



Met Office

Interpolation methods in the RTTOV radiative transfer model

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Abstract

RTTOV v9 introduced an internal interpolator which allows input profiles of atmospheric variables to be supplied to RTTOV on an arbitrary set of input levels. It is observed that this interpolation method results in artificial oscillations in calculated temperature Jacobians when the input levels are more densely spaced than the RTTOV coefficient levels.

The latest version of RTTOV, v11.2, implements four additional options for the internal interpolation. The impact of these interpolation options on simulated brightness temperatures and Jacobians is examined. The interpolation modes are also compared in the context of 1D-VAR retrievals of atmospheric temperature and water vapour profiles. These comparisons are carried out for different combinations of input pressure levels and coefficient pressure levels.

In terms of forward model simulations no single interpolation mode is optimal for all situations. When the input levels are more densely spaced than the coefficient levels, interpolation modes 4 and 5 appear better. Conversely, when input levels are less dense than the coefficient levels, modes 1 and 3 generally give better results.

When the input levels are more dense than the coefficient levels, modes 4 and 5 eliminate the oscillations observed in temperature Jacobians. When input levels are less dense than coefficient levels the resulting Jacobians are very similar from all interpolation modes, although mode 5 results in larger differences compared to the other modes.

In practical applications such as for 1D-VAR retrievals there is very little to choose between the interpolation modes because any spurious artefacts in the Jacobians are smoothed out by the vertical correlations in the background.

1. Introduction

RTTOV (Matricardi *et al* 2001, Hocking *et al* 2014) is a fast radiative transfer model for passive visible, infrared (IR) and microwave (MW) satellite-borne sensors and is used in various applications including data assimilation, atmospheric retrievals and the generation of simulated satellite imagery. RTTOV takes as input vertical profiles of pressure, temperature, water vapour and optionally other trace gases, and scattering particle parameters along with associated surface parameters. The outputs are top-of-atmosphere (TOA) radiances and brightness temperatures (BTs) for the selected instrument channels. To carry out the fast computation of optical depths RTTOV uses a linear regression to compute optical depths on a fixed set of pressure levels. The coefficients for this linear regression are pre-computed and stored in coefficient files which are specific to each instrument. Most RTTOV coefficient files are based on a fixed set of 54 levels (54L), but coefficients have also been generated on a set of 101L for some instruments.

RTTOV can accept input profiles on an arbitrary set of pressure levels. It uses an internal interpolator to map the input profile onto the coefficient levels and again to map the computed optical depths back onto the input levels. The latest version of the software, RTTOV v11.2, implements a number of different interpolation options (or modes) which are described in section 2 of this report. Sections 3, 4 and 5 examine the impact of the interpolation methods on the forward model BTs, on RTTOV Jacobians and on 1D-VAR retrievals respectively. Section 6 looks at the relative computational cost of the interpolation options and section 7 summarises the results.

2. Interpolation in RTTOV

Prior to RTTOV v9 it was necessary to interpolate input profiles onto the RTTOV coefficient levels before calling RTTOV. An internal interpolator (Rochon *et al*, 2007) was introduced with RTTOV v9 which allowed input profiles to be provided on an arbitrary set of levels. A key property of this interpolation algorithm is that *all* input levels contribute with appropriate weights to the interpolated profile which ensures that Jacobians do not exhibit artificially high or low sensitivity to atmospheric variables on particular input levels specifically as a result of the interpolation. In contrast, for example, when interpolating linearly in log-pressure (referred to henceforth as log-linear interpolation) where the two nearest input levels are interpolated to give the value on each output level, it is possible

for “gaps” to appear in Jacobians when the input levels are more dense than the output levels in the interpolation (see Figures 1 and 2).

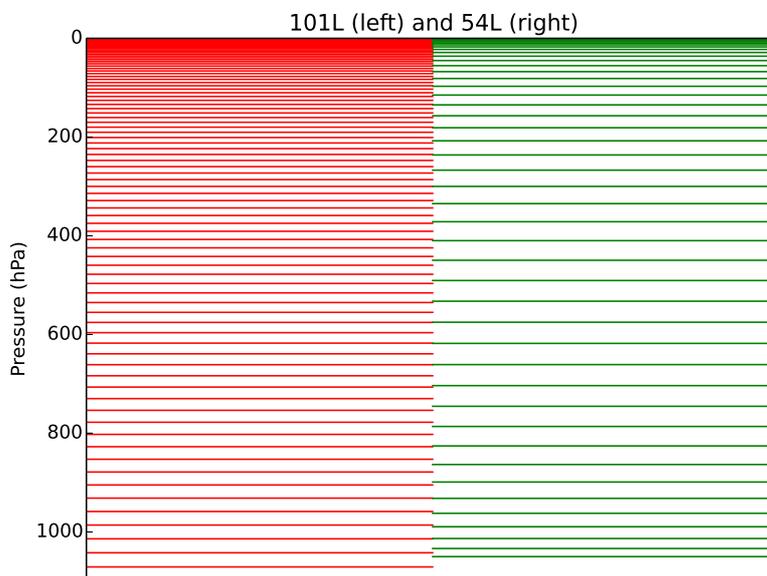


Figure 1: illustrating the standard RTTOV 101L (red) and 54L (green) pressure profiles.

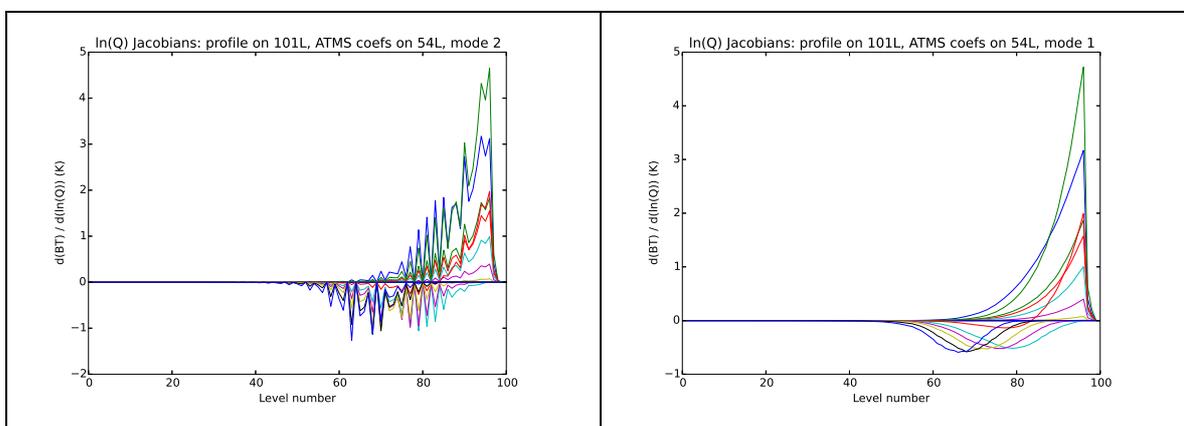


Figure 2: water vapour Jacobians for all ATMS channels calculated for a 101L input profile and 54L coefficient file (pressure levels as in Figure 1) using log-linear (in pressure) interpolation (left) and the RTTOV v9 Rochon interpolator (right). Log-linear interpolation results in excessively small and large sensitivities to water vapour throughout the profile because each input level contributes unevenly to the interpolation, and in fact some levels do not contribute at all. The Rochon interpolator ensures all input levels contribute with appropriate weights and this eliminates these artefacts.

RTTOV involves two interpolation steps as shown in Figure 3. First the input profile is interpolated onto coefficient levels. The level-to-space optical depths are calculated for the coefficient levels and these are then interpolated onto the user (input) levels. The radiative transfer equation is integrated on the user levels to obtain TOA radiances.

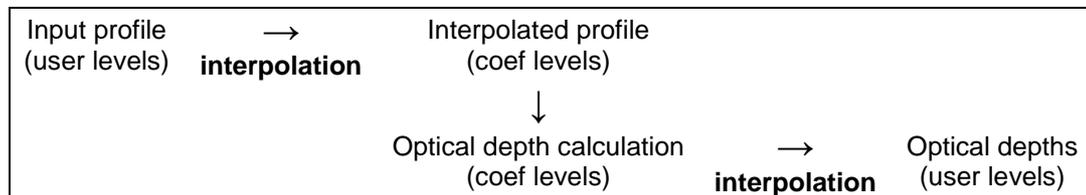


Figure 3: flow diagram of interpolation steps in RTTOV.

