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Atmospheric Measurement Techniques Discussions

Interactive comment on "Towards a 3-D tomographic retrieval for the Air-borne Limb-imager GLORIA" *by* J. Ungermann et al.

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We thank the reviewers for their insightful comments and recommendation, which were very helpful for improving the paper. In the following, we address the issues raised by the reviewers in detail except for simple typographical or technical corrections, which we simply applied.

We repeated the comments of the reviewers for convenience as indented blocks. Similarly, excerpts from the revised paper are shown as indented blocks using a smaller font size.

1 Reply to Referee 1

1. Authors start from the assumption that "the inversion of F presents a non-linear, ill-posed, and in many cases both under and over-constrained inversion problem", therefore they adopt a retrieval scheme that makes use of a-priori knowledge about the atmospheric state. With this approach the strategy is to oversample the atmospheric field of the geophysical target with an exceeding number of retrieval parameters, regularize and, a-posteriori, evaluate the entity of the oversampling by calculating the actual spatial resolution of the retrieval products. This approach is suitable (and operational) for 1D retrievals where the dimensions of the problem are relatively small. Considering the large amount of information merged by the GLORIA measurements it is not obvious (and in my opinion should be verified) that 3D tomography results in a singular inversion problem without a-priori knowledge. The authors themselves verify (at P. 3012 L. 14) "a negligible influence of a priori information" and the literature reports 2D retrievals that don't need a-priori or simply adopt a Levemberg-Marquardt scheme. The possibility to avoid a-priori would simplify the retrieval algebra, reduce the demand of computing resources, and allow to drop some approximations. On the other hand (also considering the envisaged satellite application of GLORIA) it would lead closer to an operational retrieval where atmospheric anomalies are not predictable and the routinely used retrieval grid must be defined a-priori on the basis of only the trade-off between spatial resolution and retrieval precision.

The reviewer expresses a very interesting point that we indeed did examine. We examined several different regularization techniques, including also no regularization at all, i.e. using stopping rules like the discrepancy principle. We found that due to a lack of measurement information for the atmosphere outside the volume covered by tangent points, for this region more or less random values were retrieved, which then influenced the inner area in a very detrimental way. In effect, the resulting atmosphere has no resemblance to the original structure, which we strive to reproduce.

When stating the "a negligible influence of a priori information", we were referring to a bias towards the a priori vector x_a, which is a highly mis-leading formulation and will be corrected. Indeed, we find that introducing a priori information in the form of *smoothness constraints* as described in the paper to be a necessity.

The referenced 2-D retrievals described in the literature have a very different viewing geometry (i.e. within the flight direction of the instrument, compared to orthogonal to it), which does not allow the direct transfer of all if any conclusion. On the other hand, the envisaged satellite application of GLORIA, i.e. the PREMIER proposal, will have the same robust viewing geometry, which indeed may allow to omit the inclusion of any a priori information.

Concluding, the primary task of this paper is to describe an efficient method for of large-scale regularized retrievals and demonstrate in principle the feasibility of 3-D tomographic retrievals using GLORIA measurements, which have a wildly different viewing geometry. Examining different regularization techniques for the problem at hand and optimization thereof, while tremendously interesting, is beyond the scope of this paper.

We will make the differences between "conventional" 2-D tomography and the presented 3-D viewing geometry more clear in the paper to avoid confusion by adding:

> Further, due to the different observations geometries between forward- or backward-looking satellite instruments and side-ways looking airborne instruments, the posed 3-D tomographic problem is quite different from state-of-the art 2-D tomographic re-

> trievals. It is therefore not a simple extension from the simpler 2-D tomographic retrievals and its characteristics may be vastly different.

2. In my opinion Sect. 4.5 is superfluous. It is consolidated that 2D perform better than 1D retrieval schemes: it is then straightforward the superiority of 3D w.r.t. 1D. On the other hand the discussion in Sect. 4.5 is rather convoluted.

