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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Technical Note: Regularization performances with the error consistency method in the case of retrieved atmospheric profiles" *by* S. Ceccherini et al.

S. Ceccherini et al.

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We thank the reviewer for careful reading of the manuscript. Below we discuss his specific comments.

1) A problem is said well-posed when it satisfies the conditions of Hadamard. Even if a problem is well-posed, it may still be ill-conditioned, meaning that small errors in the measured data can result into large errors in the retrieved quantities. As suggested by the reviewer the ill-conditioning of the MIPAS inversion problem can be quantified by the conditioning number of the inversion matrix at iteration steps. For the inversion problem reported in this paper the conditioning number is of the order of 10^{11}. Since the double

precision calculations provide a precision of 15 decimal digits, the algorithm is able to perform the matrix inversion without significant numeric errors (i. e. the problem is not ill-posed). However, as we can see from Fig. 1, the retrieval without regularization is affected by a large retrieval error in some altitude ranges where the retrieved profiles show large oscillations, revealing a high sensitivity of the retrieved profiles to errors in the measurements (i. e. the problem is ill-conditioned). The applied regularization determines a reduction of the retrieval errors. So the applied regularization determines a stabilization of the retrieval with respect to errors in the measurements (i. e. "improves the conditioning"). With a less mathematical expression this can be called a "cosmetic" smoothing of the profiles.

More generally, it is true that regularization is typically used both to overcome ill-posed problems and to improve the conditioning. In the papers quoted by the reviewer (Gil-Lopez et al.(2005): Retrieval of stratospheric and mesospheric O3 from high resolution MIPAS spectra at 15 and 10 μm, Adv. Space Res., Vol. 36, No. 5, pp. 943-951, doi:10.1016/j.asr.2005.05.123, N. Glatthor et al.(2006): Retrieval of stratospheric ozone profiles from MIPAS/ENVISAT limb emission spectra: a sensitivity study, Atmos. Chem. Phys., 6, 2767-2781) non operational analysis of MIPAS measurements are considered and a fine retrieval grid (1 km altitude spacing up to 44 km and 2 km above), that makes ill-posed the inversion, is adopted. In those cases regularization is used in order to overcome the ill-posed problems. The a-posteriori regularization discussed in our paper cannot solve the problem of ill-posed retrieval and indeed is only used to improve the conditioning of the inversion in the case of the new MIPAS observation mode adopted after January 2005. Therefore, the error consistency method and the a-posteriori regularization can only be applied when the inversion problem is well-posed and have the advantage that provide for further processing both the regularized solution and the non-regularized solution. This rationale will be better explained in the revised version.

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2) Since the step of the measurement grid is for some altitudes smaller than the vertical IFOV, contiguous limb scanning views have overlapping IFOVs. In this case the retrieval of the profiles on a grid equal to the measurement grid determines negative correlations between vertically contiguous values. These negative correlations produce oscillations in the retrieved profiles as those of the non-regularized profile shown in Fig. 1. In presence of anti-correlations the vertical structure observed in the retrieved profile cannot be considered to be realistic. In order to reduce these anti-correlations we use the smoothness constraint obtained with the L_1 matrix. The same kind of regularization (regularization matrix equal to the first derivative matrix and null vector for the a-priori vector) is applied in the paper quoted by the reviewer (Glatthor et al. (2006), Retrieval of stratospheric ozone profiles from MIPAS/ENVISAT limb emission spectra: a sensitivity study, Atmos. Chem. Phys., 6, 2767-2781). It is true that a thin vertical structure of the ozone profile can be masked by using a regularization that smooths the profiles. This is a reason why we apply the error consistency method that provides a weak regularization. However, the MIPAS retrieved profiles will be characterized by both the variance-covariance matrix and the averaging kernels. So the users will be able to discriminate which structures can be resolved in the MIPAS profiles, and which could be masked by the used retrieval approach. A sentence describing the reason of the choice of the smoothness constraint will be added to the paper.

3) The spatial smoothing over the instrument field of view has been taken into account in the forward model. It is not very strange to obtain a vertical resolution smaller than the IFOV when the step of the retrieval grid is smaller than the IFOV. As a prove of this it can be considered that the averaging kernel matrix is equal to the identity matrix when the Levenberg-Marquardt and the regularization parameters are zero. In our retrieval scheme when the averaging kernel matrix is equal to the identity matrix the vertical resolution is equal to the step of the limb scanning sequence and if this is smaller than the IFOV also the vertical resolution is smaller than the IFOV. Increasing the val-

ues of the Levenberg-Marquardt and regularization parameters the vertical resolution deteriorates, but can still be smaller than the IFOV.

