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Atmospheric Measurement Techniques Discussions

Interactive comment on "A non-iterative linear retrieval for infrared high resolution limb sounders" *by* L. Millán and A. Dudhia

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Response to anonymous referee # 2:

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We sincerely thank the referee #2 for his/her thoughtful comments on the previous draft, we hope this new version is more suitable for publication.

We added two figures to this new draft, one showing the averaging kernels of the Mipas implementation of the linear retrieval and one showing the linear - linearisation points.

Below are our responses in red.

1 Reviewer 2

General comments: The paper presents a retrieval method for optically thin atmospheres which is based on the linearization of the radiative transfer equation, allowing for a non-iterative linear retrieval within one single retrieval step. This method is favorable since the computational cost of the retrieval could significantly be reduced,

allowing for the use of wider spectral regions, or even an on-line retrieval approach. The paper is over large parts written in a clear and well structured way. Although the results are not as promising as one would hope, the method deserves publication since it could be the basis for further developments in this direction. Although publishable in general, I have a number of points which I would like to see addressed before the paper can go into AMT. In particular, the gain of knowledge by the linear approach, in comparison to a climatology which is assumed to represent the true state quite well already, needs to be made more obvious. The authors need to discuss the consequence in case the used climatology simply does not represent the true state of the atmosphere. The error estimates need to be interlinked with the observed biases between the iterative non-linear retrievals and the linear approach.

Please find below my specific comments.

Specific comments:
Abstract: The abstract should be more specific; instead of saying "we determine how close the linearization point needs to be ..." the authors should give precisely this information.
The abstract was changed to include: We determine that pressure and temperature retrievals can be treated linearly up to a 20% difference between the atmospheric state and the linearisation point for a 3% error margin and up to 10 K 'difference' for a 3 K error margin near the stratopause and less than 0.5 K elsewhere. Assuming perfect pT knowledge, CH_4 retrievals can be be treated linearly up to a 20% CH_4 concentration 'difference' for a 2% error margin.

Similar applies to the sentence "... suggest an adjustment to the forward model and Jacobians to propagate the change in pressure and temperature on the gas concentration retrievals." As it stands, it is not clear what the authors wanted to say

with this sentence.
That sentence was changed to: Also, an adjustment for the pT dependence of the precomputed CH_4 simulated spectra and Jacobians is introduced.

p723, l3-5: I would say here: "... linearization point, and the atmospheric estimate is corrected according to a recipe (e.g. minimization of least squares) until the given ...".
Corrected

p723, l16ff: In other words, how close any previous estimation must come to the final result which can be reached within one iteration step of the least-squares approach. This is nothing different that the iterative non-linear approach described before, the paper describes the conditions to be met within the one-but-last iteration step.
The text was changed to include: That is to say, to only perform the last iteration step in the iterative schemes.

p724, l5: The Tikhonov regularization approach in the framework of retrieval of atmospheric trace species from spectral measurements was first introduced by von Clarmann et al. (2003), and it is definitely not described by Rodgers (2000).
The reference for von Clarmann et al. (2003) was used instead of Rodgers(2000).

p724, Eq 1: Eq 1 is incomplete; the second term after the () brackets should read: $[K_i^T S_y^{-1}(y - F(x_i)) - \gamma^{-1} R(x_i - x_a)]$ (check von Clarmann et al. JGR, 2003, Eq (1))
The equation was change to:

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \left(\mathbf{K}_i^T \mathbf{S}_y^{-1} \mathbf{K}_i + \gamma^{-1} \mathbf{R}\right)^{-1} \left[\mathbf{K}_i^T \mathbf{S}_y^{-1} \left(\mathbf{y} - \mathbf{F}(\mathbf{x}_i)\right) - \gamma^{-1} \mathbf{R}(\mathbf{x}_i - \mathbf{x}_0)\right] \quad (1)$$

p724, l15: Eq 2 is incomplete as well. Check for von Clarmann et al. JGR, 2003, Eq 2 for the full form of this equation.
The following equation was used

$$\mathbf{S}_x = \left(\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K} + \gamma^{-1}\mathbf{R}\right)^{-1} \times \mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K}\left(\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K} + \gamma^{-1}\mathbf{R}\right)^{-1} \quad (2)$$

and Figure 13 was updated.

p725, l11-14: Please clarify if the perturbations in pressure and temperature has been applied simultaneously, or if two subsequent test cases are described. In case they were applied simultaneously, could there be a crosstalk between the two perturbations?
The text was changed from: To test the linearity of the forward model due to pressure and temperature changes, CO_2 spectra for midlatitude day conditions were simulated perturbing the entire pressure profile by 1, 5, 10, 20 and 50 % and by 1, 5, 10, 20 and 50 K, respectively.
To: To test the linearity of the forward model due to pressure **or** temperature changes, CO_2 spectra for midlatitude day conditions were simulated perturbing the entire pressure profile by 1, 5, 10, 20 and 50 % and **independently** by 1, 5, 10, 20 and 50 K.