It is indeed consolidated that 2-D tomographic retrievals are superior for limb-observing satellite instruments. These are usually forward or backward looking and thus have a observation geometry which lends itself very well to tomography as the tangent points of measurements evenly cover the whole 2-D plane except for the top-column. Except for the negligible border effects all line-of-sights are fully covered along their full length (except for the top-column) by tangent points of other measurements.

The 3-D observation geometry presented in this work is completely different and much less robust as technical necessities require a viewing direction orthogonal to the flight direction, which consequently leads to a less ideal distribution of tangent points in space.

The section in question demonstrates that the use case at hand was indeed problematic for conventional 1-D retrievals, and thereby justifies the significant additional effort spent on the 3-D tomographic retrieval.

Further, an analysis method is introduced that is able to quantify the distortions introduced by 1-D retrievals relying on the assumption of horizontal homogeneity that may be used to more readily compare model data and 1-D retrieval results. Such a quantification is of importance for mission planning when the peculiar flight path required for 3-D tomography needs to be justified against the needs of, e.g., in situ instruments.

However, we will try to present the material in a more understandable and concise way:

The 3-D tomographic retrieval is more robust in the presence of horizontal inhomogeneity than conventional 1-D retrievals. This section demonstrates that the employed test case is indeed a difficult one for conventional retrievals due to the horizontal inhomogeneity of ozone and develops a method to quantify the effect of horizontal inhomogeneity on 1-D retrievals based upon the assumption of horizontal homogeneity.

To compare the tomographic approach with conventional retrievals, each individual image of the standard setup was used to perform a single 1-D retrieval. To exclude secondary representation effects, only ozone within the retrieval height range was kept three-dimensionally varying; every other quantity was made horizontally homogeneous. It was found that the 1-D retrievals require a stronger vertical regularisation (i.e. $\alpha_1^z = 4{\cdot}10^6$) as the regularising influence of the horizontal smoothing is missing. Figure 13 depicts as an example the results of the 1-D retrievals at 12 km height with the true atmosphere as background. One sees clearly that ozone is severely underestimated depending on the pointing of the measurement instrument. Profiles underestimating ozone are generally derived from images pointing northwards and profiles overestimating it are generally pointing southwards. Increasing the strength of the vertical smoothing further, the noisiness of the results decreases at the cost of a worsening vertical resolution. However, the systematic under- and overestimation is not affected by a stronger or weaker regularisation.

To gain deeper insight into the cause of these systematic errors, a single retrieval with an underestimation of ≈20 % was selected for analysis, which is indicated by a broad black circle in Fig. 13. Figure 14 shows the rays of the corresponding image together with the ozone values along the line-of-sights. To compensate for the strong vertical gradient of ozone, the values have been horizontally normalised to the ozone concentration at the line defined by the tangent point respectively the horizontal instrument location above 15 km. Above 10 km altitude, one can see a strong horizontal structure with ozone concentrations decreasing away from the instrument. This gradient certainly violates the assumption of horizontal homogeneity. Figure 15b shows the row of the 1-D averaging kernel matrix corresponding to the value at 12 km. One sees the expected vertical averaging, but this is not the reason for the underestimation as the ozone concentrations at, above, and below 12 km are quite similar. No indication of a problem is given by this 1-D diagnostic.

As the usual 1-D diagnostics depend on the notion of a horizontally homogeneous atmosphere, they cannot capture the effects of 2-D structures. Instead, a mapping

of the true – in this case – 2-D atmosphere onto the 1-D results is required to gain further insight into the problem. Such a map can be generated by using the 1-D gain matrix shown in Fig. 15a and a 2-D Jacobian matrix describing the sensitivity of the measurements to a 2-D atmosphere. A 2-D Jacobian can simply be generated by creating a 2-D representation of the atmosphere and filling it with the true state of the atmosphere along this cut. This 2-D atmosphere employed by us uses the same altitude grid as the 1-D representation and uses a regular horizontal grid with a 5 km horizontal spacing. Now, the 1-D gain matrix can be multiplied with the 2-D Jacobian matrix to create a new averaging kernel matrix that maps the true 2-D state of the atmosphere to the 1-D retrieval result. This is quite similar to the way that the usual averaging kernel matrix is calculated, the only difference being the exchange of the 1-D Jacobian matrix by the 2-D Jacobian matrix. The resulting matrix is referred to as 2-D/1-D averaging kernel matrix and shown in Fig. 16. A similar technique was used by von Clarmann et al. (2009) to estimate the horizontal resolution of the MIPAS instrument.

