RTMIPAS: A fast radiative transfer model for the assimilation of infrared limb radiances from MIPAS

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Introduction

An RTTOV-type fast radiative transfer model has been developed for emitted clear-sky limb radiances from the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) onboard ESA's Envisat. MIPAS is an infrared sounder with very high spectral resolution (0.025 cm^{-1}, Table 1). It is designed to provide information on the thermal structure and chemical composition of the upper troposphere to lower mesosphere. The fast model is referred to as RTMIPAS, and it has been developed to directly assimilate limb radiances in a global variational data assimilation system (see Bormann and Healy in these proceedings).

Table 1: Main characteristics of MIPAS.

Spectral resolution	0.025 cm^{-1} unapodised
	0.035 cm^{-1} apodised
Spectral region	685-2410 cm^{-1} in 5 bands
Nominal tangent altitudes in normal scanning mode	6-42 km in 3 km steps; 47, 52, 60, 68 km
Field of view at tangent point (vertical x horizontal)	approx. 3 km x 30 km
Data coverage	Sept. 2002 - March 2004; one scan approx. every 5°

Methodology

The method adopted for RTMIPAS follows the regression-approach developed over the years for nadir-viewing geometry in fast radiative transfer models such as RTTOV (e.g., Saunders et al. 1999). RTTOV is widely used for the direct assimilation of nadir radiances at a number of numerical weather prediction centres. Details about the methods employed in RTMIPAS can be found in Bormann et al. (2004, 2005); the main characteristics adopted from the RTTOV methodology are:

- The atmosphere is represented on 81 fixed pressure levels (Fig. 1).
- Convolved level-to-satellite transmittances are parameterised through regression models for the effective layer optical depths.
- The regressions are derived from results of line-by-line (LBL) computations for a sampled set of 46 ERA-40 profiles, using the Reference Forward Model (RFM) developed at the University of Oxford (Dudhia 2005). The set of profiles has been chosen to adequately sample the atmospheric variability above 500 hPa. Horizontal homogeneity is assumed in the LBL calculations.
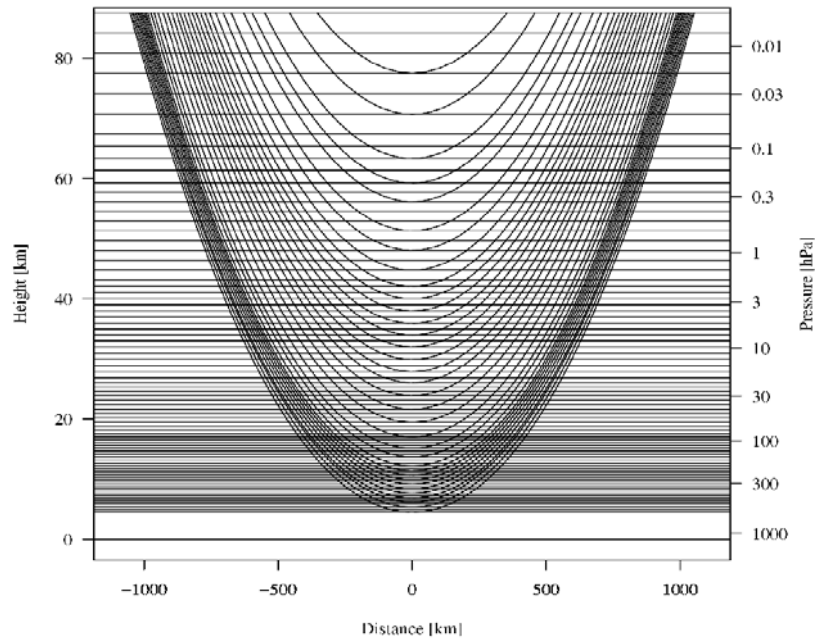
Fig. 1: Schematic representation of the levels (horizontal lines) and pencil beams (curved lines) used in RTMIPAS, mapped into a plane-parallel view.

