Intercomparison of Electromagnetic Models for Passive Microwave Remote Sensing of Snow

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Abstract—Electromagnetic models can be used for understanding the interaction between electromagnetic waves and matter, interpreting experimental data, and retrieving geophysical parameters. Comparing the results of different snow models, when driven with the same set of input parameters, can benefit remote sensing of snow. Microwave brightness temperatures of snow at 19 and 37 GHz for six different classes of snow (prairie, tundra, taiga, alpine, maritime, and ephemeral) are simulated by means of four different electromagnetic models: the Helsinki University of Technology snow emission model, the microwave emission model of layered snowpacks, a dense-medium radiative-transfer theory model, and a strong fluctuation theory model. The frequency behavior of the extinction coefficients obtained with the different models between 5 and 90 GHz is also studied. The four models are also driven with inputs derived from snow-pit data, and the outputs are compared with ground-based measurements of brightness temperatures at 18.7 and 36.5 GHz. Significant differences among the brightness temperatures and the extinction coefficients simulated with the four models in the cases of the six classes of snow are observed. Moreover, no particular model is found to be able to systematically reproduce all of the experimental data. The results highlight the need to more closely examine the relationships relating mean grain size and correlation length, introduce multiple layers in each model, and to perform controlled laboratory measurements on materials with well-known electromagnetic properties in order to improve the understanding of the causes of the observed differences and to improve model performance.

Index Terms—Author, please supply your own keywords or send a blank e-mail to keywords@ieee.org to receive a list of suggested keywords.

I. INTRODUCTION

Electromagnetic models are fundamental for improving our understanding of the physical processes involved in the interaction between electromagnetic waves and matter, for interpreting experimental data, and for retrieving geophysical parameters. From an electromagnetic point of view, snow can be considered as a dense medium composed of ice particles, air, and liquid water (in the case of wet snow), and several models have been proposed in the literature to describe the relationships between snow parameters such as mean grain size, density, snow depth, etc., and electromagnetic quantities (e.g., brightness temperatures). Modeling electromagnetic properties of snow is a complicated task because the distance among snow particles is often smaller than the wavelength, and scattering of correlated scatterers must be considered. Most of the models assume snow particles having spherical shape, and this gives rise to the problem of relating measured grain size of snow particles (which can be very different from being spherical) with the values of the inputs given to the model. In general, electromagnetic models can be classified into empirical, semiempirical, and theoretical models. Empirical models are based on the relationships obtained relating the observed electromagnetic quantities to measured snow parameters. They are very fast but have the limitation of being valid only locally, as they are not guaranteed to be valid for snow conditions different from those used for obtaining the relationships used in the models. Semiempirical models are obtained by combining theory with results from measurements. The latter can be used to determine extinction or scattering parameters of 62 snow as in the case of the Helsinki University of Technology (formerly known as HUT, but now referred to as TKK) model [64] or in the case of the microwave emission model of layer 65 snowpacks (MEMLS) developed at the University of Bern [2]. 66 Theoretical models do not use any experimental data and are 67 solely based on physical theory. The dense-medium radiative 68 theory (DMRT) [3] and the strong fluctuation theory (SFT) [9] 69 (e.g., [4]–[9]) are theoretical models that have been widely used 70 to simulate snow microwave brightness temperatures.

To our knowledge, so far, no study has been reported in the literature showing the results provided by different models for passive microwave remote sensing of snow when driven with the same set of input parameters. This is the task of this paper. The intercomparison of the electromagnetic models can provide precious information for improving retrieval techniques. Indeed, it is important to understand under which snow conditions the different models show agreement. Techniques involving data assimilation procedures or numerical inversion of electromagnetic models could also be strongly influenced whether one or another model is used. The comparison of different models can also help to understand when the different approaches provide dissimilar results so that eventual changes can be proposed. This can improve our understanding of the physical processes relating the electromagnetic quantities with snow geophysical parameters.

In the following, we compare the brightness temperatures of snow-covered terrain obtained by means of the aforementioned four electromagnetic models at 19 and 37 GHz to quantify the degree of agreement among the results of the four models. The behaviors of the extinction coefficients as a function of the 92
frequency between 5 and 90 GHz are also studied. The four models were selected because they have been widely applied to model ground-based measurements and to retrieve snow parameters from spaceborne measurements. Besides, they use completely different approaches to model the physical processes, to characterize the electromagnetic properties of snow, and to solve the radiative-transfer equations, yet they all have nearly the same input parameters (density, snow depth, snow temperature, wetness). It is therefore interesting to quantify the degree of agreement of the different approaches undertaken within the four models.