A figure showing exemplary averaging kernels will be added to the paper.

4) The total error budget of the MIPAS retrieved profiles includes two contributions: the measurement errors and the forward model errors. The measurement errors are due to the mapping of random radiometric noise into the retrieved profiles. The forward model errors are due to uncertainties in instrument characterization and in input parameters of the radiative transfer, as well as to approximations in the forward model itself. While the measurement errors are randomly distributed, the forward model errors are generally not random and often produce a bias in the retrieved profiles. The reviewer poses the question of whether the measurement error (as it is done in Eq. (8)) or the total error should be used for the calculation of the regularization parameter used in the case of the error consistency method. We believe that since most systematic errors are a bias, a conservative approach must be used and a regularization does not need to be applied to this component. We will modify the paper to make clear this point.

Regarding the smoothing error. In order to estimate the smoothing error we need to know the variance-covariance matrix of an ensemble of true states. As stated in [Rodgers, 2000, p. 49] "To estimate it [the smoothing error] correctly, the actual statistics of the fine structure must be known. It is not enough to simply use some ad hoc matrix that has been constructed as a reasonable a priori constraint in the retrieval. If the real covariance is not available, it may be better to abandon the estimation of the smoothing error, and consider the retrieval as an estimate of a smoothed version of the state, rather than an estimate of the complete state." Since we do not have an accurate evaluation of this variance-covariance matrix, we prefer to not base the discussion on the estimation of the smoothing error that could be inaccurate. The reader can evaluate the quality of the provided data on the basis of the vertical resolution that is well determined.

5) The differences between regularized and non-regularized profiles shown in Fig. 2 can differ from the retrieval errors for two reasons:

i) the effect of the off-diagonal elements of the variance-covariance matrix. As stated in the paper the simple interpretation that the differences between the regularized and the non-regularized profiles are on average equal to the errors of the regularized profile is an approximation;

ii) the compared profiles correspond to two different retrievals that use different values of the interfering species and of the initial guess of the retrieved ones. So eq. (7) is not strictly valid for the profiles whose differences are shown in Fig. 2.

Following the suggestion of the reviewer to quantify the influence of the off-diagonal elements of the variance-covariance matrix we have computed the mean of the expression in the left-hand side of eq. (7) for the 78 scans of the MIPAS orbit #17540 analysed in the paper. When the overall variance-covariance matrix is considered the mean of the expression in the left-hand side of eq. (7) coincides with the average number of the VMR profile points reported in table 1 (23.3) proving the correctness of the application of the method. When the calculation of this quantity is performed by forcing to zero the off-diagonal elements of the variance-covariance matrix we get the value 28.0. This result confirms that the off-diagonal elements of the variance-covariance matrix contribute to increase the differences between the regularized and the non-regularized profiles but cannot explain the large values observed in Fig. 2a. Therefore, reason (ii) is the main cause of the observed difference between regularized and non-regularized profiles.

Fig. 2(a) will be modified showing also the r.m.s. of the differences between regularized and non-regularized profiles of the same retrieval (that is x and $\hat{x}$ of Eq. (7)) proving

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that reason (ii) produces large differences. The implications of reason (ii) will also be discussed in the revised paper.

Responses to specific comments.

P13308L17-18: We agree with the reviewer that smoothness is not the only objective of regularization, even if this is the most frequent objective in the case here discussed of retrieval of atmospheric profiles. In this sentence the reference to the smoothness of the profile is not necessary and will be removed in the final version of the paper.

P13312L19-20: We agree with the reviewer and in the final version of the paper we will change the sentence.

P13312L22-23: As discussed in our reply to the first general comment the general objective of regularization is to make the inversion problem well-posed and to improve its conditioning ("to restore the stability of the inversion" in reviewer's words). In the application herewith discussed the problem is already well-posed and the purpose of regularization is only that of improving the conditioning. Furthermore, the choice made for the L_1 matrix (see the reply to the second general comment) is that of improving the conditioning with a reduction of the oscillations. Therefore, in this particular context the statement is correct.

P13314L15-17: What the reviewer says is quite correct and no opposite statement is made in the paper. A regularization that is constant with altitude is applied and even if the amount of regularization is the same at all altitudes, an altitude dependent effect is

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observed as in other regularization methods.

P13315: We prefer to use "reduced chi-square" that is commonly used in the context of error analysis. See for example [Bevington, P. R. and Robinson, D. K.: Data Reduction and Error Analysis for the Physical Sciences, 3rd ed. McGraw-Hill, New York, 2003] page 68.

Interactive comment on Atmos. Chem. Phys. Discuss., 6, 13307, 2006.

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