The 2-D/1-D averaging kernel matrix is closely related to the usual 1-D averaging kernel matrix. For instance, the 2-D/1-D averaging kernel matrix can be transformed to the 1-D averaging kernel matrix by summing up all elements of each row belonging to the same altitude. Consequently, the horizontal oscillations above 12 km in Fig. 16 sum up horizontally to (nearly) zero. If there were a horizontally constant ozone concentration at higher altitudes, the oscillations would not affect the retrieval result, just as the 1-D averaging kernel matrix suggests. However, there is a strong gradient, which is folded with the oscillations visible in the 2-D/1-D averaging kernel matrix and thereby contributes noticeably to the retrieval result at 12 km altitude.

The observed horizontal oscillations in the 2-D/1-D averaging kernel matrix are the consequence of the averaging kernel matrix A being a linear combination ($A = GF'(\tilde{\vec{x}})$) of the rows of the Jacobian matrix, i.e. the weighting functions. Figure 15a shows a row of the gain matrix; it depicts the coefficients used to add up the rows of the Jacobian matrix to generate the row of the averaging kernel matrix for 12 km altitude. It is foremost a weighted average of the measurements with tangent points close to 12 km. Figure 16a shows one row of the 2-D Jacobian matrix, i.e. a 2-D weighting function describing the sensitivity of one measurement with tangent point altitude close to 12 km altitude to changes of the 2-D atmosphere. Its maximum sensitivity lies close to the tangent point, but significant contributions are also present at higher altitudes. The negative entries in Fig. 15a are there to remove these contributions in the 1-D averaging kernel matrix. Ignoring the horizontal dimension, the 1-D weighting functions can be used to very closely approximate the delta function as shown in Fig. 15b. However, if the 2-D Jacobian matrix is employed, it becomes apparent that the available measurements do not in fact allow such a good spatial localisation. Only by adding additional measurements viewing the volume from multiple angles an averaging kernel matrix really resembling a delta peak can be constructed.

It is now clear, what causes the ≈ 20 percent underestimation in the case at hand. The horizontal oscillations of the 2-D/1-D averaging kernel matrix in combination with the decreasing ozone concentrations away from the instrument cause this underestimation. The effect is especially pronounced as ozone concentrations increase with height and therefore small oscillations in the 2-D averaging kernel far above the retrieved value still contribute meaningfully. For trace gas species that remain approximately constant or decrease in concentration with altitude the effect should be less pronounced due to the decrease in air pressure with height. The same problem has affected the evaluation of MIPAS measurements as demonstrated by Kiefer et al. (2010). Naturally, the oscillations of the 2-D averaging kernel matrix at higher altitudes contribute only noticeably to the result, if the atmosphere is not in fact horizontally homogeneous.

In contrast, the 3-D retrieval is able to use more measurements and thereby more weighting functions in the construction of the averaging kernel matrix. This increases the vector space spanned by the weighting functions and thereby offers better approximations to the desired delta functions.

The described technique can be used to more reliably compare 3-D model data with retrieved 1-D profiles by folding the model data with the 2-D/1-D averaging kernel matrix instead of the usual 1-D averaging kernel matrix. The method can also be used to quantify the effect of the horizontal inhomogeneity on 1-D retrieval results and thereby in combination with a chemical weather forecast help identify problematic atmospheric situations and accordingly optimise flight-paths of airborne instruments to avoid a bias in the retrieval results.

3. P 2996, L 6 and L 11, “high (spectral) resolution”: looking at the average performance of existing aircraft and space-borne atmospheric spectrometers I would not define “high” the spectral resolution of GLORIA even in the chemistry mode.

