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Interactive comment on "Characterization of model errors in the calculation of tangent heights for atmospheric infrared limb measurements" *by* M. Ridolfi and L. Sgheri

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For clarity we include also the comments of reviewer #1 using *italic text*.

General Comments

The paper describes results from investigations of the impact of various aspects of ray-tracing for the MIPAS limb-viewing infrared radiometer. While I do not doubt the correctness of the results obtained I believe that, due to the methodology used, the

results are not suitable for wider application and hence the current work is really more of an internal technical study rather than a scientific paper.

The algorithms investigated in the paper are applicable to the general problem of ray-tracing in an inhomogeneous transparent medium. This problem has to be tackled, in particular, when modelling the radiances that reach a spectrometer (or a radiometer) observing the atmosphere. While the solution to the ray-tracing problem may seem consolidated, several approximations, fully acceptable for implementation in the old 1D inversion systems, become quite rough for the more accurate 2D retrievals. Dropping approximations such as those of the iterative Snell's method implies additional calculations and a non-negligible computing effort for the inversion algorithm. This is why one should select the most accurate and computationally efficient method for ray-tracing, also taking into account the instrument performances. While updating the MIPAS retrieval algorithm we found that there are not many recent papers on the subject of ray-tracing. We therefore think that a publication analysing the main factors driving the accuracy of the ray-tracing might be very useful.

In the revised paper we will clarify this point.

Section 2: Ray Tracing. *It does not seem surprising that, given sufficiently small step-size, all three algorithms converge to the same solution.*

Note that, as mentioned in the paper, the TD method uses an approximation to avoid the calculation of the second derivatives of the path. What we show is that this approximation is of the same order of the errors involved in the numerical solution of the Eikonal equation with the EIK/AEIK methods. In principle this finding is not trivial.

The difference appears to be in the efficiency but is the computing time spent on ray-tracing really a significant over- head in the retrieval of L2 products? Furthermore, since the Curtis-Godson integration is usually performed in parallel with the ray-tracing using a numerical integration along the ray-path, it is not clear that an algorithm which finds *the tangent height with relatively few steps is any advantage since the CG integration will in any case have to sub-divide the steps.*

The ray-tracing algorithm produces the path for the CG curvilinear integrals. Several CG integrals must be calculated (on the same path) at each retrieval iteration. Furthermore, if pressure and temperature are retrieved, the ray-tracing should be recalculated at each iteration. Thus, the time spent in the CG integration is not negligible compared to the retrieval time. Our aim is to obtain the full set of nodes to be used in the CG integrals from the ray-tracing algorithm, thus avoiding the iterative refinement of the integration step. This is possible because both the curvature of the path and the atmospheric variability of the quantities to be integrated is relatively small. To apply this approach we need a computationally efficient method to calculate the ray-path on a sufficiently fine mesh.

In the revised paper we include a sentence clarifying the approach we intend to use in the retrieval code.

Section 3: Refraction Model. *The obvious way to analyse the impact of different refraction models is to use the fact that [n r sin(theta)] is conserved along a circularly symmetric path (n=refractive index, r=radius from centre, theta=angle relative to local horizontal), from which it can be seen that [n r] at the tangent point is a constant for any particular limb-view. This gives a much simpler analytical method of relating differences in refractive index models (n) to differences in tangent height (r) without any need for explicit ray-tracing. In any case, the difference in tangent height is only one aspect: perhaps more significant for L2 products is the difference in CG path amounts which are increased for a lower tangent point both by the increase in pressure and the additional length of the path (which does require ray-tracing), but there is no discussion of this.*

We had already implemented the ray-tracing algorithm for a horizontally varying atmosphere at the time of testing the refraction model. Therefore we actually did not think

about using the simpler approach suggested by the reviewer. Since in this test we assume the US76 spherically symmetric atmosphere we agree that the simpler method must provide the same results. We have checked that this is actually the case and we will mention this suggestion in the revised paper.

Note that the errors shown in Fig. 3 of the paper refer to the tangent height errors due to the combined effect of both refraction and atmospheric models. The impact of the refraction model error on the L2 temperature will be therefore a small fraction of the error shown in Fig. 3.

Section 4: Atmospheric Model. *It is of course to be expected that the atmospheric model will have the biggest impact on the tangent height: different models have different density v altitude profiles as well as horizontal structure. However the tests here just seem to be a not particularly representative sample and no attempt is made to isolate the two effects: it would have been better to use meteorological data to analyse the variation in density for a given altitude (the 1D effect) and also, perhaps sampled with MIPAS pole-to-pole orbital coverage, the variability in horizontal density gradients (the 2D effect), together with their impact on the L2 temperature and pressure profiles.*

Following this comment we made an additional test in the attempt to separate the two contributions to the tangent height error due to the vertical variation of the atmosphere and the horizontal gradient. We repeated the test reported in Fig. 2, panel (b) with the retrieved atmosphere but assuming zero horizontal gradient in the ray-tracing of each scan. We find that, on average, the corrections in the two cases are correlated and 85% of the error shown in Fig. 2 (b) is due to the vertical structure of the atmosphere and the remaining 15% is connected to the horizontal homogeneity hypothesis. We will include this finding in the revised paper.