- Humidity and ozone are treated as variable gases; for other contributing gases a fixed climatology is assumed.

The main differences and extensions to the nadir-RTTOV methodology are:
- Ray-tracing is required to determine the path conditions.
- The predictors have been extensively revised for the limb-geometry; the most fundamental change consists of replacing the secant of the zenith angle with layer path length in the predictors.
- Field of view (FOV) convolution in the vertical is required. To do this, radiances are calculated for rays with tangent pressures at a subset of the fixed pressure levels (Fig. 1). A cubic fit through these "pencil beam" radiances is used for the FOV convolution. This follows similar approaches used in ESA's routine retrieval processing (Ridolfi et al. 2000).

Validation

The RTMIPAS radiances and transmittances have been compared to RFM equivalents for a set of 53 ERA-40 profiles not used in the training ("independent set"). This characterises the errors introduced through the fast parameterisation ("fast model errors"). Errors introduced through the spectroscopy or through neglecting the variability of gases other than humidity and ozone are not addressed here. Note also that the independent set may share some of the characteristics of the training set since both were sampled from ERA-40 data.
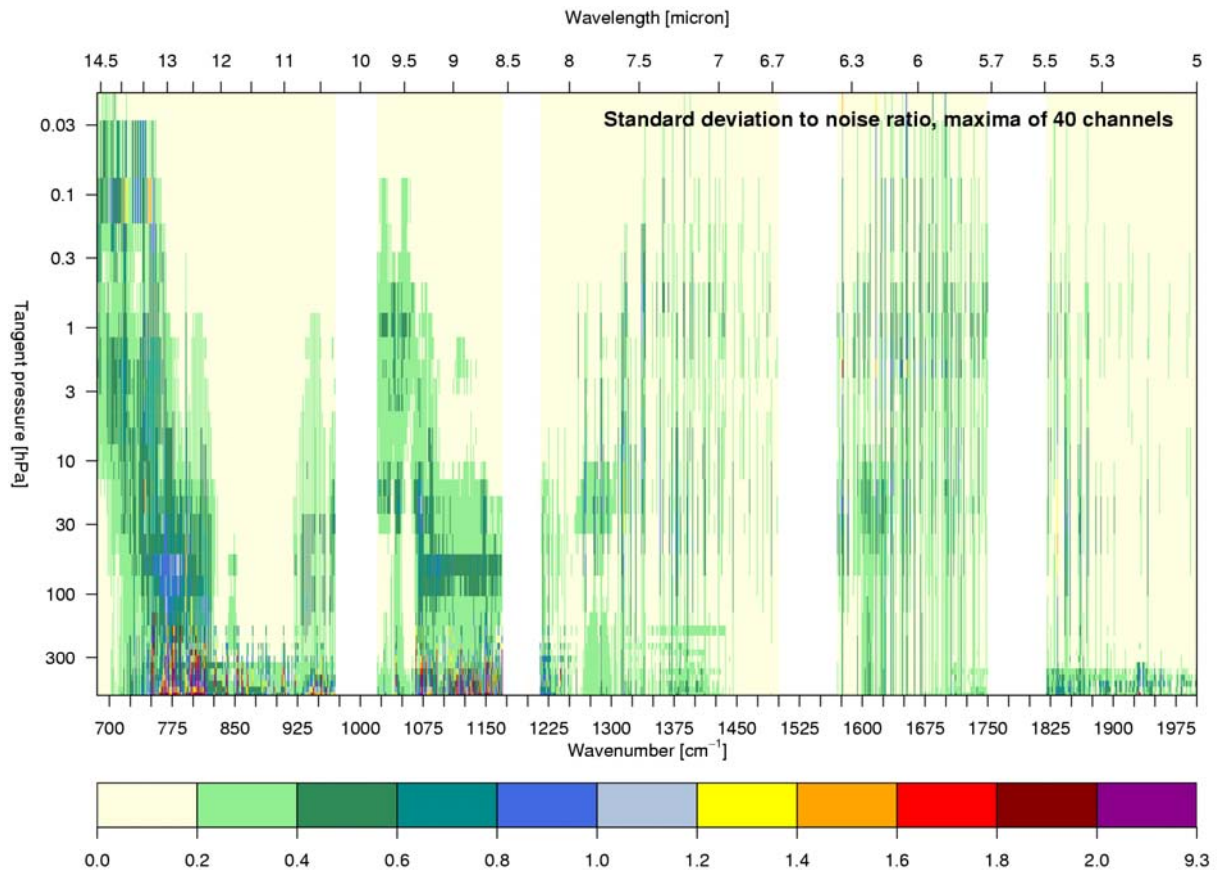
Fig. 2: Maximum over 40 channels (i.e., 1 cm-1 intervals) of the standard deviation of the RTMIPAS minus RFM radiance differences, scaled by the MIPAS noise. Note that this display emphasises the poorest performace of RTMIPAS per 1 cm-1 interval.
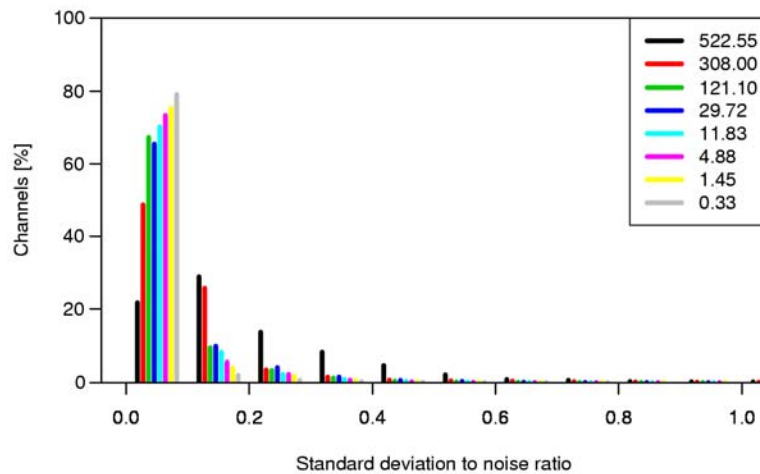