The “high” referred to the combination of spatial and spectral resolution and might

have been misleading. We reformulated to “combination of high spatial with a state-of-the-art spectral resolution”.

4. P 2996, L 10: the adjective “fast” is inappropriate in the absence of terms of reference for 3D algorithms.

The adjective "fast" has been removed.

5. Sect. 3.1: If I properly understand the Jacobian matrix is calculated numerically but, despite the fast forward model, “about 90 percent of the computation time is used for calculating the Jacobian matrix”. Did the authors consider the analytical approach for the calculation of derivatives? It should be much faster.

We do follow the track to employ automatic differentiation in a cooperative project with the RWTH Aachen, and are in preparation of a paper to be submitted to a more computer science oriented conference. However, the computation time seems to be memory bound due to frequent accesses to the look-up-tables, so we do not expect a speedup beyond, say, a single digit factor. The exploitation of the sparsity of the Jacobian matrix is really the most significant factor (100) aside the usage of a very fast radiative transfer model (1000). As the use of such techniques as automatic differentiation usually also requires a deeper discussion of the employed approach and possibly better suited minimization algorithms, it is well beyond the scope of this paper.

6. Sect. 4.1 P 3011: It is not specified whether the analyzed observations are generated using RFM or the retrieval forward model. In the second case the retrieval test carried out without instrument noise (sect. 4.2 see next point) provides a measure of the approximations introduced by the internal forward model plus those due to the retrieval scheme (e.g. smoothing error). Please specify.

As the RFM is not readily able to perform calculations in 3-D atmospheres, we do not employ it currently for generating the simulated measurements. We will update the paper to makes this expressively clear by adding "The measurements are generated by the JURASSIC radiative transfer model, which is also used for retrieval."

7. P 3011, L 18: Since the Jacobian matrix has been calculated twice, I infer that convergence required two iterations. Could the authors explicit the number of iterations required by their test case?

Using a polar atmosphere as a first guess, usually six iterations are required for the presented simulations. We will work this number into the paper and also briefly explain why only two kernel calculations were performed instead of six.

> Retrieving this baseline setup involves 6 iterations and uses roughly 60 CPU hours, respectively 9 hours of real time on an eight-core machine consuming only about 1.3 Gb of memory total. . . . We found that intermediate updates of the Jacobian matrix were of no benefit for the setup at hand.

8. Sect. 4.2, P 3012, L 8: In real analyses the influence of noise on the retrieval results is usually provided by the estimated standard deviation of the retrieved values. It is not clear if, in operational retrievals, the authors propose to deliver samples of the random errors as discussed in Sect. 3.4.

For operational retrievals, a full error analysis according to Sect. 3.4 will be performed, including the stochastic noise but also the influence of other systematic errors including amongst others instrument effects, forward model error and uncertainties of non-retrieved quantities. These can be derived using the gain matrix and various derivatives of F with respect to the quantity at hand. For brevity's sake, Sect. 3.4 did not go into detail as the process is always similar to the described noise error.

2 Reply to Referee 2

1. My only major concern with the work is the issue of temporal variations in the under-lying fields. Aircraft observations can take several hours to be completed, and UT/LS composition fields can evolve significantly during this time (particularly, for example, during strong convection). For an introductory study such as this, it is perfectly reasonable to set aside this issue, but its existence should at least be acknowledged and your choice to ignore it for the moment stated explicitly.

   Ultimately, I think one would probably have to invoke some kind of assimilation system to handle that issue 'correctly'. I recognize this is an oft-discussed topic. Some have said that assimilation should be all one needs these days, and that stand-alone retrievals should become a thing of the past. I'm generally not all that persuaded by such arguments, particularly for limb observations. However, assimilation would be a nice way to handle the temporal variation issue in this case (but it would place you at the mercy of model accuracy).

