and without any noise to isolate the pure forward model error in the absence of statistical errors.

The first approach with adding noise is the one chosen by Butz et al. (2012) for determining the XCH_4 retrieval accuracy of a GOSAT-like instrument for a similar global ensemble. They used an earlier version of the RemoTeC algorithm with a different regularization scheme and found $\langle \sigma \rangle \approx 0.6\%$ for CH_4 errors. The synthetic error scatter of CH_4 reaches only $\approx 0.4\%$ in the present study because of the lowered COT.

Figure 9 summarizes the retrieval accuracy of XCO_2 (cross and plus symbols) and XCH_4 (squares and circles) for synthetic scenarios. Black symbols denote GOSAT resolution, red symbols denote 1.5 cm^{-1} resolutions. In the left column, the scatter $\langle \sigma \rangle$ is shown for noiseless synthetic spectra. All four standard deviations fall between 0.2% and 0.3%. The XCO_2 scatter increases to some extent when the spectral resolution is lowered (from 0.20% to 0.28%); the XCH_4 scatter remains constant at 0.23%. These small errors can be interpreted as the limit of accuracy with the present algorithm and forward model. This limit is of the same order of magnitude as the retrieval precision for GOSAT spectra. The second column shows the retrieval performance if noise is added but a very high SNR of 600 is assumed. The third column shows the synthetic retrieval results with a noise model representative to GOSAT data ($\text{SNR} = 300$). For this

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



nominal synthetic scenario, we observe an increase of the error scatter when the spectral resolution is lowered: $\langle\sigma\rangle$ of XCO_2 increases from 0.40 % to 0.69 %, $\langle\sigma\rangle$ of XCH_4 almost doubles 0.42 % to 0.81 %. The errors are the combination of forward model errors and statistical errors. The right column shows the retrieval accuracy found for GOSAT spectra at original and at lowered resolution.

All twelve $\langle\sigma\rangle$ values for synthetic spectra can be directly compared with each other, since we culled the results to the same total amount of 1000 filtered retrievals. The filter method was identical to the one employed for GOSAT measurements (cf. Sect. 2.1) with the following exceptions: the offset criterion was dropped because we did not introduce spectral shifts or offsets or any calibration errors when calculating input spectra. The thresholds for χ^2/DFS and $\sigma_{\text{CO}_2}, \sigma_{\text{CH}_4}$ were adapted to have the same number of filtered retrievals for all synthetic results. For a realistic noise-model, χ^2/DFS typically reached 0.9 (at GOSAT resolution) instead of the 2.0 encountered for GOSAT spectra. This increase of the fit residuals by a factor of two is likely caused by spectroscopic errors.

We interpret the results shown in Fig. 9 as follows: if spectroscopic errors are absent, and a perfect instrument were available, retrieval accuracy does not notably depend on spectral resolution. If spectroscopic errors are still absent but a realistic noise level is introduced, lowering spectral resolution leads to a notable increase of scatter for both XCO_2 and XCH_4 . With less spectral entries, the inversion problem becomes more under-determined than at GOSAT resolution, which increases retrieval errors. The magnitude of this effect depends on spectral resolution but also on the SNR. The smaller the noise amplitude added to the spectra, the lower the retrieval errors. The relative increase of error scatter with spectral resolution also depended on the filtering criteria, but we found a relative increase of at least 30 % for both absorbers. 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.

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Comparing synthetic retrieval results to GOSAT spectra (right column in Fig. 9) reveals a further increase of error scatter for all four cases. The strongest effect is seen for XCH₄ at high resolution: its retrieval accuracy is two times better in the synthetic case, i.e., 0.42 % vs. 0.83 %. It is intriguing to interpret this increase as the effect of spectroscopic and calibration errors. We caution the reader, however, that comparison of simulated and real measurements might be misleading, because the synthetic ensemble represents the entire land surface at all seasons, whereas GOSAT measurements collocated at TCCON stations represent only a small fraction of the world (Guerlet et al., 2013). If, for instance, the synthetic retrievals are reduced to scenes with albedo values between 0.1 and 0.35 – representing the span of albedo values encountered at TCCON stations – then $\langle\sigma\rangle = 0.34\%$ and 0.58% instead of 0.42% and 0.81% for XCH₄ with default SNR = 300. This would imply a larger contribution of spectroscopic and calibration errors to the total error of GOSAT retrievals than suggested by Fig. 9.

4 Conclusions

We have studied how a lower spectral resolution of satellite observations affects retrieval accuracy of CO₂ and CH₄. Since high spectral resolution is a cost driver for a satellite mission, we also wanted to check if a resulting loss in retrieval accuracy could be mitigated by a higher SNR. To address these goals, we relied on GOSAT measurements and simulated spectra at various spectral resolutions between 0.24 and 1.5 cm⁻¹ to cover the range envisaged for future satellite missions.

For CO₂ retrieval performance, the continuous increase of error scatter from $\langle\sigma\rangle = 0.65\%$ to 0.97% is the most notable effect of lowering the spectral resolution step by step from 0.24 to 1.5 cm⁻¹. This increase is the net result of several dependencies on physical parameters (water, airmass, and albedo). The inter-station bias between six TCCON sites increases from 0.2 % to 0.3 %. The convergence rate decreases by up to 25 %, but this figure depends on the assumed measurement uncertainty. The standard

deviation of CH₄ retrieval errors increases from 0.85 % to 1.03 % and the average bias drops by 0.4 % as the resolution is lowered from from 0.24 to 1.5 cm⁻¹. The increase of error scatter, the bias shift and the dependency on physical parameters are also reproduced for two consecutive years of GOSAT measurements across Europe and Northern Africa.

Degrading single windows has shown that an increase of error scatter and bias occurs only if those windows are degraded where absorption lines of the target molecules are located. Lowering the spectral resolution in regions that are only used to provide information on scatterers has little impact on retrieval accuracy. The instrument effects in the O₂ A window of GOSAT spectra (e.g., the intensity offset) do not become obviously more detrimental to accuracy at lower resolution.

The two spectral degradation approaches give 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.

