A Fast Forward Model for ATOVS (RTATOV)

R. Saunders and M. Matricardi
European Centre for Medium-Range Weather Forecasts
Shinfield Park
Reading RG2 9AX
U.K.

1. Introduction

In recent years the use of the data from the TIROS Operational Vertical Sounder, TOVS, for global numerical weather prediction (NWP) has been changing from assimilating retrieved temperature and moisture profiles to direct assimilation of the measured radiances. The latter approach has been operational at the European Centre for Medium Range Weather Forecasts (ECMWF) in one form or other since 1992 (see Saunders et.al. 1997 for more details). This more direct use of the TOVS data has led to significant improvements in the quality of the NWP analyses and forecasts (Eyre et al, 1993, Andersson et al 1994, Derber and Wu, 1997) particularly in the southern hemisphere and tropics.

To enable the assimilation of radiances it is necessary to compute a first guess radiance from the model fields for every measured TOVS radiance which is used. The computation of radiances from atmospheric profiles is achieved using an "observation operator" for TOVS radiances. All observation types assimilated in the analysis have an "observation operator" in one form or another. For TOVS radiances the operator includes interpolating the model fields to the observation location and time and on to the 40 fixed pressure levels required for the radiative transfer computation. The interpolated/extrapolated model profile and surface parameters are input to a fast radiative transfer model, the key part of the operator, to compute the (A)TOVS infrared and microwave radiances. This is also commonly referred to as the "forward model". In the process of data assimilation the differences between the measured and computed radiances are then used to perturb the first guess profile to try and minimise the radiance differences. In 3/4DVar this is achieved using the adjoint of the observation operator which computes the gradient of the profile vector with respect to the radiances for the first guess profile. Hence the radiative transfer model and its gradient are the core of the observation operator in 3/4DVAR for (A)TOVS.

This paper documents results from an updated version of the original RTATOV radiative transfer model described by Eyre (1991) which is now used at several NWP centres. This new version is compared with the original version for both HIRS and AMSU in terms of accuracy by comparison with exact line-by-line model computations. The gradient of the new model, and hence sensitivity of the radiances to changes in the atmosphere and surface, and non-linearity about the first guess profile is also described.

2. The formulation of the ATOVS radiative transfer model

The generalised radiative transfer (RT) equation for upwelling radiances, $R_i(X)$, from the atmosphere and surface can be written for channel i in discrete notation, as:

$$R_i(X)=\tau_{i,s}\epsilon_{i,s}B_i(T_s) + \sum_{j=1}^{N}R_{i,j}^{u} + (1-\epsilon_{i,s})\sum_{j=1}^{N}R_{i,j}^{u}[\frac{\tau_{i,s}^{2}}{(\tau_{i,j-1}\tau_{i,j})}] \qquad (1)$$

where the first and third terms on the RHS of equation 1 are the radiance from the surface (emitted and reflected assuming specular reflection) and the second term is the radiance emitted by the atmosphere where $B_i(T)$ is the Planck radiance integrated over the channel i spectral response, τ_{ij} is the transmittance from level j to space and $R_{i,j}^{u}$ is defined as:

$$R^{u}_{i,j}=\frac{1}{2}[B_i(T_j)+B_i(T_{j-1})](\tau_{i,j-1}-\tau_{i,j}) \qquad (2)$$

The temperature, moisture and optionally ozone profiles supplied on j pressure levels (i.e. T_j, q_j, oz_j) and surface parameters (i.e. emissivity $\epsilon_{i,s}$ and surface skin temperature, T_s) are provided by the model first guess profile vector X. Currently for TOVS the surface emissivity is always set to unity as this is a good approximation for the infrared channels over sea and sea-ice and the microwave radiances provided to NWP centres by NESDIS have been corrected for non-unit emissivity effects. For AMSU a non-unit emissivity is assumed. The variable which has to be computed by the RT model is the atmospheric layer transmittance for each channel i, and for each discrete homogenous layer of the profile. It varies with pressure, temperature, and absorber concentrations and so the atmosphere has to be divided up into enough levels from the surface to 0.1hPa to allow the assumption of homogeneity to be valid. For RTATOV the atmosphere is divided up into 40 layers defined by pressure levels from 0.1 hPa to 1000 hPa. Other fast models divide the atmosphere up into layers of equal absorber amount (e.g. OPTRAN, McMillin et.al., 1995). Note the integration of the radiative transfer in equation 1 does not have to be on the same levels as the transmittance computation.