It is very briefly stated that we assume no advection (the largest source of temporal variation) to occur. This issue will be handled more explicit in a dedicated paragraph in Sect. 3.1 in the revised paper:

> Taking the envisioned amount of measurements for the tomographic retrieval will take several hours, as the speed of the carrier is limited. During that time, the state of the atmosphere may change significantly due to advection or chemical reactions. Handling this will require special treatment, which is beyond the scope of this paper. Therefore, we assume an unchanging atmosphere during the time required to take the measurements.

Indeed, we are currently examining various methods of addressing this issue, several of which look very promising. We believe that without full data assimilation approach meaningful results will be achievable, even though directly assimilating GLORIA measurements into a local chemical/dynamical model could be very interesting.

2. Line 8: 'The 45 (deg) to 135 (deg)' is not clearly stated, I presume 0 (deg) is the flight direction. Also (though less important) is it clockwise or anticlockwise from the aircraft (viewed from above or below)?

Current plannings envision the instrument looking "to the right", i.e. 90 (deg) clockwise as seen from above the plane. This point has been clarified in the paper.

3. Line 25: If you're going to state that 'the processes involved are among the least understood of the atmosphere', following that up by citing a 15-year-old review paper is not a good idea! Since Holton wrote that paper there have been at least 3 satellite missions including limb sensors specifically targeting this region, plus countless airborne field campaigns, not to mention many many modeling studies. Surely those have answered many of the questions Holton identifies? What are the next decade's questions in this area? You'll need stronger language than this to get GLORIA funded and flown. It would help to update this material.

   Page 2997 Line 1: This cascade is interesting perhaps, but why do we care? Why do we need to fill the observational gap? How will it improve our knowledge of things like radiative forcing etc.? Have people shown that it is this gap that makes our models wrong? It's not essential to include this kind of motivation detail in a paper like this, but it is nice to do so.

We agree that there has been progress since Holton et al., 1995, in particular by

airborne campaigns and model studies. Therefore, we highlight now the uncertainties that still exist by citing more recent publications of Solomon et al. and Stevenson et al. We also acknowledge the progress made by airborne campaigns and past limb-sounding systems and (at the same time) point to the capabilities and potential of the new limb-imaging concept. However, in general we prefer to keep the paragraphs outlining the motivation rather tight since the focus of the paper is on the tomographic methodology. The instrument is already built and will probably be flown on Geophyica next year and the new methology will be applied in this context.

The introductory paragraphs have been replaced by:

> Trace gas exchange between troposphere and stratosphere greatly contributes to UTLS composition changes and variability. Changes and variability of composition in the UTLS are, in turn, major drivers of surface climate change (e. g. Forster and Shine, 1997). Stevenson et al. (2006) highlight large model differences in the representation of stratosphere/troposphere exchange that lead to considerable uncertainties in the budget of ozone in the upper troposphere. Solomon et al. (2010) recently noted that global models are rather limited in their representation of key processes that determine the distribution and variability of water vapour in the lower stratosphere (such as stratosphere-troposphere-exchange). Consequently, these models are unable to reproduce long-term variations of water vapour in the lower stratosphere that turn out to be an important driver of decadal global surface climate change. These findings point to the need of a better quantitative understanding of processes in the UTLS (operating at different scales) that influence the spatial distribution of important greenhouse substances such as water vapour and ozone.
>
> In the past, most progress in our understanding of UTLS processes has been made by detailed in-situ airborne measurements (e.g. Hoor et al., 2004; Schiller et al., 2009) or limb-sounding satellite instruments (e. g. Hegglin et al., 2009). However, airborne observations and current limb-observations by satellites are rather limited in terms of coverage and/or spatial resolution. This limitation may be overcome in the future by new limb imaging concepts (e.g. Riese et al., 2005; ESA, 2008, Ungermann, 2010), which will greatly improve vertical sampling as well as the horizontal sampling and coverage, thereby providing an unprecedented view on meso-scale structures (e. g.

filaments, tropopause folds, mixing etc.) that play a crucial for UTLS composition and variability (e. g. Konopka et al., 2009).