Fig. 3: Distribution of the number of channels [%] versus the standard deviation of the RTMIPAS minus RFM radiance differences scaled by the MIPAS noise. Results for 8 selected pencil beams are shown, with tangent pressures indicated in the legend.

The main findings of this validation are:

- RTMIPAS can reproduce LBL radiances to an accuracy that is below the noise level of the MIPAS instrument for most channels and tangent pressures (Figures 2 and 3).
- Fast model errors tend to be larger for the lower pencil beams.
- Fast model biases are small and mainly confined to lower pencil beams (Fig. 4).
- Root mean squared (RMS) differences between RTMIPAS and LBL transmittances are typically around 10^{-4} - 10^{-5}, and the maximum RMS difference rarely exceeds 0.005 (not shown).
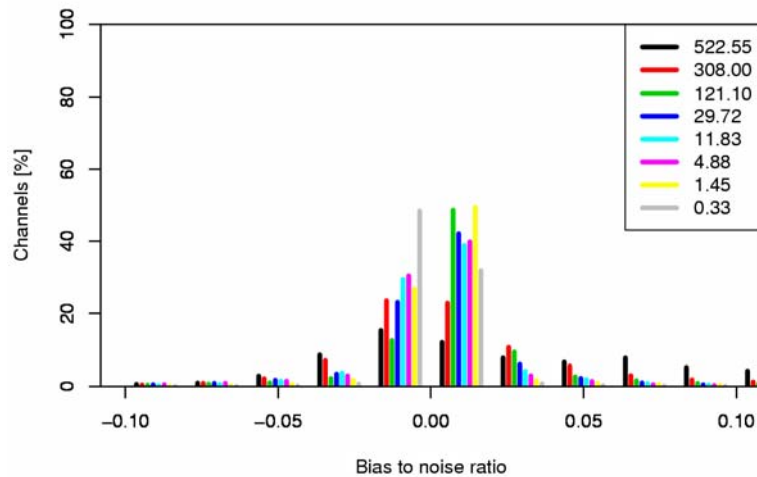

Fig. 4: As Fig. 3, but for the number of channels [%] versus the mean RTMIPAs minus RFM radiance differences scaled by the MIPAS noise.