Once the layers have been defined the transmittance to space, $\tau_{i,j}$, can be computed exactly with a line-by-line model for a diverse set of atmospheric profiles, currently 32 taken from the NESDIS 1200 profile dataset. The line-by-line models used were HARTCODE (Miskolczi et al. 1988) for the infrared channels and a combination of the Liebe 1989 MPM model (Liebe, 1989) for water vapour and the 1992 update for oxygen absorption, for the microwave channels. The "true" channel transmittances for each layer to space are computed by integrating the line-by-line model transmittances over the channel spectral responses. These spectral responses vary for each satellite for the HIRS channels but are more stable for the microwave channels allowing a single set of transmittances to be used for all satellites.

Once the "true" channel transmittances for all the profiles and mixed/variable gases have been computed they are used together with a set of predictors to compute regression coefficients which allow layer optical depths to be calculated for any given input profile and mixed/variable gas. If the layer optical depth is $d_{i,j}$ for mixed gases, water vapour or ozone then:

$$d_{i,j}= d_{i,j-1} + Y_j \sum_{k=1}^{K} a_{i,j,k}\, X_{k,j} \qquad (3)$$

where K is the number of predictors (currently 9) and the values of X_{kj} and Y_j are given in Table 1 for the current operational version of RTATOV and the new version for ATOVS. The new coefficients were derived empirically by Rayer (1995) for TOVS and at ECMWF for AMSU.

As the channel optical depths are not monochromatic it is not strictly valid to just add the optical depths of the various gases together to compute the total optical depth as discussed by McMillin et al. (1995). For this study the monochromatic optical depths due to mixed gases alone d^{mix}, mixed gases and water vapour d^{mix+wv} and ozone, d^{oz} (only for infrared), were available.

		HIRS		AMSU
	uniformly-mixed gases	old water vapour/ ozone	new water vapour/ ozone	new water vapour
X_{1j}	$\delta T_j \sec\theta$	δT_j	δT_j	δT_j
X_{2j}	$\delta T_j^2 \sec\theta$	$\overline{p\ \delta T_j}$	$\overline{p\ \delta T_j}$	$\overline{p\ \delta T_j}$
X_{3j}	$\overline{\delta T_j} \sec\theta$	δq_j	δq_j	δq_j
X_{4j}	$\overline{p\ \delta T_j} \sec\theta$	$\overline{p\ \delta q_j}$	$\overline{p\ \delta q_j}$	$\overline{p\ \delta q_j}$
X_{5j}	$(\sec\theta - 1)$	$\delta T_j (\sec\theta\ u_j)^{1/2}$	$\delta T_j (\sec\theta\ u_j)^{1/2}$	$\delta T_j (u_j)^{1/2}$
X_{6j}	$(\sec\theta - 1)^2$	$\delta T_j^2 (\sec\theta\ u_j)^{1/2}$	$\delta T_j^2 (\sec\theta\ u_j)^{1/2}$	$\delta T_j^2 (u_j)^{1/2}$
X_{7j}	$\overline{\delta T_j} (\sec\theta - 1)$	$\delta q_j (\sec\theta\ u_j)^{1/2}$	$\delta q_j (\sec\theta\ u_j)^{1/2}$	$\delta q_j (u_j)^{1/2}$
X_{8j}	$\overline{p\ \delta T_j} (\sec\theta - 1)$	$\delta q_j^2 (\sec\theta\ u_j)^{1/2}$	$(\sec\theta - 1) (\sec\theta\ u_j)^{1/2}$	0
X_{9j}	$\delta T_j (\sec\theta - 1)$	$\delta T_j\ \delta q_j (\sec\theta\ u_j)^{1/2}$	$(\sec\theta - 1)^2 (\sec\theta\ u_j)^{1/2}$	0
Y_j	*1*	$(\sec\theta\ u_j)^{1/2}$	$(\sec\theta\ u_j)^{1/2}$	$\sec\theta (u_j)^{1/2}$

Table 1: RTATOV predictors for mixed gases, and old and new versions for water vapour/ozone. The predictors are defined in Eyre (1991).

