Microwave Signatures of Snow on Sea Ice: Modeling

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Abstract—Accurate knowledge of snow-depth distribution over sea ice is critical for polar climate studies. Current snow-depth-over-sea-ice retrieval algorithms do not sufficiently account for variations in snow and ice physical properties that can affect the accuracy of retrievals. For this reason, airborne microwave observations were coordinated with ground-based measurements of snow depth and snow properties in the vicinity of Barrow, AK, in March 2003. In this paper, the effects of snowpack properties and ice conditions on microwave signatures are examined using detailed surface-based measurements and airborne observations in conjunction with a thermal microwave-emission model. A comparison of the Microwave Emission Model of Layered Snowpacks (MEMLS) simulations with detailed snowpack and ice data from stakes along the Elson Lagoon and the Beaufort Sea and radiometer data taken from low-level flights using a Polarimetric Scanning Radiometer (PSR-A) shows that MEMLS can be used to simulate snow on sea ice and is a useful tool for understanding the limitations of the snow-depth algorithm. Analysis of radiance data taken over the Elson Lagoon and the Beaufort Sea using MEMLS suggests that the radiometric differences between the two locations are due to the differences in sea-ice emissivity. Furthermore, measured brightness temperatures suggest that the current snow-depth retrieval algorithm is sufficient for areas of smooth first-year sea ice, whereas new algorithm coefficients are needed for rough first-year sea ice. Snowpack grain size and density remain an unresolved issue for snow-depth retrievals using passive-microwave radiances.

Index Terms—Advanced Microwave Scanning Radiometer (AMSR), microwave, modeling, polar regions, remote sensing, sea ice, snow.

I. INTRODUCTION

At any given time, sea ice covers approximately 25 million km² of the Earth’s surface. Thus, it greatly affects the energy and mass flux between the ocean and atmosphere and plays a crucial role in the polar climate. Snow on sea ice significantly augments these effects due to its insulative properties [6], [11], [17], [21]. Passive-microwave remote sensing techniques have been shown to be effective for snow-depth retrievals over land and sea [2], [3], [8], [10], [12]. The advantage of this approach is the continuous temporal and spatial coverage that is achieved with passive-microwave satellite-based observations. Although not specifically designed for snow applications, the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave/Imager (SSMI) have been utilized for this purpose. In 2002, the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) was launched onboard Aqua. This instrument provides even finer spatial resolution than that of the SSMI (about 12.5-km resolution) and should improve snow-depth retrievals [4], [9].

Markus and Cavalieri [12] developed a snow-depth-over-sea-ice retrieval algorithm using SSM/I, based upon the different scattering efficiencies of snow particles at 19 and 37 GHz. Brightness temperatures decrease approximately linearly with increasing snow depth (at both polarizations). The effect of scattering decreases with increasing wavelength so that brightness temperatures at 37 GHz are reduced more than brightness temperatures at 19 GHz with increasing snow depth. Generally, the greater the difference between 37 and 19 GHz, the greater the snow depth that is assumed to be present. However, other snowpack properties can greatly alter the scattering signal and thus affect the accuracy of the retrieval. Particularly important to the scattering of microwave emission are the size of the snow grains, the density, snow wetness, and layering of the snowpack. Also important to snow-depth retrievals over sea ice is the type of underlying ice. This determines the amount of radiation that is emitted and subsequently scattered by the snow layer. Snow-depth retrieval algorithms that take snowpack properties and sea-ice emissivity into account should greatly improve the accuracy of snow-depth retrievals from passive-microwave data.