In order to compare the four models, we compare their outputs (brightness temperatures) obtained using the same sets of input parameters describing six different classes of snow proposed by Sturm et al. [10]. The six classes are the following: prairie (PR), tundra (TU), taiga (TA), alpine (AL), maritime (MA), and ephemeral (EP). Each class is characterized by different snowpack properties (i.e., mean snow depth, density, mean grain size, stratification). For simplicity, we consider only dry snow conditions ($w = 0$), and the comparison will be performed assuming flat air/snow interfaces. We also compare the results of the four models with ground-based measurements of brightness temperatures at 18.7 and 36.5 GHz collected by the University of Tokyo Ground-Based Microwave Radiometer (GBMR-7) during the third and fourth intensive observation periods (IOP3, February 2003 and IOP4, March 2003) of the NASA Cold Land Processes Experiment (CLPX)-1, in Colorado. The inputs to the models to simulate the measured brightness temperatures are derived from snow-pit data collected in conjunction with radiometric measurements.

The paper is organized as follows. In Section II, we describe the main characteristics of the electromagnetic models considered for this study. In Section III, we compare the brightness temperatures obtained with the four models for the six classes of snow and analyze the spectral behavior of the extinction coefficients simulated with the four models. In Section IV, we compare simulated brightness temperatures obtained from the four models with those measured by the University of Tokyo GBMR-7 at 18.7 and 36.5 GHz. We dedicate the last section to conclusions and suggestions for future work.

II. ELECTROMAGNETIC MODELS

In this section, we report a brief description of the electromagnetic models used in this paper. More details can be found in the respective references cited for each model.

Before starting with the description of each individual model, we introduce the inputs required by the models. The snow parameters required as inputs are nearly the same for all models (snow depth, snow density, volumetric liquid water content, snowpack temperature, and surface roughness of air/snow boundary) except that the DMRT and TKK models require the “mean grain size” of snow particles as input while the SFT and MEMLS models require the “correlation length.” The mean grain size $a$ can be seen as the radius of spherical ice particles approximating the ice grains in snow. The correlation length $\ell$ is related to snow grain size, shape, and volumetric distribution of snow grains (e.g., [6]). However, this relationship is not straightforward.\(^1\) In order, to derive the values of correlation length from the values of mean grain sizes considered in the six snow classes, we used the results reported in [12]. This 151 is necessary if we want to compare the results of the models having the mean grain size or correlation length as inputs. 153 However, as a consequence of the poorly known relationship between mean grain size and correlation length, and for the sake of clarity of this paper, we will show separately the results of the comparison between the two sets of models [one having the 157 mean particle radius as inputs (TKK and DMRT) and the other 158 the correlation length (SFT and MEMLS)].

A. TKK Model

The TKK snow emission model [1] is a semiempirical approach based on radiative transfer, treating the snow cover as a single homogeneous layer. The model describes the emission contribution of a snowpack as a function of snow depth, snow density, snow grain size, snow temperature and, in the wet 165 snow case, surface roughness of the air/snow boundary, and snow wetness. In addition to the upward emitted radiation, 167 the model takes into account the contribution emitted downward and reflected upward from the snow/snow boundary, for 169 the emission contribution from underlying soil and for the 170 atmospheric radiation reflected from the snow cover. The model also considers the multiple reflections caused by snow/soil and air/snow boundaries. The basic assumption in the TKK snow emission model is that scattering is mostly concentrated in the forward direction. The coefficient representing the fraction of total scattered power within the receiving angle was empirically derived and set to 0.96 [1]. The extinction coefficient $k_e$ is mod- 177 eled by means of the equation reported in [13]. Recently, a new 178 expression for the extinction coefficient has been proposed by 179 Roy et al. [14] extending the validity range to large particle size. 180 However, in this paper, the original formula will be adopted. Ice 181 permittivity and the real part of snow permittivity are computed 182 by means of an empirical formula proposed by Mätzler in [15] 183 and [16]. The imaginary part of snow permittivity is calculated 184 by means of the Polder–Van Santen mixing formula [17]. The 185 absorption coefficient is calculated from the imaginary part of the 186 dielectric constant of snow.