This resulted in the following formulation to compute the total mean layer transmittance $\tau_{i,j}^{tot}$ from the mixed gas, water vapour and ozone optical depths given by the regression in equation 3. The optical depths for mixed gases, water vapour and ozone are first converted into transmittances and then combined to give a total transmittance,

$$\tau_{i,j}^{tot} = \tau_{i,j}^{mix} \cdot \frac{\tau_{i,j}^{mix+wv}}{\tau_{i,j}^{mix}} \cdot \tau_{i,j}^{oz} \tag{4}$$

This is not optimal for ozone, as it should be treated the same as water vapour but it was felt adequate for the results presented here. The total layer transmittance to space (i.e. $\tau_{i,j}^{tot}$) can then be used in the radiative transfer calculation defined in equation 1 to compute the top of atmosphere upwelling radiance for each channel, by summing the radiance from each layer.

3. Performance of the fast model for TOVS and ATOVS

The radiances computed from the fast models can be compared with the corresponding "true" radiances computed from the line-by-line models. For the infrared channels this was only possible for the 32 profile set from which the coefficients were computed. The AMSU channels were compared with an independent set of line-by-line radiances but the results were very similar to the dependent set and so for consistency only the performance of the models compared to the dependent set of 32 radiances for each channel are presented here.

Figure 1 shows the performance of the models for the 19 HIRS infrared channels of NOAA-14 in terms of the standard deviation of the difference between the fast and line-by-line computed radiances in units of equivalent black body brightness temperature. The mean radiance biases for each channel are all within one standard deviation of the difference, the largest bias being for HIRS channel 12 at 0.25K. Also plotted are the noise equivalent temperatures (NeΔT) for each of the channels (for a typical mean target temperature). The noise figures were taken from the HIRS/3 specification for NOAA-K. Several conclusions can be drawn from this plot. Firstly for the longwave temperature sounding channels (1-6) the accuracy of the fast model far exceeds the NeΔT values for HIRS. Therefore any errors in the computed radiances for these channels are likely to originate from the line-by-line model itself (e.g. errors in spectroscopic parameters, not included line mixing etc.) rather than the fast model. The same is true to a lesser extent (fast model errors slightly higher and NeΔT values smaller) for the shortwave temperature sounding channels (14-16). The biggest errors of the fast model in terms of both bias and standard deviation are for the water vapour channels (10-12). For channels 10 and 11 the values exceed the NeΔT values for both sets of HIRS water vapour predictors suggesting more work is needed to make an optimal fast model for the HIRS water vapour channels. Similarly for the window channels (7-8, 13) the NeΔT values are below the fast model accuracy. The difference between the different HIRS water vapour predictors as listed in Table 1 is greatest for the window channels which are affected by water vapour absorption, for instance for channels 7-10 the fast model error is halved with the new predictors. These are worthwhile improvements when compared with the corresponding NeΔT values. One way of reducing the fast model errors still further for the water vapour channels is the OPTRAN approach (McMillin et al, 1995) and initial experiments have confirmed this for the AMSU water vapour channels.

The results plotted in Figure 1 did not include ozone as a variable gas. For most channels this is at least a tolerable approximation as the effect of ozone on the channel radiances is small and so a mean ozone amount can be assumed. For HIRS channel 9 however there is a strong dependence on the ozone concentration, particularly in the lower stratosphere (Neuendorffer, 1996). To enable ozone to be included in the RTATOV model as a variable gas 35 profiles of ozone were selected from a set of 383 profiles (mainly from NESDIS but with a few Antarctic profiles included) to represent the global variability of ozone profiles and line-by-line calculations of ozone transmittance were made using HARTCODE. To demonstrate the capability of RTATOV to predict ozone transmittance the standard deviation of the difference in the transmittance profiles between the fast and line-by-line models for channel 9 using the old and new HIRS water vapour predictors listed in Table 1 but applied to the ozone concentrations was computed. The results showed the ozone transmittances could be computed by the fast model to an accuracy of 1.4% with the old predictors and 0.5% with the new predictors. It is interesting to compare the computed radiances for the HIRS longwave temperature sounding channels with ozone included as a variable gas to that with the old ozone scheme in RTATOV. For the 383 ozone profiles the mean radiance bias of HIRS channels 1-7 between the old and new schemes was -0.2K, -0.4K, -0.29K, -0.07K, 0.05K, 0.13K, 0.15K respectively.