In March 2003, seven aircraft flights over the Alaskan Arctic were carried out as part of the AMSR-E validation campaign [1]. The focus of this paper is on the flights over the Elson Lagoon and the Beaufort Sea. The main instrument on the NASA P-3 airplane was the NOAA Environmental Technology Laboratory (ETL)/Polarimetric Scanning Radiometer (PSR-A and PSR-CX), which has the same frequencies as the AMSR-E sensor (see Table I). Two of the flights were coordinated with extensive ground observations consisting of snow-depth measurements and detailed measurements of the snow and ice physical properties at selected locations (stakes) for the purpose of validation/Improvement of AMSR-E retrievals [15], [23]. Snow measurements were taken along the two transects in 25-m
For each PSR data point, the elevation of the Elson line and begins 8.6 km from the initial Elson data point. The Beaufort line is a continuation of the Elson line and ends about 11 km. The Beaufort line is a continuation of the Elson line and begins 8.6 km from the initial Elson data point. To mitigate geolocation inaccuracies and to correct for aircraft altitude, the PSR was operated with a fixed beam position. To maintain an elevation of 500 ft with a resolution of about 30 m. At this altitude, the PSR was operated with a fixed beam position. To mitigate geolocation inaccuracies and to correct for aircraft drift, these transects were overflown several times. The lines extend for about 11 km. The Beaufort line is a continuation of the Elson line and begins 8.6 km from the initial Elson data point. For each PSR data point, the in situ snow depth was recorded. Details of the field experiment can be found in [29].

In order to better understand the impact of various snow and ice conditions on snow-depth retrievals over sea ice, we conduct a study of microwave signatures using a thermal microwave-emission model for snowpacks in conjunction with surface measurements of snowpack properties and passive-microwave data taken over the Alaskan Arctic. The snowpack emission model, Microwave Emission Model of Layered Snowpacks (MEMLS), is described in Section II, followed by a brief summary of the sensitivities of the model to various snowpack properties with respect to snow-depth retrievals (Section III). The effectiveness of the model to simulate snowpack conditions at several different stakes using surface measurements of snowpack properties and microwave measurements using PSR-A that were taken from low-level flights over the Elson Lagoon and the Beaufort Sea is presented in Section IV. This is followed by an analysis of the microwave emission and snowpack and ice conditions for the entire flight path (line) over the Elson Lagoon and the Beaufort Sea using the snowpack model (Section V). Conclusions are summarized in Section VI.

### II. Model Summary

The microwave-emission model used in this paper is MEMLS [24]. It is a thermal microwave-emission model that is based on radiative transfer theory, taking multiple volume scattering (both by stratification and by granular snow structure) and absorption into account. It includes a combination of coherent and incoherent superpositions of different scattering contributions. The snow cover is considered as a stack of horizontal planar layers characterized by the correlation length (a measurement of grain size), density, temperature, and liquid-water content. Internal volume scattering is accounted for by a six-flux model (streams in all space directions, i.e., six fluxes streaming along and opposed to the three principle axes). The horizontal fluxes represent trapped radiation due to the total internal reflection (the internal incidence angle is larger than the critical angle for total reflection). This homogeneity in the horizontal directions reduces to the two-stream model (up- and downwelling radiation), where the two-stream absorption and scattering coefficients are functions of the six-flux parameters. The scattering coefficient is a function of correlation length, density, and frequency, while the absorption coefficient is a function of density, frequency, and temperature. The total emissivity (snowpack and substrate) for horizontal and vertical polarizations is calculated similar to that of Wiesmann and Mätzler [24]. MEMLS has been shown to be effective in simulating emissivities from layered snowpacks over land [19], [20], [25]. It forms part of a combined land–surface–atmosphere microwave-emission model for radiometry from satellites [30].

As previously mentioned, MEMLS characterizes the size of the snow particles within a snow layer by correlation length, which is a measure of the grain size. Grain size, $D_{\text{max}}$, is typically regarded as the maximum extent (diameter) of the prevailing grains in a snowpack, while the correlation length $p_c$ is a measure of the surface-to-volume ratio of equivalent spheres. There is a relationship between the two if the prevailing grains are spherical in shape. For a spherical snow particle, Mätzler [18] suggests the relationship to be

$$p_c = \frac{2}{3} D (1 - v)$$

where $v = (\rho_s / \rho_i)$ is the volume fraction of ice ($\rho_s$ is the density of the snowpack and $\rho_i = 917 \text{ kg} \cdot \text{m}^{-3}$ is the density of sea ice) and $D = D_{\text{max}}$. For other shapes, the two parameters are not directly related. A typical range in grain size and correlation lengths could be $0.2 \leq D \leq 3 \text{ mm}$ and $0.04 \leq p_c \leq 0.3 \text{ mm}$ (ranging from newly deposited snow to very large depth hoar snow particles), respectively.

