Dr. Nina Kirchner, Editor

Geoscientific Model Development

Subject: Revision submission

Dear Dr. Kirchner,

We thank you for handling our manuscript " MEMLS3&a: Microwave Emission Model of Layered Snowpacks adapted to include backscattering". Please find below our detailed replies to the comments by the Referees. We refer, where appropriate, to the marked-up manuscript.

We would like to express our sincere thanks to editors and reviewers for the detailed comments, which improved clarity and eliminated many larger and smaller errors.

Best regards,

Martin Proksch

on behalf of all authors

Answers to Referees

Below we address each point raised be the Referees in detail with our replies in blue and the *corrected/new text highlighted in green both in the replies below and in the revised manuscript.*

Anonymous Referee #1

General Comments: The topic of this article is a sophisticated model for simulating microwave emission and scattering of snow, which very well balances theoretical issues and practical handling. Such simulation models are essential when developing remote sensing technologies for continuous retrieval of snow properties over larger regions. Although the article is directly related to snow covers on land surfaces, it is useful also for snow on sea ice and for snow/firn of the ice sheets. The paper is very well written and structured and should definitely be published. I have only a few minor comments and questions.

We thank the reviewer for the constructive review and comments, which helped to improve the manuscript.

Specific comments

Page 2611, line 4: assumption of Lambertian reflectance: The intensity of surface scattering from ice and snow may reveal a dependence on the observer's zenith angle.Is the assumption of Lambertian reflectance (i. e. the apparent brightness of a surface does not depend on the observation angle) realistic in all cases? If not, what does this mean for the model simulations? (The text on page 2612 lines 15-19 implies that the Lambertian behavior is a consequence of the dominance of volume scattering?) Please comment.

In the model we divide specular and diffuse reflectivity. The diffuse part is indeed assumed as a consequence of volume scattering. The specular part is assumed as a consequence of specular reflections at the snow-ground interface, at the layer interfaces and at the snow-air interface. The recurrence relation of eq. 14 accounts for all these processes and finally eq. 15 gives the reflectivity of the entire snowpack-ground system. In this respect, the model is not only Lambertian. Further, the simulated brightness temperatures depend on the incidence angle as shown in Fig. 9, 10, 13.

Page 2612, line 9: How is the constant S_0 determined?

Page 2612, line 11: S_0 = 4 r_d

Page 2613: Equation 9 is the "geometric optics" (GO) model (Ulaby p. 983). The Physical Optics or Kirchhoff formulation (Ulaby p. 925-926) includes both GO and the scalar approximation.

We changed the sentence to:

"This equation corresponds to the geometrical-optics solution for undulating surfaces…"

Section 2.2. For a reader not familiar with passive radiometry one should mention how two different values of T_sky can be obtained in real measurement scenarios? (Referring to section 4.1.3 – use of measurements acquired at different air temperatures?)

In a real measurement scenario T_sky could be obtained as outlined in section 4.1.3. from radiometer measurements. Section 2.2 is only meant to derive the reflectivity r from brightness temperatures Tb1,Tb2 which were simulated for two arbitrary sky temperatures Tsky1, Tsky2, i.e. Section 2.2 does not require any measured T_sky values.

Page 2619, line15: Wasn't the snow temperature directly measured during the field measurements?

Due to time constrains, the snow temperature was not measured directly in the snow pit, but the taken from an automatic snow temperature measurements at the test site.

Page 2620, line 1: referring to the selection of the value of the frozen ground permittivity in line with Rautiainen et al. (2012) – the title of the Rautiainen-article suggests that the permittivity is valid at L-band, whereas here simulations are carried out at much higher frequencies?

Correct, the permittivities of Rautiainen were derived from L-band measurements. However, the frequency dependence of the frozen soil permittivity is not well known and therefore we used the Rautiainen et al., 2012 value as best guess.

Page 2621, Fig. 7 and Fig. 8: the latter repeats the results for CT-input already shown in Fig. 7? I would suggest to remove the CT-result from Fig. 7 and to mention that Fig. 8 specifically shows the "best" result.

A crucial part to model microwave emission/ backscatter is the derivation of the necessary input parameters. We wanted to show different methods how this can be done for MEMLS3&a, and also how those different methods compare then in terms of backscatter values. Therefore we think Fig.7 is useful and should contain the CT results, even if it is duplicated in Fig. 8.

Why did you select an incidence angle of 50° for this examples? Most satellite radar measurements are typically in the range between 25° and 40°.

50° is a standard value for radiometry. We wanted to compare the active and passive data at the same angle. For scatterometers, this corresponds to a common value, too (the fact that some radars are limited to smaller incidence angle is mainly due to technical limitations and not for physical reasons).