Inversion of synthetic spectra demonstrates that forward model errors (introduced by the simplified aerosol model for retrieval) are much smaller than the error scatter of retrieved XCO₂ and XCH₄ established from GOSAT spectra. Moreover, lower resolution does not amplify forward model errors per se. If noise is added to the spectrum, however, the resulting interference errors become more pronounced at lower spectral resolution. Part of this increase can be considered a statistical and not a systematic error contribution. Comparison of synthetic measurements and GOSAT measurements suggests that the retrieval accuracy of CH₄ at any resolution would benefit more from a further improvement of the spectroscopy than CO₂.

Our study confirms that lowering the spectral resolution of satellite observations decreases retrieval accuracy to a certain extent. For observations at lower spectral resolution, accurate spectroscopy of the target absorbers becomes of particular importance lest interference errors dominate the retrieval performance. A countermeasure for instruments with a lower spectral resolution than GOSAT is to aim at a higher SNR. The

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



impact of random detector noise on retrievals with lower spectral resolution will also be smaller than presented in this paper if the loss in spectral resolution can be traded against additional time to collect more spectra in a given time period or pixel.

Acknowledgements. The first author was supported by ESA under ESA Contract Number 4000105676/12/NL/AF. S. Guerlet acknowledges funding from ESA's Climate Change Initiative on greenhouse gases and the European Commission's seventh framework program under grant agreement 218793. A. Butz is supported by Deutsche Forschungsgemeinschaft (DFG) through the Emmy–Noether programme, grant BU2599/1-1 (RemoTeC). US funding for TCCON comes from NASA's Terrestrial Ecology Program, grant number NNX11AG01G, the Orbiting Carbon Observatory Program, the Atmospheric CO₂ Observations from Space (ACOS) Program and the DOE/ARM Program. The Darwin TCCON site was built at Caltech with funding from the OCO project, and is operated by the University of Wollongong, with travel funds for maintenance and equipment costs funded by the OCO-2 project. We acknowledge funding to support Darwin and Wollongong from the Australian Research Council, Projects LE0668470, DP0879468, DP110103118 and LP0562346. The University of Bremen acknowledges financial support of the Białystok and Orléans TCCON sites from the Senate of Bremen and EU projects IMECC, GEOmon, InGOS, and ICOS-INWIRE, as well as maintenance and logistical work provided by AeroMeteo Service (Białystok) and the RAMCES team at LSCE (Gif-sur-Yvette, France) and additional operational funding from the National Institute for Environmental Studies. ECMWF ERA Interim analyses are provided through <http://data-portal.ecmwf.int/data/d/interimdaily/>. TM4 modelled CH₄ and CO concentration fields have been made available through J. F. Meirink, Royal Netherlands Meteorological Institute (KNMI).

References

Basu, S., Guerlet, S., Butz, A., Houweling, S., Hasekamp, O., Aben, I., Krummel, P., Steele, P., Langenfelds, R., Torn, M., Biraud, S., Stephens, B., Andrews, A., and Worthy, D.: Global CO₂ fluxes estimated from GOSAT retrievals of total column CO₂, *Atmos. Chem. Phys.*, 13, 8695–8717, doi:10.5194/acp-13-8695-2013, 2013. 10409

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Boesch, H., Baker, D., Connor, B., Crisp, D., and Miller, C.: Global characterization of CO₂ column retrievals from shortwave-infrared satellite observations of the orbiting carbon observatory-2 mission, *Remote Sens.*, 3, 270–304, 2011. 10402

Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noël, S., Rozanov, V. V., Chance, K. V., and Goede, A. P. H.: SCIAMACHY: mission objectives and measurement modes, *J. Atmos. Sci.*, 56, 127–150, 1999. 10402

Buchwitz, M., Reuter, M., Bovensmann, H., Pillai, D., Heymann, J., Schneising, O., Rozanov, V., Krings, T., Burrows, J. P., Boesch, H., Gerbig, C., Meijer, Y., and Löscher, A.: Carbon Monitoring Satellite (CarbonSat): assessment of scattering related atmospheric CO₂ and CH₄ retrieval errors and first results on implications for inferring city CO₂ emissions, *Atmos. Meas. Tech. Discuss.*, 6, 4769–4850, doi:10.5194/amtd-6-4769-2013, 2013. 10402, 10403

Butz, A., Hasekamp, O. P., Frankenberg, C., Vidot, J., and Aben, I.: CH₄ retrievals from space-based solar backscatter measurements: performance evaluation against simulated aerosol and cirrus loaded scenes, *J. Geophys. Res.*, 115, D24302, doi:10.1029/2010JD014514, 2010. 10404

Butz, A., Guerlet, S., Hasekamp, O., Schepers, D., Galli, A., Aben, I., Frankenberg, C., Hartmann, J.-M., Tran, H., Kuze, A., Keppel-Aleks, G., Toon, G., Wunch, D., Wennberg, P., Deutscher, N. M., Griffith, D., Macatangay, R., Messerschmidt, J., Notholt, J., and Warneke, T.: Toward accurate CO₂ and CH₄ observations from GOSAT, *Geo. R. L.*, 38, L14812, doi:10.1029/2011GL047888, 2011. 10403, 10404, 10409, 10410, 10413

Butz, A., Galli, A., Hasekamp, O., Landgraf, J., Tol, P., and Aben, I.: TROPOMI aboard Precursor Sentinel-5 Precursor: prospective performance of CH₄ retrievals for aerosol and cirrus loaded atmospheres, *Remote Sens. Environ.*, 120, 267–276, doi:10.1016/j.rse.2011.05.030, 2012. 10409, 10417, 10418

Galli, A., Butz, A., Scheepmaker, R. A., Hasekamp, O., Landgraf, J., Tol, P., Wunch, D., Deutscher, N. M., Toon, G. C., Wennberg, P. O., Griffith, D. W. T., and Aben, I.: CH₄, CO, and H₂O spectroscopy for the Sentinel-5 Precursor mission: an assessment with the Total Carbon Column Observing Network measurements, *Atmos. Meas. Tech.*, 5, 1387–1398, doi:10.5194/amt-5-1387-2012, 2012. 10412

Guerlet, S., Butz, A., Schepers, D., Basu, S., Hasekamp, O. P., Kuze, A., Yokota, T., Blavier, J.-F., Deutscher, N. M., Griffith, D. W. T., Hase, F., Kyrö, E., Morino, I., Sherlock, V., Sussmann, R., Galli, A., and Aben, I.: Impact of aerosol and thin cirrus on retrieving and validating XCO₂ from GOSAT shortwave infrared measurements, *J. Geophys. Res.-Atmos.*, 118, 1,

