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A Fast Infrared Radiative Transfer Model for ATSR

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Abstract

There is a continuing trend towards the use of variational methods in satellite data interpretation. In these methods, the difference between measured radiances and those calculated from a particular atmospheric 'state' is minimised by making suitable adjustments to the 'state' until agreement is within what can be loosely called the system noise level. For this method to be feasible the radiance calculation, using the forward model, has to be computationally fast; full line by line methods are far too slow.

This paper describes a fast transmittance model for ATSR channels. It is based very closely on a model used by the European Centre for Medium Range Weather Forecasts for TIROS Operational Vertical Sounder (TOVS) measurements.

A line by line model is modified to calculate a base set of channel transmittances for a wide ranging set of atmospheric profiles. These are used to generate the fast model coefficients. It is found that the predictors used for the TOVS instrument channels are not optimal for ATSR channels and significant improvements are made by changes to the water transmittance terms. The final performance of the ATSR fast model would appear to be adequate for sea surface temperature (SST) retrieval applications; the transmittances are accurate to 0.3% at the surface and the full model gives brightness temperature accuracies of 0.05-0.13 K depending on the channel. Errors, of course, are with respect to the line by line results. Computation time for 3 channels on an Alpha workstation is 1.4 ms.

The opportunity is taken to study errors arising from use of the multiplicative property for water and carbon dioxide transmittances.

Introduction

The Rutherford Appleton Laboratory (RAL) ATSR radiance model, RADGEN, is an accurate hybrid scheme which draws on precalculated results from a LBL model (Zavody, 1994), integrating at 0.04 cm^{-1} across the filter response functions of the channels. At each wavenumber interval and for each of 128 vertical layers, RADGEN interpolates the mixed gas (predominantly CO_2) and water vapour attenuations from the LBL results, adds them, and calculates the top of atmosphere (TOA) radiance. The channel radiance is found by summing the high spectral resolution radiances weighted by the filter response of the channel. RADGEN consumes approximately 15s CPU on an Alpha workstation for channels 4 and 5 together, and 35s for channel 3 (which covers a wider spectral range). As an example, a physical iterative retrieval of SST from six ATSR channels (3 forward view and 3 nadir view) which required 3 iterations to converge would need approximately 300s of CPU.

The fast transmittance model used here is based very closely on RTTOV (Eyre, 1991) developed for sounding activities using the TIROS Operational Vertical Sounder (TOVS). The method adopted (McMillin and Fleming 1976, 1977, 1979) is well established and quite accurate for passive infrared channels sensing predominantly radiation emitted by CO_2 and other well mixed gases. The methods rely on a base set of LBL calculations of channel transmittances performed over a wide range of atmospheric conditions and view zenith angles, preferably at least as wide as that expected to be encountered. These LBL transmittances for each pressure level to space are linearly regressed against the temperature and humidity profiles of the atmospheres from which they were generated. The regression is made in departures from mean values and the mixed gas and water vapour transmittances are treated separately. The regression predictors are loosely arrived at by examination of the perturbation form of the absorption coefficient concerned, although in practice the final choice is made on those which can most accurately represent the LBL transmittances.

The RTTOV software package includes the gradient code, i.e. to calculate $\mathbf{K} = \mathbf{dR/dX}$ where $\mathbf{R}$ is the radiance vector and $\mathbf{X}$ is the atmospheric variable vector (temperature, humidity etc.). The gradient matrix is an essential requirement of efficient non-linear retrieval algorithms.

The regression coefficients for RTTOV (hereafter simply called 'transmittance coefficients' or just 'coefficients') are obtained, in practice, by producing a data set of channel transmittances and the profiles from which they were derived. Software supplied with RTTOV performs the regression.

Generation of the Baseline LBL transmittances

The fast model works directly with channel averaged transmittances and so extra variables were introduced into RADGEN to integrate the transmittance weighted by the filter response during the frequency loop. Additionally, RTTOV makes estimates of mixed gases and water vapour transmittances separately so that separate transmittances were required from RADGEN. A feature of the fast model is that it works on fixed pressure levels; those currently used in RTTOV are shown in Table 1. They are unlikely to be the optimum set of levels for ATSR channels since they have been designed to cover the whole atmosphere into the stratosphere. However, at this stage, we retain the standard pressure levels; a change to a more appropriate set at a later stage when the procedure is fully tested should not be difficult.

Standard pressure levels (mb)									
0.1	0.2	0.5	1	1.5	2	3	4	5	7
10	15	20	25	30	50	60	70	85	100
115	135	150	200	250	300	350	400	430	475
500	570	620	670	700	780	850	920	950	1000

Table 1: standard pressure standard pressure levels

RADGEN does not operate on a fixed pressure level set. It divides the atmosphere into 128 layers equally spaced in pressure between the surface pressure P_0 and space. Transmittances on standard pressure levels are therefore generated by interpolation (in Log(pressure)) from the 128 levels. The temperature and humidity profiles (which are additionally needed on the standard pressure levels) are obtained in the same way. There is a potential problem here in that structure present at the 128 level profile will affect the transmittances (even after interpolation to the standard pressure levels) whereas it will be lost in the standard pressure level profiles. The transmittances will then not be entirely appropriate to the standard pressure level profile.

To circumvent this we pre-interpolate all the profiles onto the standard pressure levels. When the interpolated profiles are given to RADGEN, although the 128 levels are still employed, the sonde profiles are now effectively at standard pressure level resolution and the forward and back interpolation can introduce no errors.