<table>
<thead>
<tr>
<th>Frequencies [GHz]</th>
<th>10.65</th>
<th>18.7</th>
<th>36.5</th>
<th>89.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>0.876</td>
<td>0.888</td>
<td>0.913</td>
<td>0.886</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.924</td>
<td>0.941</td>
<td>0.955</td>
<td>0.926</td>
</tr>
</tbody>
</table>

Fig. 1. Flight paths over the Barrow vicinity (including the Elson Lagoon and the inner Beaufort Sea). The Elson and Beaufort flights were flown from Fairbanks International Airport, AK, on March 13, 2003.
The main input parameters to the model, besides frequency and incidence angle, are the surface reflectivity and for each layer, the thickness, temperature, density, and correlation length of the snow grains. MEMLS simulations are run with an incidence angle of 55°, which is identical to the incidence angle of AMSR-E and close to the SSM/I and SMMR instruments. Surface reflectivities \( r \) (i.e., the reflectivities at the snow/ice interface) are derived from Eppler’s [5] first-year sea-ice emissivities \( \epsilon \), assuming \( r = 1 - \epsilon \) (neglecting transmissivity). Table I gives the AMSR-E microwave frequencies and horizontal and vertical first-year sea-ice emissivities.

III. MEMLS Sensitivity to Snowpack Properties

Single-layer MEMLS simulations are run using different snowpack densities, correlation lengths, and snow depths to examine the general sensitivities of the model to these snowpack properties and their impact on snow-depth retrievals. Snowpack densities are in the range of 100–400 kg · m\(^{-3}\) in increments of 100 kg · m\(^{-3}\), while correlation lengths equal 0.03, 0.10, 0.20, and 0.30 mm. A surface temperature of 250 K is used for each simulation.

Fig. 2 shows the modeled spectral gradient ratios (GRs) of the vertical polarization for 37/19- and 19/10-GHz channels plotted against snow depth for different densities and correlation lengths. The spectral GRs are calculated as

\[
\text{GR}^p(\nu_1/\nu_2) = \frac{\epsilon^p(\nu_1) - \epsilon^p(\nu_2)}{\epsilon^p(\nu_1) + \epsilon^p(\nu_2)}
\]

where \( \text{GR}^p \) is the spectral GR for a certain polarization \( p \) and \( \epsilon \) is the emissivity for a particular frequency \( \nu \). The brightness temperatures for individual frequencies can be substituted for the emissivities in the equation due to the negligible sky radiation in the Arctic. The spectral GR for 37/19 GHz (corrected for ice concentration) is used in the current snow-depth-overflow-sea-ice retrieval algorithm [14].

Overall, less negative GRs correspond to smaller snow depths, smaller correlation lengths, and/or higher densities, while more negative GRs correspond to larger snow depths, larger correlation lengths, and/or smaller densities. This plot shows the relative importance of correlation length over density to the sensitivity of the spectral GR using MEMLS. For
example, a change in density from 400 to 100 kg·m⁻³ results in a decrease of −0.16 for GR V (37/19), while a correlation length change from 0.03 to 0.30 mm results in a decrease of −0.19 for GR V (37/19). This is the maximum change for density and correlation length.

Generally, the correlation length and density are smallest on deposition and grow over time, depending on environmental conditions so that the two processes (correlation length growth and densification) play against one another; correlation length growth causes the GR to become less negative, while densification of a snowpack causes the GR to become less negative. Both processes can affect the accuracy of snow-depth retrievals. For example, given a single-layer snowpack that is 20 cm deep with a density of 200 kg·m⁻³, a correlation length change from 0.12 to 0.15 mm results in a change of ΔGR V (37/19) = −0.022 and would thus cause an overestimate of snow depth of 20 cm. Such an overestimate would also occur for a density change from 200 to 100 kg·m⁻³ with ρc = 0.12 mm and 20 cm of snow. For snow depths greater than about 50 cm, the 37-GHz channel becomes saturated (i.e., no further decrease in emissivity) due to the limited penetration depth at this frequency. This upper limit of 50 cm is in agreement with previous studies, e.g., Kunzi et al. [10] and is a shortcoming of the current snow-depth algorithm. However, the 19-GHz emissivity and consequently GR V (19/10) continue to decrease for snow depths of up to 100 cm, as illustrated in Fig. 2. This suggests that this combination of frequencies may be used to retrieve deeper snow, as suggested by Markus et al. [13].

