On the use of Planck-weighted transmittances in RTTOV

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Several fast radiative transfer models including RTTOV assume that the Planck function does not depend on wave number when integrating over the width of a satellite filter function. This approximation is less valid for wide spectral bands, like the MSG SEVIRI 3.8 micron channel. In the operational weather centres, that error is partly corrected downstream in a bias-correction scheme.

This paper presents an alternative approach, where the model regression predicts convolved transmittances that are weighted by the Planck function.The method is applied to RTTOV. Results are presented comparing the performance of the model to reference line-by-line computations.

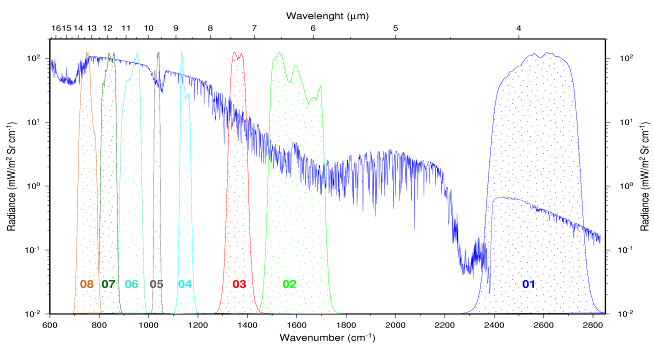
▪Line by Line

The kCarta code (v1.11, kCompressed database v24) is run over the ECMWF 60 levels reduced 52 profiles (diverse_52profiles_new) for 6 secant angles and 101 AIRS pressure levels. Space to level transmittances and Top Of the Atmosphere radiances are computed. kCarta output is reduced by averaging on 0.25cm-1 intervals. Different atmospheric gases combinations are considered in order to be able to compute RTTOV-7 predictors.

The Line-by-Line radiances are convolved by instrument filter functions. The conversion is done by an iterative process which tries to find the temperature which returns the right radiance when integrated over the IRF:

find T which meets R until increment in T is less than 0.001K

$$R = \frac{\int f(\nu)\, B(\nu,T)\, \tau(\nu)\, d\nu}{\int f(\nu)\, d\nu}$$



Top of the Atmosphere radiance for the mean profile of the dataset (profile 52), for surface conditions Ps=1100hPa, Ts=T(Ps) and Es=1.0 overlaid by SEVIRI channels response functions.

▪Fast model approximation

The transmittances are obtained by the convolution of the line-by-line transmittances by the instrument spectral response function. The transmittances resulting from the basic convolution are called Ordinary transmittances while the alternative approach taking into account the variation of the Planck function are called Planck Weighted transmittances

In clear non scattering atmosphere and black body surface, the polychromatic radiative transfer equation is

$$R = \int_{\Delta\nu} f(\nu) B_s[\nu, T(z_s)]\tau(\nu, z_s)\, d\nu + \int_{\Delta\nu} f(\nu) \int_{z_s}^{\infty} B[\nu, T(z)]\, d\tau(\nu, z)\, d\nu$$

The Fast model approximation replaces the transmittance and the Planck functions with their spectrally integrated means convoluted with the instrument response function:

$$R = \overline{B_s\tau_s} + \int \overline{B\, d\tau} \approx \bar{B}_s \bar{\tau}_s + \int \bar{B}\, d\bar{\tau}$$

where

$$\bar{\tau} = \int f(\nu)\, \tau(\nu)\, d\nu \qquad \bar{B} = \int f(\nu)\, B(\nu, T)\, d\nu$$

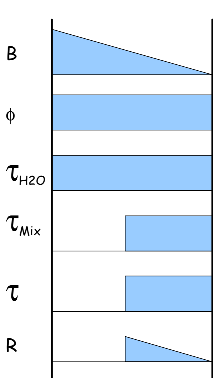
▪Planck weighted transmittances

A possible improvement is to reformulate the transmittance to appear more like BT, hence the use of Planck weighted transmittances

$$\tau_j^{PW} = \frac{\int f(\nu)\, B(\nu, T_j)\, \tau_j(\nu)\, d\nu}{\int f(\nu)\, B(\nu, T_j)\, d\nu}$$

