On Using FASTEM2 for the Special Sensor Microwave Imager (SSM/I)

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Godelieve Deblonde
Meteorological Service of Canada

1. Introduction

Fastem2 is a fast model (multiple-linear regression model) that allows the computation of the effective down-welling brightness temperature and the effective surface emissivity (English and Hewison 1998, Deblonde and English 2000, Petty 1994) at microwave frequencies over the open ocean surface. Both quantities are needed to compute the apparent surface temperature. In a previous study, the author evaluated the performance of FASTEM2 and FASTEM against a geometric optics model for the surface emissivity over the ocean for the channels of the SSM/I and AMSU instruments (Deblonde 2000 and Deblonde and English 2000). It was found that the accuracy of FASTEM2 decreases for scan angles (satellite view angle with respect to nadir) greater than 35 to 40^o. The objective of this note is to investigate this problem and find out whether a regression equation that is valid only over a narrow range of incidence angles (zenith view angle from earth) would lead to more accurate results.

In section 2, the FASTEM2 regression equation needed to compute the effective down-welling brightness temperature and its relationship to the apparent surface temperature is described. Following this, a description is given of the dependent and independent atmospheric profiles data sets that are employed to first obtain the optical depths. These are needed to compute the various radiative transfer variables from which the regression coefficients are derived. Statistics of the differences between the true and regression scattered brightness temperature are summarized in section 3. Conclusions are given in section 4.

2. Methodology

Using a data set of atmospheric temperature and humidity profiles (described below), optical depths were computed as a function of pressure and frequency with MICLBL (Liebe 1989 for water vapor absorption and Liebe et al. 1992 for oxygen absorption). MICLBL is a radiative transfer code developed by the author at the Meteorological Service of Canada. Some of the subroutines in the code are based on code obtained from the Met Office (Steve English) and ECMWF (Laurent Phalippou).

The atmospheric profiles and the optical depths were then read in by the code gotbscat.f (sub-set of MICLBL subroutines) that computes the polarized scattered brightness temperature

($Tb^{GO}_{p\,scat}$) and the polarized effective surface emissivity (E^{GO}_{p}) using a geometric optics (GO) surface model. Both these quantities are necessary to compute the apparent surface temperature (defined below). The output of the code gotbscat.f was then processed in IDL by a procedure named regscat.pro that computes the regression coefficients needed to compute the apparent surface temperature. The IDL build-in procedure regress.pro was used to compute the regression coefficients. The notation used in this note is the same as that in the NWP-SAF report (Deblonde 2000). The configuration of the GO model (i.e. slope variance, dielectric constant and foam cover models) is fully described in this report.

The apparent surface temperature may be defined as follows:

$$Tb^{GO}_{ap} = \tilde{E}^{GO}_{p}\, T_{skin} + (1 - FC)Tb^{GO}_{p\,scat} \qquad (1)$$

where

$$\tilde{E}^{GO}_{p} = (1 - FC)E^{GO}_{p} + FC\,. \qquad (2)$$

FC is the foam cover which is a non-linear function of wind speed and T_{skin} is the skin temperature. As in FASTEM2, $Tb^{GO}_{p\,scat}$ may be written as :

$$Tb^{GO}_{p\,scat} = (1 - \tilde{E}^{GO}_{p})Tb^{\downarrow}(q^{*}_{p}) = (1 - FC)(1 - E^{GO}_{p})Tb^{\downarrow}(q^{*}_{p}) \qquad (3)$$

where $Tb^{\downarrow}(q^{*}_{p})$ is the effective down-welling Tb. Consequently:

$$Tb^{\downarrow}(q^{*}_{p}) = \frac{Tb^{GO}_{p\,scat}}{1 - \tilde{E}^{GO}_{p}}\,. \qquad (4)$$

If we assume that the isothermal atmosphere approximation holds, a mean air temperature T_A is defined as follows:

$$T_A = \frac{Tb^{\downarrow}(q\ \ ) - T_c t_s}{1 - t_s} \qquad (5)$$

where $t_s = e^{-O\sec q}$, (6)