IV. RESULTS OF MEMLS SIMULATIONS OF STAKES IN THE ELSON LAGOON AND THE BEAUFORT SEA

In order to use MEMLS as a tool for studying the impact of snowpack properties on microwave signatures and hence snow-depth retrievals, we evaluate the effectiveness of MEMLS in simulating different snowpacks over sea ice. Detailed measurements of snowpack properties taken from stakes in the Elson Lagoon and the Beaufort Sea are input into MEMLS. The model results are compared with the coincident PSR-A data. There are seven stakes in the Elson Lagoon and four stakes in the Beaufort Sea. The stakes are separated by about 1 km and are measured in distance from the first observation point on the Elson line (−156°33′13.5″ longitude and 71°18′33.7″ latitude). The Beaufort line is a continuation of the Elson line and has its first stake at 8.92 km. Around each stake, data were taken from several pits that are separated by 25 m (with the farthest being 100 m). The snow properties that were recorded for each snow layer and at each pit (pertinent to this paper) include the number of snow layers, prevailing snow-particle grain size (long and short dimensions), layer density, layer thickness, snow/ice interface temperature, and surface temperature. It should be mentioned that measuring snow properties over sea ice is very difficult. Romanov [22] describes snow parameters measured on sea ice from aircraft landings on the Arctic pack ice from 1928 to 1989. After landing, the snow depth was measured at 10–20 random points and on characteristic forms of ice-surface terrain (including level ice, frozen melt ponds, and ridges). The wide range in snow depths found (as much as 30 cm) at various landings on the sea ice indicates the need for many measurements in order to obtain a representative sample. The snowpack properties measured at each stake and surrounding pit can be directly input into MEMLS, except the correlation length since this information is in the form of long and short grain sizes. Spherical snow particles are assumed throughout this paper; thus, (1) may be used with a slight modification (shown later in the text) to determine the correlation lengths from the in situ grain-size data. Tables II and III give the surface and snow/ice interface temperatures input into MEMLS for each pit at each particular stake for the Elson and Beaufort lines, respectively. Fig. 3 shows the snow depths, densities, grain sizes, and correlation lengths at each pit (in different colors). The pit averages and 50-m-averaged snow depths are also shown. The snow depths are averaged every 50 m in order to smooth the data for analysis. The correlation lengths are determined using (1), except that the constant is changed from 2/3 to 2/10. Using the original constant resulted in unrealistically large correlation lengths that when input into MEMLS resulted in erroneous brightness temperatures (much too low when compared with the PSR-A data). Using 2/10 results in realistic correlation lengths and brightness temperatures. The variability in snow properties between pits, which are separated by at most 100 m, is extremely large. At each stake, snow depths for individual pits can vary up to 25 cm, snow densities can vary up to 50 kg·m⁻³, and grain sizes can vary by 0.5 mm. Table IV gives the averages for the snow properties for the Elson and the Beaufort stakes individually and combined. Overall, the Beaufort stakes have deeper snow, larger grain sizes (correlation lengths), and smaller densities than the Elson stakes. The 50-m-averaged snow depths fall within the range of the pit snow depths and agree well with the pit averages.

The detailed snow properties (thickness, density, correlation length, and surface temperature) for each layer and at each pit are input into MEMLS. The resulting snowpack emissivities for each polarization are converted to brightness temperatures using the snow/ice interface temperature at each stake.

Fig. 4 shows the MEMLS simulated brightness temperatures for each pit (in different colors) at each stake along the Elson and the Beaufort lines. The pit averages and the closest
POWELL et al.: MICROWAVE SIGNATURES OF SNOW ON SEA ICE: MODELING

Fig. 3. Snow depth, density, grain size, and correlation length from seven stakes along the Elson line (<8 km) and four stakes along the Beaufort line (>8 km). Pits are measured in meters from each stake and are marked by different colors. Fifty-meter averages of snow-depth data are included (circles). Pit averages are weighted by the thickness of the layer (triangles). The distance for each stake is measured from the start of the Elson Line. The Beaufort line begins at a distance of 8.6 km.