RTMIPAS for horizontal cross-sections

Limb radiances are sensitive to the vertical and the horizontal structure of the atmosphere. Neglecting horizontal gradients and assuming horizontal homogeneity, as done in the above calculations, can introduce large errors in the radiance simulation for lower FOVs, and these errors can exceed by far the noise level of the instrument (Fig. 5).

RTMIPAS has been adapted to calculate radiances for a given horizontal atmospheric cross-section ("RTMIPAS-2d", Bormann and Healy 2005). To avoid the costly retraining of the regression coefficients, we employ the same regression coefficients calculated under the assumption of horizontal homogeneity, but use a 2-dimensional ray-tracer to provide the inputs for the predictor calculation. The hypothesis is that the regression coefficients are adequate as long as the atmospheric variability on both sides of the tangent point is captured in the initial set of training profiles.

To evaluate the performance of RTMIPAS-2d we compare radiances simulated with RTMIPAS-2d and the RFM (2d) for a set of 40 diverse cross-sections sampled from ECMWF model fields (Fig. 6). The cross-sections have been chosen to sample different geographical regions and seasons and to capture situations with considerable horizontal structure.

The main findings are:

- For tangent pressures of less than 300 hPa, RTMIPAS-2d performs similarly well as RTMIPAS in the horizontally homogeneous case. This suggests little benefit from retraining the regression coefficients on the basis of diverse cross-sections.
- For tangent pressures larger than 300 hPa, RTMIPAS-2d shows larger deviations from the LBL calculations than in the horizontally homogeneous case. This suggests some benefit from retraining the regression coefficients on the basis of diverse cross-sections for these tangent pressures.
- Even without retraining of the regression coefficients the fast model errors in RTMIPAS-2d are much smaller than the large error introduced for lower pencil beams by neglecting the horizontal gradients in the atmosphere (cf, Fig. 5 and 6).
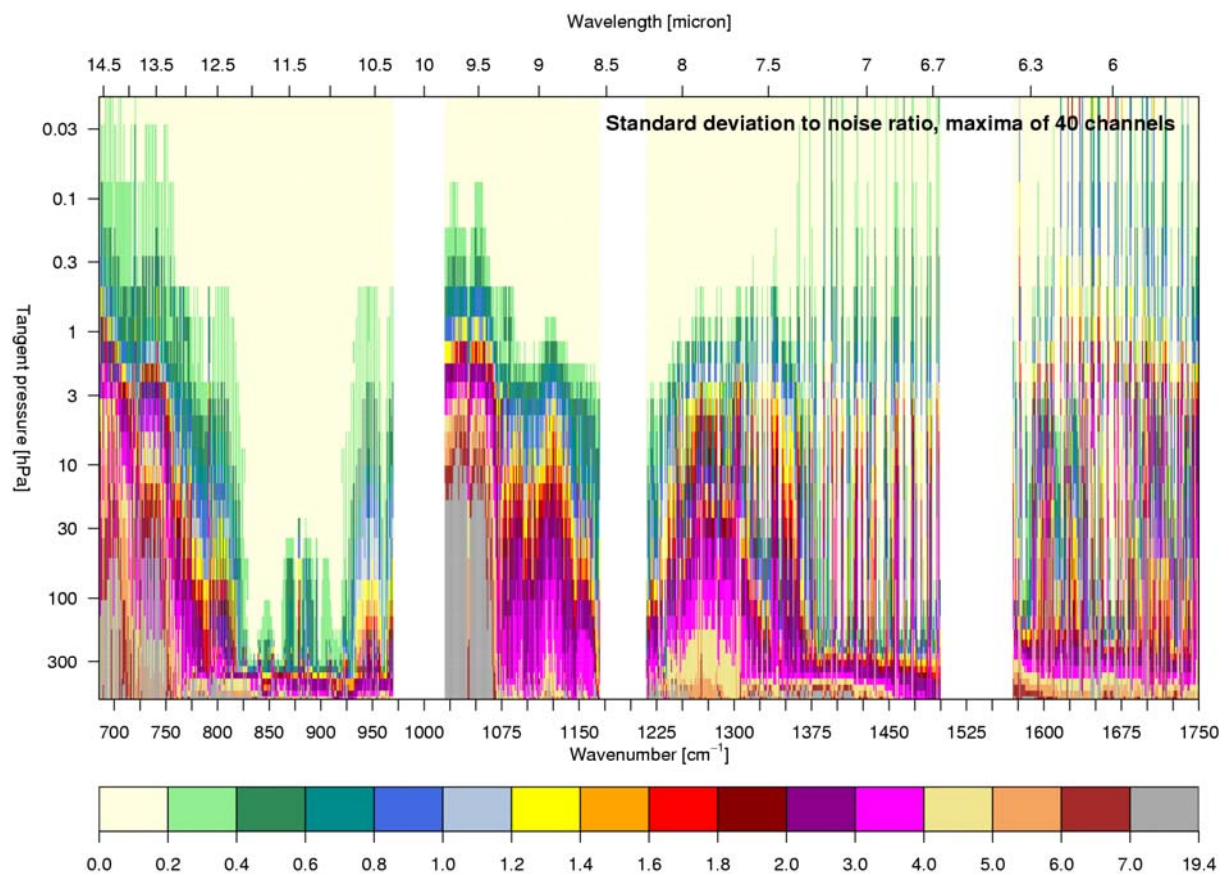