B. MEMLS Model

The MEMLS model is based on the studies carried out by 188 Wiesmann et al. [2]. The measurements of these authors lead to 190 the empirical approach to determine the scattering coefficient of 191 snow in the frequency range of 5–100 GHz and a correlation 192 length range of 0.01–0.3 mm. In MEMLS [18], [19], the 193

\(^1\)Several studies have been carried out to understand the link between grain size and correlation length. For example, linear regressions relating correlation length to the observed grain size and fractional volume have been proposed in the literature [6], [11]. A very interesting approach is reported in [12]. In this study, the author relates the value of the correlation length measured on several samples of different snow types to the “optical grain size” ($D_0$), which differs from the grain size usually measured ($D_{\text{max}}$). The latter is the maximum extent of prevailing grains where the optical grain size is close to the minimum thickness of thin plates, diameter of needles, and it represents a complement to $D_{\text{max}}$. 
snow cover is considered as a stack of horizontal layers. Each
layer is characterized by thickness, correlation length, density,
liquid water content, and temperature. The layer interfaces are
assumed to be planar. In order to combine internal scattering
and reflections at the interfaces, the sandwich model, based
on multiple-scattering radiative transfer, is used [20]. Inter-

ternal scattering is accounted for by a two-flux model
(fluxes in all spatial directions). The absorption and scatter-
ing coefficients are functions of the six-flux parameters. The
absorption coefficient can be obtained by density, frequency,
and temperature, and the scattering coefficient depends on the
correlation length, density, and frequency. The real part of the
effective permittivity of dry snow is computed in terms of
the snow density according to that in [15]. The real part of ice
permittivity is kept fixed at 3.15 where the imaginary part is
computed according to that in [21]. The scattering coefficient is
derived from experimental observations [2].

C. DMRT Model

The DMRT describes the propagation and scattering in a
dense medium, defined as a medium where the particles occupy
a fractional volume larger than 10% and where the assumption
of independent scattering is no longer valid, as there is more
than one scatterer within a wavelength distance. Several meth-
ods have been used to derive the DMRT equations. Among
them, we have the effective field approximation (EFA), also
called Foldy’s approximation [5], the quasi-crystalline approx-
imation (QCA) [5], [6], and the QCA with sticky particles [22],
[23]. In this paper, we use the equations of the DMRT derived
under the QCA approximation for moderate-size particles [23].
The Percus–Yevick equation is used to describe the pair distri-
bution function [5]. The effective propagation constant is com-
puted on the basis of the generalized Lorentz–Lorenz law and
the generalized Ewald–Oseen extinction theorem (e.g., [23]).
The extinction coefficient is then calculated from the imaginary
part of the effective propagation constant. The formula used for
ice permittivity is the same as that one used in the TKK model
[15]. The scattering and absorption coefficients are derived and
the equations of the radiative transfer theory are solved by
means of the Gaussian quadrature method and eigenvalues and
eigenvectors technique (e.g., [6]).

D. SFT

In the SFT, the snowpack is modeled as a continuous
medium with the scattering effects accounted for by making
use of random fluctuations of permittivity. The fluctuations
are described by a correlation function, with the variance
characterizing the strength of the permittivity function of the
medium and correlation lengths corresponding to the scales of
fluctuation. In the weak permittivity fluctuation, the variance
of permittivity fluctuations must be small (δ ≪ 1). However,
in many cases in nature, large permittivity fluctuations exist
and the internal field inside an inhomogeneity can be different
from that of the background medium. For this reason, an SFT
was developed, which is able to account for large permittivity
fluctuations. The SFT is developed by taking into account the 248
singularity of the dyadic Green’s function. Both observation
and source points can coincide within the domain of integration,
meaning that the scatterers can act as a source of radiation. In
the SFT, an auxiliary permittivity (ε^s_{g}(r)) is introduced and the
scatterers with permittivity ε_{s}(r) (e.g., ice grains) embedded in
a medium with permittivity ε_{b} (e.g., air) are transformed into
dipoles embedded in a medium having permittivity ε_{g}. The low-

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III. RESULTS AND DISCUSSION

In this section, we compare the brightness temperatures 265
obtained with the four models for the six classes of snow and 266
analyze the spectral behavior of the extinction coefficients.

As stated, in order to compare the results of the four electro-
magnetic models, we consider six classes of snow described by
Sturm et al. [10]. The six different snow classes are the follow-
ing: PR, TU, TA, AL, MA, and EP. Each class is identified by a
unique ensemble of textural and stratigraphic characteristics
such as the sequence of snow layers, their thickness, density,
crystal morphology, and grain characteristics within each layer. 274
As three of the four electromagnetic models treat the snowpack 275
as a single layer (only MEMLS divides the snowpack into 276
multiple horizontal layers), it was necessary to derive the values
of snow parameters for each class from the values defined by 278
Sturm et al. in [10], by averaging the snow parameters along the 279
vertical profile. The averaged values are given in Table I. They 280
also represent the inputs given to the electromagnetic models. 281
As stated in the previous section, the relationship between mean 282
grain size and correlation length is not straightforward and the 283
values of correlation length reported in Table I are estimated 284
from the values of mean grain size and fractional volume by 285
means of the results reported in [12] and assuming spherical 286
ice particles.

