Vertical grid of retrieved atmospheric profiles

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INTRODUCTION

Measurements of the vertical profile of atmospheric constituents are often obtained with the inversion of remote sensing observations and the vertical grid used for the representation of the profile is an subjective choice of the retrieval process.

A vertical grid is considered adequate when it extracts most of the information provided by the observations and provides a good visual representation of the measured vertical profile. We call *instrument dependent vertical grid* the vertical grid selected according to these requirements.

The profiles retrieved from two or more instruments observing the same species in the same portion of atmosphere can be fused into a single product. A recent paper [1] demonstrated that it is possible to perform a *complete fusion*, which reproduces the profile obtained with the *simultaneous retrieval*. We recall that the simultaneous retrieval is a single retrieval that simultaneously uses as inputs all the observations acquired by the different instruments. In the light of this result, the profile retrieved from a single instrument acquires further significance: it is not only the visualization of the measurement provided by an instrument, but also a possible contribution to subsequent data fusion operations.

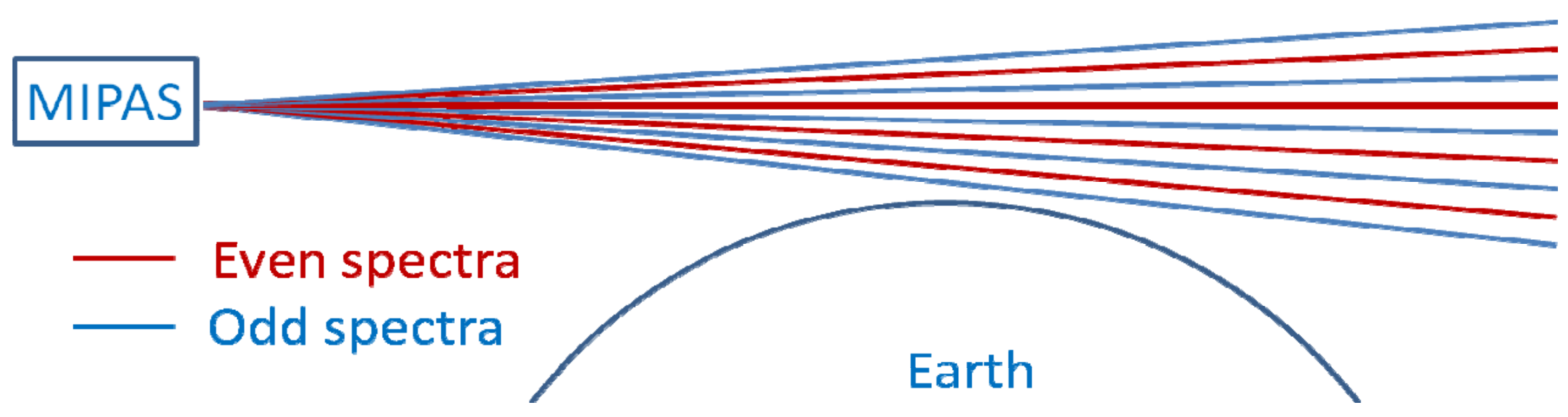
With this new perspective, we pose the problem of which is the optimal vertical grid of a retrieval. We question whether the instrument dependent vertical grid still represents the optimal vertical grid or different vertical grid requirements emerge when we consider possible subsequent data fusion applications.

To answer this question, we compare the data fusion results when the profiles to be fused (*fusing profiles*) are obtained with different vertical grids, selected according to the vertical resolution of either the single profile or the fused profile. We perform this comparison using the measurements of the MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) instrument onboard the ENVISAT satellite.

This study is a contribution to the AURORA project (http://www.aurora-copernicus.eu), which is part of the Horizon 2020 programme, and one of its objectives is the identification of the best strategy for data fusion operations of future Copernicus measurements.

DATA AND PROCEDURE

We divided a MIPAS limb sounding sequence consisting of 24 spectra in two datasets taking spectra at alternate tangent altitudes (referred to as *even* and *odd spectra*). In this way, we obtain two datasets that cover approximately the same vertical range.