In the case where the input levels are more dense than the coefficient levels the interpolator introduced in RTTOV v9 (henceforth referred to as mode 1, see Table 1) results in small oscillations in the interpolated level-to-space optical depths. These interpolated optical depths are used in the integration of the radiative transfer equation. For example, the upwelling atmospheric emission radiance from layer i (bounded above and below by levels i and $i+1$ respectively) is calculated as:

$$e^{-\tau_i} \left[J_i - e^{-\Delta\tau} J_{i+1} + \frac{1 - e^{-\Delta\tau}}{\Delta\tau} (J_{i+1} - J_i) \right]$$

where J_i is the Planck function evaluated at the temperature at level i , τ_i is the optical depth from space to level i , and $\Delta\tau = \tau_{i+1} - \tau_i$. The details of this relatively complicated expression are not important in the current context (more information can be found in, for example, Berk *et al* (1998) which describes this linear-in-tau weighting of the Planck function). What is relevant here is that the small oscillations in the interpolated level-to-space optical depths are significant in magnitude when compared with the layer optical depths ($\Delta\tau$) which feature in this expression. As a result the oscillations are visible in the temperature Jacobians (see Figure 4).

In RTTOV there are two distinct contributions to the temperature Jacobians: the first is from the atmospheric thermal emission which is calculated on the input levels, and, as just described, the oscillations in the forward model interpolated optical depths affect this contribution to the temperature Jacobian. The second contribution is from the optical depth regression on coefficient levels because the atmospheric temperature is one of the variables which feature in the predictors for the regression. The oscillations

subsequently introduced by the forward model interpolation of the optical depths do not interact with this calculation and as a result there are no oscillations present due to the Rochon interpolator in this contribution.

This is the reason that similar oscillations are not seen in the water vapour Jacobians in the right-hand plot of Figure 2: for clear-sky infrared and microwave simulations the water vapour profile does not feature in the integration of the radiative transfer equation in RTTOV. As a result the only contribution to the water vapour Jacobians comes from the optical depth regression and so, again, there is no interaction with the interpolated forward model optical depths.

To summarise, there are two distinct issues which can introduce spurious artefacts into Jacobians:

- *The use of an interpolation method which does not ensure all input levels contribute.* This is of particular importance for the interpolation of the input profile onto coefficient levels when the input levels are more densely spaced than the coefficient levels and impacts all Jacobians directly by artificially increasing or decreasing the sensitivity of TOA radiances to particular input levels (Figure 2). It is of less importance for the optical depth interpolation because level-to-space optical depths are being interpolated and these are calculated from the accumulated sum of the individual layer optical depths. As a result the output of the optical depth interpolation is always sensitive to all coefficient levels.
- *The use of the Rochon interpolation method to interpolate level-to-space optical depths when the input levels are more densely spaced than the coefficient levels.* This introduces small oscillations into the forward model interpolated optical depths which become clearly visible in the temperature Jacobians as a result of the use of the layer optical depths in the calculation of the thermal emission term in the integration of the radiative transfer equation (Figure 4).

The Rochon interpolator was explicitly designed to address the first of these issues and the new interpolation modes (in particular modes 4 and 5, described below) were implemented to address the second issue.

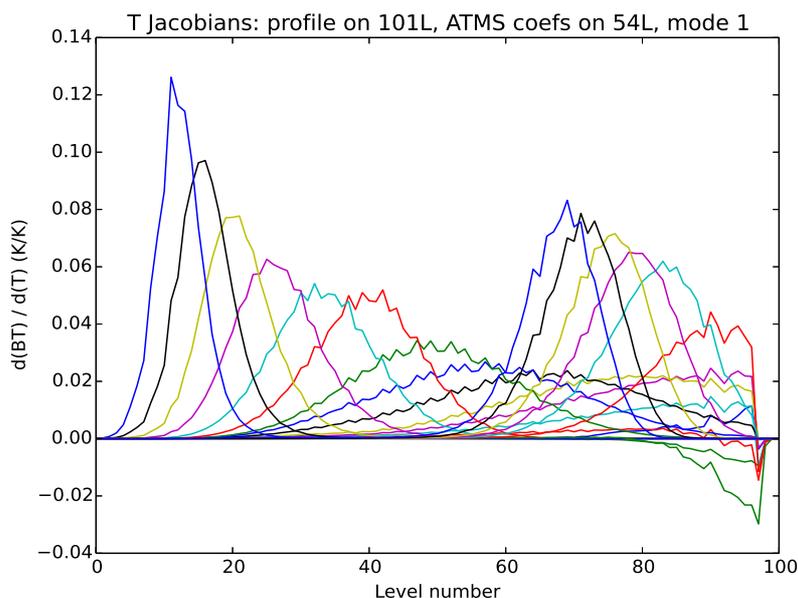


Figure 4: temperature Jacobians for all ATMS channels calculated for a 101L input profile and 54L coefficient file using the Rochon (mode 1) interpolator. The small oscillations in the interpolated optical depths result in oscillations in the temperature Jacobians.

It is important to note the artificial oscillations in the temperature Jacobians which result from the second of these two issues have not been observed to have a negative impact in retrieval or assimilation applications because the vertical correlations in the background errors smooth them out. This is demonstrated in section 5. However it is desirable that RTTOV should offer alternative interpolation options which reduce or eliminate these kinds of artefacts.

RTTOV v11.1 introduced two new interpolation modes. Mode 3 employs log-linear interpolation to the optical depths instead of the Rochon interpolation. This reduces, but does not eliminate, the oscillations in the Jacobians (Figure 5). Mode 2 employs log-linear interpolation for both the profile and optical depth interpolation steps. This mode is not appropriate for use with the RTTOV adjoint or Jacobian models as illustrated in Figure 2, but it is slightly less computationally intensive than the other modes (see section 6) and as such may be useful for forward model calculations.

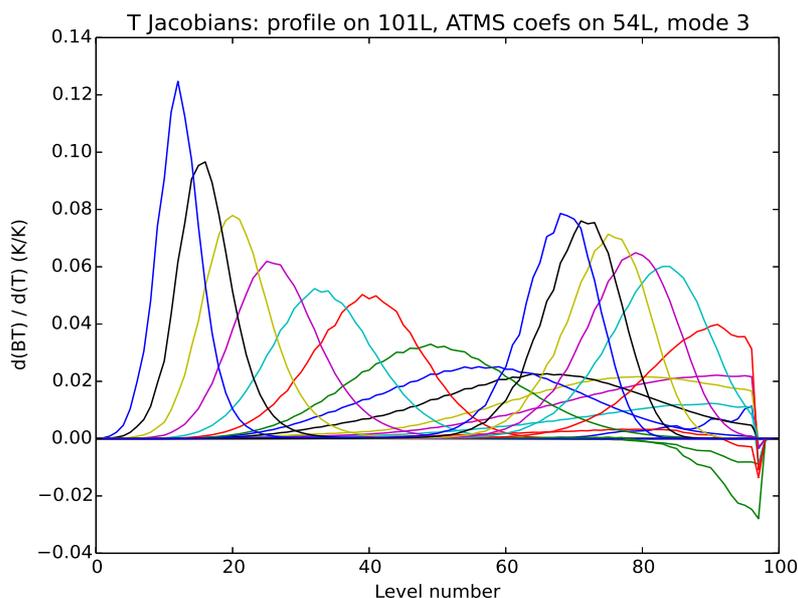


Figure 5: temperature Jacobians for all ATMS channels calculated for a 101L input profile and 54L coefficient file using interpolation mode 3. The oscillations in the temperature Jacobians are reduced, but not eliminated.

After further investigation two additional interpolation modes were introduced in RTTOV v11.2. Instead of interpolating the optical depths directly, modes 4 and 5 instead interpolate a kind of weighting function for each layer calculated as:

$$\frac{\Delta\tau}{\Delta p} = \frac{\tau_{i+1} - \tau_i}{p_{i+1} - p_i}$$

where τ_i is the optical depth from space to level i and p_i is the pressure at level i . Mode 4 uses the Rochon interpolator for this while mode 5 uses log-linear (in pressure) interpolation which is computationally cheaper. Modes 4 and 5 reduce the oscillations in the Jacobians to such a degree that they are no longer visible as shown in Figure 6. The idea behind this is that, as described above, it is the layer optical depths which appear in the radiative transfer equation and these are calculated as level-by-level differences of the interpolated level-to-space optical depths. The oscillations introduced by the Rochon interpolator are significant in size compared to the layer optical depths. Interpolating weighting functions avoids the need to take a level-by-level difference of the interpolated quantity with the result that any small oscillations introduced by the interpolation no longer impact the Jacobians.

