Evaluation of FASTEM and FASTEM2

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1. Introduction

Over the oceans, the apparent surface temperature for microwaves is modeled with a geometric optics (GO) model (e.g. Phalippou 1996). The surface emissivity is a weighted average of the emissivity over an ensemble of facets that represent the roughened sea-surface. Similarly, the reflected sky brightness temperature is computed by summing the down-welling brightness temperature times the reflectivity over the distribution of facets. GO models are fairly complex and as a result, the models are slow in the context of operational weather forecasting.

A variational assimilation model for DMSP SSM/I brightness temperatures called SSMI1DVAR and initially developed at ECMWF by L. Phalippou (Phalippou 1996) includes a radiative transfer model (RTM) that simulates microwave brightness temperatures at the top of the atmosphere. The optical depth is computed with a fast model that uses multiple linear regression equations (RTTOV). The surface emissivity model however uses the full GO model. SSMI1DVAR is used operationally at the UKMO and ECMWF. At MSC (Meteorological Service of Canada), SSMI1DVAR has been used in research mode only. SSMI1DVAR also includes the Jacobians necessary to implement the variational assimilation of SSM/I brightness temperatures.

In order to speed up the surface emissivity model, English and Hewison (1999) developed a fast model named FASTEM which parameterizes an “effective” surface emissivity that replaces the specular surface emissivity in RTTOV. However, from an intercomparison study performed at MSC by the author, it was noticed that the errors of FASTEM were fairly large in some situations and in particular for SSM/I applications. Recently, S. English developed an improved version of FASTEM (called FASTEM2) that uses an approach similar to that of Petty and Katsaros (1994). FASTEM2 computes the surface emissivity averaged over all facets representing the surface of the ocean and an effective path correction factor for the down-welling brightness temperature. The latter is different for each polarization and therefore the implementation of FASTEM2 in RTTOV would be quite complex. In this report, a simplified FASTEM2 is proposed which gives results with acceptable accuracy and which should be easily implementable in RTTOV.

As its predecessor, FASTEM2 is applicable for frequencies between 10 and 220 GHz, for earth incidence angles less than 60^o and for oceanic surface wind speeds less than 20 ms^{-1}. Thus, these models can also be used for other microwave instruments such as NOAA AMSU-A and AMSU-B.

At MSC, a general microwave line by line radiative transfer model was developed (called MICLBL). FASTEM and FASTEM2 have been implemented into this model. Furthermore, three geometric optics (GO) models were also implemented in MICLBL. As a result, in the intercomparison study presented here, all models used exactly the same transmittances. The specification of the oxygen absorption lines follows that of Liebe et al. (1992) and that of the water vapor lines and continuum follows Liebe (1989). The AMSU channel 14 does not include the Zeeman effect.

A description of the radiative transfer models embedded in MICLBL is given in Section 2. The notation is largely based on Petty and Katsaros (1994). The atmospheric profiles used to do the evaluation were taken from the Garand 42 intercomparison data set (Garand et al. 2000) and are described in Section 3. Results of the evaluation study for all the SSM/I channels and a selected subset of AMSU channels are presented in Section 4. This is followed by conclusions in Section 5.

2. Description of the radiative transfer models.

For microwave frequencies and when the plane parallel approximation holds, the polarized brightness temperature TB at the top of the atmosphere as a function of the local incidence angle θ is defined as:

$$TB_p(\theta) = TB^{\uparrow}(\theta) + \tau_s\,[E_p(\theta)T_s + TB_p^s(\theta)] \qquad (1)$$

where $TB^{\uparrow}(\theta)$ is the up-welling atmospheric brightness temperature (Section 6.1), τ_s is the atmospheric transmittance, E_p is the polarized surface emissivity, T_s is the skin temperature and $TB_p^s(\theta)$ is the reflected sky brightness temperature. p is the polarization which is either vertical (V) or horizontal (H). In the case of specular reflection (e.g. we assume that the ocean is an infinite flat surface), the reflected sky brightness temperature becomes:

$$TB_p^s(\theta) = (1 - E_p)TB^{\downarrow}(\theta) \qquad (2)$$

where $TB^{\downarrow}(\theta)$ is the down-welling atmospheric brightness temperature (Section 6.1) and E_p is computed using the Fresnel equations. The polarized apparent surface temperature (TB_{ap}) is defined as the term inside the brackets in Eq. 1. In the case where the atmosphere is assumed to be isothermal with temperature T_s Eq. 1 becomes:

$$TB_p(\theta) = (1-\tau_s)T_s + \tau_s[E_pT_s + (1-E_p)\{(1-\tau_s)T_s + T_C\tau_s\}] \tag{3}$$

where T_C is the cosmic background temperature.

2.1. GEOMETRIC OPTICS MODELS

In the GO models, an effective emissivity is computed which is a weighted average of the emissivity over an ensemble of facets that represent the roughened sea surface. The slopes of the facets are sampled from a gaussian distribution (Cox and Munk 1954). This effective emissivity will be referred to as E_p^{GO}. Similarly, the reflected sky brightness temperature $TB_p^{s\,GO}$ is computed by summing the down-welling brightness temperature times the reflectivity over the distribution of facets.

The apparent surface temperature of the GO model is defined as:

$$TB_{a\,p}^{GO} = E_p^{GO}T_s + TB_p^{s\,GO}\,. \tag{4}$$

The GO effective emissivity is defined as:

$$E_p^{GO} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e_p\rho_s w dS_x dS_y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho_s w dS_x dS_y} \tag{5a}$$

with $$\rho_s = \frac{1}{\pi VAR_f} \exp(-\frac{S_x^2 + S_y^2}{VAR_f}) \tag{5b}$$

where e_p is the emissivity of the surface for each facet computed from the Fresnel equations. $\rho_s(S_x, S_y)$ is the probability density function (Cox and Munk 1954) of the slopes S_x and S_y and $w(S_x,S_y)$ is a weighting function that is related to the viewing geometry. VAR_f is the slope variance that is adjusted for a frequency dependence. $VAR_f=VAR*F(\nu)$ and ν is the frequency. The slope variance VAR is a linear function of surface wind speed and $F=0.02\nu(GHz)+0.3$ if $\nu < 35$ GHz and F=1 for larger frequencies (Wilheit 1979). Thus the slope variance is reduced for the lower frequencies. Eq. 5a may be rewritten in discretized form as:

$$E_p^{GO} = \sum_i \sum_j (1 - R_{pij})\omega_{ij} \tag{6}$$

Following the notation in Petty and Katsaros (1994), $TB_p^{s\,GO}$ (see Eq. 4) is defined as follows:

$$TB_p^{s\,GO} = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} TB(k_{s,z})(1 - e_p)\rho_s w dS_x dS_y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho_s w dS_x dS_y} + (1 - E_p^{GO})T_C \tau_s \tag{7}$$

where $k_{s,z}$ is the z component of the unit vector giving the direction of the reflected brightness temperature. The down-welling brightness temperature has to be computed at the scattering angle of each facet sampled in the Gaussian distribution. Eq. 7 may be rewritten in discretized form as follows:

$$TB_p^{s\,GO} = \sum_i \sum_j R_{pij}\omega_{ij} TB^{\downarrow}(\theta_{ij}) \;. \tag{8}$$