We performed two retrievals of these two datasets using two different vertical grids. The first retrieval is performed on the vertical grid defined by the tangent altitudes of the spectra that are analyzed; therefore, the vertical grid is composed by 12 levels corresponding to the even tangent altitudes in the first dataset and to the odd tangent altitudes in the second dataset. These vertical grids are optimal for the analyses of the single datasets. The second retrieval of the two datasets is performed on the vertical grid defined by all the tangent altitudes of the limb sequence, therefore, it is composed by 24 levels obtained merging the two vertical grids used in the first retrieval. This vertical grid is optimal for the simultaneous retrieval of the two datasets and, accordingly, is the grid adopted for the data fusion products. In both cases the complete fusion algorithm [1] is used for the fusion of the profiles and the two results are compared in terms of values, errors, vertical resolutions and number of degrees of freedom (NDOF). In the following the two 12 level grids are referred to as *coarse grids* and the 24 level grid is referred to as *fine grid*.

COMPARISON OF THE PERFORMANCES OF THE TWO VERTICAL GRIDS FROM THE POINT OF VIEW OF PROFILE VISUALIZATION

We compare the retrievals of the even spectra performed on coarse and fine grid. We start the comparison reporting in Fig. 1 the information distributions [2] as a function of altitude corresponding to the profiles retrieved on the two different vertical grids.