Fig. 5: Error introduced by neglecting horizontal gradients for a sample of 40 cross-sections taken from ECMWF model fields. The plot shows the maximum over 40 channels (i.e., 1 cm^{-1} intervals) of the standard deviation of the RTMIPAS-1d minus RFM-2d radiances, scaled by the MIPAS noise.
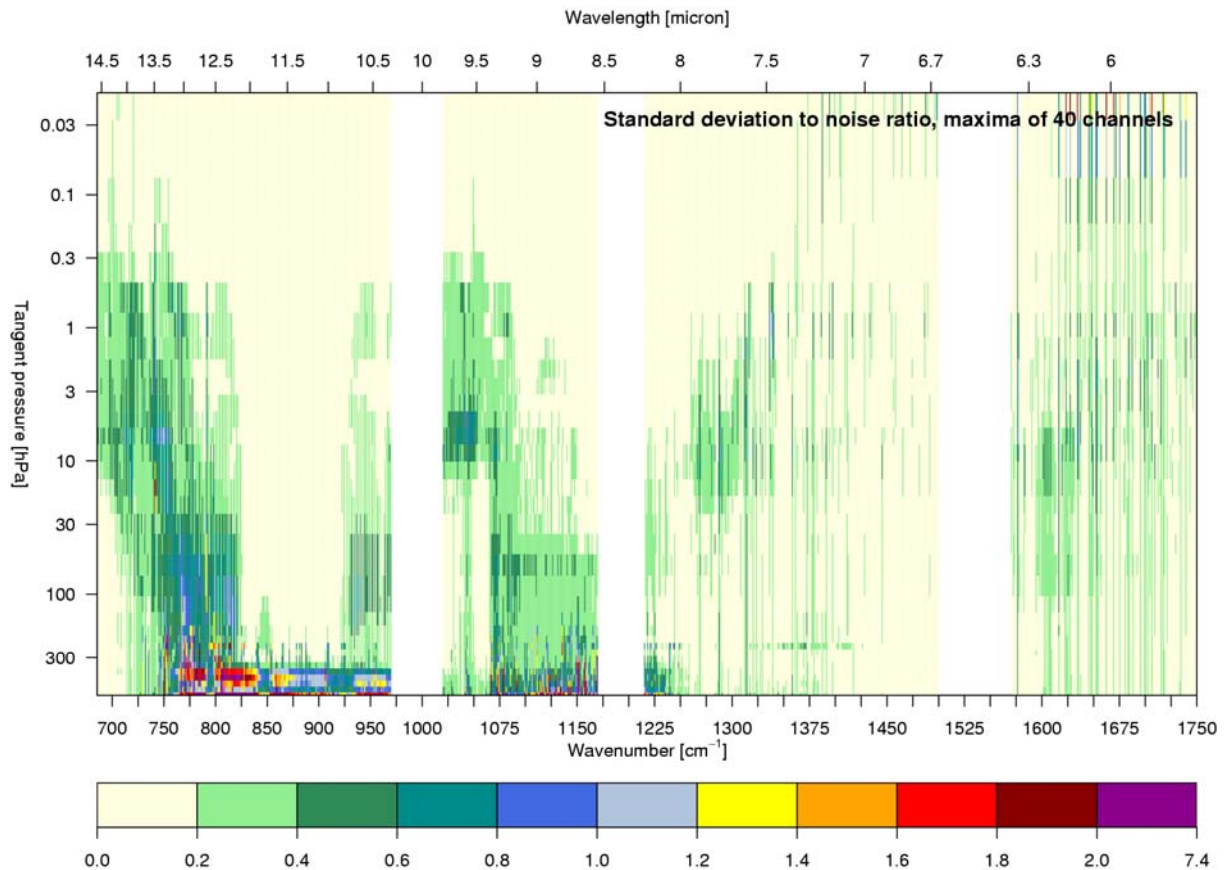
Fig. 6: As Fig. 2, but for a set of 40 cross-sections.