Finally, Eq. 4 can be rewritten in discretized form as:

$$TB_{ap}^{GO} = \sum_i \sum_j (1 - R_{pij})\omega_{ij} T_s + \sum_i \sum_j R_{pij} \omega_{ij} TB^{\downarrow}(\theta_{ij}) \tag{9}$$

Three GO models were used in this intercomparison study and are referred to as 1DVAR0, 1DVAR2 and RTM. 1DVAR0 is the same radiative transfer model as that obtained from ECMWF (Phalippou 1996) referred to as SSMI1DVAR in the introduction. However, SSMI1DVAR was re-coded at MSC to fit into MICLBL and given the name 1DVAR0. Also, the transmittances in 1DVAR0 are computed explicitely and thus do not use regression equations. RTM is based on code obtained from the UKMO in 1998 and was implemented in MICLBL with several modifications. RTM as obtained assumed the pseudo-specular approximation. For this case, the reflected sky brightness temperature is given by:

$$TB_p^{s\,GO} = (1 - E_p^{GO}) TB^{\downarrow}(\theta) \,.$$

RTM was modified to include the down-welling brightness temperature contribution reflected from each facet.

The difference between 1DVAR2 and 1DVAR0 is that (1) 1DVAR2 does not use the isothermal atmosphere approximation (See Section 2.1.1 below) and (2) the handling of multiple reflections can be done as in 1DVAR0 or RTM (See Section 2.1.2 below). In summary, MICLBL can be run with either of the 1DVAR0, 1DVAR2 and RTM setups.

2.1.1. Isothermal atmosphere approximation

1DVAR0 uses an approximation to speed up the computation of the down-welling TB. It is assumed that the atmosphere radiates at a mean temperature T_A:

$$TB^{\downarrow}(\theta) = T_A(1-\tau_s(\theta)) + T_C\tau_s(\theta)\,. \qquad (10)$$

A table of down-welling brightness temperatures is computed for regularly spaced intervals of view angle θ_r between 0 and $\frac{\pi}{2}$. $TB^{\downarrow}(\theta_r)$ is computed from $TB^{\downarrow}(\theta)$ using the equation that follows which was derived with Eq. 10.

$$TB^{\downarrow}(\theta_r) = TB^{\downarrow}(\theta)\left[\frac{1-(\tau_s(\theta))^{\frac{\sec\theta_r}{\sec\theta}}}{1-\tau_s(\theta)}\right] \qquad (11)$$

$TB^{\downarrow}(\theta_z)$ is then obtained by interpolating between $TB^{\downarrow}(\theta_r)$ values where θ_z is the scattering angle. RTM does not use this approximation and computes the down-welling TB contribution explicitly for each facet.

2.1.2. Handling of multiple reflections

When multiple reflections occur in 1DVAR0, the reflectivity of the facets is not modified and it is assumed that the down-welling TB is equal to the surface temperature. For the facets whose z-component of the scattered vector points downward with respect to the surface, multiple reflections will occur and the scattered brightness temperature of each facet is set to:

$$TB_{pij}^{s\,GO} = \sum_i\sum_j R_{pij}\omega_{ij}T_s\,. \qquad (12)$$

Using Eq. 9 it follows that the apparent brightness temperature of those facets is:

$$TB_{apij}^{GO} = \omega_{ij} T_s \qquad (13)$$

The apparent surface temperature of the facet no longer depends on the emissivity of the facet and the apparent surface temperature is not polarized for those facets.

When multiple reflections occur in RTM, it is assumed that the reflectivity of those facets takes on the square value of the reflectivity. Thus, for each facet, one has a modified emissivity such that:

$$e_{ij} = (1 - R_{ij}^2) \qquad (14)$$

where R_{ij} is the reflectivity of the facet. The scattered brightness temperature for each facet is:

$$TB_{pij}^{s\,GO} = R_{pij}^2 TB^{\downarrow}(\theta = 0)\omega_{ij}\,. \qquad (15)$$

and the apparent surface temperature becomes:

$$TB_{apij}^{GO} = (1 - R_{pij}^2)\omega_{ij} T_s + R_{pij}^2 \omega_{ij} TB^{\downarrow}(\theta = 0)\,. \qquad (16)$$

Thus, both the emissivity and the scattered TB terms are modified. To compute the down-welling TB, we have assumed a path such that $\sec\theta$ =1.0. The choice of such a path leads to a minimum value for $TB_{pij}^{s\,GO}$. If we make the further assumption that the atmosphere is isothermal with temperature T_s, then TB_{apij}^{GO} will be equal to:

$$TB_{apij}^{GO} = \omega_{ij} T_s [1 - R_{pij}^2 \tau_s(\theta = 0)]\,. \qquad (17)$$

Comparing Eqs. 17 and 13 shows that TB_{apij}^{GO} for the first approach (1DVAR0) will always be larger than that of the latter one (RTM). The number of facets for which multiple reflections occur increases with scan angle.

2.1.3. Further differences between GO models

Further differences between 1DVAR0 and RTM are listed in Table 1a. With the appropriate choice of parameters as listed in Table 1a, The selection of parameter settings for RTM was the same as that for FASTEM and FASTEM2. $TB_{ap}{}^{GO}$ was computed as follows:

$$TB_{ap}^{GO} = \{E_p^{GO}(1-FC) + E_{foam}FC\}T_s + (1-FC)TB_p^{s\,GO} \qquad (18)$$

where FC is the foam cover (which is a linear function of surface wind speed (SWS), see Table 1) and to include Bragg scattering, the reflectivity of each facet was multiplied by a correction factor defined as follows (English and Hewison 1998):

$$B(SWS,\nu,\theta) = e^{-\frac{(SWS)(\cos\theta)^2}{\nu^2}} \;. \qquad (19)$$

Thus the Bragg scattering correction factor increases with wind speed. It affects mostly the longest waves and thus the lowest frequencies. This correction term is introduced in the GO model by multiplying the term R_{pij} in Eq. 9.

The emissivity of foam is set to 1 as the foam is assumed to be a blackbody.