The generation of the data base is time consuming. For example, using the full 158 profiles of the radiosonde set and needing transmittances at 5 view angles the CPU time for channel 4,5 is about 130 minutes, for channel 3 it would be 240 minutes. This is hardly prohibitive for what is an off-line calculation needed theoretically only once. However, for the development of the model, testing different standard pressure levels for example, a reduced data set has been selected. 32 profiles were selected to span the range of precipitable water, up to about 6 cm, found in the complete set.

Errors from the monochromatic approximation

Before proceeding with the generation of fast model coefficients we can take the opportunity to examine the errors arising from treating the transmittance for water and CO_2 separately. Although for monochromatic radiation the multiplication property $t_{tot} = t_{water} \times t_{CO2}$ holds exactly, it is only approximate for channels of finite bandwidth unless certain condition regarding the lines of the two absorbers apply (see Goody & Yung 1989, p127). To test the approximation we compare the channel averaged t_{tot} calculated exactly from RADGEN (which applies the multiplication property at a monochromatic wavenumber interval and then integrates over the channel) to that obtained using the multiplication property after integration: $t_{tot} = t_{water} \times t_{CO2}$.

Figure 1 shows the difference, $t_{tot} - t_{tot}$, in the 11 and 3.7 μm channel transmittances from the surface to space and for all 32 profiles at secθ=1.5.

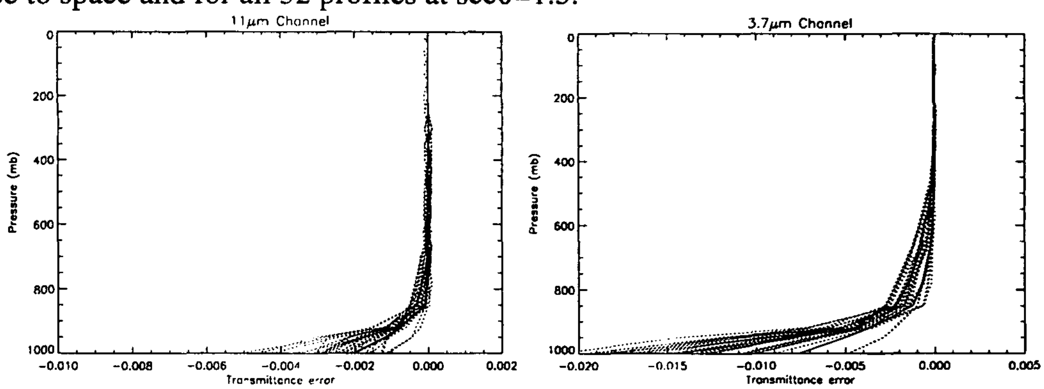

Figure 1. Errors in the monochromatic approximation

Maximum errors naturally appear near the surface and are of the order of 0.3% for the 12 μm channel. They are clearly biased suggesting that some empirical correction could be employed, however, they are small enough that this may not be necessary. At 3.7 μm the approximation is less good; errors near the surface are becoming significant at 1-1.5%. We can calculate the change in brightness temperatures resulting from these errors very simply if we assume the only effect is the change in radiance arising from the change in surface to space transmittance. Table 2 illustrates this for two typical scene temperatures and two transmittance errors for each channel (the 12 μm channel is affected in a very similar way to the 11 μm channel).

T_s	Error in 11 μm BT (K)		Error in 3.7 μm BT (K)	
	δt_s = 0.1%	0.2%	1%	2%
290 K	0.064	0.12	0.22	0.43
270 K	0.055	0.11	0.18	0.38

Table 2. Approximate brightness temperature errors resulting from surface transmittance errors shown in Figure 1.

This confirms that there is not a significant problem for the 11 and 12 μm channels. However, in the worst cases the 3.7 μm channel incurs a significant error. It should be mentioned that these estimates are potentially high in that, for example, an underestimate of transmittance, whilst increasing the radiance to space from the surface (simulated in the table) will be compensated to some extent in the full radiative calculation by a decrease in atmospheric emission. Results presented later are consistent with the tabulated values.

Coefficient Generation

Coefficients are generated using RTTOV suite software. A test program applies the coefficients to a set of test data and compares the fast model results with the RADGEN values. Because ATSR channels are windows with mainly water vapour absorption, transmittance errors are invariably largest at the surface and almost negligible in the mixed gas part. We can therefore summarise the performance of a set of predictors by quoting the standard deviation and maximum error in the 1000 mb level water transmittance, as in Table 3 which are the results for the basic predictor set used on the dependent data.

Dependent data	1000mb S.deviation %			1000mb Max error %		
	11μm	12μm	3.7μm	11μm	12μm	3.7μm
	3.26	3.48	1.11	10.5	11.0	2.9

Table 3. Transmittance error summary statistics for baseline predictor set and dependent data.

Tuning the Fast Model to ATSR

3% error in near surface transmittance is quite high, certainly high enough to degrade retrieval accuracy, although the author of RTTOV admits that the parameterization of water absorption is not close to ideal, it was certainly not optimized for window channels (Eyre, personal comm.). It should be noted that recent coefficients produced at the UKMO for TOVS give accuracies of about 1% for the 11 μm channel (Rayer, personal comm). The work differs in that the base calculations were made using different LBL code and the channels do not cover precisely similar wavelengths. The TOVS 11 μm channel covers a narrower spectral range than ATSR and for this reason may be easier to model.