TABLE IV
AVERAGED PIT DATA FOR THE ELSON AND BEAUFORT STAKES INDIVIDUALLY AND COMBINED

<table>
<thead>
<tr>
<th></th>
<th>Snow depth [cm]</th>
<th>Density [kg m(^{-3})]</th>
<th>Correlation length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elson</td>
<td>16.5</td>
<td>333</td>
<td>0.081</td>
</tr>
<tr>
<td>Beaufort</td>
<td>26.9</td>
<td>280</td>
<td>0.114</td>
</tr>
<tr>
<td>Combined</td>
<td>20.3</td>
<td>314</td>
<td>0.099</td>
</tr>
</tbody>
</table>

PSR-A brightness temperature (50 m averaged) for each stake are shown for comparison. Overall, the Elson simulated brightness temperatures agree with the PSR-A data; however, the MEMLS brightness temperatures are lower than the PSR-A data, particularly for the 10- and 19-GHz channels. This bias can be corrected for by adjusting the MEMLS simulated brightness temperatures upward. The Beaufort simulated brightness temperatures decrease with distance. This does not occur in the PSR-A data. The rather large differences in the Beaufort, PSR-A, and MEMLS brightness temperatures may be due to the sea-ice emissivities input into MEMLS. If the underlying ice emissivities used in MEMLS are too low, then the resulting emissivity from the snowpack will be too low. This appears to be the case in these simulations. While it is true that the ice in the Elson Lagoon and the Beaufort Sea is first-year sea ice, the emissivities will likely vary from Eppler’s [5]. This is because the ridging and surface roughness of the ice can change the emissivity. The Elson Lagoon has very smooth undeformed ice because it is sheltered from the open sea by land, while the Beaufort Sea has rough heavily deformed rubble ice because of its exposure to the open sea and the Beaufort Gyre. This is examined further in the next section.

V. ANALYSIS OF THE ELSON AND BEAUFORT LINES USING MEMLS

In this section, MEMLS is used to analyze the entire Elson and Beaufort lines in order to estimate the snow and ice physical properties (correlation length, density, and ice emissivity) along each line and their effect on snow-depth retrievals. Known information at each data point includes the location, brightness temperatures from the PSR-A data, and the measured snow depth. The three main factors affecting the MEMLS brightness temperatures (besides snow depth) that are assumed by the model are the correlation length, snow density, and emissivity of the underlying ice. PSR-A and snow-depth data are used to estimate these parameters along the lines. This is done in two steps. First, single-layer simulations of the Elson and Beaufort lines are run using constant values for the correlation length, density, and ice emissivity. This is referred to as the standard run. The results of the standard run allow for the quantification...
of offsets in the brightness temperatures by comparing them to the PSR-A data. These offsets can then be corrected for by adjusting the brightness temperatures accordingly. The Elson and Beaufort lines are simulated again (correcting for the offsets identified in the standard run), adjusting the correlation length, density, and emissivity of the ice so that differences between the MEMLS results and the PSR-A data are reduced. This is referred to as the adjusted simulation and results in the best estimate of sea-ice and snow conditions along the transects. While single-layer simulations are not ideal due to special signatures that arise from layering effects, it is necessary to simulate a single-layer snowpack since layer-specific information is only available for the stakes and pits along the transect. The effects of snowpack layering on microwave signatures using MEMLS have been investigated (see, e.g., [13]).

A. Standard Simulations

In order to identify offsets between MEMLS simulated and PSR-A brightness temperatures, single-layer simulations of the Elson and Beaufort lines are run using constant values of the correlation lengths, densities, and emissivities so that changes in brightness temperatures are a function of snow depth only. The average correlation length and density from the combined Elson and Beaufort pit data (see Table IV) are used. Snow/ice interface temperatures along both the Elson and Beaufort lines are calculated using a linear relationship between the interface temperature and snow-depth data (see Fig. 5) given by

$$T_{s/i}^{\text{Elson}} = 0.26 \times h_s + 252 \,[K]$$

and

$$T_{s/i}^{\text{Beaufort}} = 0.21 \times h_s + 251 \,[K]$$

where $h_s$ is the snow depth in centimeters. The average surface temperature ($= 25$ K) from the pit data is used for both lines.