The model 1DVAR2 can use any of the parameter choices listed in Table 1a and therefore, these parameters have to be specified each time the model is discussed. The specification of parameters for 1DVAR2 will be defined by an experiment number and are listed in Table1b.

Table 1a: Parameter settings for 1DVAR0 and RTM. SWS is the surface wind speed. Basic differences between the models are described in Sections 2.1.1-2.1.2.

PARAMETER	***1DVAR0***	***RTM***
Foam Cover (FC)	FC=2.95E-6 (SWS)$^{3.52}$	FC=1.95E-5 (SWS)$^{2.55}$
Dielectric Constant	Klein and Swift (1977) (depends on salinity)	Lamkaouchi et al. (1997) (does not depend on salinity)
Multiple Reflections	$TB^{\downarrow} = T_s$	E=(1-R^2), $TB^{\downarrow}(\theta = 0)$
Bragg Scattering	Not included	included, see Eq. 19.
Salinity	36 $^{o}/_{oo}$	N/A

Table 1b: Parameter specification for 1DVAR2 experiments. 1DVAR0 and RTM parameters are specified in Table 1a.

Experiment	***FOAM***	***Dielectric Constant***	***Bragg Scattering***	***Multiple Reflections***
#1	RTM	RTM	RTM	RTM
#2	1DVAR0	1DVAR0	1DVAR0	1DVAR0
#3	RTM	RTM	RTM	***1DVAR0***
#4	***1DVAR0***	RTM	RTM	RTM
#5	RTM	***1DVAR0***	RTM	RTM
#6	RTM	RTM	***1DVAR0***	RTM

2.2. FASTEM

FASTEM parameterizes the surface emissivity so that the specular reflection formulation can be used (Eq. 2) and E_p is replaced with E_p^f. E_p^f is defined as follows:

$$E_p^f = \{(1 - R_p B) + E_p^*\}(1 - FC) + FC \tag{20}$$

where B is the correction factor to include Bragg scattering, FC is the foam cover which is parameterized by an empirical formula that depends on SWS (Table 1a). R_p is the specular reflection which is computed using the Fresnel equations. In the FASTEM code, all terms in Eq. 20 are computed explicitly except for E_p^* which is obtained using a regression equation that depends on the view angle θ and the surface wind speed SWS.

E_p^* was obtained as follows. First, compute TB_{ap}^{GO} (using the full GO model, i.e. Eq. 4) with parameters selected from Table 1a under the RTM heading. Then, solve for E_f^p which must satisfy the following equation (see Eqs. 1 and 2):

$$E_p^f T_s + (1 - E_p^f) TB^{\downarrow}(\theta) \equiv TB_{ap}^{GO} \tag{21}$$

It follows that

$$E_p^f = \frac{(Tb_{ap}^{GO} - TB^{\downarrow}(\theta))}{T_s - TB^{\downarrow}(\theta)} \tag{22}$$

Finally, using Eq. 20, one has:

$$E_p^* = \frac{\{E_p^f - (1-R_pB)(1-FC) - FC\}}{\{1-FC\}} \tag{23}$$

and $E_p^* \cong C_1 + C_2\sec\theta + C_3(\sec\theta)^2 + C_4SWS + C_5(SWS)^2 + C_6(\sec\theta)SWS$, (24a)

with $C_i = C_{i0} + C_{i1}\nu + C_{i2}\nu^2$ (24b)

where SWS is the surface wind speed in ms^{-1} and ν is the frequency in GHz. E_p^* represents an increase in emissivity due to the surface roughness.

2.3. FASTEM2

With FASTEM2, the formulation of the apparent surface temperature is closer to that of the GO model by including an effective down-welling brightness temperature. Moreover, the effective surface emissivity is now an approximation to $E_p^{GO}(1-FC)+FC$ and is referred to as $\tilde{E}^{GO}$. Thus, the effective surface emissivity is defined as follows:

$$\tilde{E}{}_p^{GO} = \{(1-R_p)B + E_p^*\}(1-FC) + FC \ . \tag{25}$$

Since the LHS of the equation is now $\tilde{E}{}_p^{GO}$ and not E_p^f as was the case for FASTEM, it is important to note that E_p^* is different in the FASTEM and FASTEM2 models. E_p^* in FASTEM2 uses the same set of predictors as in FASTEM but the regression coefficients are different.

With FASTEM2, TB_{ap}^{GO} (see Eq. 18) is written as:

$$TB_{ap}^{GO} = \tilde{E}_p^{GO}(\theta)T_s + (1-\tilde{E}_p^{GO})TB^{\downarrow}(\theta_p^*) . \qquad (26)$$

Note that: $1-\tilde{E}_p^{GO} = (1-FC)(1-E_p^{GO})$

$TB^{\downarrow}(\theta_p^*)$ is the effective down-welling brightness temperature that is computed as follows:

$$TB^{\downarrow}(\theta_p^*) = (1-FC)\,TB_p^{s\,GO}(\theta) \,/\, (1-\tilde{E}_p^{GO}) .$$

θ_p^* is then obtained from $TB^{\downarrow}(\theta_p^*)$ by assuming that the atmosphere can be represented by a mean radiating temperature T_A (See Eq. 10). The down-welling TB is computed for θ_p^* and not θ as was the case for FASTEM (Eq. 21). It follows that:

$$\sec\theta_p^* = -\frac{1}{O}\ln\left[\frac{TB^{\downarrow}(\theta_p^*) - T_A}{T_C - T_A}\right] \qquad (27)$$

where O is the optical depth of the atmosphere. Furthermore, a ratio P_{rough} is introduced which is a double summation as follows:

$$P_{rough} = \frac{\sec\theta_p^*}{\sec\theta} = 1 + \sum_{n=0}^{2}\sum_{m=0}^{2}\{\sum_{i=0}^{2} A_{nmi}(\ln O)^i\}(VAR_f)^n(\sec\theta)^m \qquad (28)$$

and the terms for which m+n=3 are ignored.

Note that a mean radiative temperature cannot be computed for sounding frequencies. This is addressed in section 4.2.2.

Thus, FASTEM2 provides $\tilde{E}_v^{GO}$, $\tilde{E}_h^{GO}$, P_{rough} (H) and P_{rough}(V). A drawback with this method is that $TB^{\downarrow}(\theta_p^*)$ has to be computed for each polarization (V and H) and the implementation of FASTEM2 as is, would require major changes to RTTOV-6. However, in section

6.3 we suggest an approximation that will allow a straightforward implementation of FASTEM2 in RTTOV-6.

