Microwave Signatures of Snow on Sea Ice: Modeling

Dylan C. Powell, Thorsten Markus, *Member, IEEE*, Donald J. Cavalieri, *Member, IEEE*, Albin J. Gasiewski, *Fellow, IEEE*, Marian Klein, *Member, IEEE*, James A. Maslanik, Julienne C. Stroeve, and Mathew Sturm

***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 km^2 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 (SSM/I) 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 SSM/I (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

Manuscript received November 15, 2005; revised April 4, 2006. This work was supported by NASA under Project 291-07-66 and Project 622-82-75.

D. C. Powell was with the Department of Physics and the Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Baltimore, MD 20715 USA. He is now with Earth observing Systems, Lockheed Martin, Greenbelt, MD 20770 USA.

T. Markus is with the Hydrospheric and Biospheric Science Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (e-mail: Thorsten.Markus@nasa.gov).

D. J. Cavalieri is with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

A. J. Gasiewski is with the Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO 80309 USA.

M. Klein is with the NOAA Environmental Technology Laboratory, Boulder, CO 80305 USA.

J. A. Maslanik is with the Center of Astrodynamics Research, University of Colorado, Boulder, CO 80309 USA.

J. C. Stroeve is with the Cooperative Institute of Research in Environmental Sciences, University of Colorado, Boulder, CO 80309 USA.

M. Sturm is with the Cold Regions Research and Engineering Laboratory, Fairbanks, AK 99703 USA.

Digital Object Identifier 10.1109/TGRS.2006.882139

TABLE I
FIRST-YEAR SEA-ICE EMISSIVITIES [5] FOR AMSR-E FREQUENCIES

Frequencies [GHz]	10.65	18.7	36.5	89.0
Horizontal	0.876	0.888	0.913	0.886
Vertical	0.924	0.941	0.955	0.926

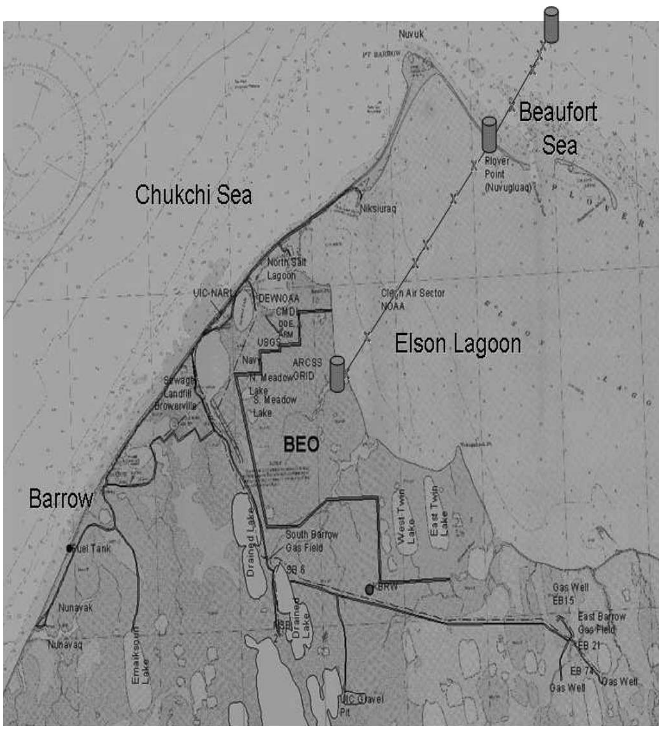

Fig. 1. Flight paths over the Barrow vicinity (including the Elson Lagoon and the inner Beaufort Sea). The Elson and Beaufort flights were flown from Fairbanks International Airport, AK, on March 13, 2003.

intervals, while detailed measurements of snowpack properties were taken every kilometer. Fig. 1 shows the two transects in the vicinity of Barrow, AK (including the Elson Lagoon and the Beaufort Sea).

PSR data were taken from the P-3 aircraft along transects flown over the Elson Lagoon and the Beaufort Sea at 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.

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 $GR^V(37/19)$ 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 *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 *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.