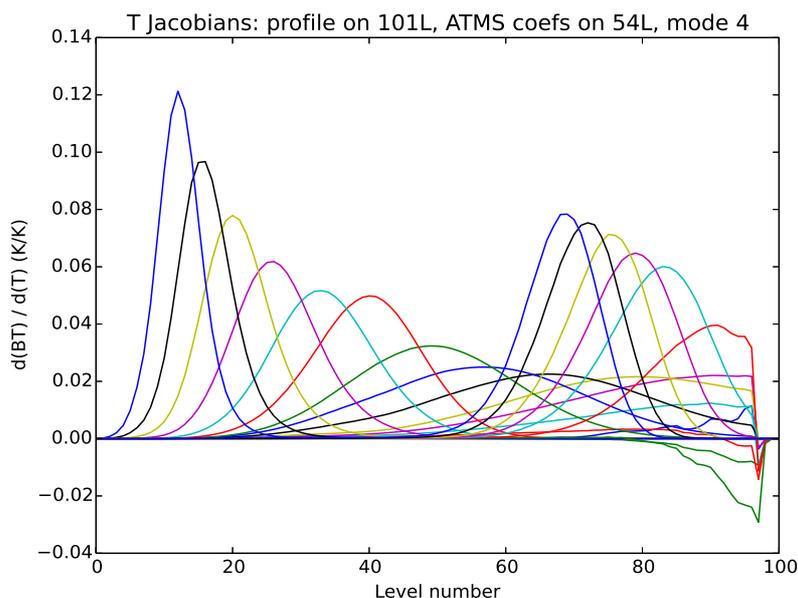


Figure 6: temperature Jacobians for all ATMS channels calculated for a 101L input profile and 54L coefficient file using interpolation mode 4. There are no longer any artefacts visible in the temperature Jacobians. Mode 5 gives similar results: section 4 examines the impact on Jacobians in more detail.

Table 1 summarises the interpolation modes available in RTTOV v11.2. The following sections of this report compare the differences between different modes on forward model BTs, on Jacobians, and on 1D-VAR retrievals.

Mode	Profile interpolation	Optical depth interpolation
1	Rochon	Rochon on optical depths
2	Log-linear	Log-linear on optical depths
3	Rochon	Log-linear on optical depths
4	Rochon	Rochon on $\Delta\tau / \Delta p$
5	Rochon	Log-linear on $\Delta\tau / \Delta p$

Table 1: interpolation modes in RTTOV v11.2.

It is necessary to consider separately the case when the input levels are more dense than the coefficient levels and the case when the input levels are less dense than the coefficient levels. For the sake of simplicity these two cases are referred to as:

- **case 1:** number of user levels > number of coefficient levels
- **case 2:** number of user levels < number of coefficient levels

Except where explicitly stated, the input levels used below are more dense (case 1) or less dense (case 2) than the coefficient levels almost everywhere in the atmosphere. However it should be remembered that it is the relative density of the levels which is important and this may not be constant throughout the atmosphere. In the general case the optimal choice of interpolation mode should be determined by experimentation.

3. Impact on forward model

In order to assess the impact on the forward model the line-by-line (LBL) model was run to obtain channel-integrated transmittance profiles for a diverse 52 profile set (Chevallier, 2002) for the ATMS microwave instrument. Similar transmittance profiles are a standard output from RTTOV and such profiles were obtained using the different interpolation modes.

These transmittances profiles were input to a simple integration of the radiative transfer equation assuming unit surface emissivity to give TOA BTs. The BTs obtained from the LBL transmittances are taken as “truth” since these are what RTTOV would ideally reproduce. The differences between the LBL and RTTOV BTs come from the errors introduced by the optical depth regression and from the interpolation. The differences between the different RTTOV BTs are due solely to the interpolation mode used.

The BTs obtained from the RTTOV transmittances for different interpolation modes were compared to the LBL BTs over the diverse profile set in order to calculate root-mean-square errors (RMSE) for each channel. This was repeated for input profiles on different sets of levels and using ATMS coefficient files on 54L and 101L.

Case 1

For this case the 54L ATMS coefficient file was used and the input profiles were interpolated onto the 101L profile illustrated in Figure 1 and onto a 65L profile, the intention being to look at cases where there is a greater and lesser difference in the relative spacing of the input and coefficient levels. Figures 7 and 8 show the RMSE in BTs for input profiles on the 65L and 101L pressures respectively.

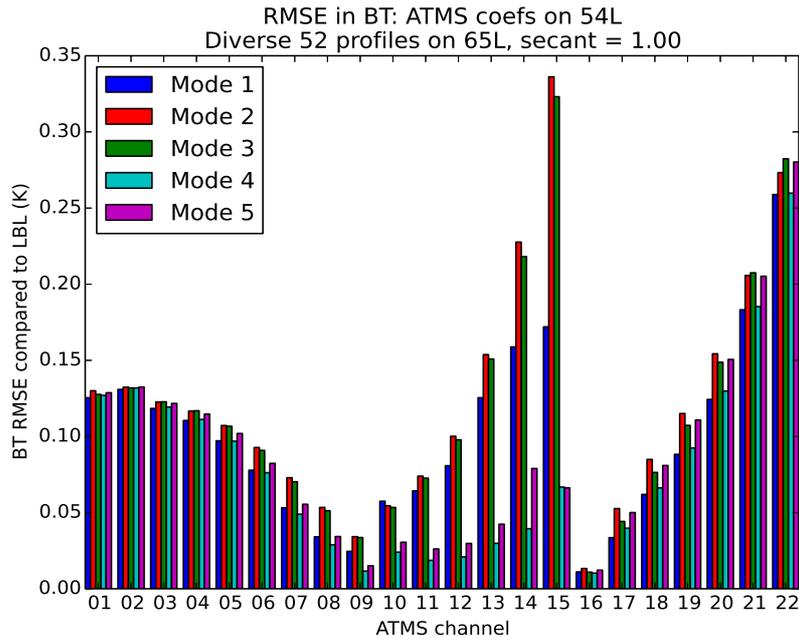


Figure 7: RMSE in BTs as compared to LBL calculations for input profiles on 65L and ATMS coefficients on 54L.

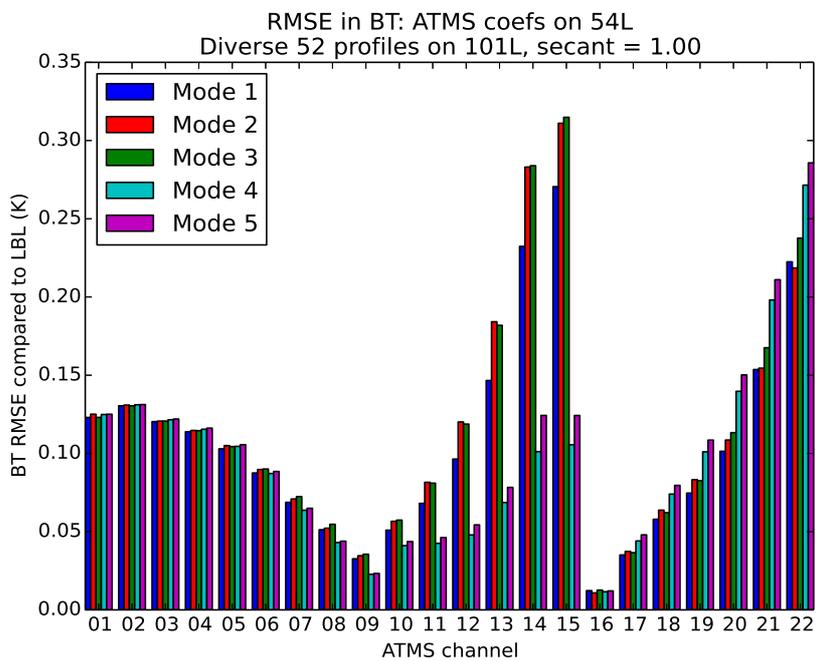


Figure 8: RMSE in BTs for input profiles on 101L and coefficients on 54L.

An important factor in the accuracy of the RTTOV simulations for a given channel is the relative density of the pressure levels across the peak of the channel weighting function as this determines how well the optical depths are represented over the region of the atmosphere to which the channel is most sensitive.

For the purposes of analysing the results the ATMS channels can be divided into three groups. Firstly channels 1-9 and channel 16 have weighting functions which typically span many levels (Figure 9). This means that the transmittance profiles for these channels are well resolved and the transmittance changes relatively slowly and smoothly from layer to layer and so the RMS errors are fairly similar for the five interpolation modes.

Channels 10-15 are higher-peaking upper-tropospheric and stratospheric temperature sounding channels with weighting functions that span fewer levels, and the number of levels spanned by the weighting function peaks decreases with increasing channel number (Figure 10). Therefore the transmittances are less well resolved for the higher channel numbers which means the RMS errors increase and the choice of interpolation method has a greater impact.

Channels 17-22 are lower-peaking water vapour sounding channels (Figure 11). Again the weighting function peaks span fewer levels as the channel number increases (particularly where there are fewer pressure levels in total) and so the RMS errors increase and the choice of interpolation method has greater impact for the higher channel numbers. There is less difference between the interpolation modes for the lower-peaking channels compared to the higher-peaking channels. This is probably due to the shapes of the quantities being interpolated (level-to-space optical depths or $\Delta\tau / \Delta p$) in different parts of the atmosphere.