Although FASTEM computes an effective surface emissivity and FASTEM2 computes an effective surface emissivity and an effective path P_{rough}, in this report, FASTEM and FASTEM2 will refer to the radiative transfer models available in MICLBL that use FASTEM and FASTEM2 respectively.

2.4. Summary of models available for the evaluation

Table 2: Summary of radiative transfer models available for the evaluation. All these models are embedded in MICLBL. MICLBL is a general microwave radiative transfer model developed by the author. Transmittances for all models are computed explicitly and in exactly the same way.

MODEL NAME	***DESCRIPTION***
1DVAR0	Same model as SSMI1DVAR (Phalippou 1996) but implemented in MICLBL. Also referred to as RTSSMI by the RTTOV developers. This is a GO model.
1DVAR2	Same model as 1DVAR0 but the down-welling TB is computed explicitly for all facets (i.e. the approximation as described in Section 2.1.1 is NOT used). Handling of multiple reflections is as in 1DVAR0 or RTM.
RTM	RTM of UKMO 1998 implemented in MICLBL with several changes. Down-welling TB is computed explicitly for all facets. This is a GO model.
FASTEM	FASTEM implemented in MICLBL. This is a fast model.
FASTEM2	FASTEM2 implemented in MICLBL. This is a fast model.

3. Description of profile data set used in the evaluation

The atmospheric profiles that were used in the evaluation were chosen among the 42 profile Garand intercomparison data set. The total precipitable water (TPW) and skin temperatures are listed in Table 3. Since the surface emissivity model is valid only over the open oceans, profiles with T_s < 275 K were discarded. The remaining number of profiles is 26. This profile data set will be referred to as the GARAND26 data set.

Table 3: Profiles used in intercomparison study (GARAND26 data set)

Profile # (out of 42)	***TPW (kgm^{-2})***	***Skin Temperature(K)***
1	41.31990	299.7100
2	29.37118	294.2100
4	21.21749	287.3500
6	14.20164	288.2000
11	7.024087	275.7800
12	9.816942	277.6500
13	10.00407	280.0200
14	15.33834	284.2600
15	26.22452	284.7200
16	16.69838	285.8600
17	51.76398	302.5400
18	33.43222	315.9100
20	10.24115	290.9400
21	13.05055	285.1100
22	19.77946	314.8100
23	22.61764	299.5000
24	33.95658	281.6900
25	37.63577	292.3900
26	45.53015	296.8800
27	53.23136	301.4400
28	60.67532	301.8400
29	62.33654	298.4200
30	69.38979	301.6300
32	26.98223	299.3500
33	37.83942	296.2800
34	12.09363	283.5900

4. Results of evaluation study

4.1. SSM/I

4.1.1. Basic differences between 1DVAR0 and RTM

The basic differences between the models are listed in Section 2.1. The two top bar plots in Fig. 1 illustrate the impact of using the isothermal atmosphere approximation (Section 2.1.1). This leads to a bias of < 0.4K and a SD of less than 0.15 K. The small values of these statistics confirm that the approximation is a reasonable one.

The method used to handle multiple reflections (Section 2.1.2) leads to a large bias (up to 3.7 K) for the horizontally polarized channels and for large wind speeds (14 and 20 ms^{-1}) (Fig. 1, bottom two bar plots). The channel with the largest impact on the bias is the 37 GHz H channel. The largest SD is 0.64 K for the 85 GHz H channel. The fact that the biases are negative is to be expected since the method used to handle multiple reflections in 1DVAR2 (#1) will lead to smaller apparent brightness temperatures (Eq. 17) than those of 1DVAR2 (#3) (Eq. 13). 1DVAR2 experiment numbers are defined in Table 1b. The differences are larger for the horizontal polarization because R_v is considerably smaller than R_h.

In conclusion, the way that multiple reflections are taken into account becomes important for high wind speeds and horizontally polarized channels. In that respect, it is important to remind ourselves that 1DVAR0 and RTM have different ways of implementing multiple reflections. The impact of the isothermal approximation is small.

4.1.2. FASTEM, FASTEM2 compared with RTM

Bar plots (as a function of surface wind speed) of biases and standard deviations between models of the apparent surface temperature are illustrated in Figs 2a-d for each of the SSM/I frequencies. There are three sets of intercomparisons and hence three sets of bars per wind speed in the plots. The three sets are intercomparing (1) FASTEM with RTM, (2) FASTEM2 with RTM and (3) FASTEM2 simplified (Section 6.3) with RTM.

4.1.2.1. Comparison of performance of FASTEM and FASTEM2

Figure 2a:

19 GHz V: biases for the lower wind speeds (0 and 3 ms^{-1}) are smaller for FASTEM2. For the larger wind speeds, the biases of FASTEM2 are larger (up to 1.75 K at 20 ms^{-1}). The SD plot shows that FASTEM2 has a SD that is smaller than that of FASTEM for all wind speeds.

19 GHz H: biases at 0 ms^{-1} are larger for FASTEM2 whereas the FASTEM2 bias ratio of improvement with respect to FASTEM increases with wind speed and the FASTEM2 biases remain below 2.1 K. The FASTEM2 SD are drastically reduced for wind speeds of 7 ms^{-1} and up. All SD are now below 0.6 K. With FASTEM, the SD reaches a value as high as 2.35 K at 20 ms^{-1} with a bias of 9.25 K.

In conclusion, at 19 GHz, FASTEM2 is a much improved fast model for the horizontal polarization except for a wind speed of 0 ms^{-1}.

Figure 2b:

22 GHz V: For the wind speeds different from 0, biases for FASTEM2 are larger than those of FASTEM whereas the SD of FASTEM2 is larger for all wind speeds except at 20 ms^{-1}.

In conclusion, at 22 GHz V, FASTEM2 does not perform better than FASTEM.

Figure 2 c:

37 GHz V: The bias and SD for FASTEM2 are smaller for all cases. The bias for FASTEM2 is < 0.23 K and the SD < 0.5 K.

37 GHz H: The bias and SD behavior of this channel is similar to that of the 19 GHz channel. The bias for FASTEM2 is < 2.0 K and SD < 0.75 K.

In conclusion, at 37 GHz, FASTEM2 is a much improved fast model for the horizontal polarization except at wind speeds of 0 ms^{-1}. The 37 GHz V apparent surface temperature model is better for FASTEM2.

Figure 2d:

85 GHz V: For low wind speeds (0, 3, 7 ms^{-1}), the biases are of similar magnitude for FASTEM and FASTEM2. For higher wind speeds, the FASTEM2 bias is much lower. The SD for FASTEM2 is reduced only for speeds ≥ 7 ms^{-1}.