A. Comparison of Brightness Temperatures

Fig. 1 shows the brightness temperatures at 19 and 37 GHz
computed by means of the TKK (continuous lines) and the 290
DMRT (dashed lines) models for the six classes of snow (left 291
axes). In the same figure, the differences between the brightness 292
temperatures computed by the TKK model and those computed 293
by the DMRT model (TKK–DMRT) at vertical and horizontal 294
Obtained results show that for observation angles between 0° and 60°, the TKK model tends to underestimate the brightness temperature with respect to the DMRT model, with the exception of the case for the TA snow class at 37 GHz. At 19 GHz and for an observation angle of 0° (nadir), the best matching is obtained in the case of the EP class (−1 K). The largest difference is obtained in the case of the TA class (∼ −18 K) while all remaining classes show difference values around −5 K. In the case of 37 GHz, for an observation angle of 0°, best matching cases are obtained in the cases of TA (∼ 0 K) and EP classes (∼ −2 K). Large differences are obtained in the cases of AL (∼ −18 K), MA (∼ −32 K), and TU (∼ −15 K) classes. The remaining case of PR class shows a difference value around −6 K. The differences between the TKK and DMRT at vertical-polarization results increase with the observation angle between 0° and 60°, while the values at horizontal polarization remain almost constant. For observation angles between 60° and 90°, an inversion in the trend is observed, and the differences between TKK and DMRT brightness temperatures increase with the observation angle.
Fig. 3. Comparison between SFT (continuous line) and MEMLS (dashed line) brightness temperatures and relative differences (lines with points) in the cases of (a) PR, (b) TU, (c) TA, (d) AL, (e) MA, and (f) EP snow classes.

Fig. 4. Differences between MEMLS and SFT (MEMLS–SFT) brightness temperatures at 0° (dark gray) and 50° (light gray) versus snow classes.

means of the TKK model. It is important to remind here that many observations are carried out at observation angles lower than 60° so that the results for cases of observations above 60° are not of interest for practical applications. Results also suggest that the differences at 0° are lower than or comparable to the differences at 50° (Fig. 2). In the case of 19-GHz vertical polarization, the difference between TKK and DMRT at 0° is relatively small, but it dramatically increases at 50°.

Fig. 3 shows the brightness temperatures (left axes) at 19 and 37 GHz computed by means of the SFT (continuous lines) and the MEMLS (dashed lines) models for the six classes of snow. The differences between the brightness temperatures computed by the MEMLS model and those computed by the SFT model (MEMLS–SFT) at vertical and horizontal polarizations are also reported on the right axes with stars representing the differences between the vertical polarizations and circles representing the differences between the horizontal polarizations. We observe that at 19 GHz, the SFT and MEMLS models produce very similar values of brightness temperatures in the cases of PR, AL, and EP snow classes, with absolute differences lower than 15 K. The remaining cases show absolute differences lower than 15 K. At 37 GHz, the results obtained in
the cases of TA and EP classes show good agreement (less than 5 K). In the cases of PR and AL classes, the maximum observed difference is around 10 K, while in the case of TU and MA, it can exceed 40 K. The differences between the MEMLS and SFT results show a weaker dependence with the observation angle than the results obtained with the TKK and DMRT models (Fig. 4). The difference is less sensitive to observation-angle variations. However, contrary to what happens in the case of the TKK and DMRT models, the difference between the vertical polarizations is more stable with the observation angle.

B. Comparison of the Extinction Coefficients

After comparing the brightness temperatures simulated by means of the four models, in the following, we show the comparison of the extinction coefficients obtained with the different approaches as a function of the frequency, ranging between 5 and 90 GHz. We perform this comparison in order to quantify the differences more directly related to the modeling of the electromagnetic quantities.

Fig. 5 shows the extinction coefficients, in decibels per meter, computed with the four models for the six classes of snow as a function of frequency. In the case of the two models using mean grain size as input (TKK and DMRT), we observe that the TKK model systematically provides values of the extinction coefficient much higher than those computed by the DMRT model. Obtained results support the idea that the different approaches used to describe the extinction characteristics results are responsible for the fact that the TKK model tends to underestimate the brightness temperatures with respect to the DMRT model. We would like to remark that the formula adopted for evaluating the extinction coefficient in the TKK model is based on the fitting of experimental data obtained from snow samples collected in different conditions while the approach in the DMRT is completely theoretical. The TKK model makes use of observations of optical grain-size values and relates them to the measured extinction coefficient, while the DMRT approach uses the effective grain size at microwave frequencies, which is the mean of a log-normal distribution describing the particles’ position.