In tuning the model we have tried to keep a view to the underlying physics but inevitably the choice of predictor variables becomes somewhat empirical. The basic RTTOV water model is:

$$\delta(d_{ij} - d_{i,j-1}) = S_k\, a_{ijk}\, X_{kj}$$

where $\delta(d_{ij} - d_{i,j-1})$ is the change in optical depth to space in channel i in going from level j to j-1, the δ showing it is a deviation from the reference value. X_{kj} are the predictors and a_{ijk} are the coefficients. Index $_k$ runs from 1-10 and the original specification of X is as follows:

X_{1j}	$\delta T_j\,(\sec\theta\, u_j)^{1/2}$	X_{6j}	$\delta T^2_j\,(\sec\theta\, u_j)$
X_{2j}	$p\delta T_j\,(\sec\theta\, u_j)^{1/2}$	X_{7j}	$\delta q_j\,(\sec\theta\, u_j)$
X_{3j}	$\delta q_j\,(\sec\theta\, u_j)^{1/2}$	X_{8j}	$\delta q^2_j\,(\sec\theta\, u_j)$
X_{4j}	$p\delta q_j\,(\sec\theta\, u_j)^{1/2}$	X_{9j}	$\delta T_j\,\delta q_j\,(\sec\theta\, u_j)$
X_{5j}	$\delta T_j\,(\sec\theta\, u_j)$	X_{10j}	$(\sec\theta\, u_j)^{1/2}$

δT_j and δq_j are departures of the temperature and water mixing ratio respectively from the reference profile at level j. The term $p\delta T_j$ is defined as $2/p_j^2 S^j_{l=1}\, p_l \delta T_l (p_l - p_{l-1})$ and $p\delta q_j$ as $2/p_j^2 S^j_{l=1}\, p_l \delta q_l (p_l - p_{l-1})$; they are pressure weighted means of the profile departures from the top of the atmosphere down to level j. u_j is the mass of water in the layer j,j-1, i.e. $u_j = \frac{1}{2}(q_j + q_{j-1})(p_j - p_{j-1})$ so that $(\sec\theta . u_j)$ represents the mass of water in the optical path between levels j,j-1.

For a detailed description of the origin of the above terms see the McMillin and Fleming and Eyre papers. Here we simply note that linear and quadratic terms in temperature and humidity are present to explain up to second order terms in the expansion of the perturbation form of the transmittance equation. Higher order terms have not been found to be necessary. The pressure weighted mean departures are included to account for the finite frequency range of the channels. In the pure monochromatic case, the increase in optical depth to space between levels j,j-1 is purely a function of the atmospheric conditions in the layer bounded by the levels. In the polychromatic case this is not true; the increase depends on the transmission of the whole atmosphere above. The pressure weighted means (known as scaling terms) are included to help account for for this.

The weighting of terms by ($\sec\theta . u_j$) arises because of the dependence of transmittance on the layer absorber mass present. The different powers are intended to cover different categories of line absorption; the equivalent width of weakly absorbing lines is proportional to the mass of absorber, that of strong lines is proportional to the square root of the mass (Goody & Yung, 1989, p131). It is possible to show that this dependence should be retained through to the differential optical depth, $\delta(d_{ij} - d_{i,j-1})$, employed in RTTOV.

It is at this point that we can see that the model may not be optimised to ATSR channels. Figure 2 shows the transmittance of a typical midlatitude atmosphere in the 11-12 µm region and it can be seen there are few absorption lines that can be considered strong, i.e. have a transmittance of zero at the surface. The terms weighted by $(\sec\theta\ u_j)^{1/2}$ may therefore be of less use than is the case for some TOVS channels. The figure also shows, though less convincingly, that even weak lines are relatively unimportant compared to the continuum absorption present. There is no convenient analogue of equivalent width to characterise the continuum absorption but it is generally reckoned (e.g. Grant, 1990) to have a squared absorber mass dependency.