85 GHz H: The biases for FASTEM2 are larger for low wind speeds (0 and 3 ms^{-1}) and lower for higher wind speeds. The SD are lower for all wind speeds and overwhelmingly so for the largest wind speeds (7, 14 and 20 ms^{-1}).

In conclusion, at 85 GHz, FASTEM2 is an improved fast model for the horizontal polarization except at wind speeds of 0 ms^{-1}. The 85 GHz V apparent surface temperature model FASTEM2 has smaller biases compared with the RTM.

Overall, at the SSM/I frequencies, FASTEM2 provides a more accurate fast substitute to a complete GO model than FASTEM. The largest improvements are for the horizontal polarizations and the largest wind speeds. The results are summarized in Table 4.

Table 4: Maximum bias (absolute value) and maximum SD between the apparent surface temperatures obtained with the models FASTEM, FASTEM2 and RTM for the SSM/I frequencies and a scan angle with respect to nadir of 44.93°. Surface wind speed values range between 0 and 20 ms^{-1}. The biases and SD were computed at each wind speed (0, 3, 7, 14, and 20 ms^{-1}) for the Garand 26 data set and the maximum values are tabulated here for each frequency including both polarizations except for the 22 GHz channel.

	FASTEM-RTM		FASTEM2-RTM	
SSM/I Frequencies	BIAS (K)	SD(K)	BIAS(K)	SD(K)
19 GHz V and H	9.25	2.3	2.1	0.6
22 GHz V	0.25	0.47	1.5	0.51
37 GHz V and H	6.6	1.6	2.5	0.7
85 GHz V and H	4.8	1.5	2.2	0.5

4.1.2.2. Comparison of FASTEM2 and FASTEM2 simplified

Difference statistics of FASTEM2 and RTM with FASTEM2 simplified and RTM (Figs. 2a-d) show that FASTEM2 simplified (Section 6.3) has a comparable performance to that of FASTEM2 for all SSM/I frequencies. This approach should speed up and simplify the implementation of FASTEM2 in future versions of RTTOV.

4.1.3. FASTEM, FASTEM2, RTM compared with 1DVAR0

Some of the results presented here are directly comparable to those presented in Fig. 14 of the “RTTOV-6 -SCIENCE AND VALIDATION REPORT” available from the NWP SAF web site. Fig.14 illustrates the biases between simulated brightness temperatures at the top of the atmosphere for the RTTOV-6 and RTSSMI models. Since the surface emissivity in RTTOV-6 is simulated with FASTEM, RTTOV-6 is similar to the model FASTEM in this report and RTSSMI is similar to 1DVAR0 (Table 2). The word “similar” is employed here rather than the word “same” because both RTTOV-6 and RTSSMI use regression coefficients to compute the optical depths and 1DVAR0 computes the optical depths using a LBL model.

The top left bar plot (with the biases) in Fig. 3 (FASTEM -1DVAR0) can therefore be compared with Fig. 14. The biases in Fig. 3 are somewhat higher than those in Fig. 14 but have the same behavior. The top wind speed considered in Fig. 14 was 10 ms^{-1} whereas here it is 20 ms^{-1}. Fig. 3 also illustrates the SD (top right bar plot) for the same intercomparison case and reaches a maximum of 2.2 K. It is reminded that channel 4 in the figure (or the 22 GHz H channel) is not an SSM/I channel and the results are displayed here for simplicity in the plotting routines.

The bottom bar plots in Fig. 3 illustrate the results for the intercomparison of FASTEM2 with 1DVAR0. Basically, similar biases remain but are often smaller (except for a surface wind speed of 20 ms^{-1}) and the magnitude of the reduction in bias varies with wind speed. The SD are also reduced except for the 85 GHz and 22 GHz channels.

4.1.4. Impact of parameter settings on GO models

Table 1a lists the differences in parameter choices (foam cover , dielectric constant, Bragg scattering, multiple reflections) for the GO models. In this section, difference statistics are computed to find out which parameter choice causes the largest differences between RTM and 1DVAR0. To do this, models 1DVAR2 and 1DVAR0 are used. First, a reference case is setup which computes the difference statistics between 1DVAR2 (#1 see Table 1b, uses RTM parameters) and 1DVAR0. Subsequently, one parameter at a time is changed in 1DVAR2 and the new value assigned to that parameter is that of the 1DVAR0 setup. Thus, if the difference statistics of any of these experiments are very close to the reference case, then the parameter that was changed can be identified as the one that causes a large difference in the RTM and 1DVAR0 models. The reason that 1DVAR2 was chosen for this task is because the handling of multiple reflections is flexible in 1DVAR2: one can choose either the RTM or 1DVAR0 setup.

Figures 4a-d illustrate the difference statistics as a function of wind speed for the 4 SSM/I frequencies. The series of 5 bars in the bar plots for each wind speed correspond to the following setups: (1) 1DVAR2 (#1) - 1DVAR0 (this is the reference case), (2) 1DVAR2 (#1)-1DVAR2 (#4) (foam change), (3) 1DVAR2 (#1)-1DVAR2 (#5) (dielectric constant change), (4) 1DVAR2 (#1)-1DVAR2 (#6) (Bragg scattering change) and (5) 1DVAR2 (#1)-1DVAR2 (#3) (multiple reflection change).

For wind speeds of 0, 3 and 7 ms^{-1}, clearly, changing the ***dielectric constant*** in 1DVAR2 from the RTM setup to that of 1DVAR0 explains most of the differences between RTM and 1DVAR0. The choice of the dielectric constant also impacts the largest wind speeds (14 and 20 ms^{-1}).

For wind speeds different from zero, the impact of the ***Bragg scattering*** (Eq. 19) being turned off increases with wind speed and as expected has the largest influence on the lowest frequencies. The effect on horizontally polarized channels is somewhat larger than vertically polarized channels.

The choice of ***foam cover*** as a function of wind speed affects mostly the highest wind speeds (14 and 20 ms^{-1}) and has a higher impact on channels with horizontal polarization. Table 5 lists the values of foam cover as a function of wind speed for 1DVAR0 and RTM. At 7 ms^{-1}, the foam covers are the same. Above 7 ms^{-1} the foam cover of the 1DVAR0 increases at a much faster rate and therefore also has a larger impact. At 20 ms^{-1}, the foam cover is 3 times larger in 1DVAR0 than in RTM.

Finally, the impact of the handling of ***multiple reflections*** is noticeable only for the largest wind speeds (14 and 20 ms^{-1}) and the same conclusions as in Section 4.1.1 hold: largest impact for the highest frequencies and horizontal polarizations.

Table 5: Foam cover as a function of surface wind speed for 1DVAR0 and RTM.