T_c is the cosmic Tb and O is the atmospheric total optical depth at nadir. Furthermore,

$$\sec q_p^* = -(\frac{1}{O})\ln\left[\frac{Tb^{\downarrow}(q_p^*) - T_A}{T_c - T_A}\right] \qquad (7)$$

and

$$F_p(q^*, q) = \frac{\sec q_p^*}{\sec q}. \qquad (8)$$

It is then also possible to write:

$$Tb^{\downarrow}(q_p^*) = Tb^{\downarrow}(q)\left[\frac{1 - t_s^{F_p}}{1 - t_s}\right] \qquad (9).$$

The sensitivity of Tb to q_p^* is:

$$\frac{\P Tb}{\P q_p^*} = \frac{\P t_s^*}{\P q_p^*}[T_c - T_A] = -O \sec q_p^* \tan q_p^* t_s^* \left[\frac{T_c - Tb^{\downarrow}(q)}{1 - t_s}\right] \qquad (10)$$

and

$$t_s^* = e^{-O \sec q_p^*} \qquad (11)$$

In FASTEM2, F_p (Eq. 8) is expanded as follows:

$$F_p - 1. = B_0 + B_1 ANG + B_2(g^2) + B_3 ANG(g^2) + B_4 ANG^2 + B_5(g^2)^2 \quad (12)$$

where $ANG = \sec q$ and g^2 is the slope variance (which is a linear function of wind speed and also depends on frequency) and

$$B_i = A_{0i} + A_{1i}(\ln O) + A_{2i}(\ln O)^2. \qquad (13).$$

The term (1-FC) in Eq. 3 is not really needed and experiments have been performed without this term. For this case, 2 more terms were added to Eq. 12. The new expansion is given by:

$$N_p - 1 = B_0 + B_1 ANG + B_2(g^2) + B_3 ANG(g^2) + B_4 ANG^2 + B_5(g^2)^2 + \\ + B_6 ANG^2 g^2 + B_7 ANG(g^2)^2$$

(14)

and

$$Tb^{\downarrow}(\theta_p^*) = \frac{Tb_{p\,scat}^{GO}}{1 - E_p^{GO}} \; .$$

2.1.1. Data sets used to develop regression coefficients for $\frac{\sec\theta_p^*}{\sec\theta}$

2.1.1.1. Dependent data sets

As a dependent data set, the Garand 26 warm profile data set (referred to hereafter as Garand26) was used (i.e. the regression coefficients were computed with this data set). The Garand et al. 2001 data set contains 42 profiles but only those with the lowest level temperature > 275.0 K were kept. Two data sets were generated:

(1) A data set with an incidence angle (θ) that varied between 0 and 60^o (by steps of 10^o). The frequency ranged from 15 to 220 GHz by steps of 5 GHz, the wind speed varied between 0 to 20 ms^{-1} by steps of 1 ms^{-1} and the skin temperature was fixed at 278.15, 288.15 K and 298.15 K.

(2) A data set with incidence angle that varies between 50 and 56^o (by steps of 3^o). The same frequencies, wind speeds and skin temperatures were used as for the above data set.

It was found that the regression results did not depend much on the choice of skin temperature and therefore the results presented here only used T_{skin}=288.15 K.

2.1.1.2. Independent data sets

Two independent data sets were created:

(1) The TIGR3 warm profiles were used (i.e. temperature of lowest level > 275 K). This sub-selection lead to a count of 1193 profiles. Various radiative transfer variables were computed for the same frequencies as the dependent data sets and for wind speeds of 0, 3, 7, 10, 15 and 20 ms^{-1}. The skin temperature was set to 288.15K and the incidence angle was fixed at 53^o.

(2) The TIGR3 1193 warm profile data set was also used to compute various radiative transfer variables for only the SSM/I frequencies of (i.e. 19.35, 22.235, 37 and 85.5 GHz). The remainder of the variables were the same as those chosen for the set described above.