The performance of the RTATOV model for AMSU is plotted in Figure 2 in the same format as Figure 1 but note the 5 times increase in range of brightness temperature. As for HIRS all the temperature sounding channels (4-14) have fast model errors well below the NeΔT values. However for the window channels (2-3, 15-17)

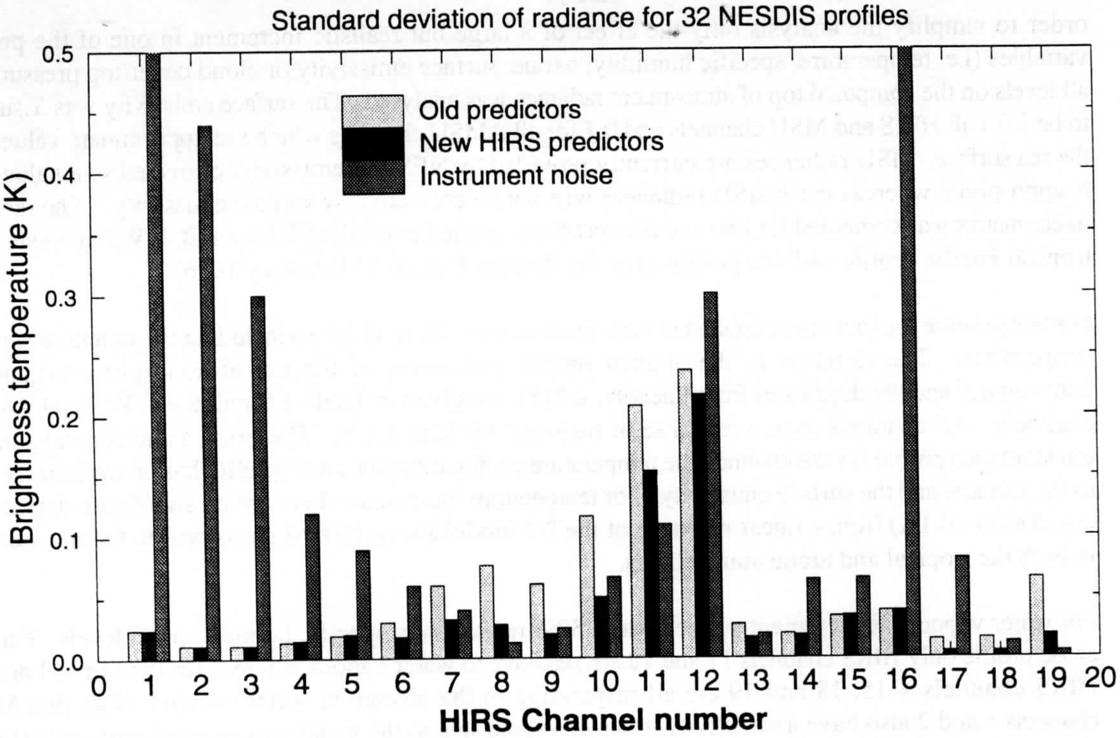

Figure 1 Standard deviation of HIRS brightness temperatures for RTATOV

and water vapour channels (1,18-20) the standard deviations of the fast model with the old predictors far exceed the NeΔT values in most cases. The AMSU water vapour predictors decrease the standard deviations by up to a factor of 10 resulting in fast model errors at least close to or less than the NeΔT values. AMSU channels 19 and 20 appear to be the most difficult ones in terms of accuracy of the fast model when compared to the NeΔT values.

4. The gradient of the fast model

For variational assimilation the gradient of the radiative transfer model about the initial first guess profile is also required in one form or other. The tangent linear matrix is *dRi(X)/dX* which is the gradient of the channel i radiance with respect to all the profile variables (i.e.*dRi/dT(p), dRi/dQ(p) etc)*. The adjoint is the gradient of the profile with respect to the radiances *dX/dRi(X)*. For RTATOV the gradient values can be computed by calling a similar but parallel set of subroutines to those used in the forward model calculation.

The tangent linear matrix of the fast model gives a measure of the sensitivity of (A)TOVS radiances to changes in the profile vector (e.g. temperature, water vapour profiles or surface parameters). It is also of interest to determine how linear the gradient of the fast model is about the first guess profile in order to assess how often the radiances should be recomputed during the minimisation process in 1/3/4DVar. The non-linearity $\Delta R(X)$ is defined as:

$$\Delta R(X)=R(X+\Delta X)-R(X)-\frac{dR(X)}{dX}.(X+\Delta X) \qquad (5)$$

where ΔX is the profile increment and $\frac{dR(X)}{dX}$ is the tangent linear of R for the profile vector X. In order to simplify the analysis only the effect of a large but realistic increment in one of the profile variables (i.e. temperature, specific humidity, ozone, surface emissivity or cloud cover/top pressure) at all levels on the computed top of atmosphere radiance was analysed. The surface emissivity was assumed to be 1 for all HIRS and MSU channels and 0.7 for all AMSU channels which are approximate values for the sea surface. MSU radiances are currently provided by NESDIS emissivity corrected so a value of 1 is appropriate whereas the AMSU radiances will not be corrected for surface emissivity. The tangent linear matrix was computed for two extreme profiles selected at random from an ECMWF analysis (one tropical Pacific profile and one profile over the Hudson Bay on 20 February 1996).