The extinction coefficients calculated with the MEMLS and SFT models show a better agreement than those obtained in the cases discussed above. Best matches are obtained in the cases of PR, AL, and EP snow classes. In the cases of TU and MA, the difference between the extinction coefficients obtained with the two models increases with the frequency. It should be noted that the SFT model used here has a limitation on frequency (e.g., low-frequency limit). The value of frequency up to which the model is guaranteed to work correctly is 37 GHz, even if this value is not fixed and can change with the correlation-length value. Hence, the increase of the difference with the frequency observed in the cases of TU and MA could be due to the limitation on frequency of the SFT model. For each snow class, the simulated extinction coefficients are modeled by using

\[ k_{\text{ext}} = \alpha \cdot X^2 \cdot \text{freq}^\beta \]  

where X can be either the diameter D or two times the correlation length \( l \), and the coefficients \( \alpha \) and \( \beta \) are fitted with a 396 least square fitting method. Tables II and III show, respectively, the values of \( \alpha \) (Table II) and \( \beta \) (Table III) computed for the four snow classes and for the six snow classes. The values of \( \alpha \) in the case of the DMRT and TKK models are considerably different. The 400 values in the case of the TKK model are constant, according to the formula proposed by Hallikainen \textit{et al.} in [13]. Even if 402 different from those of the TKK model, the values of \( \alpha \) in the 403

<table>
<thead>
<tr>
<th>Snow class</th>
<th>MEMLS</th>
<th>SFT</th>
<th>TKK</th>
<th>DMRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>0.094</td>
<td>0.125</td>
<td>0.0018</td>
<td>0.4599</td>
</tr>
<tr>
<td>TU</td>
<td>0.095</td>
<td>0.2312</td>
<td>0.0018</td>
<td>0.4156</td>
</tr>
<tr>
<td>TA</td>
<td>0.094</td>
<td>0.0992</td>
<td>0.0018</td>
<td>0.4348</td>
</tr>
<tr>
<td>AL</td>
<td>0.097</td>
<td>0.1714</td>
<td>0.0018</td>
<td>0.5826</td>
</tr>
<tr>
<td>MA</td>
<td>0.093</td>
<td>0.1760</td>
<td>0.0018</td>
<td>0.5229</td>
</tr>
<tr>
<td>EP</td>
<td>0.092</td>
<td>0.3209</td>
<td>0.0018</td>
<td>0.8333</td>
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<table>
<thead>
<tr>
<th>Snow class</th>
<th>MEMLS</th>
<th>SFT</th>
<th>TKK</th>
<th>DMRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR</td>
<td>1.62</td>
<td>2.44</td>
<td>2.8</td>
<td>1.9602</td>
</tr>
<tr>
<td>TU</td>
<td>0.95</td>
<td>2.34</td>
<td>2.8</td>
<td>1.9672</td>
</tr>
<tr>
<td>TA</td>
<td>2.9636</td>
<td>2.301</td>
<td>2.8</td>
<td>2.019</td>
</tr>
<tr>
<td>AL</td>
<td>2.07</td>
<td>2.2538</td>
<td>2.8</td>
<td>1.9096</td>
</tr>
<tr>
<td>MA</td>
<td>1.7581</td>
<td>2.485</td>
<td>2.8</td>
<td>1.9095</td>
</tr>
<tr>
<td>EP</td>
<td>1.797</td>
<td>2.2218</td>
<td>2.8</td>
<td>1.8235</td>
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</table>
404 case of the DMRT model are almost constant. On the contrary, 405 the $\alpha$ coefficient changes with the different snow classes in 406 the cases of the MEMLS and SFT models. This could be due 407 to the fact that the relationship between mean grain size and 408 correlation length is not linear and other parameters (such as 409 fractional volume) could be involved in the relationship. Hence, 410 the parameter $\alpha$ may account for the nonlinearity and for the 411 dependence from other parameters.

412 The values of $\beta$ reported in Table III show that a strong 413 dependence with the frequency exists for the different snow 414 classes in the case of the DMRT model. The values of $\beta$ 415 are constant in the case of the TKK model, according to 416 Hallikainen et al. [13]. In the cases of the SFT and MEMLS 417 models, a variation of the coefficient is observed for the dif- 418 ferent classes, although these variations are much smaller than 419 those observed in the case of the DMRT model.