In particular, limb-emission measurement techniques provide high spatial resolution and good coverage at the same time. Trace gas fields obtained from global infrared limb-emission sounding (e.g. LIMS (Gille and Russel III, 1984), SAMS (Drummond et al., 1980), CRISTA (Riese et al., 1997; Offermann et al., 1999), or MIPAS (Fischer et al., 2008)) greatly contributed to our understanding of the 3-D composition, structure and large-scale dynamics of the middle atmosphere (e.g. Riese et al., 2002). However, the spatial resolution obtained even by these sensors is relatively coarse compared to the scales of structures in the tropopause region and must by adequately improved in the future (e. g ESA, 2008). Current airborne limb-emission sensors such as MIPAS-STR (e.g. Hoepfner et al., 2001; Keim et al., 2008) and CRISTA-NF (e.g. Spang et al., 2008; Hoffmann et al., 2009) on-board the high-flying Russian aircraft Geophysica provide adequate spatial sampling in two dimensions (vertical and along the flight track). However, they are limited by a relative broad weighting function (about 200 km) of the observations in the viewing direction (perpendicular to the flight track).

4. Page 2999 Lines 8-9: It would be helpful to also give these angles in terms of distances at the tangent point. I imagine it varies with altitude a little, so just giving typical values would be fine.

The lower angle corresponds to a tangent point being 375 km away from the instrument. The upper angle does not have a tangent point in the viewing direction, so a measure of distance is not very meaningful here. The distance for the lower angle has been worked into the paper.

5. Page 2999 Lines 12-14: Just curious - some instruments look forward / backwards. It might be nice to discuss the relative merits of side viewing (apart from the mundane issues of shielding your optics from debris). Is the side-viewing geometry more favorable for these kind of tomographic observations? Your figures seem to make the case that it is - it would seem harder to do this kind of multi-vantage point viewing in a forwards/backwards geometry.

The viewing geometry is partly due to design constraints of the instrument, which should not have an uncalibrated window, thereby requiring a blackbody to be placed for in-flight calibration outside the outermost window. Technical requirements then practically enforce a window-less opening of the belly pod and a side-viewing geometry to reduce airflow.

That aside, the side-viewing geometry is also more versatile as it allows *both* tomographic retrievals as presented *and* the measurement of large volumes of air without tomographic evaluation (conventional 1-D retrieval) for arbitrary flight paths. For conventional retrievals, a forward- or backward-viewing geometry would usually allow only a much smaller air-volume to be measured than the employed side-viewing geometry.

6. Page 3003 Line 10-15: Why do you not do analytic Jacobians, these are almost always more accurate and much faster?

Please refer to the reply to 5 in Sect. 1.

7. Page 3008 Line 25: I would have thought CO would be a better choice than O3 this time round, as there are fewer sources and processes affecting it. On the other hand, perhaps there is not a strong enough signal in your spectral region.

Indeed, the signal of ozone is much better in the spectral region covered by GLORIA. Ozone was also chosen, because of its relevance for the radiative forcing.

8. Page 3009 Line 9: I would have said 'resolution' rather than 'sampling'

We try to consistently use sampling when talking about (measurement or atmosphere) grid spacing and reserve the word resolution for the diagnostic entity derived from the averaging kernel matrix or instrument specifics. While this is not exactly standard nomenclature, it saved us from quite a bit of confusion in internal discussions. For the GEM-AQ data, both sampling and resolution should refer to the same thing.

9. Page 3004 Line 5: You don't make it clear which of alpha or L is unitless. I know it doesn't matter in the end, but I think it helps to be clear. So, does the L operator have numbers around one, with the alphas scaling them into state (mixing ratio) space, or is the L operator a variable with some kind of unit and the alpha is varied around unity? Appendix A1 doesn't make this clear either.

   Page 3010 Line 4: OK, so does alpha have units (see page 3004 line 5 comment)? Given that the value is as high as 8e8 I presume the answer is yes, (so L is dimensionless, or perhaps has dimensions of inverse length). I think it would be good to work out what the units on alpha are and quote them.