For temperature the increment applied to both profiles was -2K at all levels including the radiative surface temperature. The response to the applied profile increments of the top of atmosphere brightness temperatures and the departures from linearity, $\Delta R(X)$, are given in Table 2 for all the TOVS and AMSU channels. All channels have a response of between 1.0 K to 2.1 K. The exact value depends on the transmittance profile for the channel, the temperature profile (note the arctic profile has an inversion close to the surface) and the surface emissivity. For temperature increments there are no significant departures (i.e. $\Delta R(X) < 0.1$K) from a linear response of the RT model about the first guess profile for all channels in both the tropical and arctic atmospheres.

For water vapour the increment applied was a 50% reduction in specific humidity at all levels. For the arctic profile only HIRS channels 11 and 12 are sensitive to water vapour whereas for the tropical profile HIRS channels 4-15, 18 and 19 are all responding to the change in water vapour. Note that MSU channels 1 and 2 also have a sensitivity to water vapour due to the water vapour continuum at 50 GHz. The values of $\Delta R(X)$ in Table 2 show that there is a significant departure from linearity of up to 1K for the tropical profile of the HIRS water vapour channels (11 and 12). If the water vapour absorption is weak then a linear response to changes in absorber amount is predicted whereas if the channel is in a part of the spectrum with strong water vapour absorption then a non-linear response is expected (see Houghton et. al., 1986 for more details). AMSU channels 1-4 and 15-20 are all sensitive to water vapour for both the tropical and to a lesser extent the arctic profile. Note that for the channels which "see" the surface the change in brightness temperature is of opposite sign to the HIRS water vapour channels. AMSU water vapour channels (17-20) are highly non-linear (departures up to 7.5K in the tropics) due to the non-unit emissivity of the sea surface.

The response to changes in total column ozone was only computed for the HIRS channels as it is believed the microwave channels are not sensitive to ozone (with the possible exception of AMSU channel 18). For a 10% increase in total column ozone, from the global mean profile, HIRS channels 1-7 all have a small response (about 0.1K or less) but channel 9 changes by more than 1K. As for water vapour the response is non-linear for the ozone sensitive channel (HIRS-9) where the absorption is strong.