420 Understanding the observed discrepancies requires a more 421 detailed analysis of the hypotheses and equations within each 422 model. In general, it can be seen that the deviation in higher 423 frequency becomes large, because the high frequency is more 424 sensitive to the large coarser particle, refrozen ice layering, 425 etc., as already observed in [24]. This will be a subject of a 426 future study. However, here, we can advance some preliminary 427 hypotheses. The systematic underestimation (overestimation) 428 of the DMRT extinction coefficient (brightness temperature) 429 with respect to the TKK model could be related to the fact 430 that the DMRT takes into account the particle-size distribution 431 while the TKK model assumes that all particles within the 432 snowpack have the same size. As a consequence, in the case 433 of the DMRT model, there will be a number of particles that 434 will be smaller than the mean value (given as input to the 435 model), and hence, they will give a small contribution to the 436 extinction. It is interesting to note that the snow classes where 437 the difference between the outputs of the TKK and DMRT are 438 high (AL and MA) are characterized by high values of snow 439 depth. Eventually, high values of snow depth tend to enhance 440 the differences between the extinction coefficients simulated by 441 the two models. The differences between the SFT and MEMLS 442 models are high in correspondence of snow classes having 443 high values of fractional volume (TU and MA). Eventually, 444 the use of density in the regression formula used to calculate the 445 effective permittivity of dry snow in MEMLS could affect the 446 results. However, as stated, more investigation is required and 447 will be carried out in the future. In the following, the outputs of 448 the four models are compared with ground-based observations.

IV. COMPARISON WITH EXPERIMENTAL DATA

450 The results reported in the previous section show that the 451 four electromagnetic models can provide considerably different 452 results for different theoretical configurations of snow parame- 453 ters. In this section, we compare the outputs of the four models 454 with ground-based measurements of brightness temperatures in 455 order to understand the degree of agreement of the four models 456 when detailed snow-parameter measurements are used as in- 457 put data. Brightness temperature observations were collected 458 during the CLPX-1 (www.nohrsc.nws.gov/~cline/clpx.html). 459 During the CLPX-1, detailed snow-parameter measurements

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TABLE IV
SNOW-PIT DATA COLLECTED DURING THE CLPX AT THE LOCAL SCALE OBSERVATION SITE (LSOS) TEST SITE ON FEBRUARY 20, 2003 (IOP3)

<table>
<thead>
<tr>
<th>Height above ground [cm]</th>
<th>Density [kg/m³]</th>
<th>Temperature [°C]</th>
<th>Small grain size [mm]</th>
<th>Medium grain size [mm]</th>
<th>Large grain size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>139</td>
<td>-4</td>
<td>0.25</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>73</td>
<td>200</td>
<td>-7</td>
<td>0.2</td>
<td>0.45</td>
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</tr>
<tr>
<td>63</td>
<td>228</td>
<td>-8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>213</td>
<td>-6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>218</td>
<td>-5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>246</td>
<td>-3</td>
<td>1.25</td>
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</tr>
<tr>
<td>23</td>
<td>269</td>
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<tr>
<td>13</td>
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<td></td>
</tr>
<tr>
<td>3</td>
<td>n/a</td>
<td>-1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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TABLE V
SNOW-PIT DATA COLLECTED DURING THE CLPX AT THE LSOS TEST SITE ON MARCH 25, 2003 (IOP4)

<table>
<thead>
<tr>
<th>Height above ground [cm]</th>
<th>Density [kg/m³]</th>
<th>Temperature [°C]</th>
<th>Small grain size [mm]</th>
<th>Medium grain size [mm]</th>
<th>Large grain size [mm]</th>
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<tbody>
<tr>
<td>77</td>
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<td>291</td>
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SNOW PARAMETERS DERIVED FROM SNOW-PIT MEASUREMENTS AND USED AS INPUTS TO THE ELECTROMAGNETIC MODEL TO SIMULATE MEASURED BRIGHTNESS TEMPERATURES

<table>
<thead>
<tr>
<th></th>
<th>18.7 GHz</th>
<th>36.5 GHz</th>
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<tbody>
<tr>
<td></td>
<td>TKK</td>
<td>DMRT</td>
</tr>
<tr>
<td>CLPX-1, IOP3</td>
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<td></td>
</tr>
<tr>
<td>n (mm)</td>
<td>0.59</td>
<td>0.79</td>
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<tr>
<td>f</td>
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<tr>
<td>T_s [K]</td>
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<td>270.2</td>
</tr>
<tr>
<td>CLPX-1, IOP4</td>
<td></td>
<td></td>
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<tr>
<td>n (mm)</td>
<td>0.37</td>
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<tr>
<td>f</td>
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<td>0.3</td>
</tr>
<tr>
<td>T_s [K]</td>
<td>272.4</td>
<td>272.5</td>
</tr>
</tbody>
</table>