The test of Fig. 2, panel (b) refers to a single MIPAS orbit, however we also carried-out the same test on a sample of 12 orbits spanning the four seasons of the year 2010. We found that the amplitudes of the tangent height errors are very similar, therefore in the paper we report only the results for a single orbit (the one for which we also have correlative RO measurements). In the revised paper we will mention that the presented results are representative of a larger sample of analyzed orbits.

Specific comments

p7702, l16: Since the early limb sounders on the Nimbus satellites in the 1970s it has been known that the on-board line-of-sight pointing is inadequate to define the tangent height to useful accuracy and that tangent pressure derived from the limb radiances themselves (with little a priori constraint on absolute altitude) have formed the vertical coordinate of the product. So, I disagree that good knowledge of the tangent height is of much benefit to the scientific L2 products except for the purposes of converting from pressure to absolute altitude, and even here may be more accurately performed by registration with (eg ECMWF) meteorological analyses.

The ESA L2 retrieval code for MIPAS actually retrieves also pressure at the tangent points. In the measurements acquired after 2004, however, the spectral resolution (0.0625 cm^{-1}) is not so fine and the tangent pressure error resulting from an unconstrained retrieval would be quite large ($\approx 5\%$). In order to reduce this error, the retrieval algorithm constrains pressure using the tangent altitude increments provided by the engineering pointing system and assuming their value to be correct within an a-priori uncertainty of ± 80m. This constraint reduces the retrieved pressure error to about 0.5%. Of course, a further reduction of this error could be obtained by reducing the a-priori uncertainty on the pointing step. Absolute pointing is important to reconstruct the absolute altitude grid of the retrieved profiles, as it may be necessary for comparison to correlative measurements (such as those obtained from lidars) that are intrinsically represented on an absolute altitude grid. Reconstruction of the absolute altitude grid with ECMWF meteorological analyses is often possible only for the off-line processing,

furthermore meteorological analyses may not be equally accurate in the whole altitude range covered by the limb-scan. In the revised version of the paper we will introduce a sentence to better explain this issue.

p7702, l19: One of the biggest sources of uncertainty is the instrument pointing. It is of little benefit performing ray-tracing to 10m tangent height accuracy if the (geometric) instrument pointing is itself uncertain to 100m. What is the assumed absolute pointing uncertainty for MIPAS here?

MIPAS pointing errors are estimated by the engineers to be of the order of ± 100m, however this number includes only the errors due to the instrument pointing system, possible errors due to the ray-tracing so far are not included in this budget. In the revised paper we will add this information.

p7704, l3: I couldn't find the reference to Stiller 2000, although on the KOPRA web-site I found a report by Hopfner and Hase dealing with ray-tracing. Perhaps this would be a better reference with an explicit link to this document in the bibliography?

In the revised paper we will add the reference mentioned by the reviewer. This is actually Chapter 4 of the KOPRA manual cited in our original paper.

p7704, l8: I don't think there's any problem in using Snell's Law to calculate refraction angle; the problem seems to be with the assumption that the angle is relative to an altitude surface when it should be relative to a refractivity/density surface?

Correct, it is Thayer implementation of Snell's law which uses the hypothesis that the level lines for the refractivity coincide with the altitude levels. The reference Hobiger (2008) removes this assumption, at the price of a substantial increase in the code complexity. We will correct this mistake in the revised paper.

p7707, l10: The RO refractivity measurements presumably only give the fine vertical structure of refractivity along the path without any horizontal information. To simulate the MIPAS observation with its finite FOV you would have to first smooth these data with the appropriate kernel, as well as assume no horizontal variation.

In the forward model we first simulate the radiances corresponding to pencil beams with infinitesimal aperture, then we convolve the simulated radiances with the actual MIPAS FOV (see Ridolfi et al. 2000). Therefore we provide in input to the ray-tracing algorithm RO profiles smoothed and interpolated to vertical resolution and grid compliant to those employed in the forward model. Of course RO measurements are assumed horizontally constant. In the revised paper we will include this information.

p7707, l18: It would have been simpler to start with the satellite location and viewing angle and avoid the back-calculation altogether. Perhaps these data were unavailable?

While the satellite position and pointing angles are available, we do not have access to the algorithm calculating the L1b tangent heights but only to its results. We verified that the L1b tangent heights are very similar to the ones calculated from the satellite using Edlen's refraction model and the US76 atmosphere. There are however some minor differences, so we preferred to start from the L1b calculated tangent heights and back-trace the ray-path to avoid any inconsistencies with the values used in the ESA retrieval. In the revised paper we will justify this choice.

p7715 (Fig caption): 'Error profiles ... T_L1b' - there should be some expansion of this to a proper sentence if it is to convey any more information than already given in the legend. What sort of errors?

These are the errors due to the mapping of the measurement noise into the retrieved temperature. In the revised paper we will better specify the origin of the reported error curves.

Typographical errors

p7708, l15: 'elaborate' rather than 'elaborated'.

ok.

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