p726, l10ff: Do you have any explanation for the oscillations occurring in this retrieval? Is it a regularization issue? I think some comments are necessary.
An error was found in the implementation of the Jacobian units change which resulted in the oscillations, the figure was updated.

p728, l10: I think it must still read F(x_o) at the left-hand side of the equation (as long as you don't introduce a K_{xo}(x-x_o) term on the right-hand side.
The equation now says F*(x_o) at the left-hand side.

p728, l19: The deviation is almost 70% at 45 km; could you, again, comment on the oscillations, and whether you consider a profile oscillating as much as this one as useful?
The text was changed to: As shown, for a 10 K perturbation the errors induced are less than ∼20% except around 45 km where the deviation is almost 70%. This deviation is caused by oscillations in the linear retrieval presumably induced by the 10 K constant difference between the linearisation profile and the atmospheric state. In practice, this constant difference will not happen avoiding these oscillations and hence avoiding the 70% deviation.

p731, l22: The analysis of CH4 variability was done for a single month, January, which does not allow for a generalization as made here - that a climatology with a latitudinal resolution of at least 20 deg is required. This may vary with season, and, in particular, for other trace species.
Unfortunately, there was a typo in the text, the variability was performed for June, July and August (the labels in the figure were correct). In the Climatological variability section the text was updated to include: Note that these climatology latitudinal resolutions are only tentative guidelines, they will vary with season and in particular for other trace species.

p732, Eq 15: why is the third term dimensionless [(p-p_o)/p_o] while the others are not?
The equation was changed so the first and last term are represented by a ratio, that is to say [(v-v_o)/v_o] and [(p-p_o)/p_o] because Δ_v and Δ_p are in percent. The following sentence was added to the text: Note that Λ_v and Λ_{vp} are in percent and Λ_{vT} is in kelvins.
Furthermore, the pressure and temperature linearisation approximation errors were also changed to represent the % and K difference (see text).

p733, l10ff: Does this mean that you improve your "knowledge" of the true state from 20% uncertainty (from climatology) to just 14% uncertainty (afterlinear retrieval)? In this case, I would just start from the climatology with a non-linear retrieval which should converge quickly if set-up appropriately. I think your argument wrt using the linear approach as a step prior to an iterative scheme is a bit weak and should be rethought.
That is correct, in the worst case scenario, the uncertainty might drop only from 20% (from climatology) to just 14%, however as I say that is in the worst case scenario, when the VMR, the pressure and temperature linearisation points are completely off. However, in general, one would expect better climatological values. The text was changed to say: As shown in Figure 13, the error in the linear pT or VMR retrieval, at least in the worst case scenario, when the deviation between the retrieved profile equals the maximum deviation allowed, might be too high for scientific results. In an operational retrieval many linearisation points can be tested (see section 7.3) to find the one closest to the true atmospheric state, hence avoiding the maximum deviation allowed. Furthermore, if the linear approximation error is still to big, in those cases, the linear retrieval could be used as a first iteration of an iterative scheme, presumably reducing its computing time considerably.

p735, section 7.2.1: Could you provide a number which percentage of the available spectral grid points finally was used within the retrieval after application of the criteria given in Eqs. 16 and 17?
The text was changed to: The combination of these two masks disregards around 90% of the spectral points available, around upper mesospheric heights due to a combination of emission from other gases and nonLTE effects and lower down only due to emission from other gases.
Also, in the section 7.5 the following sentence was added: In this case, the combination of these two masks disregards around 88% of the spectral points available, mainly due

to emission from other gases.

p738, section 7.4: In all what follows now the limitation to an optically thin atmosphere where linearization might be less serious (and the linearization as developed in the appendix relies on) has given up, and comparisons are shown down to almost 100 hPa. Has this been done on purpose? Has the impact on the retrieval results been assessed?
All the Linear regimes wer computed up to 18 km roughly 100 hPa. So the impact of the radiances not being optically thin have already been assesed. The appendix was included for the VMR jacobians pT adjustment section discussion. To avoid confusion the conclusion was changed from: This algorithm exploits the linear properties of an optically thin path making it possible to perform the inversion without re-running the radiative transfer model...
to: This algorithm performs the inversion without re-running the radiative transfer model...

p738, l19-24: If the plots show (linear - MLS/MORSE) as indicated in the header, I'd read them the other way round: the linear approach overestimates temperatures for pressures < 0.03hPa and underestimates temperature in a band between 0.1 and 1 hPa for (linear - MORSE) and around 1 hPa for (linear - MLS). Further, the underestimation is up to 9 K, so I wouldn't say there is good agreement at pressures larger than 0.1 hPa.
the text was changed to: However, as seen in the absolute difference subplot, compared to MORSE and MLS the linear retrieval seems to underestimate the temperatures for pressures between 0.1 and 0.01 hPa at all latitudes and underestimate the temperature for pressures between 1 and 0.1 hPa. For pressures greater than 1 hPa in general there seems to be no significant difference (less than 3 K) between the linear, MORSE and the MLS results.