α_0 is unitless and L_0 has the inverse unit of the retrieval target as its diagonal consists of the inverse of the standard deviations. The L_1 operator matrices are differential operators, meaning in this case that they map x in [unit of target] onto [unit of target]/km, i.e. the entries of L_1 have the unit km^{-1}. To retain the connection with covariance matrices, the α_1 need to be in km/[unit of target]. Using diagonal scaling matrices instead of real number for the α would tidy it a bit up, but would make the description even more complicate than it already is.

The units have been worked into the paper as noted.

10. Page 3010 Line 10: 'L-curve optimal' - I think I know what that means (but only though having done similar work) - you ought to define it really.

We added a bit of introduction and a reference to further work:

> A parameter study showed that these overall and relative weights deliver the visually best results. Further, varying the overall regularization strength, i.e. scaling all α with a factor, and plotting the L-curve, i.e. the deviation of the measurements against the

> constraint divided by the scaling factor (e.g. Hansen and O'Leary, 1993) shows that the regularization strength is L-curve optimal, i.e. it represents a good balance between fidelity to the measurements and smoothening due to the constraint.

11. Page 3011 Line 17: So, are you saying you only do the 'outer' iteration twice? That seems quite a small number. Or do you do several outer iterations without recomputing the Jacobians?

Please refer to the reply to 7 in Sect. 1.

12. Page 3012 Line 7: Within 5 percent? It's hard to tell that from the figures - the continuous color scale makes it hard for the reader to interpret quantitatively. We'll take your word for it of course, but you might want to consider a more discrete color scale (5 reds, grey, 5 blues)? This goes for all your plots.

We follow the advice of using plots with discrete color scales. While this hides some details, for a printed version without access to the underlying data, it may indeed be advantageous.

13. Page 3012 Line 10: It would be good to be more quantitative here - what does our 5% become?

It has been clarified that the effect of noise on the retrieval result is rather small compared to the inherent artifacts introduced by the tomographic reconstruction. Within the volume covered by tangent points removing the artificial noise slightly reduces the error as can be seen by the size reduction of the non-white area in the new discrete color plots.

> The influence of noise on the retrieval result can be well seen by comparing Fig. 5 with Fig. 6, where the same setup is simulated without instrument noise. The deviations from the true value outside of the central region are still present, which indicates that these are not an effect of noise, but of insufficient measurement information. Further simulations (not depicted) indicate that decreasing the noise by means of averaging

over time does not improve the result as fewer measurements deliver less spatial resolution.

14. Page 3012 Lines 13-15: This sentence is a bit unclear, please give more details.

We clarified that indeed not the influence of a priori information is negligible, but the bias towards the x_a vector. The influence of the a priori smoothing constraint is indeed relevant and cannot be quantified by the measurement contribution.

15. Page 3012 Line 29: Delete comma after 'measure'. Also, 'banana' shapes are not the only problems you could have - an ellipsoidal volume that was not aligned with any useful axes (vertical, along/across track) would be another (perverse I admit) example.

We clarified that the ellipsoids in question are in fact nicely aligned. As indicated by the 'e.g.' outside the well-resolved region, banana shapes are not necessarily the worst one can get.

16. Figure 13: All the points have black rings around them. If there is one that is broader than the others, I can't spot it. Please make this clearer somehow.

A wrong figure was supplied, which will be corrected.

17. Figure 14: Last sentence of the caption is unclear - what are we supposed to look at? Give us the altitude/distance of the region you're talking about. Is it everything from 400-800km, 4-16km or are there particular layers of interest?

This is indeed misleading. The content in question will be moved to the main body and will be clarified by mentioning the relevant altitude region of 10 km and above:

Above 10 km altitude, one can see a strong horizontal structure with ozone concentrations decreasing away from the instrument. This gradient certainly violates the assumption of horizontal homogeneity.

Interactive comment on Atmos. Meas. Tech. Discuss., 3, 2995, 2010.