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

doi:10.1002/jgrd.50332, 2013. 10403, 10404, 10405, 10406, 10409, 10410, 10411, 10412, 10413, 10414, 10417, 10420

Hasekamp, O. P. and Butz, A.: Efficient calculation of intensity and polarization spectra in vertically inhomogeneous scattering and absorbing atmospheres. *J. Geophys. Res.*, 113, D20309, doi:10.1029/2008JD010379, 2008. 10404

Ingmann, P., Veiðelmann, B., Langen, J., Lamarre, D., Stark, H., and Courrèges-Lacoste, G. B.: Requirements for the GMES Atmosphere Service and ESA's implementation concept: Sentinels-4/-5 and -5p, *Remote Sens.*, 120, 58–69, 2012. 10402, 10403

Kuze, A., Suto, H., Nakajima, M., and Hamazaki, T.: Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse gases observing satellite for greenhouse gases monitoring, *Appl. Optics*, 48, 6716, doi:10.1364/AO.48.006716, 2009. 10402, 10407

Lamouroux, J., Tran, H., Laraia, A. L., Gamache, R. R., Rothman, L. S., Gordon, I. E., and Hartmann, J.-M.: Updated database plus software for line-mixing in CO₂ infrared spectra and their test using laboratory spectra in the 1.5–2.3 μm region, *J. Quant. Spectrosc. Ra.*, 111, 2321–2331, 2010. 10404

Liu, Y., Yang, D. X., and Cai, Z. N.: A retrieval algorithm for TanSat XCO₂ observation: Retrieval experiments using GOSAT data, *Chinese Sci. Bull.*, 58, 1520–1523, doi:10.1007/s11434-013-5680-y, 2013. 10402

Morino, I., Uchino, O., Inoue, M., Yoshida, Y., Yokota, T., Wennberg, P. O., Toon, G. C., Wunch, D., Roehl, C. M., Notholt, J., Warneke, T., Messerschmidt, J., Griffith, D. W. T., Deutscher, N. M., Sherlock, V., Connor, B., Robinson, J., Sussmann, R., and Rettinger, M.: Preliminary validation of column-averaged volume mixing ratios of carbon dioxide and methane retrieved from GOSAT short-wavelength infrared spectra, *Atmos. Meas. Tech.*, 4, 1061–1076, doi:10.5194/amt-4-1061-2011, 2011. 10403, 10410

Oshchepkov, S., Bril, A., Yokota, T., Wennberg, P. O., Deutscher, N. M., Wunch, D., Toon, G. C., Yoshida, Y., O'Dell, C. W., Crisp, D., Miller, C. E., Frankenberg, C., Butz, A., Aben, J., Guerlet, S., Hasekamp, O., Boesch, H., Cogan, A., Parker, R., Griffith, D., Macatangay, R., Notholt, J., Sussmann, R., Rettinger, M., Sherlock, V., Robinson, J., Kyrö, E., Heikkinen, P., Feist, D. G., Morino, I., Kadyrov, N., Belikov, D., Maksyutov, S., Matsunaga, T., Uchino, O., and Watanabe, H.: Effects of atmospheric light scattering on spectroscopic observations of greenhouse gases from space, Part 2: Algorithm intercomparison in the GOSAT data pro-

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



cessing for CO₂ retrievals over TCCON sites, *J. Geophys. Res.-Atmos.*, 118, 1493–1512, doi:10.1002/jgrd.50146, 2013. 10403, 10410

Parker, R., Boesch, H., Cogan, A., Fraser, A., Feng, L., Palmer, P. I., Messerschmidt, J., Deutscher, N. M., Griffith, D. W. T., Notholt, J., Wennberg, P. O., and Wunch, D.: Methane observations from the Greenhouse Gases Observing SATellite: comparison to ground-based TCCON data and model calculations, *Geo. R. L.*, 38, 2–7, doi:10.1029/2011GL047871, 2011. 10403, 10410

Petri, C., Warneke, T., Jones, N., Ridder, T., Messerschmidt, J., Weinzierl, T., Geibel, M., and Notholt, J.: Remote sensing of CO₂ and CH₄ using solar absorption spectrometry with a low resolution spectrometer, *Atmos. Meas. Tech.*, 5, 1627–1635, doi:10.5194/amt-5-1627-2012, 2012. 10412

Reuter, M., Bovensmann, H., Buchwitz, M., Burrows, J. P., Connor, B. J., Deutscher, N. M., Griffith, D. W. T., Heymann, J., Keppel-Aleks, G., Messerschmidt, J., Notholt, J., Petri, C., Robinson, J., Schneising, O., Sherlock, V., Velasco, V., Warneke, T., Wennberg, P. O., and Wunch, D.: Retrieval of atmospheric CO₂ with enhanced accuracy and precision from SCIAMACHY: Validation with FTS measurements and comparison with model results, *J. Geophys. Res.*, 116, D04301, doi:10.1029/2010JD015047, 2011. 10403, 10410

Rothman, L. S., Gordon, I. E., Barbe, A., Benner, D. C., Bernath, P. F., Birk, M., Boudon, V., Brown, L. R., Campargue, A., Champion, J., Chance, K., Coudert, L. H., Dana, V., Devi, V. M., Fally, S., Flaud, J., Gamache, R. R., Goldman, A., Jacquemart, D., Kleiner, I., Lacombe, N., Lafferty, W. J., Mandin, J., Massie, S. T., Mikhailenko, S. N., Miller, C. E., Moazzen-Ahmadi, N., Naumenko, O. V., Nikitin, A. V., Orphal, J., Perevalov, V. I., Perrin, A., Predoi-Cross, A., Rinsland, C. P., Rotger, M., Šimečková, M., Smith, M. A. H., Sung, K., Tashkun, S. A., Tennyson, J., Toth, R. A., Vandaele, A. C., and Vander Auwera, J.: The HITRAN 2008 molecular spectroscopic database, *J. Quant. Spectrosc. Ra.*, 110, 533–572, 2009. 10404, 10415

Schepers, D., Guerlet, S., Butz, A., Landgraf, J., Frankenberg, C., Hasekamp, O., Blavier, J.-F., Deutscher, N. M., Griffith, D. W. T., Hase, F., Kyrö, E., Morino, I., Sherlock, V., Sussmann, R., and Aben, I.: Methane retrievals from Greenhouse Gases Observing Satellite (GOSAT) shortwave infrared measurements: Performance comparison of proxy and physics retrieval algorithms, *J. Geophys. Res.*, 117, D10307, doi:10.1029/2012JD017549, 2012. 10403, 10409, 10410, 10413, 10417