Surface Wind Speed (ms^{-1})	Foam Cover 1DVAR0	Foam Cover RTM
0.0	0.00000	0.00000
1.0	2.95000e-06	1.95000e-05
2.0	3.38413e-05	0.000114199
3.0	0.000141023	0.000321140
4.0	0.000388216	0.000668787
5.0	0.000851523	0.00118143
6.0	0.00161776	0.00188070
7.0	***0.00278335***	***0.00278634***
8.0	0.00445347	0.00391664
9.0	0.00674149	0.00528875
10.0	0.00976837	0.00691886
11.0	0.0136623	0.00882238
12.0	0.0185584	0.0110140
13.0	0.0245982	0.0135080
14.0	0.0319295	0.0163178
15.0	0.0407065	0.0194566
16.0	0.0510886	0.0229372
17.0	0.0632415	0.0267719
18.0	0.0773359	0.0309727
19.0	0.0935480	0.0355514
20.0	0.112059	0.0405192

4.1.5. Sensitivity of brightness temperature to surface wind speed

The sensitivity of the brightness temperature at the top of the atmosphere with surface wind speed (i.e. $\frac{dTB}{dSWS}$) was computed using finite differences:

$\frac{dTB}{dSWS} \cong TB(SWS+1.)-TB(SWS)$ where SWS is in ms^{-1}.

$\frac{dTB}{dSWS}$ was also reported in the “RTTOV-6 SCIENCE AND VALIDATION REPORT” for the SSM/I frequencies and for models FASTEM and RTSSMI. Thus a direct comparison of results will again be possible. $\frac{dTB}{dSWS}$ was computed here for 4 different models: FASTEM, FASTEM2, RTM and 1DVAR0. If FASTEM and/or FASTEM2 are accurate fast model (and approximations) to RTM, then $\frac{dTB}{dSWS}$ of these models should be the same as that of RTM. This is particularly important in the context of variational assimilation.

Figs. 5a and 5b illustrate the sensitivities for the 4 models.

Vertical polarizations:

The sensitivity of 1DVAR0 is low for low wind speeds and increases rapidly with wind speed with the largest sensitivity > 1.5 K/ms^{-1} for the 19 and 37 GHz channels and a surface wind speed of 20 ms^{-1}. At 85 GHz, the increase in sensitivity with surface wind speed is considerably lower. The sensitivity of RTM is similar to that of 1DVAR0 for low wind speeds but increases at a much slower rate for higher wind speeds with the maximum sensitivity being less than 1/3 of that of 1DVAR0. It is suspected here that the difference in parameterization for foam in the models (larger foam cover in 1DVAR0 model at high wind speeds) is responsible for this discrepancy (See Section 4.1.6).

The sensitivities of the brightness temperatures to surface wind speed of FASTEM, FASTEM2 and RTM are quite similar.

Horizontal polarizations

At 19 GHz, FASTEM sensitivities are too high at low wind speeds. For large wind speeds (14 and 20 ms^{-1}), the 1DVAR0 sensitivities become very large: > 3 K/ms^{-1} at 19 and 37 GHz. At low wind speeds, the sensitivities of FASTEM2, 1DVAR0 and RTM are fairly similar.

In summary, for vertical polarizations, FASTEM and FASTEM2 behave not too differently. AT 19 GHz H and at low wind speeds, FASTEM exhibits a larger sensitivity to wind speed than that of RTM. 1DVAR0 differs mostly from RTM at higher wind speeds (14 to 20 ms^{-1}) with 1DVAR0 being more sensitive by a factor of ~3 at 20 ms^{-1}. The results in Fig. 15 of the "RTTOV-6 SCIENCE AND VALIDATION REPORT" are in agreement with the results presented here.

4.1.6. Impact of parameter settings on the sensitivity of TB to surface wind speed

In this section, the impact on $\frac{dTB}{dSWS}$ of changing parameters in 1DVAR2 (with RTM parameters for the reference case) to those in 1DVAR0 is studied. The approach here is similar to that of Section 4.1.4 except that only biases are computed. In Fig. 6 a and b, the sensitivity of six models are plotted side by side (as a bar plot) as a function of surface wind speed. The six models are: (1) 1DVAR2 (#1, RTM setup used as a reference) and (2) 1DVAR0 (used as a reference), (3) 1DVAR2(#4)—foam change, (4) 1DVAR2(#5)—dielectric constant change, (5) 1DVAR2(#6)—Bragg scattering, (6) 1DVAR2(#3)—multiple reflections change.

An obvious result from these graphs is that the increased sensitivity of 1DVAR0 for large wind speeds (14 and 20 ms^{-1}) is largely due to the different specification of the foam cover. The foam cover for 1DVAR0 increases much more quickly than that of RTM for wind speeds larger than 7 ms^{-1} (Table 5). The increased foam cover leads to a larger sensitivity of brightness temperature with surface wind speed. At 3 and 7 ms^{-1} for all horizontal frequencies, all the models give a similar sensitivity and thus the parameter changes have little impact.

4.2. AMSU

Unlike the SSM/I which is a conical scanner and has a constant scan angle, AMSU is a cross-track scanner and the scan angle varies with scan position. Thus, the accuracy of FASTEM and FASTEM2 also has to be evaluated as a function of scan angle.

4.2.1. Window channels

The AMSU window channels are listed in Table 6. Sounding channels are identified by S and window channels by W. Fig. 7a illustrates the differences in apparent surface temperature between RTM and FASTEM for a profile (#18 in Table 3) with a TPW of 33 kgm^{-2} as a function of satellite view angle from nadir for both polarizations of the AMSU channel #3 (50.3 GHz) and for 5 different wind speeds (0, 3, 7, 10, 14 and 20 ms^{-1}). The same plots but differencing RTM and FASTEM2 this time are shown in Fig. 7b. The differences in Fig 7b are the smallest for a scan angle of ~ 25^o. Comparing Figs 7a and b, one may notice that FASTEM2 performs much better than FASTEM as an approximator to RTM. In particular, one may note that the bias at 0^o is reduced for FASTEM2 for all wind speeds except 0 ms^{-1}.

Figs. 7c-e illustrate the bias and SD of the apparent surface temperature (both polarizations) over the GARAND26 profile data set for view angles of 0, 30 and 45^o respectively. The results for only a subset of the window AMSU channels (see Table 6) are presented here. The top bar plots intercompare RTM with FASTEM and the bottom plots RTM with FASTEM2. For a scan angle of 0^o, the SD drops from a maximum of 2.6 K for FASTEM to 0.4 K for FASTEM2, at 30^o from 2.9 K for FASTEM to 0.2 K for FASTEM2 and at 45^o from 2.45 K for FASTEM to 0.9 K for FASTEM2. At 45^o, the maximum biases for FASTEM2 are < 3.0 K whereas it is < 8.5K for FASTEM. The biases of FASTEM2 are < 0.75 K for a scan angle of 30^o and < 1.8 K for a scan angle of 0^o. These statistics are summarized in Table 7.