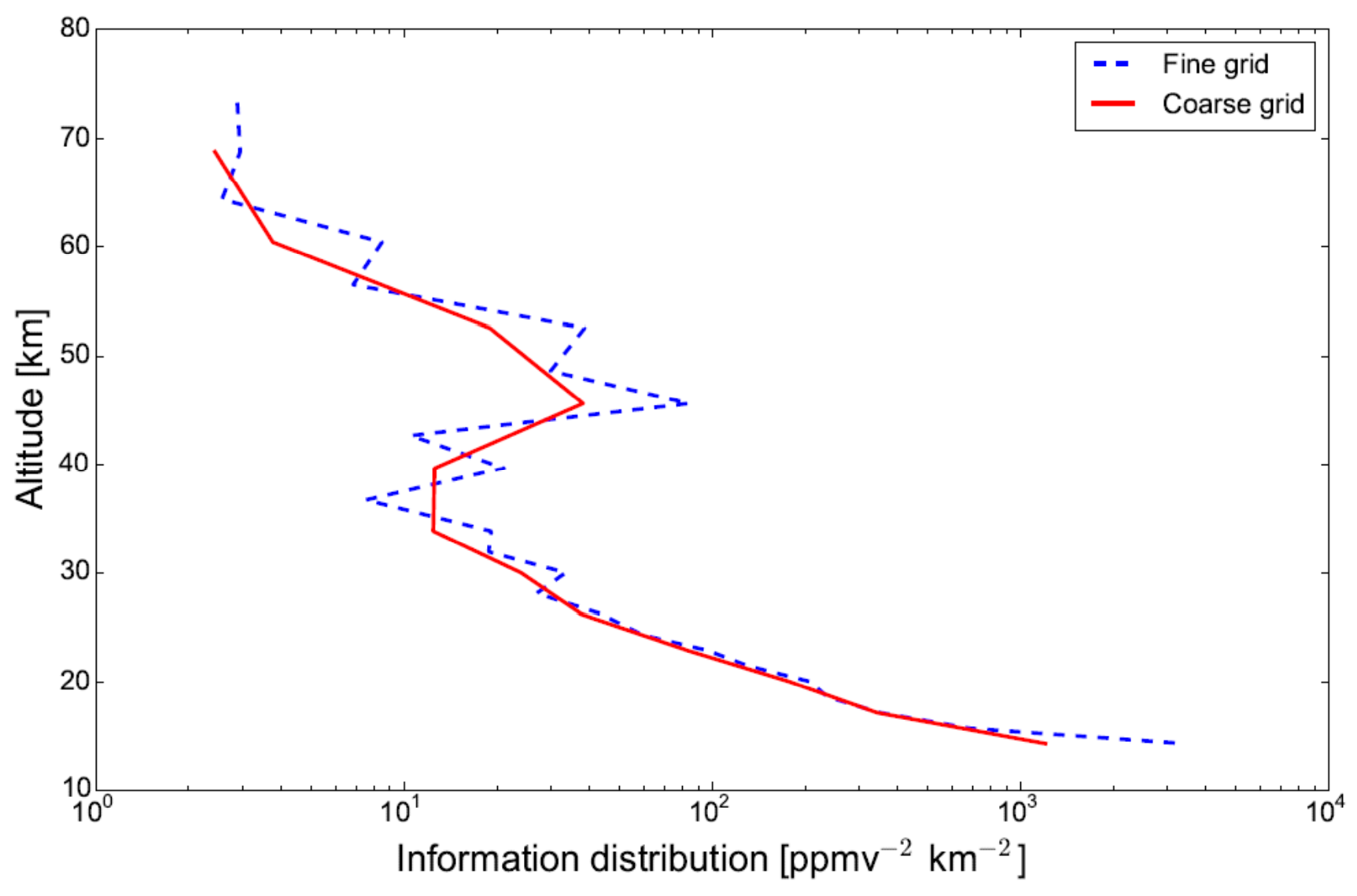


Fig. 1. Information distribution as a function of altitude of the profiles retrieved from the even spectra using the fine and coarse grids.

The information distribution is a quantifier that is characteristic of the set of the analyzed observations and is independent of the applied constraint and of the vertical grid. As expected, the information distributions of the two profiles have different values, because they are plotted on different grids, but, since the same observations are considered, their piecewise linear curves have similar envelopes.

A more stringent comparison is provided by retrieval errors and vertical resolutions. However, these quantifiers depend on the strength of the applied constraint. In order to make a meaningful comparison we used constraints that produce the same NDOF for the two retrievals (equal to 11.5). With this NDOF constraint, in Fig. 2 we compare the retrieved values, the errors and the vertical resolutions of the two profiles.