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Tran, H. and Hartmann, J.-M.: An improved O₂ A-band absorption model and its consequences for retrievals of photon paths and surface pressures, *J. Geophys. Res.*, 113, D18104, doi:10.1029/2008JD010011, 2008. 10404

Wunch, D., Toon, G. C., Wennberg, P. O., Wofsy, S. C., Stephens, B. B., Fischer, M. L., Uchino, O., Abshire, J. B., Bernath, P., Biraud, S. C., Blavier, J.-F. L., Boone, C., Bowman, K. P., Browell, E. V., Campos, T., Connor, B. J., Daube, B. C., Deutscher, N. M., Diao, M., Elkins, J. W., Gerbig, C., Gottlieb, E., Griffith, D. W. T., Hurst, D. F., Jiménez, R., Keppel-Aleks, G., Kort, E. A., Macatangay, R., Machida, T., Matsueda, H., Moore, F., Morino, I., Park, S., Robinson, J., Roehl, C. M., Sawa, Y., Sherlock, V., Sweeney, C., Tanaka, T., and Zondlo, M. A.: Calibration of the Total Carbon Column Observing Network using aircraft profile data, *Atmos. Meas. Tech.*, 3, 1351–1362, doi:10.5194/amt-3-1351-2010, 2010. 10409

Wunch, D., Toon, G. C., Blavier, J.-F. L., Washenfelder, R. A., Notholt, J., Connor, B. J., Griffith, D. W. T., Sherlock, V., and Wennberg, P. O.: The total carbon column observing network, *Phil. Trans. R. Soc. A*, 369, 2087–2112, doi:10.1098/rsta.2010.0240, 2011a. 10403

Wunch, D., Wennberg, P. O., Toon, G. C., Connor, B. J., Fisher, B., Osterman, G. B., Frankenberg, C., Mandrake, L., O'Dell, C., Ahonen, P., Biraud, S. C., Castano, R., Cressie, N., Crisp, D., Deutscher, N. M., Eldering, A., Fisher, M. L., Griffith, D. W. T., Gunson, M., Heikkinen, P., Keppel-Aleks, G., Kyrö, E., Lindenmaier, R., Macatangay, R., Mendonca, J., Messerschmidt, J., Miller, C. E., Morino, I., Notholt, J., Oyafuso, F. A., Rettinger, M., Robinson, J., Roehl, C. M., Salawitch, R. J., Sherlock, V., Strong, K., Sussmann, R., Tanaka, T., Thompson, D. R., Uchino, O., Warneke, T., and Wofsy, S. C.: A method for evaluating bias in global measurements of CO₂ total columns from space, *Atmos. Chem. Phys.*, 11, 12317–12337, doi:10.5194/acp-11-12317-2011, 2011b. 10403, 10410

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Table 1.** Overview of spectral ranges used for inversion.

description	wavenumber range (cm ⁻¹)	absorbing species
O ₂ A band	12 920–13 195	O ₂
SWIR1a	6170–6277.5	CO ₂ , H ₂ O, CH ₄
SWIR1b	6045–6138	CH ₄ , H ₂ O, CO ₂
SWIR2	4806–4896	CO ₂ , H ₂ O

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Table 2. Retrieval performance for XCO₂ with respect to TCCON results, PF: Park Falls, LA: Lamont, OR: Orléans, BI: Białystok, DA: Darwin, WO: Wollongong. For each spectral resolution, the three rows denote from top to bottom: number of filtered retrievals, scatter, and bias. The bias and scatter are given as relative deviation from TCCON results in %.

Station	PF	LA	OR	BI	DA	WO	total
GOSAT (0.24 cm ⁻¹)	307	654	201	155	125	192	1634
	0.58	0.49	0.53	0.62	0.75	0.94	$\langle\sigma\rangle = 0.65$
	-0.64	-0.66	-0.76	-0.64	-0.41	-0.07	$\langle b\rangle = -0.53, \sigma_b = 0.22$
FWHM = 0.5 cm ⁻¹ , convolution	272	545	182	127	209	163	1498
	0.62	0.55	0.65	0.75	0.69	0.99	$\langle\sigma\rangle = 0.71$
	-0.87	-0.88	-1.01	-0.87	-0.71	-0.33	$\langle b\rangle = -0.78, \sigma_b = 0.20$
FWHM = 1.0 cm ⁻¹ , convolution	258	521	166	115	124	156	1340
	0.80	0.65	0.83	0.99	0.89	1.13	$\langle\sigma\rangle = 0.88$
	-0.59	-0.49	-0.75	-0.68	-0.3	+0.10	$\langle b\rangle = -0.46, \sigma_b = 0.27$
FWHM = 1.2 cm ⁻¹ , truncation	187	660	N/A	N/A	N/A	N/A	
	0.88	0.76					
	-0.94	-0.67					
FWHM = 1.5 cm ⁻¹ , convolution	239	460	127	95	127	146	1194
	0.94	0.69	0.91	1.05	1.01	1.23	$\langle\sigma\rangle = 0.97$
	-0.51	-0.21	-0.63	-0.55	-0.03	+0.26	$\langle b\rangle = -0.28, \sigma_b = 0.32$

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Table 3. Retrieval performance for XCH₄ with respect to TCCON results. Same format as Table 2.