In conclusion, for the AMSU channels, FASTEM2 is a much more accurate model than FASTEM to simulate apparent surface temperatures.

Table 6: AMSU channels (W=Window channel, S=Sounding channel)

Channel #	***Frequency (GHz)***	***Channel #***	***Frequency (GHz)***
1-W (results shown)	23.8	12-S	57.2903
2-W (results shown)	31.4	13-S	57.2903
3-W (results shown)	50.3	14-S	57.2903
4-W (results shown)	52.8	15-W	89.0
5-S/W	53.596	16-W (results shown)	89.0
6-S	54.4	17-W (results shown)	150.0
7-S	54.94	18-W/S	183±1
8-S	55.5	19-W/S	183±3
9-S	57.2903	20-W/S	183±7
10-S	57.2903		
11-S	57.2903		

Table 7: Maximum biases (absolute values) and maximum SD between the apparent surface temperatures obtained with the FASTEM, FASTEM2 and RTM among the selected AMSU frequencies (i.e. 23.8, 31.4, 50.3, 52.8, 89, 150 GHz) and both polarizations. Surface wind speed values range between 0 and 20 ms^{-1}. The biases and SD were computed at each wind speed (0, 3, 7, 14, and 20 ms^{-1}) and for each channel and polarization over the Garand 26 data set. The maximum values are tabulated here.

	FASTEM-RTM		FASTEM2-RTM	
Scan angle with respect to nadir	BIAS (K)	SD(K)	BIAS(K)	SD(K)
0^o	7.0	2.6	1.8	0.4
30^o	4.7	2.9	0.75	0.2
45^o	8.5	2.45	3.0	0.9

As illustrated in Fig. 7a and b, the magnitude of the biases between the fast models and RTM varies considerably as a function of scan angle and the biases can become quite large for scan angles with respect to nadir > 40^o. The scan angle of the SSM/I is ~ 45^o. To obtain a better performance of a fast model for large scan angles, it is suggested that the regression coefficients be calculated for small variations around a particular scan angle rather than covering all scan angles as is currently done with FASTEM and FASTEM2.

4.2.2. Sounding channels

In Table 6, the 183 GHz channels (strong water vapor absorption line) are identified as window or sounding. Whether a 183 GHz channel is a window or sounding channel will depend on the water vapor burden in the profile. Among channels 18 to 20, channel 18 peaks the highest in the atmosphere and channel 20 the lowest in the atmosphere. For very dry atmospheres, channel 18 can be a window channel since its weighting function will peak low in the atmosphere.

The isothermal approximation (Section 2.1.1) is not valid for sounding channels. This approximation was used in the development of the FASTEM and FASTEM2 models and for the computation of the reflected sky brightness temperature in 1DVAR0. As a consequence, the apparent surface temperatures generated by FASTEM, FASTEM2 and 1DVAR0 are no longer valid for sounding channels. However, this does not present a problem since for those channels the atmospheric transmittance is very low (tends to zero) and multiplies the apparent surface temperature and only the term $TB^{\uparrow}$ in Eq. 1 contributes to TB at the top of the atmosphere. An example of this is illustrated in Fig. 8 for a profile with a TPW of 33 $\mathrm{kgm^{-2}}$ (profile # 18 in Table 3) and for AMSU channel 19. Fig. 8 illustrates the apparent surface temperature as a function of view angles for the 3 models 1DVAR0, FASTEM and FASTEM2. As the view angle increases, the optical depth increases and the isothermal approximation becomes invalid yielding erroneous apparent surface temperatures. Models 1DVAR2 and RTM do not use the isothermal approximation and the apparent surface temperature remains valid for all view angles.

5. Conclusions

An evaluation of FASTEM and FASTEM2 was performed by intercomparing them with 3 geometric optics models: 1DVAR0, 1DVAR2 and RTM. FASTEM, FASTEM2 and the three GO models are all embedded in the same general radiative transfer code (called MICLBL) developed at MSC by the author. The fact that the models share many common subroutines (for example they all compute transmittances in the same manner) makes the intercomparison straightforward. RTM is a model that has the same parameter settings as FASTEM and FASTEM2 (Table 1a).

1DVAR0 has the same parameter settings as SSMI1DVAR or RTSSMI (Table 1a). Finally, 1DVAR2 can have parameter settings as those of RTM or SSMI1DVAR.

To perform the intercomparisons, a subset of 26 profiles (with skin temperatures > 275 K) were selected among the 42 profiles of the GARAND data set.

Apart from the fact that RTM and 1DVAR0 have different parameter settings, the 2 models also have differences which are “hard-coded” into the models. These differences are: (1) the isothermal atmosphere approximation is used to compute the down-welling brightness temperature in 1DVAR0 and not in RTM, (2) the handling of the multiple reflections is done differently in RTM and 1DVAR0. Among these differences (only evaluated for the SSM/I channels in this report), only the last one significantly affects the computed apparent surface temperature at the largest wind speeds and for horizontally polarized channels.

The apparent surface temperature of the models FASTEM and FASTEM2 were each intercompared with those of RTM. For the SSM/I frequencies, FASTEM2 provides a more accurate fast substitute to a complete GO model than FASTEM for the horizontal polarization except at zero wind speed. A faster version (and much easier to implement in RTTOV) of FASTEM2 named FASTEM2 simplified is presented in Section 6.3. The intercomparison of FASTEM2 and FASTEM2 simplified shows that FASTEM2 simplified is accurate enough to be considered for implementation into RTTOV.

For the SSM/I frequencies, FASTEM, FASTEM2 and RTM brightness temperatures (at the top of the atmosphere) were intercompared with those of 1DVAR0. Results of the intercomparison of FASTEM and 1DVAR0 are in agreement with those presented in Fig. 14 of the “RTTOV-6 - SCIENCE AND VALIDATION REPORT”.

It was found that for the SSM/I frequencies and for the lowest wind speeds (≤ 7 ms^{-1}), the parameter that most affected the differences in apparent surface temperature between RTM and 1DVAR0 was the specification of the dielectric constant. The choice of foam cover formulation leads to considerably larger foam cover for large wind speeds in the 1DVAR0 model and at high wind speed this parameter contributes to a large portion of the difference between RTM and 1DVAR0.