The inputs to the models were computed by dividing the snowpack into \( N \) layers having 10-cm thickness. For each layer, the recorded values of snow parameters were weighted according to the optical depth of the upper layers. The formula used is

\[
\langle SP \rangle = \frac{\sum_{i=1}^{N} A_i \sum_{j=1}^{i-1} -e^{-k_{e,j}d_j} - \cos(\theta_j)}{\sum_{i=1}^{N} \prod_{j=1}^{i-1} e^{-k_{e,j}d_j} - \cos(\theta_j)}
\]

with \( A_i \) given by

\[
\langle A_i \rangle = \begin{cases} 
  1 & i = 1 \\
  a_i & i > 1 
\end{cases} \prod_{j=1}^{i-1} e^{-k_{e,j}d_j} - \cos(\theta_j).
\]

\( N \) is the number of layers and \( k_{e,j}, d_j, \) and \( \theta_j \) are, respectively, the extinction coefficient, the thickness, and the observation angle in the \( j \)th layer. The thickness value of each layer in which the snowpack was divided is related to the snow-pit measurements, which were carried out every 10 cm. The values of averaged snow parameters are reported in Table VI.

Figs. 6–9 show the GBMR-7-measured versus simulated brightness temperatures at 18.7 GHz (Figs. 6 and 7) and at 36.5 GHz (Figs. 8 and 9). The results obtained with the TKK model are represented by squares, those with the DMRT with circles, those with the SFT model with stars, and finally, those with the MEMLS model are represented with triangles.

Results show that at 18.7-GHz vertical polarization, the brightness temperatures simulated by means of the MEMLS model on IOP4 agree well with measured brightness temperatures, although in the IOP3 case, the model tends to underestimate the experimental data. The DMRT model produces brightness temperatures comparable with the observed ones for the IOP4 data, but it underestimates the data collected during the IOP3. The TKK (SFT) model tends to slightly underestimate (overestimate) the data for both IOP3 and IOP4. At 18.7-GHz horizontal polarizations, the trend is similar to that observed in the vertical-polarization case. However, the values simulated by the TKK model are considerably close to those observed during the IOP4 periods.

At 36.5 GHz, the TKK model is able to well reproduce the measured brightness temperatures recorded during IOP3, but it tends to overestimate those acquired during the IOP4. The DMRT model well simulates the IOP4 bright-ness temperatures but it strongly underestimates the brightness temperatures.
temperatures collected during the IOP3. Both SFT and MEMLS models tend to overestimate the brightness temperatures collected during IOP3 and IOP4.

Figs. 9 and 10 show the percentage error between measured and simulated brightness temperatures averaged over all data at disposal from (a) IOP3 and (b) IOP4. Results show that the TKK is able to simulate the measured brightness temperatures with good accuracy for both IOP3 and IOP4, showing a maximum percentage error around 10%. The DMRT model is able to match well the brightness temperatures in the case of IOP4 data (maximum percentage error around 3%) but it shows a percentage error around 45% for the data collected during the IOP3. Both SFT and MEMLS show a low percentage error at 18.7 GHz (less than 5%) but the error at 36.5 GHz is between 15% and 20%. It is very important to remind here that care must be taken when comparing the results of the

V. SUMMARY AND SUGGESTIONS

Brightness temperatures at 19 and 37 GHz of different snow classes simulated by means of four different electromagnetic models (TKK, DMRT, SFT, and MEMLS) were compared in order to investigate how different models, widely used within the remote sensing community, simulate the electromagnetic response of snow-covered terrain when using the same inputs. All models have common inputs even if two of them require as input mean grain size (TKK and DMRT) and the remaining two require correlation length (SFT and MEMLS). Because of the

SFT and MEMLS models with experimental data. Indeed, the values of correlation length used as inputs to these models were estimated from the measured values of mean grain size and fractional volume. Hence, no measurement of correlation length was carried out, and a fraction of the error between modeled and measured brightness temperatures could derive from the not-well-known relationship between mean grain size and correlation length. We would like to point out that the results obtained for the two experimental data sets cannot be used to derive general considerations about which of the four models works better. Indeed, although the snow conditions during IOP3 and IOP4 were considerably different, they cannot be considered as representative of the variety of snow conditions that can occur worldwide. Comparing the results of the models with other data sets and with laboratory-controlled experiments could help to test the consistency of the results here obtained.
nonstraightforward relationships between mean grain size and correlation length, we separately compared the results from the models having mean grain size and correlation length as inputs. In the case of the TKK and DMRT models, the TKK model tends to systematically underestimate the brightness temperature with respect to the DMRT model for observation angles between 0° and 60°, with the exception of the case for the TA snow class at 37 GHz. At 19 GHz, the minimum difference between brightness temperatures is obtained in the case of the EP class (∼ −1 K). The remaining cases show a maximum absolute difference smaller than 8 K at the nadir. However, the difference increases as the observation angle increases, especially for the vertical polarization, reaching values around 20–25 K. At 37 GHz, small differences are obtained in the cases of TA (∼ 0 K) and EP classes (∼ −2 K) at the nadir. The remaining classes show differences ranging between 15 and 30 K. The differences between the TKK and DMRT results increase with the observation angle between 0° and 60° for the values of the vertical polarization, while they remain almost constant in the case of the horizontal polarization.