Station	PF	LA	OR	BI	DA	WO	total
GOSAT (0.24 cm ⁻¹)	265 0.76 -0.33	642 0.76 -0.20	179 0.77 -0.43	144 0.78 -0.40	125 0.84 -0.43	186 1.21 -0.17	1541 $\langle\sigma\rangle = 0.85$ $\langle b\rangle = -0.33, \sigma_b = 0.11$
FWHM = 0.5 cm ⁻¹ , convolution	252 0.80 -0.71	540 0.80 -0.55	167 0.92 -0.91	115 0.80 -0.98	109 0.77 -0.72	162 1.25 -0.67	1345 $\langle\sigma\rangle = 0.89$ $\langle b\rangle = -0.76, \sigma_b = 0.17$
FWHM = 1.0 cm ⁻¹ , convolution	267 0.93 -0.69	520 0.84 -0.61	152 1.01 -1.09	106 0.90 -1.17	124 0.85 -0.60	159 1.30 -0.70	1328 $\langle\sigma\rangle = 0.97$ $\langle b\rangle = -0.81, \sigma_b = 0.27$
FWHM = 1.2 cm ⁻¹ , truncation	190 0.90 -0.28	664 0.80 -0.44	N/A	N/A	N/A	N/A	
FWHM = 1.5 cm ⁻¹ , convolution	250 1.00 -0.59	466 0.94 -0.44	121 1.21 -1.16	88 0.92 -1.19	127 0.89 -0.55	149 1.23 -0.60	1201 $\langle\sigma\rangle = 1.03$ $\langle b\rangle = -0.76, \sigma_b = 0.34$



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Table 4. Retrieval performance for XCO₂ with respect to TCCON results, same format as Table 2, but the data were reduced to the identical retrievals for all resolutions.

Station	PF	LA	OR	BI	DA	WO	total
GOSAT (0.24 cm ⁻¹)	117 0.53 -0.70	364 0.44 -0.63	108 0.46 -0.82	80 0.59 -0.74	92 0.60 -0.43	105 0.82 -0.07	866 $\langle\sigma\rangle = 0.57$ $\langle b\rangle = -0.57, \sigma_b = 0.24$
FWHM = 0.5 cm ⁻¹ , convolution	117 0.62 -0.97	364 0.49 -0.81	108 0.55 -1.12	80 0.61 -1.04	92 0.65 -0.72	105 0.89 -0.32	866 $\langle\sigma\rangle = 0.64$ $\langle b\rangle = -0.83, \sigma_b = 0.25$
FWHM = 1.0 cm ⁻¹ , convolution	117 0.76 -0.67	364 0.56 -0.44	108 0.74 -0.75	80 0.82 -0.82	92 0.78 -0.21	105 1.06 +0.08	866 $\langle\sigma\rangle = 0.79$ $\langle b\rangle = -0.47, \sigma_b = 0.31$
FWHM = 1.2 cm ⁻¹ , truncation	117 0.79 -0.84	364 0.60 -0.62	N/A	N/A	N/A	N/A	
FWHM = 1.5 cm ⁻¹ , convolution	117 0.84 -0.55	364 0.62 -0.20	108 0.86 -0.55	80 0.93 -0.59	92 0.85 +0.08	105 1.15 +0.37	866 $\langle\sigma\rangle = 0.88$ $\langle b\rangle = -0.24, \sigma_b = 0.36$

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Table 5. Retrieval performance for XCH₄ with respect to TCCON results. Same format as Table 4.

Station	PF	LA	OR	BI	DA	WO	total
GOSAT (0.24 cm ⁻¹)	102 0.74 -0.14	363 0.76 -0.16	98 0.81 -0.46	72 0.71 -0.53	92 0.70 -0.46	106 1.12 -0.20	833 $\langle\sigma\rangle = 0.81$ $\langle b\rangle = -0.33, \sigma_b = 0.19$
FWHM = 0.5 cm ⁻¹ , convolution	102 0.74 -0.64	363 0.81 -0.51	98 0.98 -1.03	72 0.72 -1.14	92 0.74 -0.75	106 1.14 -0.68	833 $\langle\sigma\rangle = 0.86$ $\langle b\rangle = -0.79, \sigma_b = 0.26$
FWHM = 1.0 cm ⁻¹ , convolution	102 0.78 -0.57	363 0.84 -0.53	98 1.09 -1.15	72 0.75 -1.19	92 0.79 -0.60	106 1.20 -0.65	833 $\langle\sigma\rangle = 0.91$ $\langle b\rangle = -0.78, \sigma_b = 0.32$
FWHM = 1.2 cm ⁻¹ , truncation	102 0.79 -0.28	363 0.80 -0.45	N/A	N/A	N/A	N/A	
FWHM = 1.5 cm ⁻¹ , convolution	102 0.80 -0.53	363 0.94 -0.42	98 1.19 -1.20	72 0.82 -1.18	92 0.84 -0.53	106 1.24 -0.65	833 $\langle\sigma\rangle = 0.97$ $\langle b\rangle = -0.75, \sigma_b = 0.36$

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

Table 6. Impact of lowering the GOSAT spectral resolution to 1.5 cm^{-1} for the European dataset. “Dependency” denotes the slope of a linear regression of retrieval errors against physical parameter over the entire parameter range.

	XCO ₂	XCH ₄
number of filtered retrievals	3532	3340
scatter σ [%]	0.64	0.62
bias b [%]	+0.23	−0.42
H ₂ O dependency [%]	$+1.62 \pm 0.09$	$+1.20 \pm 0.09$
airmass dependency [%]	-1.14 ± 0.06	-0.54 ± 0.07
albedo dependency [%]	$+0.21 \pm 0.07$	$+0.35 \pm 0.06$
optical thickness dependency [%]	-0.03 ± 0.05	-0.25 ± 0.05
aerosol size parameter dependency [%]	-1.85 ± 0.07	-0.45 ± 0.07