Modes 4 and 5 result in the smallest RMSE in the higher-peaking channels (10-15). The differences between the modes are much smaller in channels 17-22 and for the remaining channels there is nothing to choose between the modes. On this basis, when considering forward model calculations only, modes 4 and 5 are generally the best choice. Mode 4 is slightly more computationally expensive than mode 5.

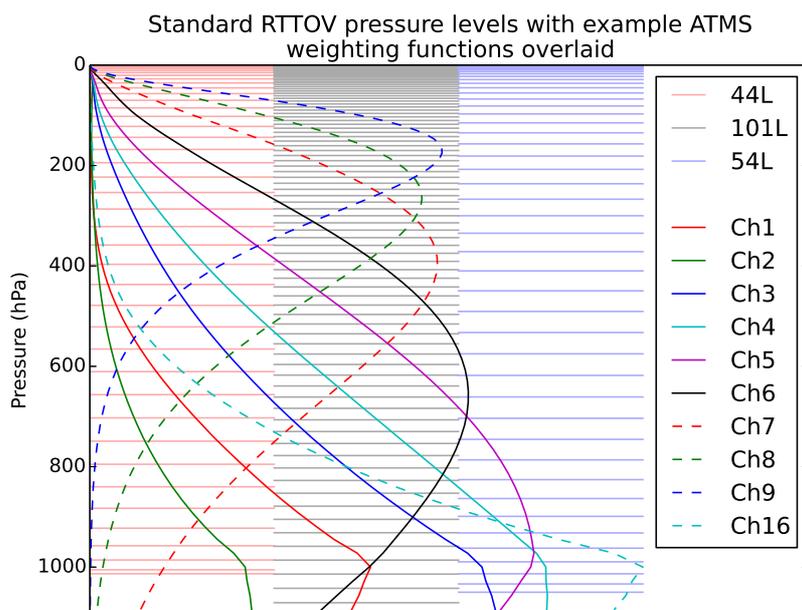


Figure 9: Illustrative weighting functions for ATMS channels 1-9 and 16 overlaid on the 44L, 101L and 54L pressure level profiles. These weighting functions span many levels and are reasonably well represented on all level sets. These weighting functions and those in Figures 10 and 11 were calculated for the mean profile of the 52 diverse profile set.

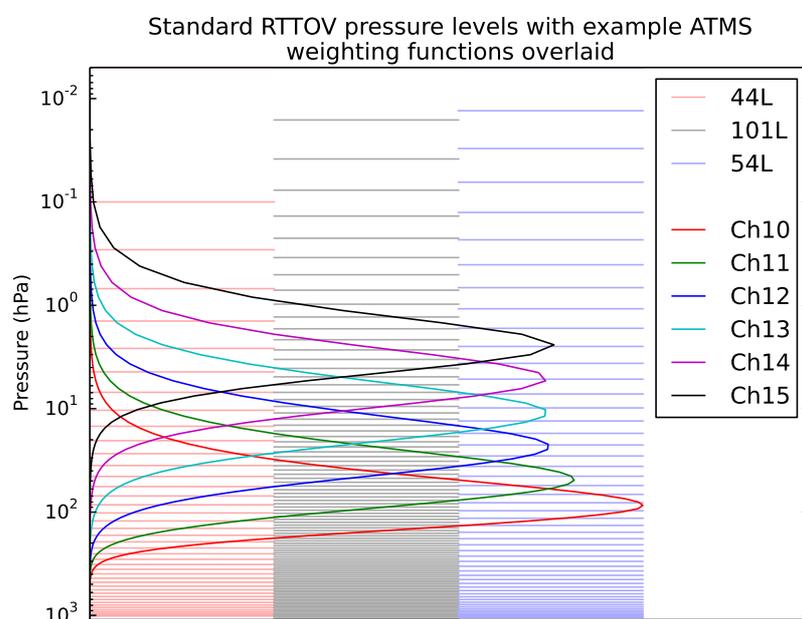


Figure 10: Illustrative weighting functions for ATMS channels 10-15 overlaid on the 44L, 101L and 54L pressure level profiles. These weighting functions peak over a relatively small number of levels (particularly in the 44 and 54L profiles, and particularly for the higher channel numbers) and so are less well resolved resulting in larger interpolation errors.

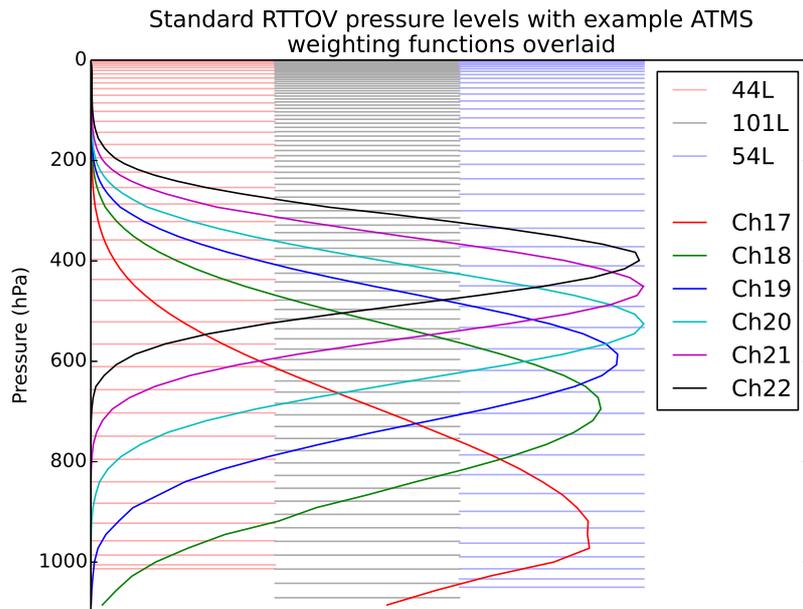


Figure 11: Illustrative weighting functions for ATMS channels 17-22 overlaid on the 44L, 101L and 54L pressure level profiles.

Case 2

Figures 12 and 13 show the BT RMSE for input profiles on 44L for coefficients on 54L and 101L respectively.

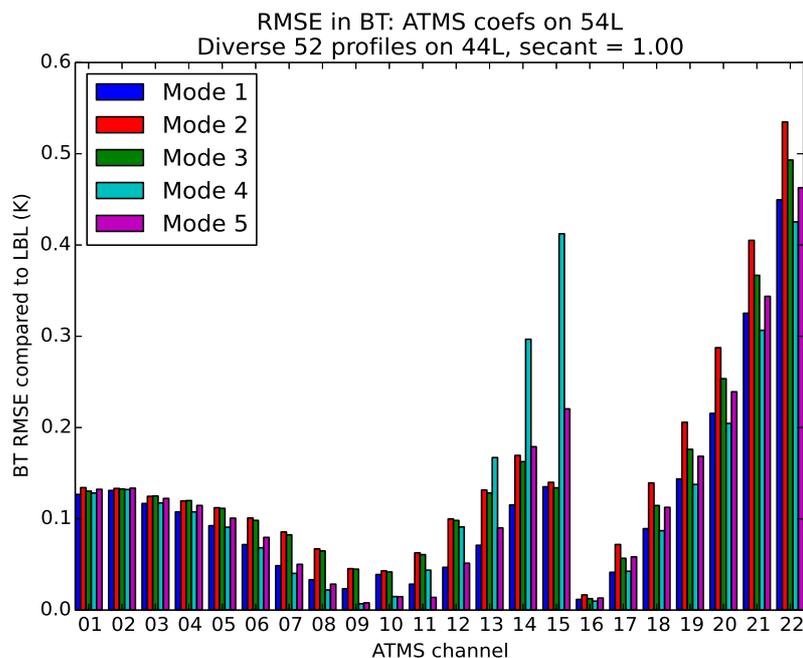


Figure 12: RMSE in BTs for input profiles on 44L and coefficients on 54L.