The sensitivity of the brightness temperatures at the top of the atmosphere to surface wind speed for the SSM/I channels was computed for FASTEM, FASTEM2, 1DVAR0 and RTM. The intercomparison of results for FASTEM and 1DVAR0 were also reported for FASTEM and RTSSMI in Fig. 15 of the “RTTOV-6 - SCIENCE AND VALIDATION REPORT”. Again, the results obtained in the report are in agreement with those presented here. For the vertical polarizations, the sensitivities of FASTEM, FASTEM2 and RTM are quite similar. For the 19 GHz horizontally polarized channel, FASTEM sensitivities are too high at low wind speeds whereas FASTEM2 sensitivities closely follow those of RTM for all horizontally polarized channels. For high wind speeds and both polarizations, the sensitivity of the 1DVAR0 model to wind speed becomes quite large compared to that of RTM and is due mainly to the different specification of the foam cover.

In the case of the AMSU channels, the accuracy of FASTEM and FASTEM2 has to be evaluated as a function of scan angle. Results were presented for a selected subset of AMSU window channels and the intercomparisons were also performed for the GARAND26 data set. In most cases, it was found that FASTEM2 is a much more accurate model than FASTEM and that FASTEM2 is most accurate for scan angles around 25^o. At 30^o, the bias and SD for FASTEM2 compared with RTM were < 0.75 K and < 0.2 K respectively whereas for FASTEM compared with RTM, these were < 4.7 K and 2.9 K. It is not expected that the conclusions would change if all the AMSU channels that are sensitive to the surface had been considered.

It should be noted that for sounding channels, the FASTEM, FASTEM2 and 1DVAR0 produce erroneous apparent surface temperature because they use the isothermal atmosphere approximation. However for such cases, the atmospheric transmittance tends to zero and therefore the use of this approximation does not lead to an erroneous computation of brightness temperatures at the top of the atmosphere.

The increase in accuracy obtained by using FASTEM2 rather than FASTEM to compute the apparent surface temperature is significantly larger for the AMSU instrument for scan angles < $\sim 40^o$ than for the SSM/I instrument. The SSM/I instrument has a large scan angle (45^o) and the fast models do not perform as well for large scan angles. It may be necessary to develop a fast model that is only applicable for a particular range of scan angles for large angles in order to improve the accuracy.

6. Appendices

6.1. Computation of $TB^{\downarrow}(\theta)$ and $TB^{\uparrow}(\theta)$

The up-welling atmospheric brightness temperature is defined as:

$$TB^{\uparrow}(\theta) = (1/2)\sum_j (T_j + T_{j-1})(\tau_{j-1} - \tau_j) \qquad \text{(A.1)}$$

where j is the level, τ_j is the transmittance from level j to space and T_j is the atmospheric temperature at level j. The down-welling atmospheric brightness temperature is:

$$TB^{\downarrow}(\theta) = \{(1/2)\sum_j \frac{(T_j + T_{j-1})(\tau_{j-1} - \tau_j)}{\tau_j \tau_{j-1}} + T_c\}\tau_s \qquad \text{(A.2)}$$

where τ_s is the transmittance from the surface level to space or the atmospheric transmittance and T_C is the cosmic background temperature.

The transmittance at level j is computed as follows:

$$\tau_j = e^{-\sec\theta \sum_{l=1}^{j-1} O_l} \qquad \text{(A.3)}$$

where O_l is the optical depth of layer l.

Level 1 is the top level and the level number increases towards the surface, thus,

$$\tau_1 = 1.0 \qquad \text{(A.4)}$$

$$\tau_2 = e^{-O_1 \sec\theta} * \tau_1$$

$$\tau_3 = e^{-O_2 \sec\theta} * \tau_2 * \tau_1$$

etc. ,…

6.2. Implementation of FASTEM2 into MICLBL

The implementation of FASTEM2 in MICLBL (a general microwave radiative transfer code -forward model only, developed at MSC) was done as follows:

Compute optical depths as before (optdepth.f)

Compute transmittances as before (transmittance.f)

Compute effective path (need to know transmittance from surface to space at nadir).

(Transmittance.f)

Compute $TB^{\downarrow}$ and $TB^{\uparrow}$ (using rtint.f) as before. Only intend to use $TB^{\uparrow}$.

Compute $TB^{\downarrow}(\theta_p^*)$ *for vertical AND horizontal polarizations (rddnfix.f).*

This includes recomputing the optical depths and the transmittances to compute the down-welling brightness temperature for vertical and horizontal polarizations. ***This can be sped up by using the same approximation as described in section 2.1.1 (See section 6.3)***

Compute E^{GO} *using fast_emiss.f. Also use* $TB^{\downarrow}(\theta *)$ *computed for both polarizations and compute scattered brightness temperature for both polarizations.*

Compute effect of foam as before (addfoam.f)

Compute TB at the top of the atmosphere as before (budtoa.f)

6.3. FASTEM2 simplified

A simpler way to introduce the effective path correction term ($P_{rough} = \dfrac{\sec\theta_p^*}{\sec\theta}$) is described. For the microwave window channels, the following approximation is done (See also Section 2.1.1):

$$TB^{\downarrow}(\theta_p^*) = TB^{\downarrow}(\theta)\left[\frac{(1-\tau_s^{\frac{\sec\theta_p^*}{\sec\theta}})}{(1-\tau_s)}\right]. \qquad \text{(A.5)}$$

This follows from assuming that the mean radiating temperature of the atmosphere does not change with view angle (or the isothermal approximation). τ_s is the atmospheric transmittance at view angle θ.

The apparent surface temperature for FASTEM2 is:

$$TB_{ap}^{GO} = \tilde{E}_p^{GO}\, T_s + (1-FC)TB_p^{s\,GO} \qquad \text{(A.6)}$$

where p is the polarization index (V or H). Substituting Eq. A.5 in A.6 leads to:

$$TB_{ap}^{GO} = \tilde{E}_p^{GO}\, T_s + (1-FC)(1-\tilde{E}_p^{GO})TB^{\downarrow}(\theta)\left[\frac{(1-\tau_s(\theta)^{\left(\frac{\sec\theta_p^*}{\sec\theta}\right)}}{1-\tau_s(\theta)}\right] \qquad \text{(A.7)}$$

or $TB_{ap}^{GO} = \tilde{E}_p^{GO}\, T_s + \tilde{R}_p^{GO}\, TB^{\downarrow}(\theta)$, (A.8)

where

$$\tilde{R}_p^{GO} = (1-FC)(1-\tilde{E}_p^{GO})\left[\frac{(1-\tau_s^{\left(\frac{\sec\theta_p^*}{\sec\theta}\right)})}{(1-\tau_s)}\right]. \qquad \text{(A.9)}$$

Thus, the RTTOV code only has to be modified to compute a reflectivity term as well as an emissivity term for both polarizations.

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