Conclusions

A regression-based fast radiative transfer model for emitted clear-sky radiances has been adapted to the limb geometry for the first time. The model can simulate radiances for all channels of the MIPAS instrument in the 685-2000 cm^{-1} wavenumber range, taking into account effects of variable humidity and ozone. Tangent linear and adjoint routines have also been developed.

The validation of RTMIPAS shows that for horizontally homogeneous atmospheres the error introduced through the fast parameterisation is below the instrument noise for most channels and tangent altitudes. RMS differences between RTMIPAS and LBL transmittances are typically around 10^{-4} - 10^{-5}, and the maximum RMS rarely exceeds 0.005. This indicates a performance comparable to RTIASI for the nadir geometry. The model extends well to atmospheres with horizontal gradients, for which the assumption of horizontal homogeneity introduces considerable errors for lower tangent altitudes or channels in more strongly absorbing spectral regions.

The small errors introduced by the fast transmittance parameterisation in RTMIPAS are unlikely to give a significant contribution to the total forward model error, compared to uncertainties in the spectroscopy. In any case, the effect of the "fast model errors" on the assimilation of MIPAS data can be minimised by avoiding channels with larger "fast model errors" at the channel selection stage. This can be done using channel selection methods which take into account sources of forward model error (e.g., Dudhia et al. 2002). Such channel selection is necessary due to the prohibitive number of

observations provided by MIPAS. The performance of RTMIPAS is thus expected to be adequate for data assimilation purposes. However, it should be noted that the fast model errors and other forward model errors in general are likely to be correlated between channels, similar to findings for high-resolution nadir sounders (Sherlock 2000).

RTMIPAS shows that a regression-based approach to transmittance modelling can be successfully adapted to the limb geometry, and the method could be used for radiative transfer modelling for other limb sounding instruments. The RTMIPAS method has already been successfully adapted to the Microwave Limb Sounder (MLS) on EOS-Aura (Liang Feng 2005, pers. communication).

A separate contribution summarises the first experiences with assimilation of MIPAS limb radiances in the ECMWF system (Bormann and Healy in these proceedings).

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