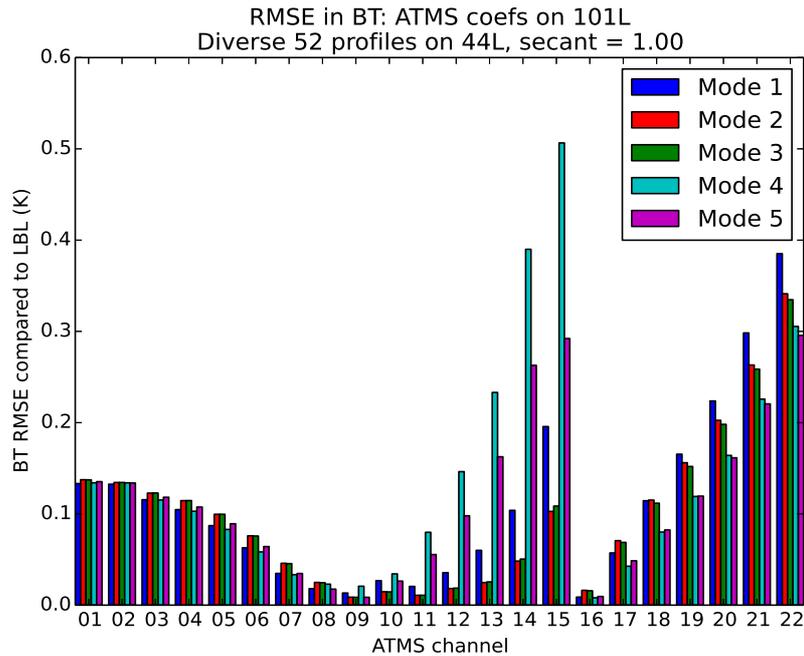


Figure 13: RMSE in BTs for input profiles on 44L and coefficients on 101L.

Mode 4 introduces the largest errors for the higher-peaking channels. For these channels $\Delta\tau$ is changing rapidly around the weighting function peak and Δp is smaller higher in the atmosphere so this increases the size of the peak in the quantity being interpolated which can result in larger interpolation errors. The interpolated layer optical depths are obtained by multiplying the interpolated $\Delta\tau/\Delta p$ by Δp for the user levels and so any interpolation error is increased by this factor. For case 2 the user levels are relatively sparse so Δp is relatively large and therefore the interpolation errors are larger than in case 1 where Δp is relatively small for the user levels. In addition, interpolation errors are generally smaller for case 1 when interpolating from less dense to more dense levels. It is not immediately obvious why mode 5 is not as bad as mode 4 for case 2, but the Rochon interpolator is not designed to minimise interpolation errors and may result in larger errors than log-linear interpolation under these conditions.

There is a clear difference in the relative performance of modes 4 and 5 for the high-peaking channels compared to the low-peaking water vapour channels. This is almost certainly due to the difference in shape of $\Delta\tau/\Delta p$ at different heights in the atmosphere: higher up Δp is small so the value of $\Delta\tau/\Delta p$ changes more rapidly with

the peak of the weighting function and as such is more susceptible to interpolation errors of the kind described above.

These observations beg the question: what about an alternative formulation for the weighting function such as $\Delta\tau/\Delta\log(p)$? This was also tested and while it does reduce the errors in the high-peaking channels for case 2 (as would be predicted because it reduces the size of the peaks being interpolated), it did not give smaller errors than the other modes across all channels and it resulted in much larger errors than the other modes for case 1.

Overall modes 1 or 3 seem reasonable choices when considering forward model simulations alone, with mode 3 being preferred where there is a particularly large difference in the relative density of input and coefficient levels.

Additional test cases

To demonstrate that it really is the relative density of levels near the weighting function peaks that is important, a set of 55 pressure levels was created which is more dense than the 54L in the upper atmosphere and less dense than the 54L in the lower atmosphere (Figure 14). Figures 15 and 16 show the BT RMSE for profiles on these levels using the 54L and 101L coefficients respectively. For the 54L coefficients, the upper atmosphere is like case 1 (input levels more dense) and the relative RMS errors for the interpolation modes in channels 10-15 are similar to those in the case 1 plots above. Similarly, the lower atmosphere is like case 2 (input levels less dense) and the RMS errors for the water vapour channels 17-22 more closely resemble those from case 2 above.

For the 101L coefficients the results are rather different again with the lower atmosphere falling under case 2, but the relative density of levels being more similar between the input and coefficient profiles in the upper atmosphere. In this example mode 1 gives the largest RMSE in most channels. (Note that this 55L profile was created to emphasise the point that the relative density of levels is the important factor: it is not being suggested as a suitable set of levels for the representation of atmospheric profiles).

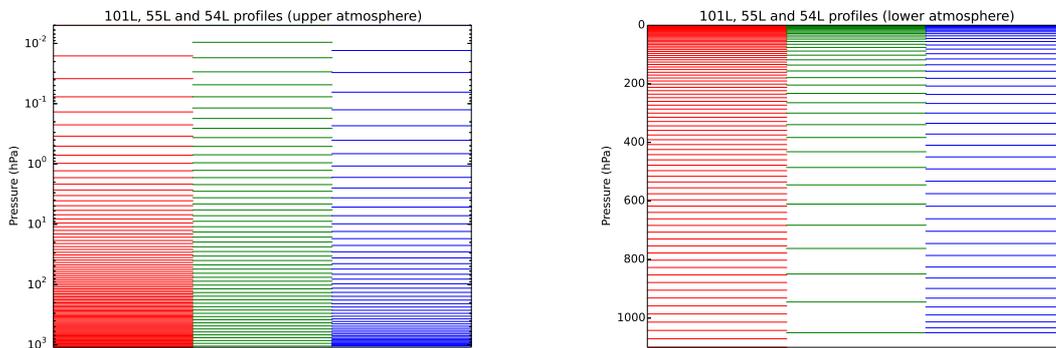


Figure 14: Pressure levels on 101L (red), 55L (green) and 54L (blue) in upper atmosphere (left) and lower atmosphere (right). The 55L are more dense than the 54L in the upper atmosphere and less dense in the lower atmosphere.

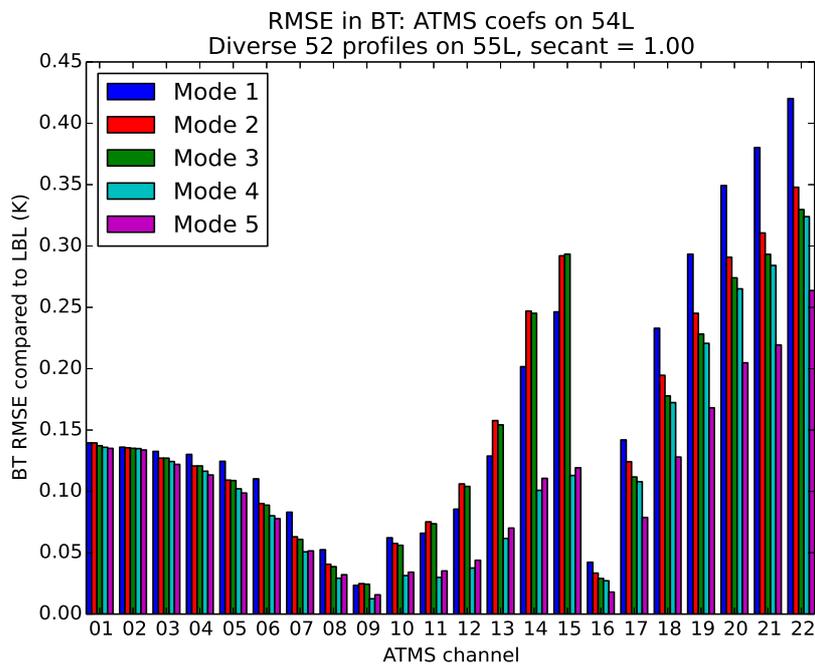


Figure 15: RMSE in BTs for input profiles on the 55L as in Figure 14 and coefficients on 54L.

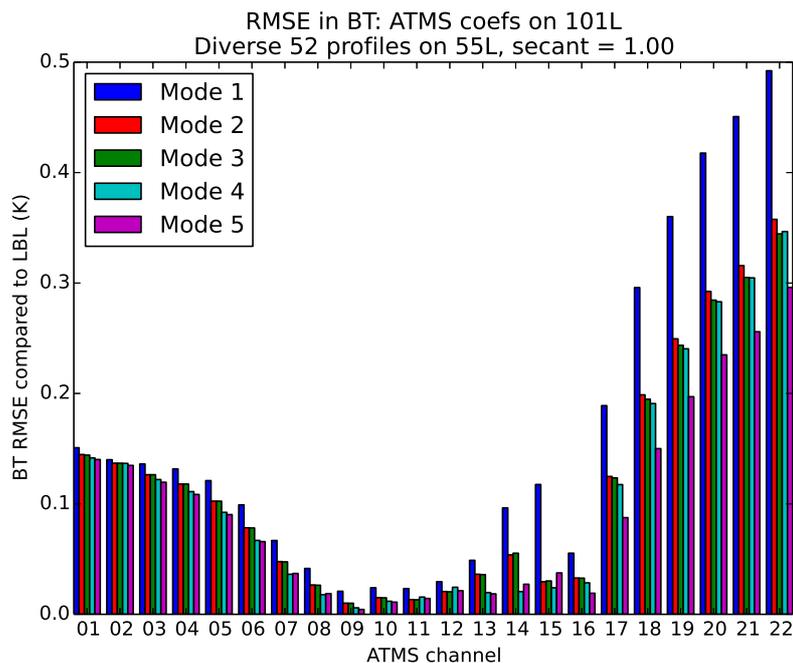


Figure 16: RMSE in BTs for input profiles on the 55L as in Figure 14 and coefficients on 101L.