The scattered brightness temperatures computed from the independent data sets using a GO model were compared with those obtained with the regression equation whose coefficients were computed from the dependent data set.

2.1.2. Choice of weights for the regression

Two choices of weights for the regression were considered:

(1) The inverse of the optical depth (weight of 1 at O=0.05 and weight of 0 at O=3.0) as defined for the FASTEM2 model. This is based on the fact that when the atmosphere becomes opaque, the contribution of the apparent surface temperature to Tb at the top of the atmosphere becomes negligible.

(2) The square of the sensitivity $\frac{¶Tb^{\downarrow}(q_p^*)}{¶q_p^*}$ (Petty 1994) was chosen. The sensitivity is low for low optical depths (<<0.4). This is so because there is not much atmosphere that will change the effective down-welling $Tb^{\downarrow}(q_p^*)$ compared with the down-welling $Tb^{\downarrow}(q)$ itself. The sensitivity is the largest for optical depths around 0.4 and it becomes again very small for larger optical depths since the surface is no longer seen. The largest sensitivity was found to be around 3.5 K per angular degree for the Garand26 data set.

The results overall were not at all improved by using option (2) compared with those when option (1) was used and so option (1) was used.

2.1.3. Angular predictor for the SSM/I

The coefficients of the expansions in Eqs. 12 and 14 were also calculated for the Garand26 data set with an incidence angle variation around 53^o. For this case, ANG in Eqs. 12 and 14 becomes:

$$ANG = (q - 53^o).$$

For all cases, the optical depth was limited to < 2.1 otherwise the regression coefficients could not be computed.

3. Results

3.1.1. Dependent data set results

Fig. 1 illustrates the true minus regression bias and standard deviation (black plus symbols) for the scattered brightness temperature $Tb_{p\,scat}^{GO}$ as a function of incidence angle (over all wind speeds and for O < 2.1). The regression equation that was used is that of Eq. 12 with secθ as the angular predictor. This case will hereafter be referred to as case A (see Table 1) and replicates the expansion of FASTEM2. The most accurate regression occurs for θ=20^o for both V and H polarizations. The (V, H) polarization biases at this angle are (0.03 K, 0.01 K) and the SD is (0.13 K, 0.15 K). For V polarization, θ=40^o has the highest SD (0.26 K) and biases for all angles do not exceed 0.1 K. For H polarization, θ=60^o has the highest SD (1.03 K). The 50^o angle has the largest bias (–0.33 K) with a SD of 0.7K.

Table 1: Description of the experiments

Experiment name	Regression Equation Used	Angular Predictor
Case A (as in FASTEM2)	12	secθ
Case B	14*	secθ
Case C	12	θ-53^o
Case D	14*	θ-53^o

* Note that when Eq. 14 is used, the term (1-FC) is dropped in Eq. 3.

As a first attempt at improving the accuracy of the regression, the number of predictors was increased as per Eq. 14 while keeping secθ as the angular predictor (this will be referred to as case B). The red star symbols in Fig. 1 illustrate the statistics for this case. At 50^o, this case shows worse results for V polarization and leads to only a small improvement for H polarization.

Statistics for the regression equation that uses θ-53^o as an angular predictor with Eq.12 are illustrated by the green diamonds (referred to as case C) in Fig. 1. Statistics for Eq.14 using the same angular predictor (referred to as case D) are illustrated with blue triangles in Fig. 1. For both H and V polarizations, this angular predictor improves the accuracy of the regression around 53^o and Eq. 14 or case D provides the most accurate results. The statistics in this figure were computed over all O < 2.1 and wind speeds ranging between 0 and 20 ms^{-1}. It is also important to study the behavior of these statistics as a function of surface wind speed and optical depth.