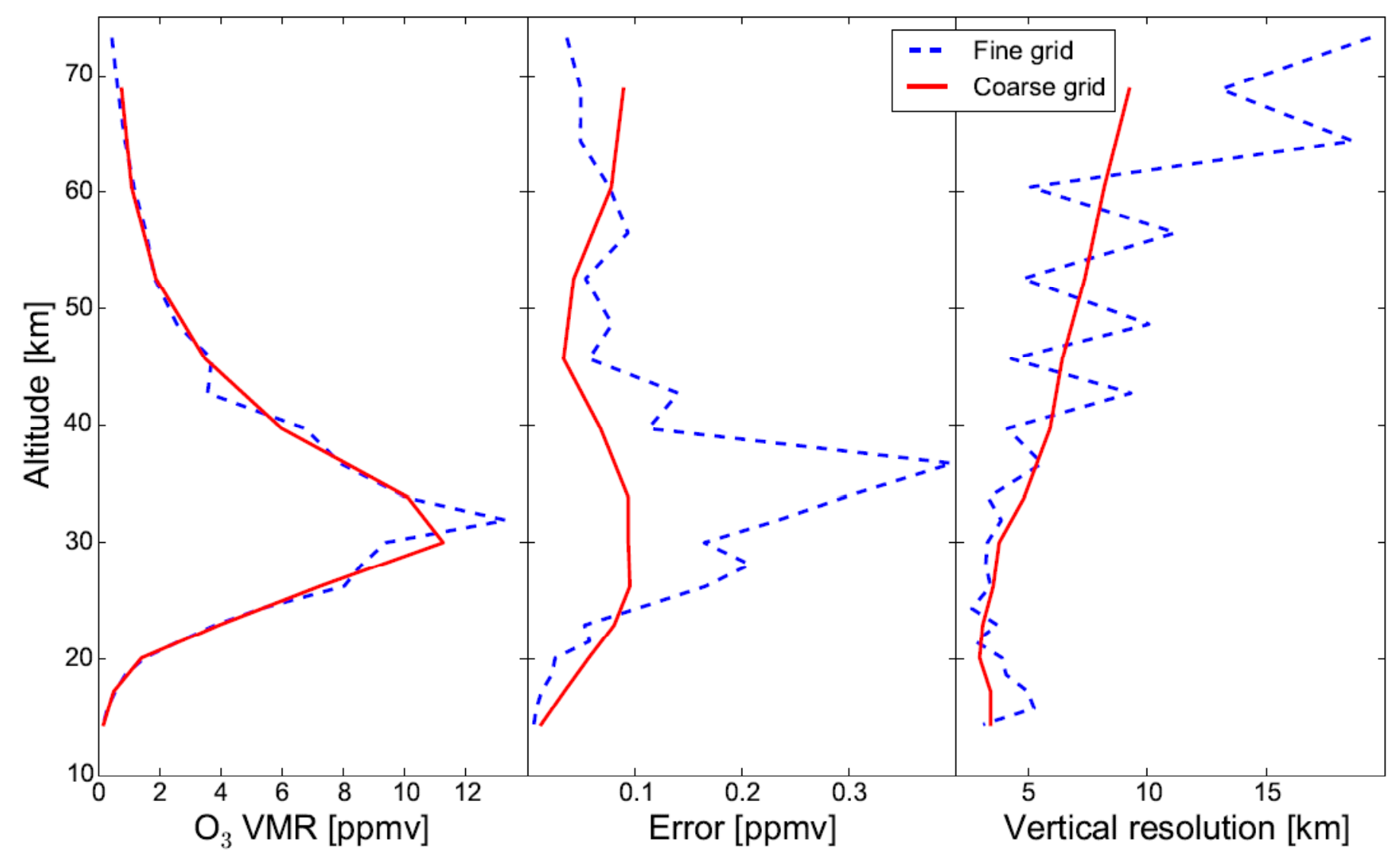


Fig. 2. Comparison of the retrieved values (left panel), of the errors (central panel) and of the vertical resolutions (right panel) of the profiles retrieved from the even spectra using the fine and coarse grids.

The two profiles have comparable vertical resolutions, but at intermediate altitudes the profile retrieved on the fine grid is characterized by larger oscillations and larger errors.

The comparison of Fig. 2 shows that no evident advantage is obtained with the use of a finer grid. Instead the choice of an optimized vertical grid, such as that given by the tangent altitudes in the case of limb sounding observations, provides a well-balanced distribution of the information as a function of altitude and a profile that is more suitable for the purpose of a visualization.

COMPARISON OF THE PERFORMANCES OF THE TWO VERTICAL GRIDS FROM THE POINT OF VIEW OF THE DATA FUSION

We compare the products of the complete data fusion of the two datasets when the fusing profiles are retrieved on the fine and coarse grids. We recall that the complete data fusion uses the following expression [1]:

$$\mathbf{x}_f = \left(\sum_{i=1}^{2} \mathbf{A}_i^T \mathbf{S}_i^{-1} \mathbf{A}_i + \mathbf{S}_a^{-1} \right)^{-1} \left(\sum_{i=1}^{2} \mathbf{A}_i^T \mathbf{S}_i^{-1} \boldsymbol{\alpha}_i + \mathbf{S}_a^{-1} \mathbf{x}_a \right) \quad (1)$$