The brightness temperatures obtained with the SFT and the MEMLS models are generally closer to each other than those obtained in the case of the TKK and DMRT models. At 19 GHz, in the cases of PR, AL, and EP, the SFT and MEMLS models’ brightness temperatures show the best agreement with a maximum difference around 5 K, with the remaining cases showing absolute differences lower than 15 K. At 37 GHz, the results obtained in the cases of TA and EP classes show good agreement with absolute differences smaller than 5 K. In the cases of PR and AL classes, the maximum observed difference is around 10 K, and in the cases of Tundra and Maritime, it can exceed 40 K. The differences between the MEMLS and SFT results show a weaker dependence with the observation angle than that observed in the case of the TKK and DMRT models. The difference between the vertical polarizations is less sensitive to observation-angle variations than the difference between horizontal polarizations, contrary to what happens for the differences observed with the remaining two models.

The behavior of the extinction coefficients simulated with the different models as a function of frequency was also studied. Results show that the TKK model overestimates the extinction coefficient with respect to the DMRT model. In the case of the SFT and MEMLS models, a better agreement between the extinction coefficients was observed. The spectral behaviors of the simulated extinction coefficients were fitted by means of a function as the square of the mean grain size (correlation length) times a power of the frequency. The coefficients to be determined by the fitting procedure were the scaling factor and the power of the frequency. Results show that the scaling factors in the cases of the TKK and DMRT models do not change significantly with the snow classes, meaning that there is no dependence from the grain size and frequency. On the contrary, in the cases of the SFT and MEMLS models, these coefficients are not constant. The fact that the relationship between mean grain size and correlation length is not linear and that it might depend from other snow parameters, such as density, can be among the reasons of the observed variations. All extinction coefficients show an almost stable frequency dependence with the exception of the one computed by means of the DMRT. In this case, strong variations of the coefficients of the power function are observed for the different snow classes.

Brightness temperatures simulated with the four models when driven with snow input parameters derived from snow-pit data were compared with those measured by the GBMR of the University of Tokyo during the CLPX-1. The TKK model was able to simulate the measured brightness temperatures with good accuracy for both IOP3 and IOP4. The DMRT model was able to match well the brightness temperatures collected during the IOP4 data but not during the IOP3. Brightness temperatures measured with the SFT and MEMLS models show a good matching with experimental data at 18.7 GHz. However, the performance of the models deteriorated at 36.5 GHz. These results cannot be used to generalize the capabilities of one of the models to reproduce experimental data as more comparison experiments, eventually from laboratory-controlled experiments, must be performed.

Further studies and investigations are required to understand the conditions under which the different considered electromagnetic models can provide matching simulations of brightness temperatures. From this paper, we can identify three major issues to be resolved to help in understanding more deeply the causes of the observed differences among the results of the four models. First, it is important to better understand the relationships relating mean grain size and correlation length in order to compare the results of the models making use of the mean grain size as inputs with those of models making use of the correlation length. The second issue is with regard to the number of layers in which the snowpack can be divided. It is desirable that all models could make use of multiple layers to model the brightness temperatures of snowpacks. This would avoid the operation of averaging measured snow parameters along the vertical profile to derive the inputs to the single-layer models, reducing the degree of error introduced by the averaging process. The final issue is with regard to experimental data. In order to reduce the uncertainty related to snow measurements (e.g., mean grain size of nonspherical particles, distribution of grain size, stratigraphy, and soil electromagnetic effects), it is required that controlled laboratory measurements be performed on materials with well-known electromagnetic properties. These data would provide precious information about the values of brightness temperatures and/or extinction coefficients, which can be considered as a reference for deciding which of the models must be improved and which changes must be operated.

ACKNOWLEDGMENT

The authors would like to thank Prof. Mätzler (University of Bern, Switzerland), Prof. Pulliainen and Prof. Hallikainen (TKK), Prof. Jin (Fudan University, Shanghai), and Prof. Tsang (University of Seattle, WA) for providing some of the computer codes used for this paper and for fruitful discussions. They would also like to thank Dr. T. Graf and Prof. Koike (University of Tokyo) for the GBMR-7 data, and J. Hardy (CRREL) for the snow-pit data.
REFERENCES


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