The results in this section show that there is no interpolation mode which is clearly optimal for forward model simulations for all combinations of input and coefficient pressure levels. Some general recommendations can be made (namely modes 4 or 5 in case 1, and modes 1 or 3 in case 2), but RTTOV users may find it beneficial to carry out experiments for their particular application: the best choice depends on the particular channels of interest and the relative spacing of the pressure levels near the peaks of the weighting functions of those channels.

4. Impact on Jacobians

This section examines how the interpolation modes affect RTTOV Jacobians. It is important to reiterate that although some interpolation modes result in Jacobians with artificial jaggedness, these oscillations are usually smoothed out by the vertical correlations in typical assimilation and retrieval applications (see section 5). Therefore whether or not the artefacts discussed in this section are detrimental in practice will depend on the particular application. Also recall that mode 2 is not suitable for adjoint or Jacobian calculations and is not considered in this section.

Case 1

For this case ATMS Jacobians have been plotted for the mean profile of the diverse 52 profile set on 101L using a 54L coefficient file. The temperature Jacobians for modes 1, 3 and 4 are shown in Figures 4-6. Modes 4 and 5 generally give very similar, smooth Jacobians. However for mode 5, small artefacts can appear in Jacobians for window (and window-like) channels in which there is relatively little atmospheric emission (compare Figures 17 and 18). For such channels the contribution to the Jacobian from the optical depth regression is significant and as such the Jacobian of the interpolation of $\Delta\tau / \Delta p$ can visibly impact the final Jacobians. In contrast, for those channels with significant thermal emission the contribution to the Jacobian of the optical depth regression can be an order of magnitude smaller than that from the atmospheric emission and so the choice of interpolator (mode 4 or mode 5) for the optical depths is less important.

The artefacts in these particular channels do not result solely from the use log-linear interpolation because they are not observed in the mode 3 Jacobians which also use log-linear interpolation. Instead they are specifically due to the use of log-linear interpolation on the weighting functions ($\Delta\tau / \Delta p$).

It is not obvious that such small artefacts would in practice cause problems for many applications, but it is worth being aware that the use of mode 5 can produce these features in the Jacobians. This also applies to water vapour Jacobians and those for other optional trace gases where provided.

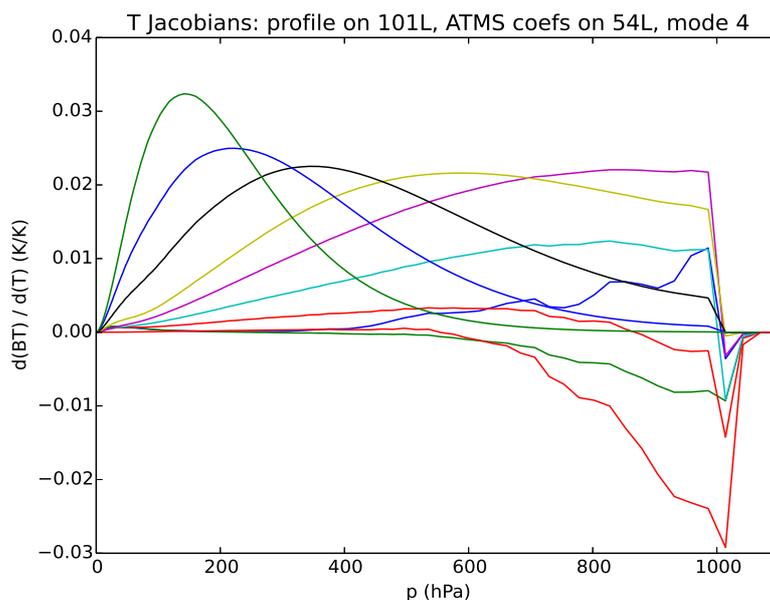


Figure 17: Temperature Jacobians for ATMS window-like channels (1-9 and 16) for input profiles on 101L and coefficients on 54L using mode 4.

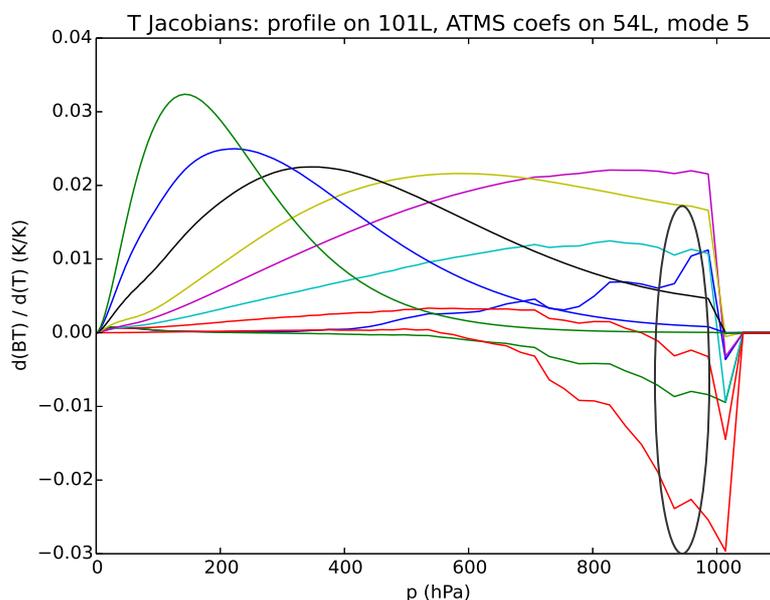


Figure 18: Temperature Jacobians for ATMS window-like channels (1-9 and 16) for input profiles on 101L and coefficients on 54L using mode 5. The use of log-linear interpolation on $\Delta\tau/\Delta p$ results in a small “kink” in some Jacobians where the radiances appear to have increased sensitivity to one particular level.

Case 2

Figure 19 shows ATMS temperature Jacobians for the mean profile of the diverse 52 profile set on 44L using a 101L coefficient file for modes 1, 3, 4 and 5. Here the optical depth interpolation is mapping from more dense to less dense levels and in this case the Rochon interpolator does not introduce any spurious oscillations in the interpolated optical depths for mode 1. Of the four interpolation modes considered, mode 5 is the most different with some small artefacts appearing as in case 1: again these do not appear in the Jacobians for mode 3 and so are a particular feature of using log-linear interpolation on weighting functions.

Figure 20 shows the water vapour Jacobians: as with the temperature Jacobians, the mode 5 Jacobians show the largest differences between the modes.

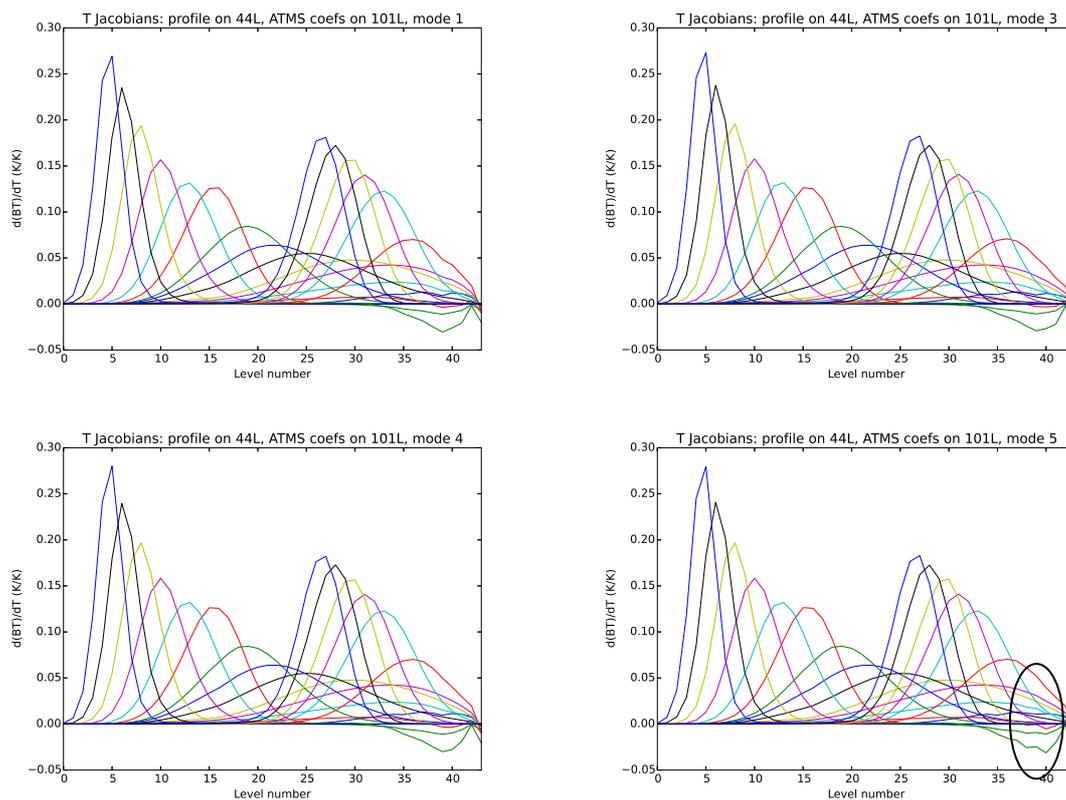


Figure 19: Temperature Jacobians for all ATMS channels for input profiles on 44L and coefficients on 101L using interpolation modes 1, 3, 4 and 5. As in case 1, mode 5 results in some small artefacts being visible in some window channels.