Fig. 6 gives the brightness temperatures for the MEMLS simulations and the PSR-A data using a 200-m running mean. As expected, there are offsets in the MEMLS data compared to the PSR-A data that are similar to those in the pit simulations (Section IV). The mean offsets (or bias) for each frequency and polarization for the Elson line are given in Table V, along with the standard deviation in the bias $\sigma_{err}$.

These offsets are relatively constant, as suggested by the low $\sigma_{err}$. Therefore, the MEMLS brightness temperatures are adjusted for each channel by the appropriate bias. However,
there will still be an offset between the Beaufort simulated brightness temperatures and the PSR-A data for the Beaufort line. The Beaufort offset may be due to the assumption of first-year sea-ice emissivities (input as reflectivities in the model). This is evident in the 10-GHz data. Relative to the other frequencies, 10 GHz is rather insensitive to snow-depth and snow-property changes, owing to its large penetration depth. Therefore, changes in the 10-GHz channel are largely a function of ice emissivity. Except for the beginning (<0.5 km) and end (>7.5 km) of the Elson line, the 10-GHz PSR-A brightness temperatures are lower for the Beaufort line compared to that for the Elson line. This suggests that there may be a change in sea-ice emissivity from the Elson Lagoon to the Beaufort Sea and that the emissivity changes along the Elson line. This is a reasonable conclusion, considering the different ice conditions in the Elson Lagoon and the Beaufort Sea.

Fig. 7 shows GR\textsuperscript{V}(37/19) for both the PSR-A and MEMLS data for the Elson and Beaufort lines. The snow depth for the Elson and Beaufort lines is shown on the right axis (gray lines). The thick lines represent the 200-m running means.
B. Adjusted Simulations

Single-layer simulations are run for the Elson and Beaufort lines, correcting for the offsets previously identified and adjusting snow density, correlation length, and sea-ice reflectivity (emissivity) so that MEMLS more accurately reflects the PSR-A data. For each data point along both lines, an initial correlation length (assuming spherical particles) and density equal to the average values of the combined Elson and Beaufort pit data ($\rho_c = 0.099$ mm and $\rho_s = 314$ kg $\cdot$ m$^{-3}$) are used. Similar to the standard run, the surface temperature is 250 K, the snow/ice interface temperatures are determined by (3) and (4) for the Elson and Beaufort lines, respectively, and Eppler’s [5] sea-ice emissivities are used. These initial conditions are input into MEMLS. The resulting brightness temperatures are adjusted by the offsets identified in Table V. The MEMLS brightness temperatures are then compared at each location with the PSR-A brightness temperatures. In order to remove the dependence of the brightness temperature on the snow/ice interface temperature, ratios are compared. Each ratio is compared one by one, adjusting the correlation length, density, and sea-ice reflectivity so that the differences between the PSR-A and MEMLS ratios are minimized, resulting in the best estimate of the snow properties and ice conditions for the Elson and Beaufort lines. This is done by calculating seven ratios, three spectral GRs, and four polarization ratios (PRs). PRs are calculated for each of the four channels (10, 19, 37, and 89 GHz) by

$$\text{PR}(\nu) = \frac{T_B(\nu, V) - T_B(\nu, H)}{T_B(\nu, V) + T_B(\nu, H)}$$  \hspace{1cm} (5)

where $V$ and $H$ refer to vertical and horizontal polarizations, respectively. GRs are calculated for the 89/19, 19/10, and 37/19 vertical channel combinations for both the PSR-A and MEMLS data and compared.

Fig. 8 shows snow depth as a function of GR$^V$(37/19) for the Elson and Beaufort lines using the 200-m running mean. The MEMLS results and the PSR-A data are represented by squares and stars, respectively. The AMSR-E regression line used for snow-depth retrievals is plotted for reference (solid line). The algorithm regression line agrees very well with the Elson results; however, snow-depth retrievals using this line would slightly underestimate the Elson snow depths. Markus and Cavaliere [12] observed that SSM/I-derived snow depths underestimated Antarctic in situ values by 3.5 cm on average. Adding this bias to the regression line improves the agreement. However, this is not the case for the Beaufort line. While there is still a linear relationship between the GR and snow depth (the correlation coefficient is $-0.77$), the Beaufort data suggest a steeper slope and have more negative values for GR.