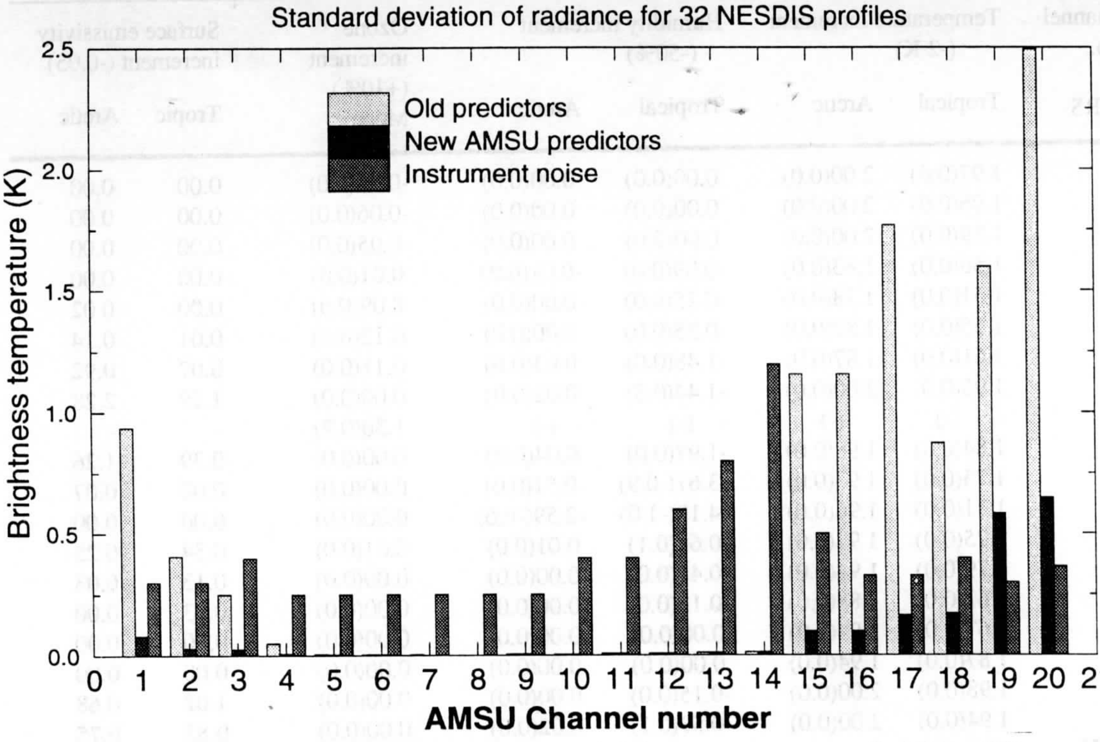

Figure 2 Standard deviation of AMSU brightness temperatures for RTATOV

The sensitivity to surface emissivity for all channels is also given in Table 2 where for HIRS and MSU the nominal emissivity of 1.0 is reduced by 0.05 whereas for AMSU the nominal emissivity of 0.7 was reduced by 0.1. This reflects the uncertainty in the emissivities for HIRS and the "emissivity corrected" MSU radiances and uncorrected AMSU radiances respectively. The sensitivity figures given in Table 2 are useful to assess if a channel can be used over land without allowing for surface emissivity. In the tropics HIRS channels 7-10 and 13, 14, 18 and 19 and MSU channels 1 and 2 are all sensitive to changes in surface emissivity and in the arctic channels 6 and 11 also start to "see" the surface. For AMSU, only channels 1-5 and 15-17 "see" the surface in the tropics but channels 18-20 also "see" the surface for arctic profiles. Unlike HIRS channel 12 care will have to be taken in using even AMSU channel 18 (the most opaque water vapour channel) over land. The response to changes in surface emissivity however is completely linear for all HIRS and AMSU channels as would be expected from theory assuming a specular emissivity model. Note the change of emissivity with windspeed and sea surface temperature is not linear and so the tangent linear assumption will not be valid for retrievals of these variables from AMSU.

Finally, for the HIRS channels only, the sensitivity to cloud top pressure and cloud amount for a tropical profile were computed together with the departure from linearity. The non-linearity of the RT model for a 50 hPa increment in cloud top pressure at 800 hPa is small (<0.1K) whereas for the same increment to a cloud top at 400 hPa the departure from linearity is almost 1K for nearly all HIRS channels. Responses to changes in cloud amount are more linear although the departures from linearity are still significant for a 400 hPa cloud top. These results apply to a cloud top which is "black" at all HIRS channel wavelengths (i.e. an optically thick cloud).