Page 2622, lines 3-5: The variations of the backscattered intensity due to fading can be estimated. Considering that the number of independent looks seems to be close to 40, the variations of the backscattering coefficient should be rather small. Can the authors definitely exclude variations of snow and ground properties? Looking at the results e. g. shown in Figs 9 and 10, this should be discussed more carefully.

We agree with the reviewer and added a comment about the influence of spatial variability:
The SnowScat observations at different incidence angles show a certain amount of scatter, which we attribute to the heterogeneity of the ground and snowcover at the test site.

Page 2624: I am somewhat uncertain whether I agree that the simulations are in "good" agreement with the SnowScat observations. Maybe "reasonable" is a better word, considering the results shown in Figs. 9 and 10, and also the problems with unknown input parameters (q, m, microstructure correlation function, frozen ground characteristics…)

We agree with the referee and changed the corresponding paragraphs.

Discussion: It would be useful to get an impression concerning the individual magnitudes of the surface/interface and the volume contribution (in particular for the case of dry snow).

We agree to the referee and included the following figure and text in the discussions on page 2625, line 12 ff.:

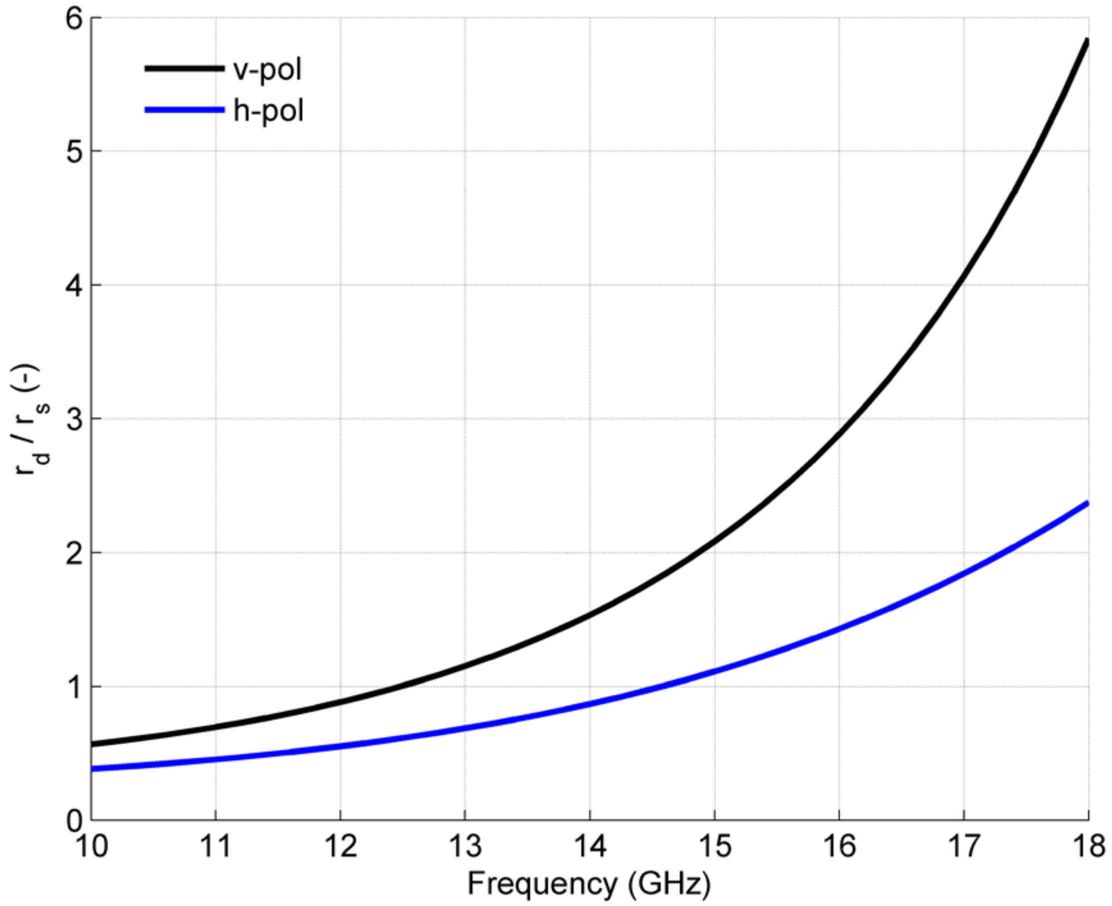


Fig: 16: Ratio of the simulated diffuse (r_d) and specular (r_s) reflectivity at 50° incidence angle per frequency, for the best fit parameters according to Fig 8.