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

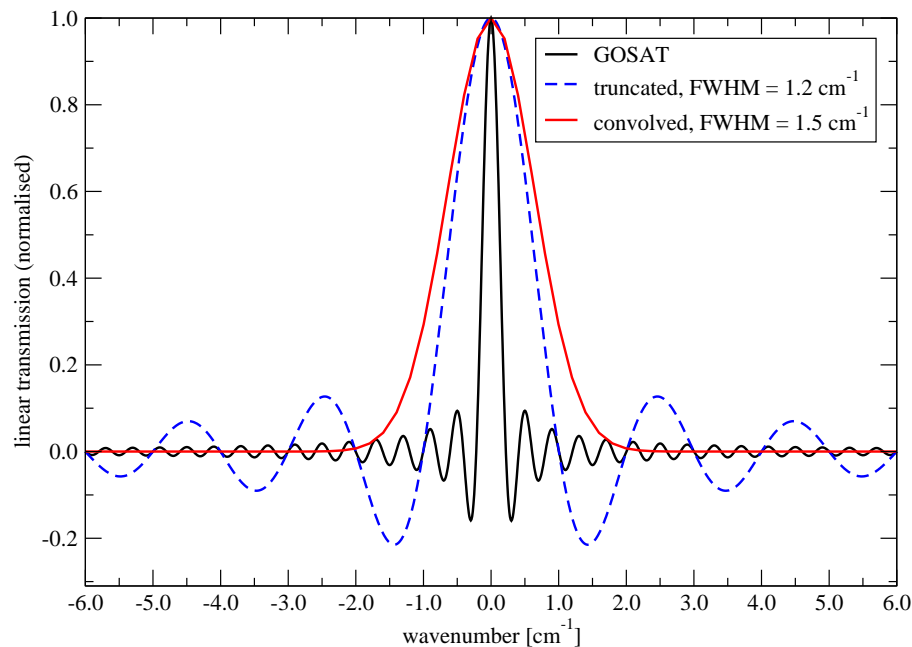


Fig. 1. Instrument line shapes for three different resolutions. Black line: GOSAT resolution, blue dashed line: truncated interferogram (effective FWHM = 1.2 cm^{-1}), and red line: GOSAT ILS convolved with a Gaussian (effective FWHM = 1.5 cm^{-1}).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

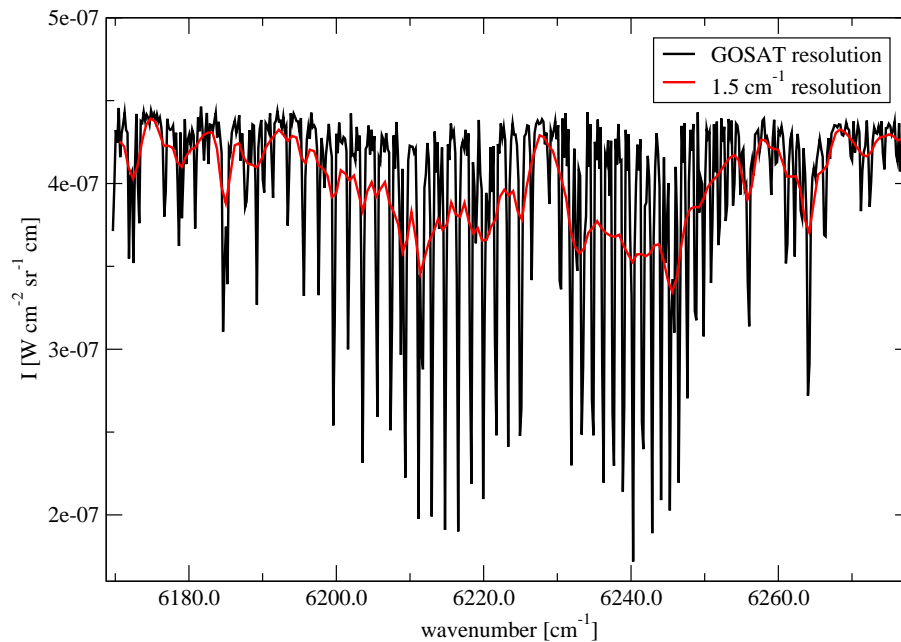


Fig. 2. Spectral intensity in the SWIR1a window, for GOSAT resolution (black) and for a spectrum convolved to $\text{FWHM} = 1.5 \text{ cm}^{-1}$ resolution (red).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

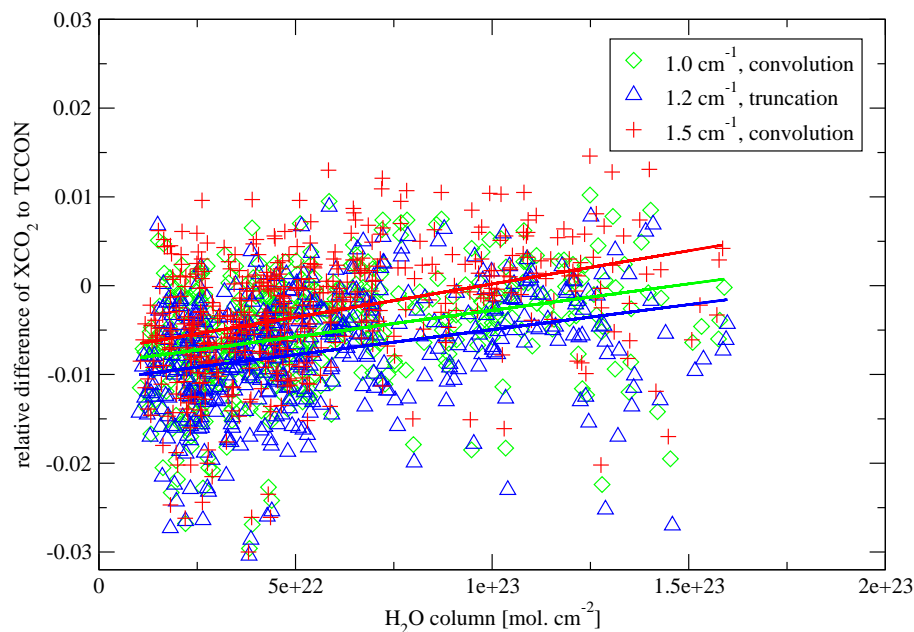


Fig. 3. Retrieval errors of XCO₂ as a function of water content of the atmosphere, identical filtered retrievals at Park Falls and Lamont for all three resolutions. The linear regressions of XCO₂ vs. water are shown as straight lines: green (1.0 cm⁻¹ convolution approach), blue (1.2 cm⁻¹ truncation approach), and red (1.5 cm⁻¹ convolution).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