with

$$\boldsymbol{\alpha}_i = \hat{\mathbf{x}}_i - \left(\mathbf{I} - \mathbf{A}_i \right) \mathbf{x}_{ai}, \quad (2)$$

where, indicating with index i either of the two products, $\hat{\mathbf{x}}_i$, $\mathbf{S}_i$, $\mathbf{A}_i$ and $\mathbf{x}_{ai}$ are, respectively, the retrieved profile, the covariance matrix, the averaging kernel matrix (AKM) and the a-priori profile of the fusing profiles, $\mathbf{I}$ is the identity matrix and $\mathbf{x}_a$ and $\mathbf{S}_a$ are the constraint applied to the fused profile.

When the fusing profiles use the fine grid, all the quantities defined in Eq. (1) use the same grid and can be easily combined together. When the coarse grids are used the fusing profiles have different vertical grids and in order to apply Eq. (1) it is necessary to transform their AKMs so that the second index refers to a common vertical grid. We performed this transformation from the individual coarse grids to the common fine grid calculating the new AKMs $\mathbf{A}_i'$ as:

$$\mathbf{A}_i' = \mathbf{A}_i \mathbf{H}_i^{\#}, \quad (3)$$

where $\mathbf{A}_i$ are the original AKMs and $\mathbf{H}_i^{\#}$ are the generalized inverses of the linear interpolation matrices $\mathbf{H}_i$, that calculate the profiles on the fine grid from the profiles on the coarse grids.