▪Ordinary and PW transmittances for a basic case

Consider a single atmospheric layer in which the Planck function is linear with the wave numbers and a spectral instrument response function of 1 over the bandwidth. The distribution of the absorption by water vapour and mixed gases is different in the two cases. The left case reproduce somehow the SEVIRI 3.8mu channel. The line by line total radiance is compared to the fast model approximation with ordinary and Planck weighted transmittances.



$$\bar{B} = \int f(\nu)\, B(\nu, T)\, d\nu = 1/2$$

$$\bar{\tau} = \int f(\nu)\tau(\nu)\, d\nu = 1/2$$

$$\tau^{PW} = \frac{\int f(\nu) B(\nu, T)\tau(\nu)\, d\nu}{\int f(\nu) B(\nu, T)\, d\nu} = \frac{1/8}{1/2} = 1/4$$

$$\overline{\tau_{Mix}} = \int f(\nu)\, \tau_{Mix}(\nu)\, d\nu = 1/2 \qquad \overline{\tau_{H2O}} = \frac{\bar{\tau}}{\overline{\tau_{Mix}}} = 1$$

$$\tau_{Mix}^{PW} = \frac{\int f(\nu)\, B(\nu, T)\, \tau_{Mix}(\nu)\, d\nu}{\int f(\nu)\, B(\nu, T)\, d\nu} = \frac{1/8}{1/2} = 1/4 \qquad \tau_{H2O}^{PW} = \frac{\tau^{PW}}{\tau_{Mix}^{PW}} = 1$$

Line-by-Line $R = \overline{B\tau} = \int f(\nu)\, B(\nu, T)\tau(\nu)\, d\nu = 1/8$

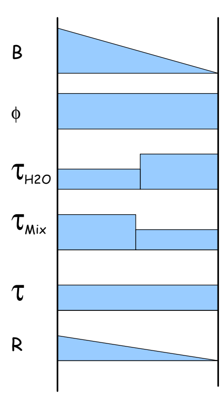
With ordinary transmittances

$$\bar{B}\bar{\tau} = \bar{B}\, \overline{\tau_{Mix}}\, \overline{\tau_{H2O}} = \frac{1}{2}\frac{1}{2}1 = 1/4$$

With Planck weighted transmittances

$$\bar{B}\, \tau^{PW} = \bar{B}\, \tau_{Mix}^{PW}\, \tau_{H2O}^{PW} = \frac{1}{2}\frac{1}{4}1 = 1/8$$

Line-by-line total radiance is 1/8. The fast model approximation with the Planck weighted transmittances is able to reproduce the right result but the Ordinary transmittances fail. This is the typical case where PW can improve the fast model.



$$\bar{B} = \int f(\nu)\, B(\nu, T)\, d\nu = 1/2$$

$$\bar{\tau} = \int f(\nu)\tau(\nu)\, d\nu = 1/2$$

$$\tau^{PW} = \frac{\int f(\nu)\, B(\nu, T)\tau(\nu)\, d\nu}{\int f(\nu)\, B(\nu, T)\, d\nu} = \frac{1/4}{1/2} = 1/2$$

$$\overline{\tau_{Mix}} = \int f(\nu)\, \tau_{Mix}(\nu)\, d\nu = 3/4 \qquad \overline{\tau_{H2O}} = \frac{\bar{\tau}}{\overline{\tau_{Mix}}} = 2/3$$

$$\tau_{Mix}^{PW} = \frac{\int f(\nu)\, B(\nu, T)\, \tau_{Mix}(\nu)\, d\nu}{\int f(\nu)\, B(\nu, T)\, d\nu} = \frac{5/16}{1/2} = 5/8$$

$$\tau_{H2O}^{PW} = \frac{\tau^{PW}}{\tau_{Mix}^{PW}} = 4/5$$

Line-by-Line $R = \overline{B\tau} = \int f(\nu)\, B(\nu, T)\tau(\nu)\, d\nu = 1/4$

With ordinary transmittances

$$\bar{B}\bar{\tau} = \bar{B}\, \overline{\tau_{Mix}}\, \overline{\tau_{H2O}} = \frac{1}{2}\frac{3}{4}\frac{2}{3} = 1/4$$

With Planck weighted transmittances

$$\bar{B}\, \tau^{PW} = \bar{B}\, \tau_{Mix}^{PW}\, \tau_{H2O}^{PW} = \frac{1}{2}\frac{5}{8}\frac{4}{5} = 1/4$$

Line-by-line total radiance is ¼. Both transmittances are giving the right result.