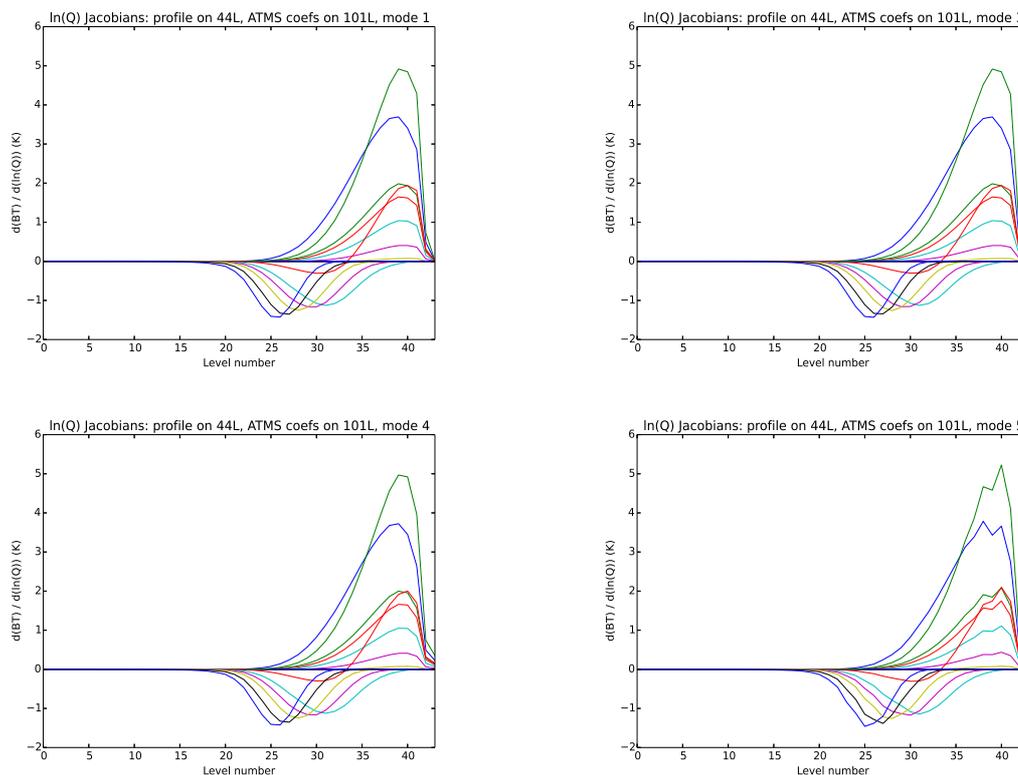


Figure 20: Water vapour Jacobians for all ATMS channels for input profiles on 44L and coefficients on 101L using interpolation modes 1, 3, 4 and 5. Mode 5 results in the largest differences.

In summary the results show that for case 1, interpolation mode 4 introduces the fewest spurious features in the Jacobians of all the modes. In case 2 there seems to be little to choose between the interpolation modes except that, as for case 1, some small artefacts are observed in the mode 5 Jacobians. Whether these features are of practical importance depends on the application, but the results of the next section suggest that they may not be significantly detrimental in typical retrieval or assimilation applications.

5. Impact on 1D-VAR retrievals

This section examines the impact of the choice of interpolation method in a practical application of RTTOV. The Met Office 1D-VAR software (Weston *et al*, 2013) was used to run simulated 1D-VAR retrievals for the diverse 52 profile set.

A 70 level model background error matrix (B matrix) has been generated from Met Office Unified Model statistics (K. Lean, personal communication). The profile set was interpolated onto an appropriate set of 70 pressure levels. This provided the “truth” for the retrieval. The B matrix was used to add noise to the temperature and water vapour profiles to create the background profiles for the retrievals. Noise was added to RTTOV simulated radiances (without interpolation) of the unperturbed profile set to generate a set of simulated observations for each profile. The variances for this observation noise were the values used for ATMS in the Met Office Observation Processing System and are intended to account for the instrument noise and forward model error. The background profiles and observations were then passed through the 1D-VAR software using each interpolation mode and the retrieved temperature and water vapour profiles were compared to the truth for each profile giving RMS errors for each level. Only ATMS channels 10-15 and 17-22 were used for the retrievals since these are the channels most affected by the choice of interpolation mode.

The choice of 70L for the input profiles allows case 1 and case 2 to be tested by using 54L and 101L coefficient files respectively.

Case 1

Figure 21 shows the differences in RMSE in retrieved temperature for each level between interpolation modes 3, 4 and 5 and the RMSE for interpolation mode 1 with the 54L ATMS coefficient file. Figure 22 shows the same for water vapour. The differences are less than 0.005 K for temperature and less than 0.001 in $\ln(q)$ (equivalent to a $\sim 0.1\%$ difference in q). There is clearly little to choose between the interpolation modes.

Case 2

Figure 23 shows the differences in RMSE in retrieved temperature for each level between interpolation modes 3, 4 and 5 and the RMSE for interpolation mode 1 with the 101L ATMS coefficient file. Figure 24 shows the same for water vapour. As with case 1 there is little to choose between the interpolation modes here.

The results suggest that in 1D-VAR retrievals the choice of interpolation mode may not be critical. This is in accordance with the results of assimilation experiments carried out by Lupu and Geer (2014) who found a neutral impact with modes 3 and 5 compared to mode 1 for case 1 (more input levels than coefficient levels).

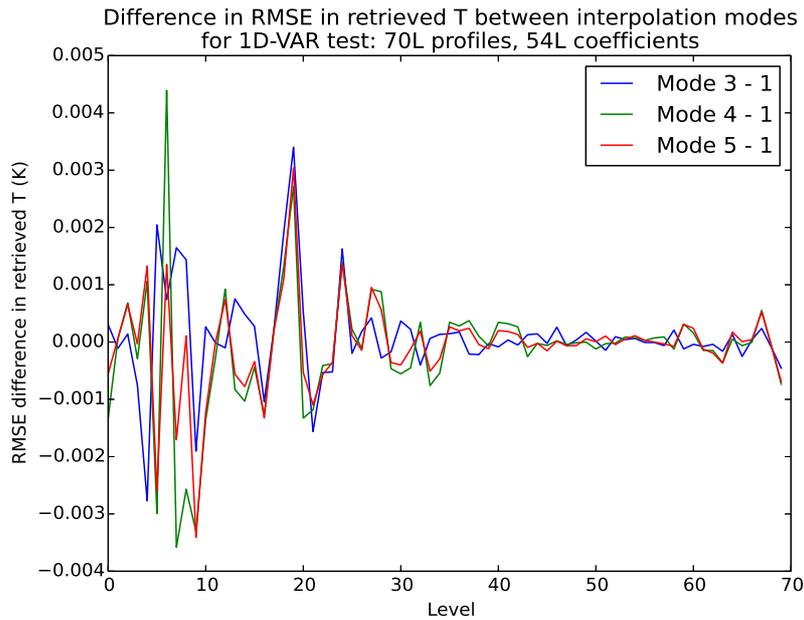


Figure 21: Difference in retrieved temperature RMSE in each level for interpolation modes 3, 4 and 5 compared to mode 1 for 54L coefficients.