The individual magnitudes of the specular and diffuse contributions are shown in Figure 16. Towards higher frequencies the diffuse component increases and outweighs the specular reflectivity from 12.5 GHz for v-pol and from 14.5 GHz for h-pol. Note that the magnitude of the specular component also depends on the undulation of the surface and therefore on the value of m. However, a pronounced impact of m is limited to small incidence angles (Fig. 13 and section 4.2.2) for reasonable values of m (m ~ 0.1).

Is the correlation length really a much better characteristic for quantifying the snow microstructure? The advantages of this approach are well described in the discussion (p. 2627) but I wonder whether situations may occur in which the knowledge of grain size distributions and grain cluster characteristics are better quantifiers of the snow microstructure, at least with regard to microwave scattering (theoretical scattering models based on the permittivity's correlation function also have limitations).

The correlation function is a classic descriptor of porous media (e.g. Torquato 2002, Löwe et al., 2011) such as snow. Models of grain size distributions would need at first a precise definition of grain size, which is often not congruent to what the microwave models use as microstructure length scale. In this respect, the correlation length/function provides an attractive starting point, as it is exactly the same parameter used in the model which is measured in the field. Correlation length can also be used to derive a second length scale (e.g. using the Teubner-Strey form) which then could be used to account for effects like "clustering". A particular advantage of MEMLS3&a is that different types of correlation function could be included in the model by adapting the calculation of the scattering coefficient

Anonymous Referee #2

The author provides a clear detailed review of MEMLS3&a model. The extension of including the backscattering is documented with formulation, parameters setup and validation. In general, the paper is well written and the code provided is very useful to reproduce the results in the paper. However, there are still a few elements need to be elaborated and explained.

We thank the reviewer for the constructive review and comments, which helped to improve the manuscript.

1. Figure 13 needs more explanation. On page 2622, line21, the statement " The effect of m is limited to small incidence angles: : :" only explains the curves of m = 0.05 and m = 0.1. When m increase to 0.25, there is a dramatically change over 30-50 degree. However, compared to the SnowScat measurement, it seems when the MEMLS model match well with small m setting. Is that mean a smooth surface is sufficient for the match-up?

We agree that the formulation "The effect of m is limited to small incidence angles..." is not correct with respect to Figure 13 and deleted it. Page 2622, line21 now reads: *"A larger value of m represents a stronger undulated surface and increases the spectral component of the backscatter, in particular at small incidence angles. Fig. 13 shows this behavior, with increasing backscatter for increasing values of m and decreasing incidence angles. Given values smaller than 0.1, m has no effect at incidence angles larger than 25°. Further, cross polarization is in general not affected by m. Note that… "*

However, m is currently an empirical parameter, introduced to calculate specular backscatter from a slightly undulated slope, but remains a free parameter in the model so far. In principle, a "physical" value for m could be obtained from a detailed analysis of the snow surface (page 2625, line 3-10), and the values given in the literature (0.14) and used in this paper (0.1) are similar, but the relation between this "physical" or measured m and the m required by the model is not clear. As such, we can't really state that a smooth surface is sufficient for the match-up, but only that small values of m are sufficient.

2. The soil backscattering contribution can be significant in the lower frequency. It will be very helpful to include a sensitivity analysis of the soil permittivity in a reasonable range for frozen ground instead of a fix number of 3.6 + 0.9i.