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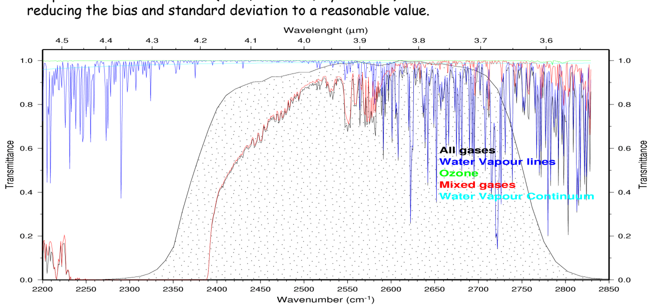
▪Validation

Two sets of RTTOV-7 coefficients are produced, one with the ordinary transmittances (referred as ORD) and the other with PW transmittances. There is no difference in the fast model code, only the nature of the data inside the input coefficient files is different. For the PW we have 2 possibilities concerning the radiance-temperature conversion, according to the selection of band correction (referred as PWBC) or not (referred as PW), keeping the same central wave number.

The validation of PW transmittances is performed by comparing the line-by-line kCarta results with RTTOV-7. The fast model is run over the same set of profiles and for the same viewing and surface conditions. The profile dataset is the same as the one used for the creation of the fast model transmittances, it is a "dependent" test.

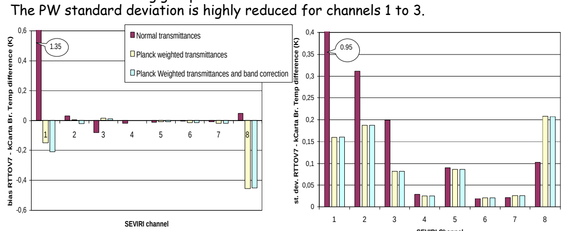
▪MSG-1 SEVIRI

3.8µ m of MSG-1 SEVIRI instrument is a very wide channel partly covering the CO2 absorption band and the 3.7µ m window, the Planck function varies a lot inside this wavenumber range. The RTTOV simulation of this channel shows large bias when compared with other models (RFM, Modtran, Synsatrad..). The PW transmittances are reducing the bias and standard deviation to a reasonable value.

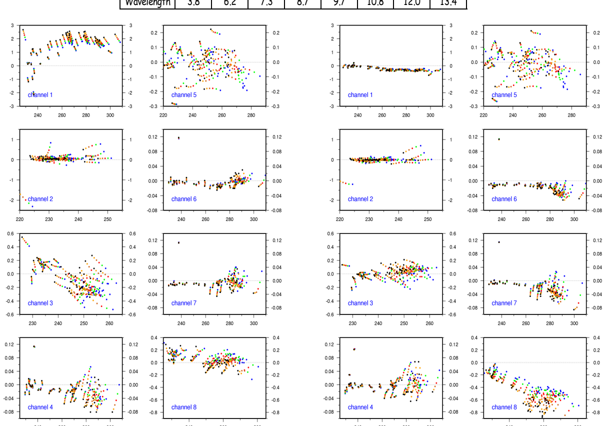


Total transmittance for the mean profile of the dataset (profile 52) for different gases combinations, and the MSG-1 SEVIRI 3.8mu response function.

Below are presented the results for MSG-1 SEVIRI channels of RTTOV-7 minus kCarta in brightness temperature. The bias in channel 3.8mu (1.35K channel number 1) which was observed for RTTOV-7 43 levels is confirmed by ORD with a standard deviation close to 1K. Channels 2 and 3 present also large standard deviation values for the comparison on dependant profile data set.
The PW transmittances reduce the bias for the 3 channels to an acceptable value. The channel 8 (13.4mu) is degraded by 0.4K, same order was observed by Turner (October 2002 ORD=-0.27 PW=-0.78 at nadir, =0.5K difference), this indicates spectral overlap between the absorbing groups .
The PW standard deviation is highly reduced for channels 1 to 3.