The sea-ice emissivity (or effective emissivity, i.e., $\epsilon = 1 - r$), correlation length, and density derived using MEMLS are shown in Fig. 9. The sea-ice emissivity is low for the Beaufort line and at the very beginning and end of the Elson line. This result is reasonable given that the correlation length and density result in realistic values. Both show trends similar to that of the pit data (Fig. 3). As in the pit data, the correlation length gradually gets larger from the beginning of the Elson line to 5 km. Overall, the density for the Beaufort line is lower compared to that for the Elson line. This is also supported by the pit data (Fig. 3). These data are a reasonable best estimate of snow and ice conditions along the Elson and Beaufort lines. It is clear from the results that differences in GR for the Elson and Beaufort lines are due to the differences in sea-ice emissivity.

VI. Conclusion

This paper presents results from a comparison of microwave brightness temperatures measured by the PSR-A instrument over the Elson Lagoon and the Beaufort Sea, detailed measurements of snowpack properties from several locations along the flight paths and snow depths along the entire distance, and results of simulations using the snowpack radiative transfer model (MEMLS). Model simulations at specific stakes and surrounding pits in the Elson Lagoon and the Beaufort Sea make use of ground-based measurements of various snowpack properties, particularly, the number of layers, thickness, density, surface and snow/ice temperature, and prevailing grain size of each layer (converted to correlation length). MEMLS is used to approximate the microwave response of different snowpack conditions over sea ice. There are biases in the simulated data that can be corrected for. These biases may exist for a number of reasons. One possibility is our lack of knowledge of the sea-ice emissivity. Another reason is that MEMLS was developed for fresh snow and does not account for the bottom saline layer of snow, which was observed at 0–5 cm. Regardless of the offsets, MEMLS is useful for understanding the limitations of the snow-depth algorithm.

The measured brightness temperatures and snow depths in the Elson Lagoon and the Beaufort Sea further confirm the
linear relationship between \( \text{GR}^{V} (37/19) \) and snow depth (see Fig. 8). However, there are large differences between the Elson and Beaufort results. The Elson results agree with the current snow-depth retrieval algorithm if a bias of 3.5 cm is corrected for. This bias may be due to the smoothing of high \textit{in situ} snow depths by the large AMSR-E footprint. The Beaufort results do not agree with the current algorithm regression line and indicate that a new set of algorithm coefficients needs to be derived.

MEMLS analysis suggests that the differences in brightness temperatures between the Elson Lagoon and the Beaufort Sea are due to the differences in sea-ice conditions (sea-ice emissivity) (see Fig. 9). The Elson Lagoon has smooth first-year sea ice and resulting higher emissivity, while the Beaufort Sea has very rough first-year sea ice and lower emissivity. Therefore, the current algorithm is sufficient for areas of smooth first-year sea ice, while for areas with rough first-year sea ice, new coefficients for the algorithm would need to be used. A method for characterizing the sea-ice surface is also needed in order to determine which coefficients to use for retrievals. An analysis of the current AMSR-E frequencies does not reveal a means for accomplishing this. However, there are several tools that may be utilized to determine the ice type. SAR systems such as Canada’s RADARSAT and the Multi-Angle Imaging Spectroradiometer onboard NASA’s Terra satellite have been used to determine sea-ice type and roughness, respectively (e.g., [26]). Sea-ice type and roughness can also be determined using scatterometer data [27] and laser altimeters such as ICESat. Kwok \textit{et al.} [28] showed that the precision of elevation estimates over flat sea ice is \( \approx 2 \) cm. Variability in these elevation estimates can be used to derive surface roughness. Additionally,
the combined use of laser and radar altimeters may be a promising method for remotely measuring snow depth. This method is currently being investigated (e.g., Geoscience Laser Altimeter System cryospheric applications [7]).

It does not appear likely that specific grain size and density information is retrievable with the current AMSR-E microwave frequencies. Markus et al. [13] showed that the 89-GHz channel may be used to delineate between new snow-fall events and grain-size growth, but actual-grain-size maps are not possible at this time, especially given the horizontal variation in grain size over the large area of the AMSR-E footprint that is coupled with vertical variations in grain size between layers within the snowpack.

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REFERENCES


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