We indicate with *profile A* the data fusion of the profiles retrieved on the fine grid and with *profile B* the data fusion of the profiles retrieved on the two coarse grids and compare them with the simultaneous retrieval obtained fitting simultaneously all the 24 spectra of the limb sequence. The simultaneous retrieval and both fusions use the same a priori.

In Fig. 3 we compare the three profiles. The NDOF of the simultaneous retrieval is 20.4, the NDOF of profile A is 20.5 and the NDOF of profile B is 19.5.

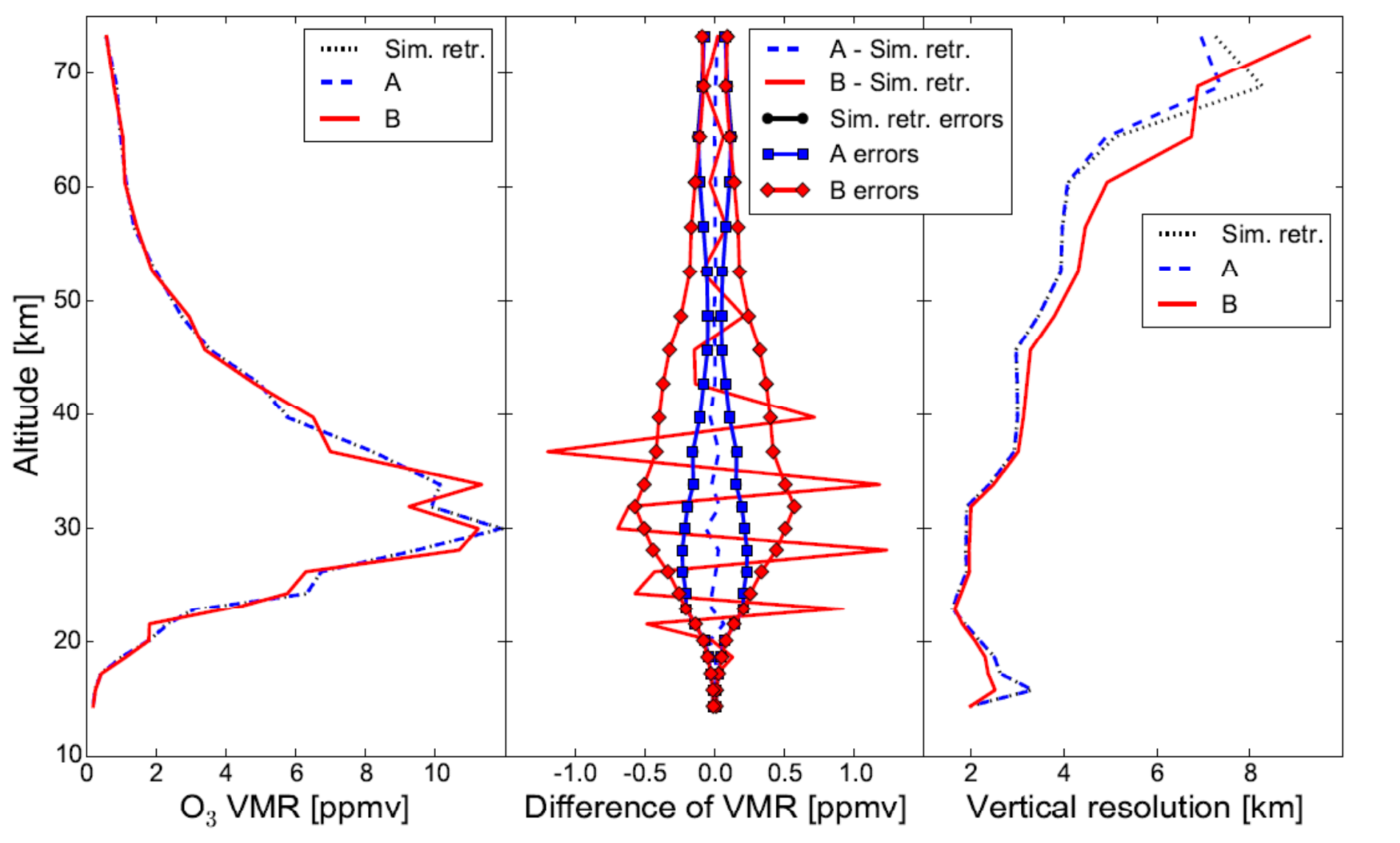


Fig. 3. The left panel shows the profiles obtained with simultaneous retrieval, fusion A and fusion B. The central panel shows the differences of the profiles obtained with fusion A and fusion B, with respect to the profile obtained with simultaneous retrieval, and compares them with the errors of these profiles. The right panel shows the vertical resolutions of the three profiles reported in the left panel.

Profile A (as already demonstrated in [1]) perfectly reproduces the results of the simultaneous retrieval with equal errors and NDOF (in the three panels of Fig. 3 the curves of the simultaneous retrieval are often covered by those of profile A). Profile B has an oscillating behavior and, with respect to the simultaneous retrieval, has large differences, one degree of freedom less as well as much larger retrieval errors.

Other comparisons of profiles A and B were made using for B a different constraint selected so that the two profiles have comparable retrieval errors. In this case, not shown here, profile B has a less oscillating behavior than in Fig. 3, but has almost five degrees of freedom less than the simultaneous retrieval and shows relative to it differences larger than the retrieval errors (probably due to smoothing errors caused by the missing degrees of freedom).

These results clearly show that the quality of profile B is worse than that of profile A.

In order to understand the reasons of this result we analyze the eigenvalues of the Fisher information matrix. While the information distributions reported in Fig. 1 are calculated using only the diagonal elements of the Fisher information matrix, the eigenvalues are calculated using all the elements of the matrix and, therefore, reflect properties that are more comprehensive. In Fig. 4 we report the eigenvalues of the Fisher information matrices of profiles retrieved from the even spectra using the fine and coarse grids. In the case of the profile retrieved on the coarse grid, the Fisher information matrix $\mathbf{F}$ was transformed into a matrix with a fine grid by the transformation $\mathbf{H}^{\#T}\,\mathbf{F}\,\mathbf{H}^{\#}$.