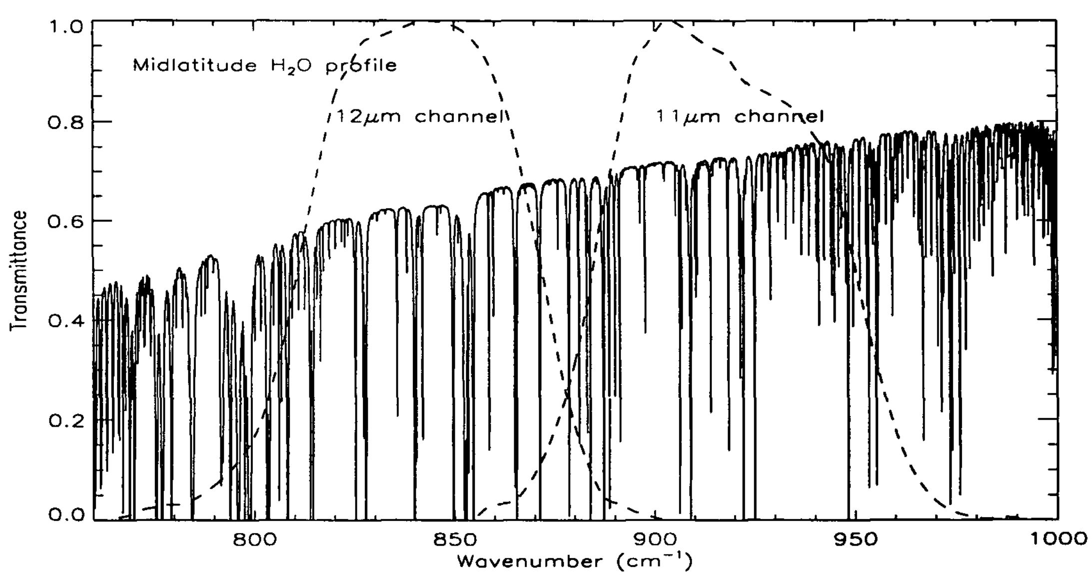

Figure 2. Transmittance spectrum for typical midlatitude atmosphere

The mixed gas model in RTTOV employs two terms not present in the water model (see Eyre 1991) which deal purely with angular effects; because in this case there is no constituent variable there are spare terms (within the 10) to accommodate them. The terms are ($\sec\theta$-1) and $(\sec\theta-1)^2$. This form of term arises because of the way the regression is made about mean atmosphere transmittances at a *particular* reference angle (see McMillin and Fleming, 1977 p1367); if the reference angle used was θ_0 (and not θ=0 as here), then the terms would be ($\sec\theta-\sec\theta_0$) and higher order powers. They represent the Taylor expansion terms about the reference angle. In the RTTOV water model it was thought (Eyre, personal comm.) that the absorber mass factors present in each term, especially X_{10}, would adequately describe the angular effects.

Following the above discussion, we studied the effect of using terms with absorber mass squared weighting, particularly in place of the 'strong line' predictors X_1-X_4, and the effect of using the pure angular terms.

The first experiments were concerned with the power of u_j associated with terms linear and quadratic in δT and δq. In all cases it appeared that u_j^2 was the optimum power and other results are not presented here. Table 4 shows the errors for each of the modifications made *individually.*

Weighting by the mass squared appears to be almost equally beneficial with the notable exception of the $p\delta q_j$ term where performance is actually degraded in the 3.7 μm channel. Notice that little impact is made on the maximum errors found; these were almost always for the extreme view zenith angle.

Quadratic mass term	1000mb S.deviation %			1000mb Max error %		
Predictor modification:	11μm	12μm	3.7μm	11μm	12μm	3.7μm
Baseline: None	3.26	3.48	1.11	10.5	11.0	2.9
$X_{1j} \Rightarrow \delta T_j (\sec\theta\, u_j)^2$	2.33	2.47	0.78	10.5	11.1	3.0
$X_{3j} \Rightarrow \delta q_j (\sec\theta\, u_j)^2$	2.87	3.15	1.05	10.4	10.6	3.2
$X_{6j} \Rightarrow \delta T^2_j (\sec\theta\, u_j)^2$	2.43	2.54	0.92	10.4	10.4	4.0
$X_{8j} \Rightarrow \delta q^2_j (\sec\theta\, u_j)^2$	2.72	2.84	0.91	10.6	11.2	2.9
$X_{2j} \Rightarrow p\delta T_j (\sec\theta\, u_j)^2$	2.38	2.54	0.80	10.9	11.6	2.9
$X_{4j} \Rightarrow p\delta q_j (\sec\theta\, u_j)^2$	3.16	3.39	1.36	10.4	10.4	3.6

Table 4. Experiments on absorber mass dependency

The cumulative effect of these changes is less encouraging than the individual effects might suggest. Table 5 shows the errors as the predictors are changed cumulatively:

Cumulative effect	1000mb S.deviation %			1000mb Max error %		
Predictor modification:	11μm	12μm	3.7μm	11μm	12μm	3.7μm
Baseline: None	3.26	3.48	1.11	10.5	11.0	2.9
$X_{1j} \Rightarrow \delta T_j (\sec\theta\, u_j)^2$	2.33	2.47	0.78	10.5	11.1	3.0
$+X_{6j} \Rightarrow \delta T^2_j (\sec\theta\, u_j)^2$	2.26	2.39	0.86	10.5	11.2	3.1
$+X_{8j} \Rightarrow \delta q^2_j (\sec\theta\, u_j)^2$	2.27	2.40	0.80	10.5	11.1	3.0
$+X_{3j} \Rightarrow \delta q_j (\sec\theta\, u_j)^2$	2.52	2.81	1.02	10.4	10.4	4.3
$+X_{2j} \Rightarrow p\delta T_j (\sec\theta\, u_j)^2$	Fails matrix inverse					

Table 5. Cumulative effect of change to predictors

It is clearly not beneficial to have a full set of linear and quadratic terms all weighted by $(\sec\theta\, u_j)^2$. Further tests showed that modifications to just X_1 and X_2 were sufficient and these modification are present in all the following.

Whilst some improvement has been made, the accuracy is still not good and the maximum errors remain unacceptably high. The next tests were made using the (secθ-1) angular factors substituted for X_6 and X_8 (found by experiments to be best). Some results are shown in Table 6.