Channel No.	Temperature increment (-2 K)		Humidity increment (-50%)		Ozone increment (+10%)	Surface emissivity increment (-0.05)	
HIRS	Tropical	Arctic	Tropical	Arctic	Mean	Tropic	Arctic
1	1.97(0.0)	2.00(0.0)	0.00(0.0)	0.00(0.0)	-0.03(0.0)	0.00	0.00
2	1.96(0.0)	2.00(0.0)	0.00(0.0)	0.00(0.0)	-0.06(0.0)	0.00	0.00
3	1.89(0.0)	2.00(0.0)	0.00(0.0)	0.00(0.0)	-0.05(0.0)	0.00	0.00
4	1.56(0.0)	1.83(0.0)	-0.09(0.0)	-0.01(0.0)	0.01(0.0)	0.00	0.00
5	1.51(0.0)	1.78(0.0)	-0.25(0.0)	0.00(0.0)	0.09(0.0)	0.00	0.02
6	1.55(0.0)	1.82(0.0)	-0.55(0.0)	0.00(0.0)	0.12(0.0)	0.01	0.14
7	1.61(0.0)	1.87(0.0)	-1.48(0.0)	0.03(0.0)	0.11(0.0)	0.07	0.92
8	1.95(0.0)	2.00(0.0)	-1.44(0.3)	0.02(0.0)	0.00(0.0)	1.19	2.28
9	- (-)	- (-)	- (-)	- (-)	1.30(0.2)	-	-
10	1.84(0.0)	1.98(0.0)	-1.97(0.0)	0.04(0.0)	0.00(0.0)	0.39	1.26
11	1.73(0.0)	1.93(0.0)	-3.67(-0.9)	-0.51(0.0)	0.00(0.0)	0.00	0.07
12	1.71(0.0)	1.96(0.0)	-4.18(-1.0)	-2.59(-0.6)	0.00(0.0)	0.00	0.00
13	1.75(0.0)	1.92(0.0)	-0.60(0.1)	0.01(0.0)	0.01(0.0)	0.34	0.25
14	1.79(0.0)	1.94(0.0)	-0.41(0.0)	0.00(0.0)	0.00(0.0)	0.13	0.03
15	1.62(0.0)	1.88(0.0)	-0.13(0.0)	0.00(0.0)	0.00(0.0)	0.03	0.00
16	1.67(0.0)	1.94(0.0)	0.00(0.0)	0.00(0.0)	0.00(0.0)	0.00	0.00
17	1.87(0.0)	1.94(0.0)	0.00(0.0)	0.00(0.0)	0.00(0.0)	0.00	0.00
18	1.98(0.0)	2.00(0.0)	-0.15(0.0)	0.00(0.0)	0.00(0.0)	1.02	0.68
19	1.94(0.0)	2.00(0.0)	-0.59(0.1)	0.02(0.0)	0.00(0.0)	0.85	0.75
MSU							
1	2.07(0.0)	2.03(0.0)	-0.34(0.1)	0.01(0.0)	0.00(0.0)	6.23	5.71
2	1.79(0.0)	1.94(0.0)	-0.08(0.0)	0.00(0.0)	0.00(0.0)	0.18	0.15
3	1.83(0.0)	1.96(0.0)	0.00(0.0)	0.00(0.0)	0.00(0.0)	0.00	0.00
4	1.96(0.0)	1.97(0.0)	0.00(0.0)	0.00(0.0)	0.00(0.0)	0.00	0.0
AMSU						Increment (-0.10)	
1	1.46(0.0)	1.41(0.0)	8.51(0.6)	0.56(0.0)	-	11.27	11.61
2	1.31(0.0)	1.38(0.0)	3.86(-0.1)	0.20(0.0)	-	12.95	11.44
3	1.36(0.0)	1.38(0.0)	3.59(-0.2)	0.16(0.0)	-	7.26	5.79
4	1.88(0.0)	1.87(0.0)	0.88(0.0)	0.04(0.0)	-	1.76	1.37
5	1.79(0.0)	1.93(0.0)	0.13(0.0)	0.01(0.0)	-	0.32	0.23
6	1.74(0.0)	1.93(0.0)	0.00(0.0)	0.00(0.0)	-	0.01	0.00
7	1.79(0.0)	1.96(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
8	1.93(0.0)	1.99(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
9	1.99(0.0)	1.98(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
10	1.93(0.0)	1.98(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
11	1.91(0.0)	1.96(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
12	1.91(0.0)	1.94(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
13	1.91(0.0)	1.93(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
14	1.96(0.0)	1.97(0.0)	0.00(0.0)	0.00(0.0)	-	0.00	0.00
15	1.01(0.0)	1.34(0.0)	14.67(0.6)	0.90(0.0)	-	9.09	10.90
16	1.01(0.0)	1.34(0.0)	14.67(0.6)	0.90(0.0)	-	9.09	10.90
17	1.18(0.0)	1.38(0.0)	23.90(7.5)	3.01(0.0)	-	3.53	10.63
18	1.92(0.0)	1.89(0.0)	-4.07(-1.2)	6.47(5.3)	-	0.00	0.21
19	2.02(0.0)	1.76(0.0)	-4.71(-1.3)	15.34(5.9)	-	0.00	1.73
20	2.08(0.0)	1.47(0.0)	-2.26(1.1)	13.04(1.6)	-	0.01	6.22

Table 2. Response of TOVS and AMSU brightness temperatures in degK to increments of profile variables. Values in brackets are departures from linearity.

5. Summary

The RTATOV fast RT model for (A)TOVS has been modified by changing the predictors for the water vapour layer optical depth. The set of predictors recommended by Rayer (1995) work best for the HIRS channels but an alternate set was found to give better results for the AMSU channels. There was a clear benefit to select the optimal predictors for HIRS and AMSU despite the problems of increased complexity of the model. The model has also been enhanced to include ozone as a variable gas in the same way as water vapour which allows a realistic prediction of HIRS channel 9 radiances and improved prediction of the other HIRS longwave sounding channels. The accuracy of the fast model for the temperature sounding channels of both HIRS and AMSU is well below the instrument noise. However for the water vapour and window channels of both instruments the accuracy is close to, or in some cases, exceeds the instrument noise. In the longer term it is recognised the OPTRAN approach where the layering is by equal absorber amounts should give more improvements in the performance of the model for the window, water vapour and ozone channels and so there is collaboration with NESDIS on comparing the OPTRAN performance with the RTATOV performance for the ATOVS channels.