Statistics as a function of wind speed for θ=50^{o} are illustrated in Fig. 2. For the H polarization, case B leads to a more accurate regression than case A for low wind speeds (< 7 ms^{-1}). This is not the case for the higher wind speeds. Case D (blue triangles) has a SD (standard deviation) that is smaller by a factor of least 2 compared with case A and a bias that is closer to zero and much more uniform over the range of wind speeds. For small wind speeds (0 and 1 ms^{-1}), case D has a much lower SD than case C. For V polarization, case B shows no improvement over case A. Case D shows improved results at all wind speeds compared to case A except for the mid-range values (7 to 10 ms^{-1}). The bias as a function of wind speed is also much more uniform and close to zero for case D.

Fig. 3 shows the bias and SD as a function of nadir optical depth for a wind speed of 3 ms^{-1} and θ=50^{o}. The SD for both polarizations is the highest for O ~0.2 to 0.5. The bias is lower for cases C and D than for cases A and B and is also more constant with optical depth. The SD for cases C and D is lower than that of case A for H polarization and O < 1.0. For V polarization and O < 0.7, case D has a higher SD than case A. Fig. 4 shows the same statistics but for a wind speed of 20 ms^{-1}. Again the bias is lower and more uniform for case D while the SD performance varies with optical depth.

In summary, case D leads to biases that are lower and more constant with surface wind speed and optical depth. For the H polarization and for O < 2.1, case D gives a SD that is at least twice smaller (< 0.35 K see Fig. 2) than that of case A (< 0.8 K see Fig. 2). The improvement is the largest for low wind speeds.

3.1.2. Independent data set results

The independent data sets were described above (Section 2.1.1.2). The statistics for the scattered polarized brightness temperature for the first independent data set are illustrated in Fig. 5. The regression coefficients were obtained from the dependent data set and the true values from the independent data set. The maximum differences in absolute value between the true and regressed scattered Tb are also given (bottom graphs). The curves of SD and bias as a function of wind speed for O < 2.1 are very close to those obtained with the depended data set (Fig. 2).

For both the H and V polarizations, the bias for case D is lower and more uniform over the range of wind speeds which is a sought after behavior for a regression. For the H polarization, the SD of case D is considerably smaller than that of case A for both low and high wind speed while at the 7 ms^{-1} wind speed the values are closer. The maximum difference values are also reduced by a factor of two for the higher and lower wind speeds with the mid-range values remaining the same. For V polarization, the main improvement is only for the lowest wind speeds.

The results for the second independent data set are illustrated in Fig. 6. The only frequencies considered in this case are those of the SSM/I instrument. The curves have similar shapes to those in Fig. 5 and Fig. 2 except for the V polarization where the SSM/I only frequency data set exhibits a larger bias for cases C and D than case A at high wind speeds.

4. Conclusions

The performance of FASTEM2 against a geometric optics model for the channels of the SSM/I and AMSU instruments was evaluated in Deblonde (2000). It was found that the accuracy of FASTEM2 decreased for scan angles (satellite view angle with respect to nadir) greater than 35 to 40^o. The objective of this note is to investigate this and find out whether a regression equation that is valid only over a narrow range of incidence angles would lead to more accurate scattered brightness temperatures (compared to those of the GO model) for an incidence angle of ~ 53^o which is the incidence angle of the SSM/I.

To compute the effective down-welling brightness temperature at the incidence angle of the SSM/I, the FASTEM2 regression formulation was modified in two ways. First, a new angular predictor (θ -53^o) was implemented and secondly, 2 more terms (of order 3) were added to the expansion. Compared with the FASTEM2 formulation (case A), the SD of this new regression (case D) at both low and high wind speeds is lower by a factor of at least 2 for the horizontal polarization. The gain for the vertical polarization is limited to the very lowest wind speeds. For both polarizations, the bias as a function of wind speed is considerably lower and is more constant with wind speed when the new formulation is used.

Considering the above results, it is recommended that the expansion according to Eq 14 with angular predictor of θ-53^o be used for the SSM/I (Case 4). These changes can be implemented in FASTEM2 in a straightforward manner. The final decision as to whether the new regression equation should be used for the SSM/I will of course depend on the values of the observation minus first guess statistics. If the latter are considerably larger than the values of the error statistics presented here than the change in the regression equation need not be implemented.

5. REFERENCES

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