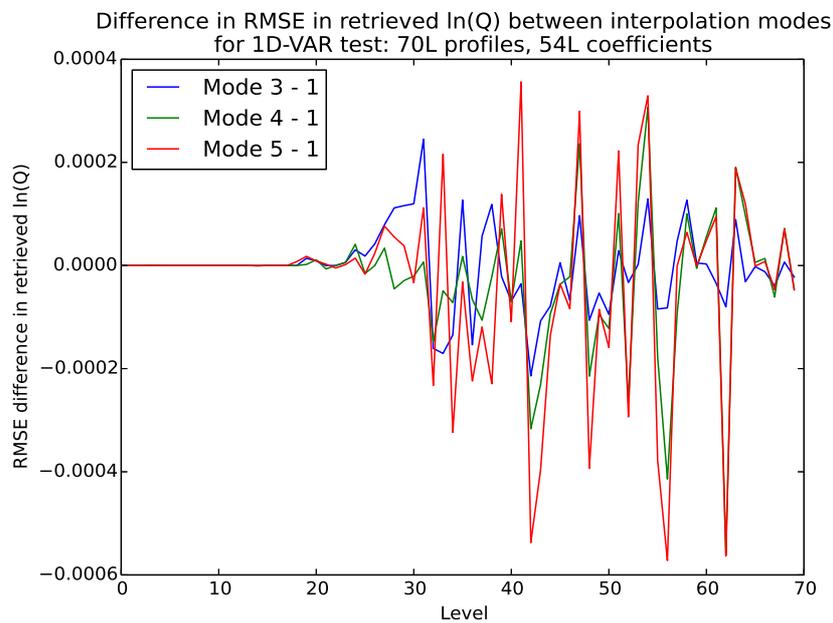


Figure 22: Difference in retrieved water vapour ($\ln(q)$) RMSE in each level for interpolation modes 3, 4 and 5 compared to mode 1 for 54L coefficients.

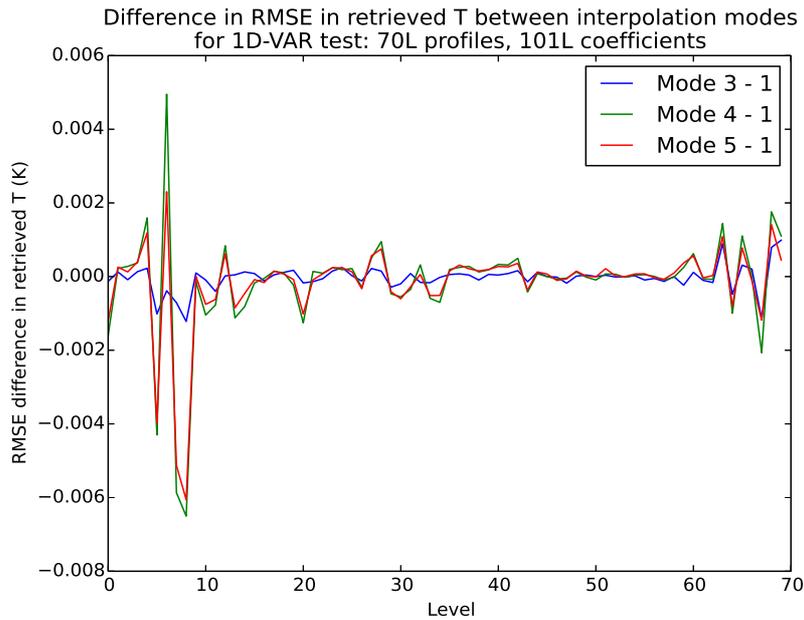


Figure 23: Difference in retrieved temperature RMSE in each level for interpolation modes 3, 4 and 5 compared to mode 1 for 101L coefficients.

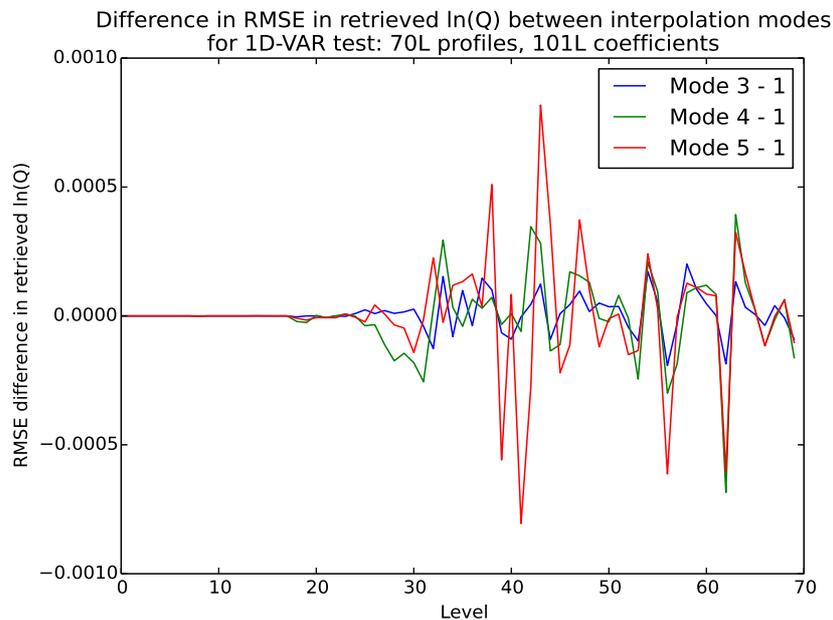


Figure 24: Difference in retrieved water vapour ($\ln(q)$) RMSE in each level for interpolation modes 3, 4 and 5 compared to mode 1 for 101L coefficients.

6. Computational cost of interpolation

Table 2 below gives an idea of the relative performance of interpolation modes 2-5 compared to mode 1 for a 101L input profile and 54L coefficients. One advantage of the Rochon interpolator (and also of log-linear interpolation) is that the interpolation weights are determined solely by the input and output pressure levels and are independent of the values being interpolated. This allows the weights calculated for the profile and the optical depth interpolations to be re-used for all profiles and channels that are on the same set of user pressure levels. Despite this efficiency the interpolator is relatively expensive compared to running RTTOV without the internal interpolation: Table 3 compares run times for a 54L profile and 54L coefficients with the internal interpolation switched on and switched off.

Model	Mode	Mode X:Mode 1	Mode X:Mode 1 Active p
Direct	2	0.95	N/A
	3	0.97	
	4	1.08	
	5	1.05	
TL+AD	2	N/A	
	3	0.97	0.94
	4	1.09	1.10
	5	1.05	1.05
K	2	N/A	
	3	0.98	0.78
	4	1.06	1.04
	5	1.04	0.81

Table 2: Illustration of relative performance of the RTTOV v11.2 interpolation modes. Values are ratios of runtimes for clear-sky simulations using modes 2-5 compared to mode 1 for a 101L input profile and 54L ATMS coefficients for the RTTOV direct, TL+AD (tangent linear and adjoint) and K (full Jacobian) models. The “Active p” column shows results when pressure is an active variable in the TL, AD and K.

Model	Mode 1:no interpolation	Mode 1:no interpolation Active p
Direct	1.16	N/A
TL+AD	1.15	1.27
K	1.17	2.57

Table 3: Illustration of relative performance of mode 1 compared to no interpolation for a 54L input profile and 54L ATMS coefficients for the RTTOV direct, TL+AD and K models. Values are ratios of run-times with and without interpolation for clear-sky simulations.

7. Conclusions

The results presented above clearly demonstrate that it is not possible to recommend a single interpolation mode that will perform optimally for all channels in either case 1 or case 2, and for simulations where the input and coefficient levels do not fall into either case 1 or case 2 the optimal interpolation method can only be determined by experiment.

If RTTOV users have been using mode 1 without any problems, the results presented here do not indicate that the artificial oscillations in Jacobians which can occur in case 1 are necessarily a cause for concern. Experiments with 1D-VAR retrievals and the results of the assimilation experiments by Lupu and Geer lend support to the idea that the choice of interpolation method is not a critical factor in these applications of RTTOV.

However it is understandable that users with applications in the case 1 category may wish to use a different interpolation method which does not introduce such features into the Jacobians. In that case it is recommended that users carry out experiments with mode 4 or 5 in their application to determine whether they offer any benefit. In addition, the forward model tests suggest modes 4 and 5 reproduce the LBL BTs with smaller errors than mode 1 in some cases.

For users whose application falls under case 2, mode 1 remains a good choice although they may wish to consider mode 3 as an alternative.

It should be noted that all results shown above were for a nadir view (i.e. satellite zenith angle of 0°). All experiments were also carried out for a zenith angle of ~64°

corresponding to a secant of 2.25 which is the largest angle over which the RTTOV coefficients are trained. All results were consistent with the nadir-view case.

The new interpolation methods allow RTTOV to calculate Jacobians that are free from artificial features which result specifically from the interpolation. There is scope for further work to look at the impact of modified versions of the interpolation methods discussed here. For example there is some indication that interpolating linearly in pressure (instead of log-pressure) may reduce the BT RMS errors in the forward model, which is perhaps a counter-intuitive result. However, based on the results shown above, it is expected that alternative interpolation options would not usually have a large impact on applications such as atmospheric retrievals.

8. Acknowledgements

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