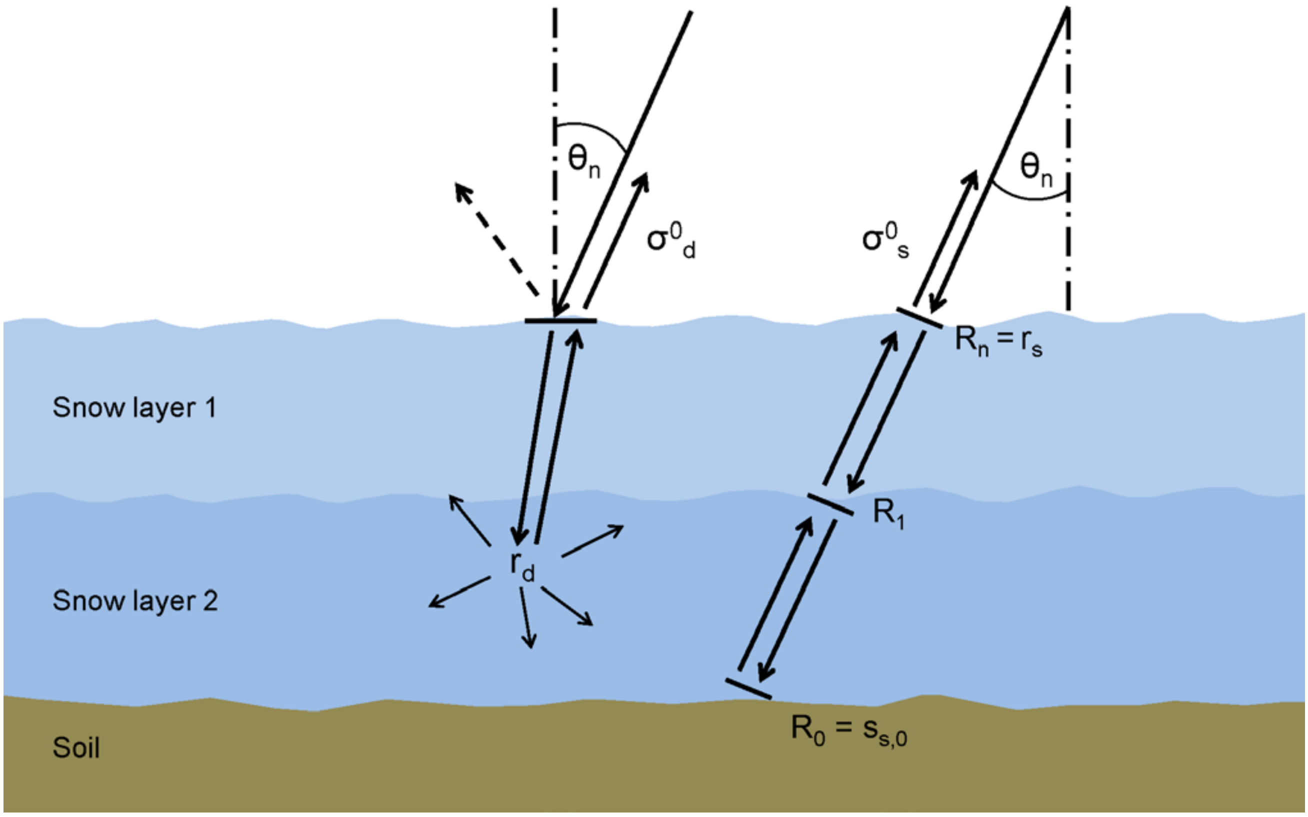
We agree that the soil contribution in the lower frequency limit can be significant. However, we used a value derived from a study (Rautiainen et al., 2012) which was dedicated to derive soil permittivity, which lies in the range of previously published values. Our approach was not to treat the soil permittivity as optimization parameter, as for the soil type in Sodankylä measurements (e.g. Hallikainen et al., 1985) and retrievals (e.g. Rautiainen et al., 2012) for the permittivity were available.

3. In the model results, the vv is always slightly higher than hh. However, the SnowScat data shows more variability of the vv/hh ratio. Please provide some insights for both model results and data analysis.

We attributed the high variability in the SnowScat signal in general to the heterogeneity of the ground and snowcover at the test site (see also Referee 1, comment on page 2622, lines 3-5). In particular Figure 9 and 10 show a variable backscatter signal measured by SnowScat when the incidence angle and therefore the measurement location is changed. The model runs, however, were only preformed for one pit and cannot contain variability. The effect of the spatial variability on microwave emission is demonstrated in Figure 14 and section 4.2.3. However, a more detailed discussion of the variability of the vv/hh ration was not a particular subject of the paper.

4. In the figure 1, it will be more clear to mark the rs, rd in the plot as well as the sigma0, sigma_d from both snow-air and snow-ground interface.

We agree and included the parameters in Figure 1 and modified the caption accordingly:



Snowpack (blue) with slightly undulated snow surface and layers.Waves incident at nadir angle θ_n are refracted at the snow surface followed by volume scattering with backscatter σ_0d (left); Specular backscatter σ _0 s from a slightly tilted patch of the surface, soil and layer interfaces (right). Diffuse r_d and specular reflectivities r_s = R_n, R_0 and R_1 are indicated.

5. In the backscattering plot, figure(7-13), it's more common to use dB as the unit for backscattering. I suggest to convert the y-axis into dB scale for better illustration and cross-comparison with other papers.

In order to relate the data to radiometry we used a linear scale. However, we agree that the cross-comparison to other paper is enhanced by using dB but in this study we only focused on the performance of the model and not on an intercomparison of models.

6. In equation (9), what is sigma_n refer to?

We could not find sigma_n in eq.9.
θ_n is the zenith angle, with μ_n = cos (θ_n), as defined on page 2610 line 21.

References:

Hallikainen, M., Ulaby, F., Dobson, M., El-Rayes, M., and Wu, L.: Microwave dielectric behavior of wet soil – Part 1: Empirical models and experimental observations, IEEE T. Geosci. Remote, 23, 25–34, 1985

Löwe, H., Spiegel, J. K., and Schneebeli, M.: Interfacial and structural relaxations of snow under isothermal conditions, J. Glaciol., 57, 499–510, doi:10.3189/002214311796905569, 2011

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Torquato, S.: Random Heterogeneous Materials, Springer, New York, 2002