The sensitivity of the radiances to changes in the profile vector have shown that all the AMSU water vapour and window channels are more sensitive to changes in the water vapour profile than HIRS channel 12 due to the non-unit surface emissivity. The response is also highly non-linear for AMSU water vapour channels with the sign of the gradient of radiance with respect to water vapour changing between the two extreme profiles for AMSU channels 18-20. Note that all the AMSU water vapour channels can see the surface at least for an arctic atmosphere in contrast to HIRS channel 12 which is not sensitive to the surface at least at sea-level. The HIRS longwave sounding channels have a sensitivity to changes in ozone amount but this only becomes significant for ozone amounts far from the global mean value (i.e. >20%).

The results presented in Table 2 indicate that for TOVS and AMSU the tangent linear approximation of the RT model, RTATOV, is valid for temperature increments to the first guess profile. Hence if (A)TOVS radiances are only used to influence the temperature profile the RT model and its gradient need only be computed once for each profile. However if the TOVS radiances are also used to adjust the humidity or ozone fields the significant non-linearities of the forward model means the gradient of the RT model must be computed several times during the minimization in a variational assimilation. The non-linearity for the AMSU water vapour and window channels is much larger than for HIRS and shows how the reflection from the surface increases the non-linearity. This will mean a fast model will be necessary to provide a good estimate of the surface emissivity before the AMSU water vapour and window channel radiances can be used effectively in a variational analysis.

6. Acknowledgements

The HARTCODE transmittances were provided by R. Rizzi (Univ. of Bologna). Discussions with L. Phalippou (ECMWF), P. Brunel (MeteoFrance), J. Derber (NCEP) and S. English (U.K. Met. Office) were also useful during the course of this work.

7. References

Andersson E., Pailleux J., Thepaut J-N, Eyre J.R., McNally A.P., Kelly G.A. and Courtier P. 1994 Use of cloud cleared radiances in three/four dimensional variational data assimilation. *Q.J.Roy. Meteorol. Soc.* **120** *pp 627-653.*

Derber J. and Wu W. 1997 The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system. Mon. Wea. Rev. *(in press).*

Eyre J.R. 1991 A fast radiative transfer model for satellite sounding systems. *ECMWF Research Dept. Tech. Memo.* **176** *March 1991 (available from the librarian at ECMWF).*

Eyre J.R., Kelly G.A., McNally A.P., Andersson E. and Persson A. 1993 Assimilation of TOVS radiance information through one-dimensional variational analysis. *Q.J.Roy. Meteorol. Soc.* **119** *pp 1427-1463.*

Houghton, J.T. 1986 The Physics of Atmospheres *Cambridge University Press pp 45-46*

Liebe H. J. 1989 MPM- an atmospheric millimetre wave propogation model. *Intnl. J. Infrared and Millimetre Waves* **10** *pp 631-650.*

McMillin L.M., Crone L.J. and Kleespies T.J. 1995 Atmospheric transmittance of an absorbing gas. 5. Improvements to the OPTRAN approach. *Appl. Optics* **34** *pp 8396-8399.*

Miskolczi F., Rizzi R., Guzzi R. and Bonzagni M.M. 1988 A new high resolution atmospheric transmittance code and its application in the field of remote sensing. *Proc IRS'88 Current problems in Atmospheric Radiation, Lille 18-24 August 1988 pp 388-391.*

Neuendorffer A.C. 1996 Ozone monitoring with TIROS-N operational vertical sounders. *J. Geophys Res.* **101** *D13 pp 18807-18828.*

Rayer P.J. 1995 Fast transmittance model for satellite sounding. *Appl. Optics,* **34** *pp 7387-7394.*

Saunders, R.W., Andersson, E., Kelly, G., McNally, A. and Harris, B. 1977. The direct assimilation of TOVS radiances at ECMWF. *Proc. of ITSC-IX, Igls, Feb 20-26, 1997.*

TECHNICAL PROCEEDINGS OF
THE NINTH INTERNATIONAL TOVS STUDY CONFERENCE

Igls, Austria

20-26 February 1997

Edited by

J R Eyre

Meteorological Office, Bracknell, U.K.

Published by

European Centre for Medium-range Weather Forecasts
Shinfield Park, Reading, RG2 9AX, U.K.

May 1997