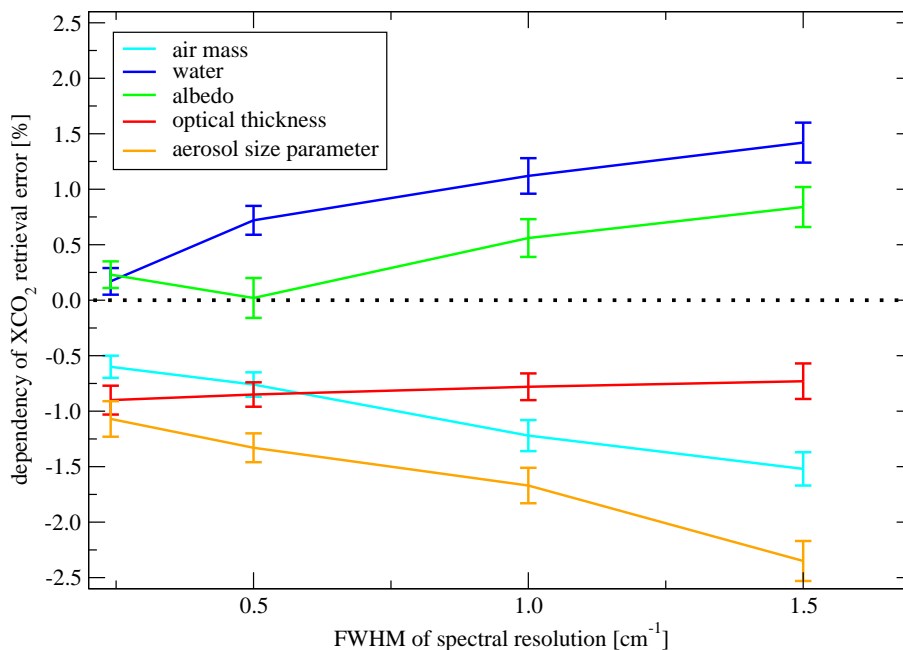


Fig. 4. Linear dependence of XCO₂ retrieval errors on physical parameters as a function of spectral resolution. Shown are the slopes of the linear regression of retrieval errors vs. air mass (light blue), water abundance (dark blue), surface albedo at 1.6 μm (green), retrieved optical thickness at the O₂ A band (red), and the inverse of the aerosol size parameter (orange).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

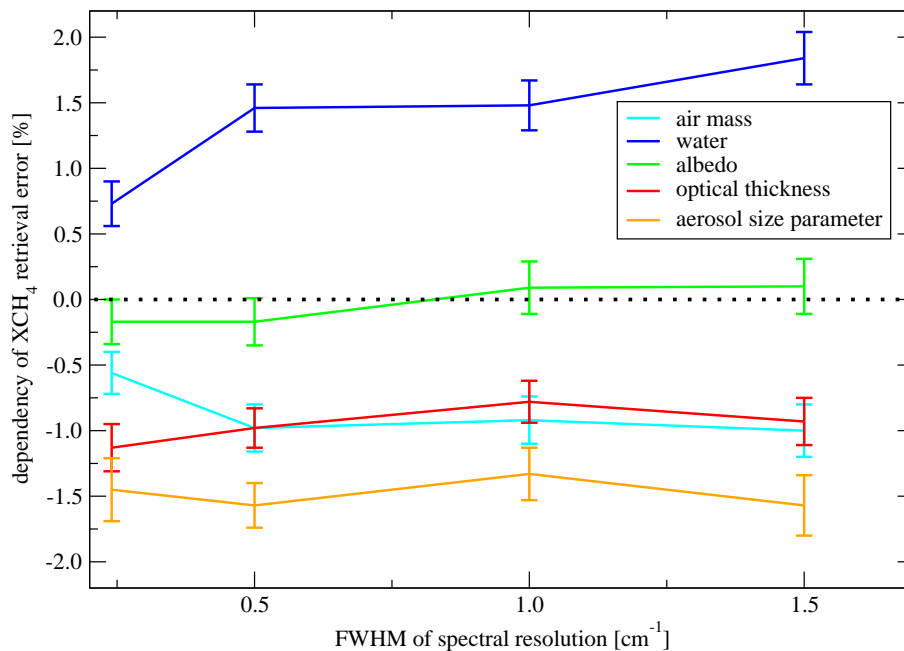


Fig. 5. Linear dependence of XCH₄ retrieval errors on physical parameters as a function of spectral resolution. Same format as Fig. 4.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

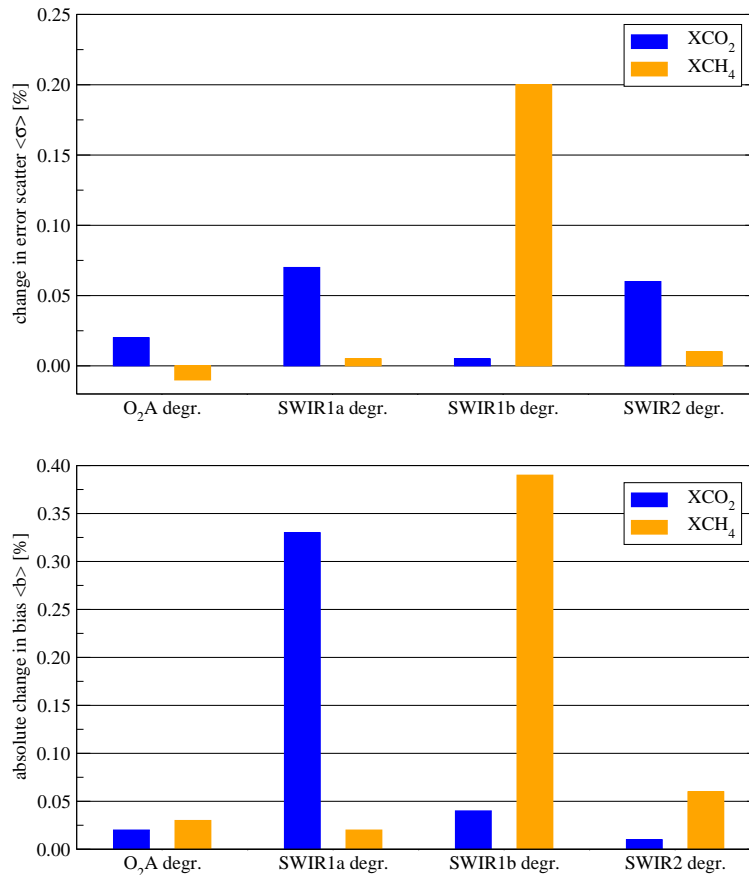


Fig. 6. Results for spectral degradation of single windows from GOSAT to 1.5 cm^{-1} resolution, averaged over all six TCCON stations. Upper panel: change of error scatter $\langle\sigma\rangle$ relative to results at GOSAT resolution, lower panel: absolute change of bias $\langle b\rangle$ relative to GOSAT resolution. Blue columns denote XCO₂, orange columns denote XCH₄.