<u>Angular terms</u>	1000mb S.deviation %			1000mb Max error %		
Predictor modification:	11µm	12µm	3.7µm	11µm	12µm	3.7µm
Baseline: X_1 and X_2 as above	2.28	3.48	1.11	10.5	11.0	2.9
$X_{8j} \Rightarrow (\sec\theta-1)^2$	1.75	1.90	0.63	7.3	7.7	2.1
$X_{8j} \Rightarrow (\sec\theta-1)^2$ <u>and</u> $X_{6j} \Rightarrow (\sec\theta-1)$	1.51	1.73	0.54	6.4	6.7	1.9
$X_{8j} \Rightarrow (\sec\theta-1)^2(\sec\theta\, u_j)^{1/2}$	1.26	1.44	0.51	3.4	4.8	1.6
$X_{8j} \Rightarrow (\sec\theta-1)^2(\sec\theta\, u_j)^{1/2}$ <u>and</u> $X_{6j} \Rightarrow (\sec\theta-1)(\sec\theta\, u_j)^{1/2}$	0.53	0.68	0.28	2.3	3.2	1.0
$X_{8j} \Rightarrow (\sec\theta-1)^2(\sec\theta\, u_j)$	1.25	1.33	0.58	3.5	3.8	1.7
$X_{8j} \Rightarrow (\sec\theta-1)^2(\sec\theta\, u_j)$ <u>and</u> $X_{6j} \Rightarrow (\sec\theta-1)(\sec\theta\, u_j)$	**0.22**	**0.29**	**0.29**	**0.8**	**1.2**	**1.0**
$X_{8j} \Rightarrow (\sec\theta-1)^2(\sec\theta\, u_j)^{3/2}$ <u>and</u> $X_{6j} \Rightarrow (\sec\theta-1)(\sec\theta\, u_j)^{3/2}$	0.22	0.29	0.33	0.8	1.2	1.0
$X_{8j} \Rightarrow (\sec\theta-1)^2(\sec\theta\, u_j)^2$ <u>and</u> $X_{6j} \Rightarrow (\sec\theta-1)(\sec\theta\, u_j)^2$	0.34	0.38	0.36	1.3	1.4	1.1

Table 6. Experiments on angular term dependency

From the significant improvement obtained it is clear that pure angular effects need to be modelled more strongly than in the original formulation. The highlighted version gives the best performance we have been able to achieve despite trying many predictor choices not shown here. This is not to suggest a better parameterisation is not possible, especially if the number of predictors is not limited to 10. However, an accuracy of 0.003 in transmittance with maximum errors around 0.01 can be considered adequate in light of the uncertainties in the spectroscopic data that give the baseline LBL calculations and in the approximations of the multiplicative property. The former is especially pertinent in the case of water vapour where the continuum absorption is poorly known.

In summary, the 'ATSR optimised' coefficients will be based on the following predictor variables:

X_{1j}	$\delta T_j (\sec\theta\, u_j)^2$	X_{6j}	$(\sec\theta-1)(\sec\theta\, u_j)$
X_{2j}	$p\delta T_j (\sec\theta\, u_j)^2$	X_{7j}	$\delta q_j (\sec\theta\, u_j)$
X_{3j}	$\delta q_j (\sec\theta\, u_j)^{1/2}$	X_{8j}	$(\sec\theta-1)^2(\sec\theta\, u_j)$
X_{4j}	$p\delta q_j (\sec\theta\, u_j)^{1/2}$	X_{9j}	$\delta T_j\, \delta q_j (\sec\theta\, u_j)$
X_{5j}	$\delta T_j (\sec\theta\, u_j)$	X_{10j}	$(\sec\theta\, u_j)^{1/2}$

The errors achieved above are from the dependent data used to calculate the coefficients; a more relevant check is obtained by applying the coefficients to an independent sample of atmospheres. 32 profiles were picked at random from the larger 158 sonde data base and the error statisitcs generated using the optimum coefficients as defined above are shown in Table 7:

<u>Independent data</u>	1000mb S.deviation %			1000mb Max error %		
Predictor modification:	11µm	12µm	3.7µm	11µm	12µm	3.7µm
ATSR optimised set	0.26	0.47	0.5	1.6	3.7	2.3

Table 5. Transmittance error summary statistics on independent data.

As expected, the errors are larger when independent data is considered, but remain well within acceptable bounds.

Band Correction Coefficients

Converting between temperature and radiance for a finite bandwidth channel cannot be achieved accurately by simple use of the Planck function and it's inverse since there is no single wavelength at which to perform the operation. To go from temperature to radiance it is possible, and exact, to use the planck function weighted by the filter function at each monochromatic frequency interval; $R_{chan} = \Sigma f_n B(T)_n dn / \Sigma f_n dn$. This is naturally how RADGEN does the conversion in integrating the radiative transfer equation. If this operation is performed over all plausible scene temperatures T then the resulting $R_{chan}(T)$ can be used as as look-up table to convert from any R_{chan} to its 'equivalent brightness temperature', BT_{chan} and, of course, the inverse procedure from brightness temperature to radiance. This method can be made to be as accurate as required by reducing the interval between consecutive scene temperature values at the expense of increasing the time needed to search the table for the values required.

RTTOV uses a faster method which, however, cannot be made arbitrarily accurate. A central frequency is chosen for the channel and the planck function and inverse are employed in the usual manner but with the temperature T replaced by an 'effective temperature' T_{eff}, where $T_{eff} = C1T + C2$; C1 and C2 being the so called 'band correction coefficients'. Thus the conversion from temperature to radiance becomes $R_{chan} = B(T_{eff}) = B(C1T + C2)$, and from radiance to temperature, $T = T_{eff}/c1 - c2 = B^{-1}(R_{chan})/c1 - c2$.

Here, we calculate band correction coefficients for ATSR channels in the following way. The 3.7, 11 and 12 µm channels were designated central wavenumbers 2681.0, 910.0 and 842.0 respectively and planck radiances at these wavenumbers were calculated for scene temperatures T_{scene} from 260 to 310 K. These radiances were then converted to equivalent brightness temperatures, BT, using the RADGEN interpolation method. Linear regression of BT with T_{scene} gives the coefficients C1 and C2. Results of this procedure for the 12 µm channel are shown in Figure 3.