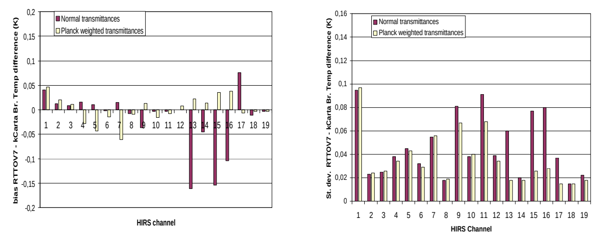
Channel	1	2	3	4	5	6	7	8
Wavelength	3.8	6.2	7.3	8.7	9.7	10.8	12.0	13.4



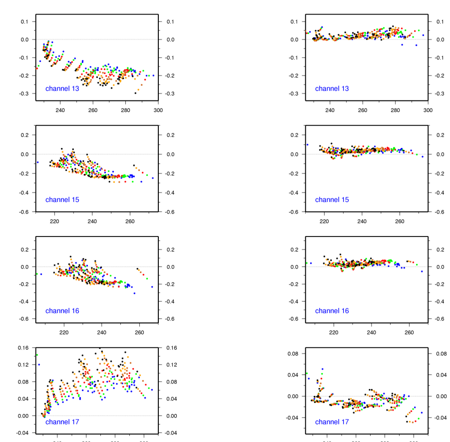
Brightness temperature difference for RTTOV – kCarta for all profiles and all secant angles (colours) as a function of the BTs. Left plot is for Ordinary transmittances while right plot is for Planck Weighted transmittances. Few profiles (1, 3, 11, 50 and 51) may introduce large biases in both cases. Those profiles are representing extreme cases, (1)tropical with the highest surface temp, (3) polar winter very dry, (11) polar summer with the warmest stratopause (307K) and synthetic (50) very dry and (51) moist profiles.

▪NOAA-17 HIRS

Same test as for SEVIRI is performed for NOAA-17 HIRS. The ordinary transmittances give a good agreement with kCarta for most channels, bias is less than 0.05K, standard deviation is less than 0.10K except for channels 13, 15 and 16 (4.57, 4.47, 4.45 µ m) where bias is larger than 0.10K. For all channels PW transmittances do a good job resulting in bias always less than 0.06K and standard deviation less than 0.07K (except channel1). Especially the bias values for channels 13, 15 and 16 are now below 0.04K with standard deviation less than 0.03K.



RTTOV – kCarta for ordinary and Planck weighted transmittances over the 52 profiles for all NOAA-17 HIRS channels. Bias (left) and standard deviation (right)



Brightness temperature difference for RTTOV – kCarta for all profiles and all secant angles as a function of the BTs. Only the most improved channels are shown (13, 15, 16 and 17). Results obtained from ordinary transmittances are plotted on left and Planck weighted on right.

▪Independent test

Chris Merchant (University of Edinburgh) and Pierre Le Borgne (MétéoFrance) compare brightness temperatures simulated for SEVIRI on MSG for channels 3.8 8.7 , 11 and 12 µm (id 1, 4 6 and 7). The radiative transfer models are RTTOV7 MODTRAN (v3.5 and v4.0) RAD7 and RFM (v4.20). The profile dataset is made of 58 ocean profiles extracted from the ECMWF 60 levels reduced profiles (60L_SDr) and converted to RTTOV 43 pressure levels. RTTOV7 is run with/without coefficients derived from Planck weighted transmittances. Results below confirm the current experiment, for nadir case:

Model	3.8		8.7		11		12	
	bias	st.dev.	bias	st.dev.	bias	st.dev.	bias	st.dev.
RTTOV7	1.76	0.13	-0.11	0.09	-0.04	0.02	0.00	0.04
RTTOV7 PW	-0.09	0.05	-0.08	0.08	-0.05	0.03	-0.02	0.04
MODTRAN 3.5	0.25	0.04	-0.05	0.11	-0.02	0.10	0.02	0.14
MODTRAN 4	0.14	0.04	-0.22	0.12	-0.03	0.10	-0.06	0.15
RAD7	0.02	0.04	-0.36	0.11	0.00	0.10	0.07	0.14

Models – RFM difference for nadir case for some MSG-1 SEVIRI channels