Impact of spectral resolution on retrieval accuracy

A. Galli et al.

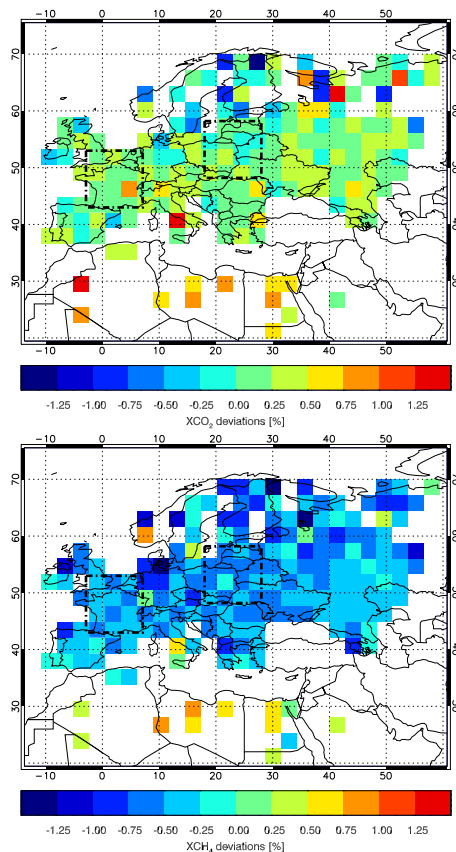


Fig. 7. Maps showing the relative differences in retrieved XCO₂ (top) and XCH₄ (bottom) between 1.5 cm⁻¹ and GOSAT resolution in Europe and Northern Africa from May 2009 to May 2011. Dash-dotted squares: collocation boxes around the TCCON stations Orléans and Białystok.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

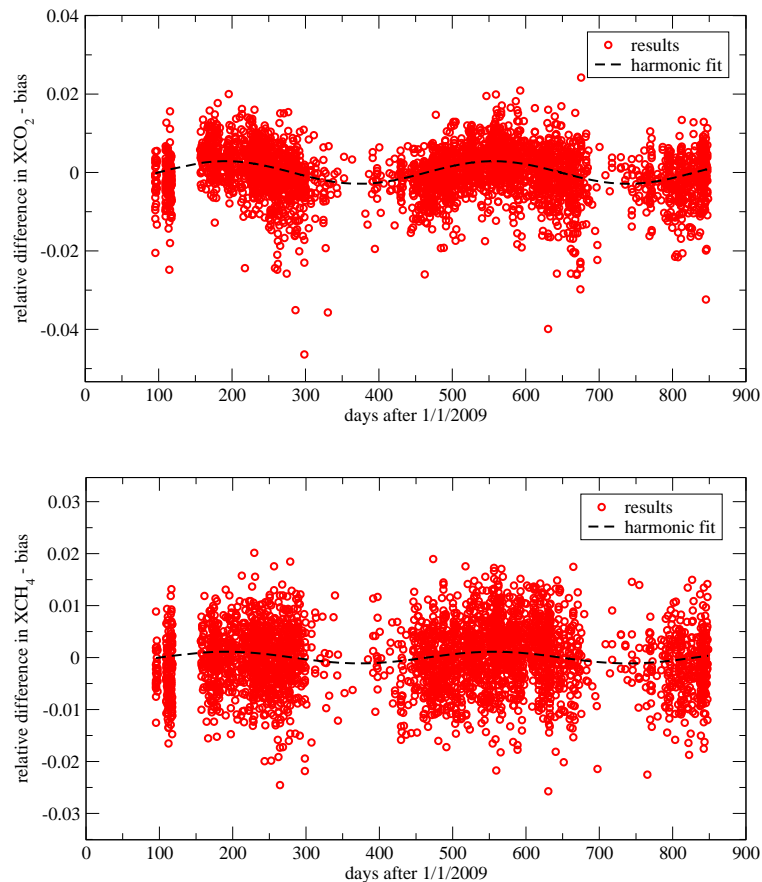


Fig. 8. Seasonal biases introduced by lowering the spectral resolution. Shown are the relative differences in retrieved XCO_2 (top) and XCH_4 (bottom) between 1.5 cm^{-1} and GOSAT resolution for all filtered GOSAT retrievals in Europe. Amplitude of harmonic fit (black dashed lines) equals 0.0029 for CO_2 and 0.0011 for CH_4 .

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Impact of spectral resolution on retrieval accuracy

A. Galli et al.

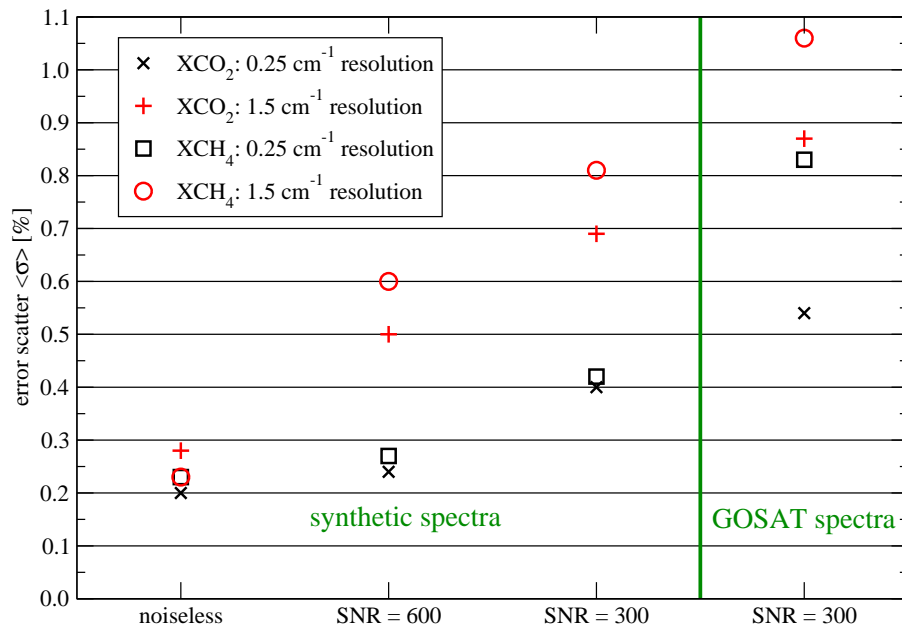


Fig. 9. Standard deviations of relative XCO₂ and XCH₄ retrieval errors for synthetic noiseless spectra (first column), for synthetic spectra with a very high SNR = 600 (second column), for synthetic spectra with nominal noise (third column), and for GOSAT spectra collocated at TC-CON stations (fourth column).