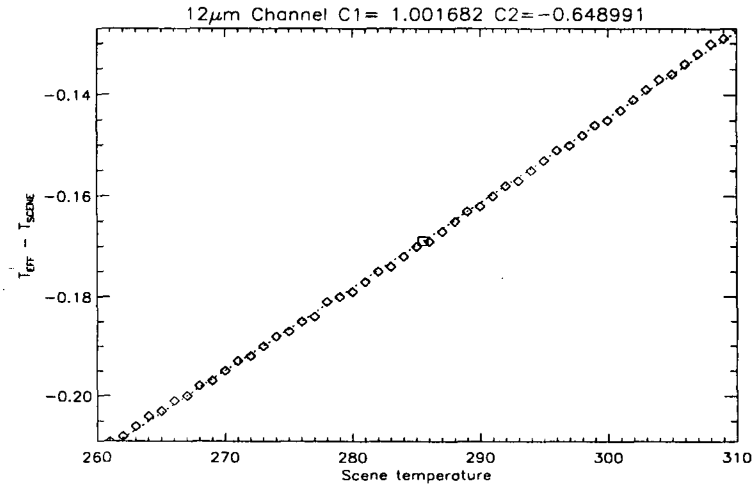

Figure 3. Band correction coefficients for the 12 µm channel

Diamonds show the difference $BT\text{-}T_{scene}$ plotted against T_{scene} and the coefficients are given at the top the plot. The reconstructed difference, $T_{eff}\text{-}T_{scene}$ is shown as a dotted line and shows the skill to which the coefficients reproduce the true brightness temperatures. The worst case fit appears in the 11µm channel but even here the error is less than 0.01 K.

The band correction model appears to work with adequate accuracy and is appropriate in the framework of fast radiative transfer models. By adopting it we incur no conversion work to RTTOV and it's gradient code. Table 5 gives the band coefficients for the three channels.

Channel	Wavenumber	C1	C2
3	2681.0	1.005042	-2.041717
4	910.0	0.999009	1.015081
5	842.0	1.001682	-0.648991

Table 8. Band correction coefficients for ATSR-1 channels

Testing the full radiative transfer calculation

To this point we have described and evaluated the accuracy of various techniques and approximations of the fast model. These are; the monochromatic approximation (MA) that $t_{tot} = t_{water} \times t_{CO2}$ holds for the spectrally averaged quantities, the fast transmittance model (FTM) and the band correction approximation (BCA) for converting between radiance and brightness temperature. It was suggested that the MA would be accurate to ~0.1 K for the 11 and 12 μm channels and to 0.4 K for the 3.7 μm channel. The FTM was shown, after modifications to be capable of reproducing ground to space transmittances to an accuracy of 0.3% in all channels, comparable to the MA at 11 and 12 μm and rather better than the MA at 3.7 μm. The BCA was shown to introduce errors of around 0.01 K in all channels and therefore appears not to be a significant factor.

This section evaluates the total system error; the net effect of all the above, by comparing the brightness temperatures that result from full radiative transfer calculations made using RTTOV and the, for present purposes exact, RADGEN code. Brightness temperatures were calculated for the 32 dependent sondes and at each of the 5 angles. The differences are shown in Figure 4. The errors are broadly in line with previous discussion; it is likely that the MA dominates the 3.7 μm error which has, as suggested, a maximum of around 0.4 K. The errors are biased though and the resultant standard deviation is 0.13 K which is probably acceptable for most purposes. The 11 and 12 μm channels are relatively unbiased and have acceptably low standard deviations.

RTTOV has radiance tuning facilities in the form of two channel dependent parameters. The first parameter, γ, is intended to correct for absorption coefficient errors and does so as an exponent on the transmittance, thus $t' = t^{\gamma}$, all levels being treated by a single γ. Application of γ can reduce variance in errors. The second parameter, β, is a simple brightness temperature correction applied at the end of the RTE integration and corrects only mean errors. They are normally intended to be estimated by comparison of fast model results to real measured data thus correcting for errors in the basic spectroscopic line data. Indeed, it may seem a little odd to suggest using these parameters to tune a fast model to the LBL model to which it is already, by definition, the best fit in some sense.

However, as discussed, the formulation of the fast model does not allow one to avoid the MA error and bias and variance errors from this source are apparent in the fast model results. Tuning by means of γ and β, although crude, is potentially a means of reducing these errors. It would appear only to justify effort in the case of the 3.7 μm channel. Figure 5 shows the result of applying γ values between 0.95 and 1.05 to the channel transmittance errors. Reasonably strong minima are found in the 11 and 12 μm channels and a very weak one in the 3.7 μm channel. In all cases the γ value at the minimum is close to 1 and does not significantly reduce the errors.

We conclude that tuning by γ at this stage is not warranted. Use of β, at least for the 3.7 μm channel, is appropriate.