Although indirectly deducible from the Figures 16 and 17 shown, I'd appreciate seeing an additional comparison MORSE - MLS. This would help to cancel out the instrument and forward algorithm effects.
This figure was considered unnecessary because the main focus of the paper was not the validation of the linear retrieval or MORSE, but rather the feasibility of the method. If some point in the future, this method is applied operationally, a proper validation paper will follow.

Fig 18 and related text: A direct comparison (linear - climatology) and (MORSE - climatology) would be helpful to judge if the retrieval indeed provides information not already contained in the 20% threshold for the variability in the climatological latitude bins. The difference between linear and MORSE sometimes exceeds 50% and is between 10 and 30% over wide latitude/altitude regions. In order to judge if this comes from strong deviations between the true atmospheric state and the climatology, or if the linear approach does not add information to the climatology, I strongly suggest to add these difference plots to the figure.
A figure showing the linear retrieval - linearisation points was added. The text was updated to include:
"Figure 21 shows VMR, pressure and Temperature zonal means $\mathbf{x} - \mathbf{x}_0$ 'distances', or in other words the separation between the retrieved atmospheric state and the linearisation points used. For most altitudes and latitudes, these 'distances' are greater that the requirements to fall within the linear regime (see section 7.4) suggesting that the linear retrieval results should improve once a more reasonable linearisation point climatology is used."
Also, the error estimation using section 6 equations is shown.

This figure, however, poses an inherent problem of the approach: what if the climatol-

ogy is biased and the chosen linearization point is not a good representative of the true state around which the 20% variation is allowed? This is a question which could and should be discussed on basis of Fig 18.
This was addressed after fig 21. see comments below.

Fig 19: The bias between the MORSE-retrieved CH4 vmr and the linearly retrieved vmr comes close to or exceeds the 20% limit from the climatology over wide regions.

Again we would need the deviation between climatology and the MORSE retrieval to judge if the observed situation is simply not part of the climatology ensemble (in this case the linearization point is questionable) or if the linear retrieval deviates as much or even more from the real atmosphere as the climatology does. I consider a thorough discussion of this point as absolutely necessary.
following the discussion of the figure showing the linear retrieval - linearisation points, this text was added:
In the case where the linearisation point is not a good representative of the atmospheric state, the linear retrieval results may be used as a first iteration in an iterative scheme, or if the linear retrieval error is greater than the expected climatological variation, the iterative scheme can be used starting from the best initial guest available.

p742, l6: As already mentioned earlier this might be an improper generalization since the latitudinal variability of CH4 vmr has been tested for one case only, namely the month of January.
Although already specified in the Climatological Variability section, the text was changed to say that the 20deg climatology was 'suggested' instead of 'needed'.

p742, l12: The comparisons have shown that the linear retrieval is within a 3 K range difference on average, and not "for most of the time"! Individual differences might be

by far larger than 3 K, but may cancel out in the mean.
The text was changed to: The pT comparisons revealed that linear retrieval is within a 3 K range difference on average for pressures greater than 0.1 hPa ...

Appendix: you should be careful not to mix up the symbol for wavenumber (as used in the appendix) and the symbol for vmr (as used in the main part).
Corrected

Minor and technical comments:

p723, l7: typo "Fischer"; Fischer et al., ACP, 2008 would probably better suit as a reference here (also p733, l17)
We added the reference to Fischer, 2008 and corrected the spelling.

p726, l7: shouldn't this be dB... instead of δB...?
Corrected

Figs 6-8: You should mention in the figure captions that these climatologies have been derived from MIPAS data (and not from a model etc.)
In Figure 6, 7 and 8, the text was changed to: ... latitude bin profiles for the the MIPAS MA mode days available in Jauary 2007, 2008 and 2009.

p729, Eq. 6 and 7: explain the meaning of v_j
At the beggining of that section the text was changed to: As the forward model has been adjusted to the temperature and pressure of the scene, in a similar manner, the VMR, v, Jacobians can be adjusted using...

p735, l9: Clarify "Due to the high *spectral* resolution ..."
Corrected

p738, l1-3: This sentence is difficult to understand, consider re-phrasing.
The sentence was changed to: As can be expected, this criterion is selecting for the south pole (the winter pole in June) mostly the polar winter linearisation profile while for the north pole (the summer pole in June) mostly the polar summer linearisation profile.