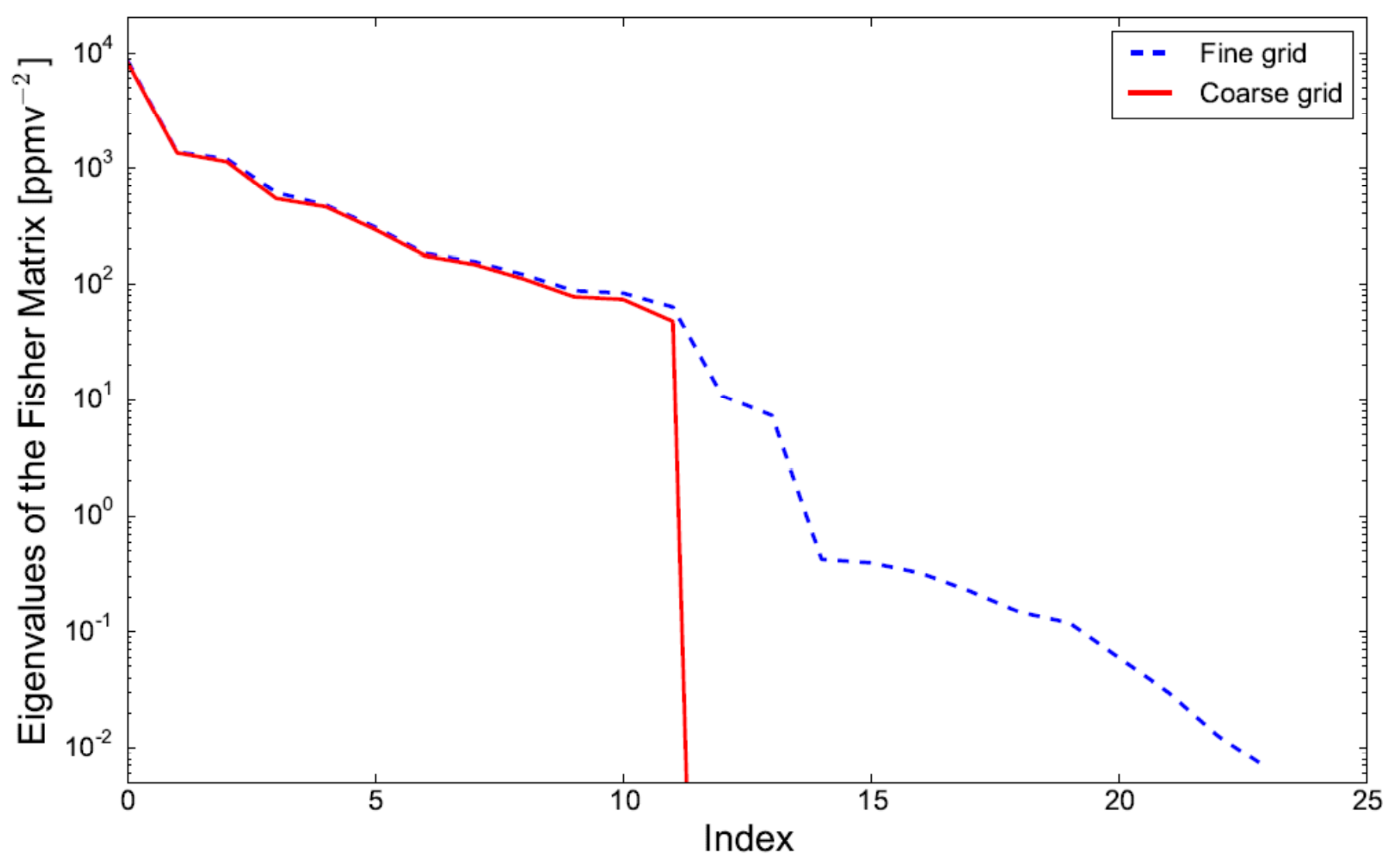


Fig. 4. Eigenvalues of the Fisher information matrices of profiles retrieved from the even spectra using the fine and coarse grids.

In Fig. 4 we can see that the first 12 largest eigenvalues have similar values in both cases, the remaining 12 eigenvalues are zero in the case of the retrieval on the coarse grid while they are different from zero in the case of the retrieval on the fine grid. These 12 extra eigenvalues show that the retrieval on the fine grid is able to extract more information than the retrieval on the coarse grid. This additional information, which is made of small eigenvalues, is irrelevant in the case of the analysis of a single set of observations where we look for a representation of the profile with less than 12 degrees of freedom. However, in the case of data fusion, where we look for more than 12 degrees of freedom, a better result is obtained using fusing profiles that contain information on all the analyzed degrees of freedom.

CONCLUSIONS

From the point of view of profile visualization no evident advantage is obtained with the use of a vertical grid finer than the instrument dependent vertical grid. On the other hand, the instrument dependent vertical grid provides very poor results when used as input for data fusion applications. A loss of about a quarter of the degrees of freedom is observed when the data fusion is made using the instrument dependent vertical grids instead of the vertical grid optimized for the data fusion product for the fusing profiles.

This result is explained by the analysis of the eigenvalues of the Fisher information matrix, which shows that the retrieval on the fine grid is able to extract more information than the retrieval on the coarse grid.

As a final conclusion we can state that the vertical grids of products that will be used for subsequent data fusion operations must be chosen taking into account the expected quality of the fused profiles, rather than using the choices made for the representation of the results of the individual retrievals.

S. Ceccherini, B. Carli and P. Raspollini, *Vertical grid of retrieved atmospheric profiles*, Journal of Quantitative Spectroscopy and Radiative Transfer, Vol. **174**, 7-13 (2016)

[1] S. Ceccherini, B. Carli and P. Raspollini, *Equivalence of data fusion and simultaneous retrieval*, Optics Express, Vol. **23**, 8476-8488 (2015).

[2] S. Ceccherini, B. Carli and P. Raspollini, *Quality quantifier of indirect measurements*, Optics Express, Vol. **20**, 5151-5167 (2012)