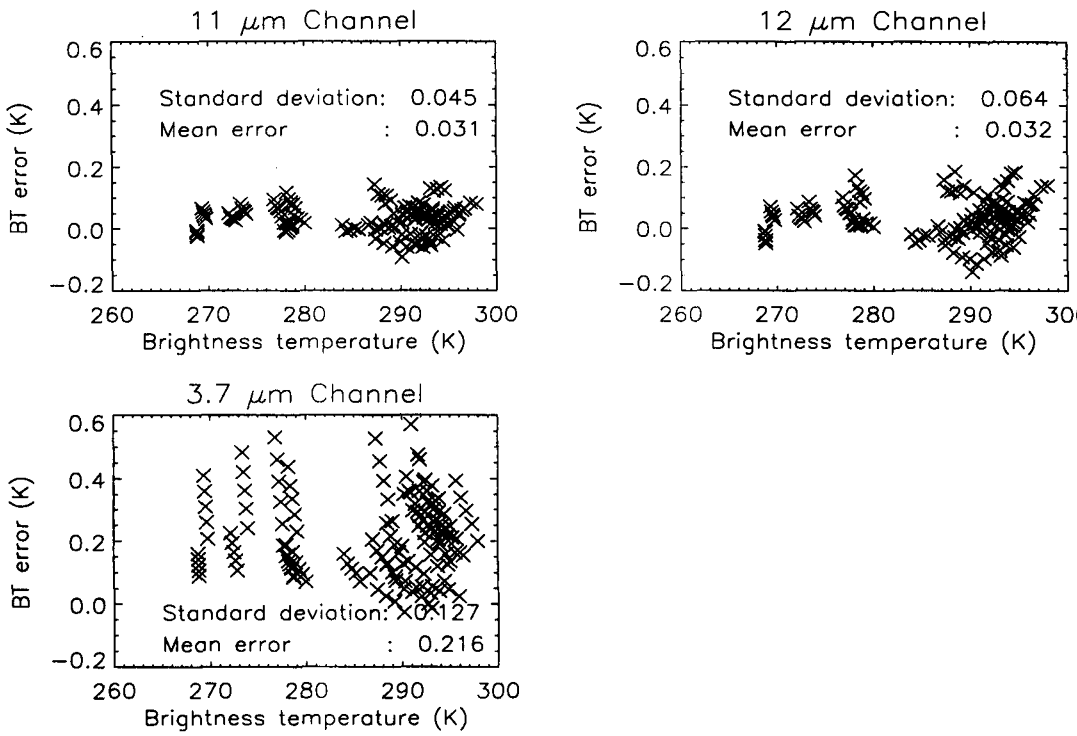

Figure 4. Total RTTOV error on dependent set in terms of brightness temperature.

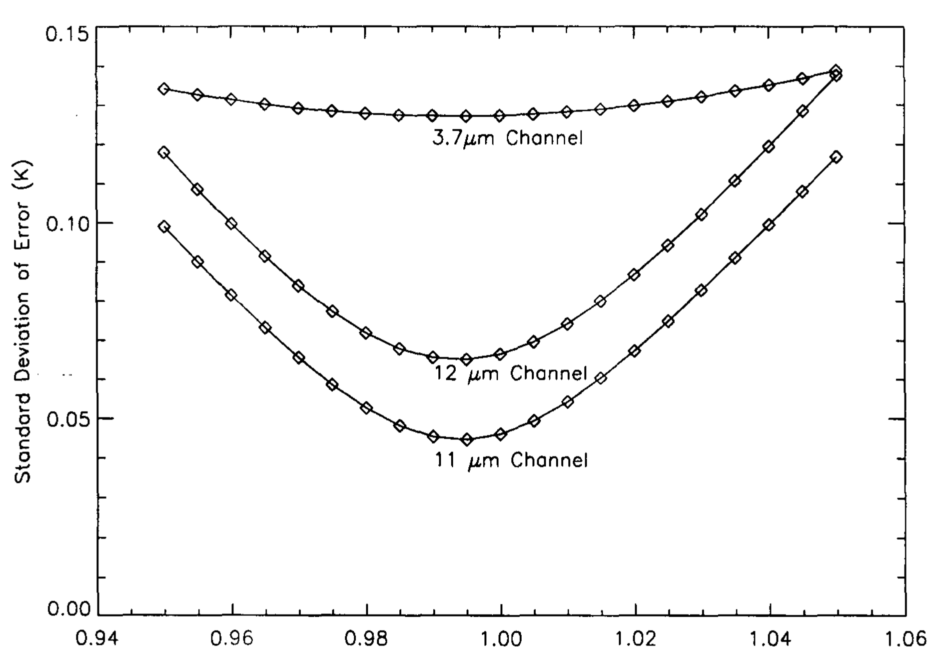

Figure 5. Effect of γ factor on random error in brightness temperature

Cloud Radiative Properties

Although the emphasis of this report is towards the gaseous absorption and emission at the infrared wavelengths of ATSR, mention should be made of the model cloud parameterisation. The model is extended beyond the original due to Eyre (which carries cloud fraction and pressure) with cloud parameters effective drop size R_{eff} and optical depth (at 0.55μm). These define the bulk cloud reflectivity, transmissivity and emissivity through interpolation of tables calculated using discrete ordinates multiple scattering code (DISORT, Stamnes et al. 1988). Solar (i.e. beam) reflectivity and transmission are a function of solar and satellite view zenith angles, the relative azimuth angle optical depth and R_{eff}. Only the 3.7 μm channel has significant solar reflection. Diffuse emission, transmission and reflection are a function only of satellite zenith, optical depth and R_{eff}. RTTOV uses the appropriate terms in the radiative transfer integration routine (RTINT) and an array flag can be set to switch various cloud effects on or off.

Surface radiative properties

The extended RTTOV also has a more sophisticated scheme for sea surface emissivity than the original. The spectral and angular dependence of sea emissivity is incorporated. Nadir view emissivities are assumed constant for each channel since there is no significant angular variation until the zenith angle reaches 35° or more. The angular dependence of the forward view emissivities ('forward' defined in the code as when the zenith angle is greater than 45°) are parameterised according to eqn. 6.3 from Watts et. al. 1996 with an assumed wind speed of zero. Note that the parameterisation is derived for and should therefore only be applied to forward view angles in the region 51–56°. Explicit modelling of the sea state (wind) effects, although feasible, includes modelling the effect of broad reflection lobes and multiple reflections (Watts et. al. 1996) and, because of the rather small *net* effect, is not used here. Reflection is assumed equal to 1-emission and to be from the specular direction.

At present, becasue of the lack of a better model, land surface emissivities are treated as nadir (i.e. constant with angle) sea surface values.

Fast model speed

Timing runs were performed on the Alpha workstation for the full RTTOV suite to calculate brightness temperatures; the elapse time for one calculation of 3 channel brightness temperatures is 1.4 ms[1].

The gradient (K-matrix) calculation, though not timed here, is expected to take a little longer than the forward calculation.

As an example of the implications of this performance for SST retrieval suppose we have a 512x512 pixel image with 50% cloud cover and an average of three iterations required per pixel, then the SST image could be produced in approximately 40 minutes. This figure is quite approximate because it is not clear what the cost of processing other than the radiative transfer forward and gradient models would be. However, it is clear that full resolution retrievals would be feasible on an offline research basis at least. An operational implementation might need to use area averaged data to give reasonable speed, but the full resolution could probably be recovered at acceptable accuracy by taking the 'atmospheric deficit' resulting from the area average retrieval and adding it to the full resolution brightness temperatures. This is tantamount to assuming no change in water content over the area average.

[1] RTTOV was written with a view to producing efficient vectorised code. On a CRAY-YMP computer the execution time was 40% less when blocks of 50 profiles were processed compared to single profile processing (Eyre, 1991).

Another way of increasing speed may be to use the results from one pixel to provide the initial guess at the next (adjacent) pixel. The number of iterations to convergence may then be reduced.

Improvements

A number of improvements to the model are possible.

The levels used are not optimised to the ATSR channels and there are too many high in atmosphere and possibly too few in the boundary layer. 10 to 20 levels from the surface to 200 mb might be more reasonable with one or two higher levels to allow future modelling of stratospheric aerosol. A lesser number of levels give a faster model.

The angles employed are also not ATSR specific and cover the range 0 – 60° in a uniform manner. It is possible that better accuracy might be achieved with separate coefficients dedicated to 'nadir' (0–22°) and 'along-track' (51–56°) view geometries.

The 3.7 µm channel fast model accuracy perhaps only just meets requirements for physically-based SST retrievals. Most of the error appears to arise from the monochromatic approximation for mixed and variable gas transmittances and an alternative formulation which could avoid this approximation might be useful in reducing errors in this channel.

Summary

An accurate line by line based high resolution radiative transfer model has been modified to produce ATSR channel transmittances on a set of fixed standard pressure levels. The transmittances, for a diverse set of atmospheric profiles and viewing angles, form the dependent set of data from which coefficients for a fast transmittance model are derived. It was found necessary to modify the predictors in the fast model in order that it reproduced the dependent set transmittances to acceptable accuracy; with this done, rms errors around 0.3% were achieved. Combined with other errors arising from a strictly inappropriate use of the multiplicative property of water and mixed gas transmittances we find overall standard errors in the fast forward model to be around 0.05 K in the longwave channels 4 and 5 and 0.13 K in the shortwave channel 3. The small biases (0.03, 0.03, 0.21 K) can be removed by corrections already built into the fast model code. An attempt to reduce the small random errors by use of a second correction term applied as a transmittance exponent was not successful.

Band correction coefficients for rapid conversion between radiance and brightness temperature were derived and supporting calculations made to allow radiance calculations in cloud covered atmospheres. Timing showed the model is likely to be fast enough to allow physical iterative retrievals of SST at full resolution in reasonable elapse time using an Alpha computer.

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References

Eyre J.R. 1991, 'A fast radiative transfer model for satellite sounding systems'. Technical Memorandum no.176, European Centre for Medium Range Weather Forecasts, Shinfield Park, Reading, UK.

Fleming H,E., McMillin L,M. 1977, 'Atmospheric transmittance of an absorbing gas. 2: A computationally fast and accurate transmittance model for slant paths at different zenith angles', Appl. Opt. **16** no.5

Goody & Yung, 1989, 'Atmospheric Radiation, Theoretical Basis', 2nd edition, Oxford University Press.

Grant W.B. 1990, 'Water vapour absorption coefficients in the 8-13 μm spectral region: a critical review', Appl. Opt. **29** no.4 pp451-462

McMillin L,M., Fleming H,E. 1976, 'Atmospheric transmittance of an absorbing gas: a computationally fast and accurate transmittance model for absorbing gases with constant mixing ratios in inhomogeneous atmospheres', Appl. Opt. **15** no.2 pp358-363

McMillin L,M, Fleming H,E. and Hill, M,L. 1979, 'Atmospheric transmittance of an absorbing gas. 3: A computationally fast and accurate transmittance model for absorbing gases with variable mixing ratios', Appl. Opt. **18** no.10 pp1600-1606

Sidrin M. 1981, 'Broadband reflectance and emissivity of specular and rough water surfaces', Appl. Opt. **20** no.18 pp3176-3183

Stamnes K., Tsay S.C., Wiscombe W., Jayaweera K. 1988, 'Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple-scattering and emitting layered media' Appl. Opt., 1988, **27**, No.12, pp.2502-2509

Watts P.D. 1993, 'Cloud microphysical parameters from TOVS: A practical scheme and geometrical considerations', Tech. Proc. ITSC VII Igls, Austria, 10-16 Feb 1993. Ed J.R.Eyre, ECMWF, Shinfield Park Reading. pp543-554

Zavody A.M. 1995, 'A radiative transfer model for sea surface temperature retrieval for the along track scanning radiometer'. *J. Geophys. Res.* **100** no. C1.