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Ku-, X- and C-band measured and modeled microwave backscatter from a highly saline snow cover on first-year sea ice

Vishnu Nandan [a,*], Torsten Geldsetzer [a], Tanvir Islam [b], John. J. Yackel [a], Jagvijay P.S. Gill [a], Mark. C. Fuller [a], Grant Gunn [c], Claude Duguay [c]

[a] Cryosphere Climate Research Group, Dept of Geography, University of Calgary, AB, Canada
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
[c] Dept of Geography and Environmental Management, University of Waterloo, Canada

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ABSTRACT

In this study, we inter-compare observed and modeled Ku-, X- and C-band microwave backscatter for two snow temperature conditions for a highly saline snow cover on smooth first-year sea ice. A new surface-based multi-frequency (Ku-, X- and C-bands) microwave scatterometer system is used quasi-coincident with in situ geophysical snow measurements. A multilayer snow and ice backscatter model is used to calculate the total co-polarized backscatter coefficient for two snow temperature conditions. The model provides the surface and volume scattering contributions for each snow layer, as well as the frequency-dependent penetration depth. These results aid interpretation of observed backscatter. Joint use of Ku-, X- and C-band microwaves provide an enhanced understanding of diverse variations in geophysical, thermodynamic and electrical state of snow/sea ice system. Our results indicate that the effect of dielectric loss associated with highly saline snow covers is the dominant factor affecting microwave penetration and backscatter from all three frequencies. The observed and modeled C-band backscatter shows good agreement, followed by X- and Ku-bands, at both snow temperature conditions. Microwave backscatter shows greater sensitivity to variations in plot-scale surface roughness, for all three frequencies. Additionally, Ku-band wavelength exhibits greater sensitivity to snow grain radius, over X-, and C-bands. Our results demonstrate the future potential of a multi-frequency approach towards the development of snow thickness and snow water equivalent algorithms on first-year sea ice.

1. Introduction and background

The Arctic is on the path to a new climate regime influenced by thinner first-year ice (FYI). In contrast to Antarctic sea ice, Arctic cryosphere has recently undergone significant changes, highlighted by substantial decline in sea ice thickness and extent (Nghiem et al., 2007), extensive loss of multi-year ice (MYI) replaced by FYI (Comiso, 2012), and decline in spring snow depth (Webster et al., 2014). These changes can significantly affect the Arctic marine ecosystem, and directly impact the Arctic marine navigation (Geldsetzer et al., 2007). Accumulation and redistribution of snow on sea ice occurs at different rates, and exhibits high spatiotemporal variability (Iacozza & Barber, 2010; Yackel & Barber, 2007), and plays a central role in the mass and energy exchange across the ocean-sea ice-atmosphere interface by modulating sea ice ablation and accretion processes (Curry et al., 1995). Snow covers on FYI in a warming Arctic are likely to be thinner and these thinner snow covers may become more saline due to the increased vapor and thermodynamic gradients between the atmosphere and ocean (Blanchard-Wrigglesworth et al., 2015). Snow depth and/or snow water equivalent (SWE) and its spatial distribution on FYI is highly dependent on the amount of snow accumulation over a regional scale and by the predominant winter and spring wind directions during snow accumulation and redistribution events (Yackel & Barber, 2007). Additionally, a warming Arctic facilitates delayed sea ice "freeze-up" which could lead to thinner FYI, thereby reducing sufficient time for snow accumulation on FYI (Webster et al., 2014). All these above mentioned issues related to snow distribution retrievals make timely large-scale parameters such as SWE on FYI extremely difficult to obtain and quantify.

Historically, direct measurements of snow on sea ice have been logistically difficult and sparse in space and time (Iacozza & Barber, 2010). Active microwave sensing have been proven to be an efficient tool to characterize the thermodynamic state of snow covered FYI (Barber & Nghiem, 1999; Yackel & Barber, 2007; Fuller et al., 2014), where snow cover plays a pivotal role in microwave propagation and scattering within the snow/sea ice system (Yackel et al., 2007; Komarov et al., 2015). Snow cover affects microwave interactions on

* Corresponding author at: Cryosphere Climate Research Group, Department of Geography, University of Calgary, 2500 University Dr NW, Calgary, AB T2N 1N4, Canada.
E-mail address: vishnunandan.nandaku@ucalgary.ca (V. Nandan).

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FYI through scattering from snow geophysical properties such as salinity, density and grain radius and shape, and through thermodynamic controlled effects on snow dielectrics (e.g. snow wetness and brine volume) (Barber et al., 1998). At near-range incidence angles (~ 21° ≤ θ_{inc} ≤ ~30°), surface scattering (for C-band) dominates the microwave backscatter (Tjuatja et al., 1992). At medium (mid-range) to higher (far-range) incidence angles (~33° ≤ θ_{inc} ≤ ~60°), volume scattering (dependent on brine inclusions and volume within the snow, and snow grain size) dominates (Tjuatja et al., 1992). During cold, dry snow conditions, microwave energy (C-band) attains near complete penetration through the snow pack with little attenuation (C-band followed by X- and Ku-bands), and brine at the snow/sea ice interface contributes to the primary backscattering and attenuation (Barber et al., 1998).

Brine volume in the basal snow layer on FYI is a salient physical parameter towards understanding the electro-thermo-physical behavior of microwaves with snow on FYI (Drinkwater & Crocker, 1988; Barber et al., 1998). Depending on the snow thickness on FYI, fluctuations in near-surface air temperature change the snow temperature. This modifies brine volume at/or near the snow/sea ice interface following the eutectic phase distribution curve, whereby changing thermal, dielectric and scattering properties of the snow cover (Cox & Weeks, 1983; Barber & Nghiem, 1999; Drinkwater & Crocker, 1988). Moreover, with increasing snow thickness, snow thermodynamics play a vital role in total backscatter contribution (Barber & Nghiem, 1999). This may mask relatively small temperature and salinity variations at the base of the snow cover, essential for snow thickness estimation on FYI using microwave remote sensing.

Exploiting the electro-thermo-physical dependence of multi-frequency microwave interactions to better understand microwave interactions from different snow cover types on Arctic FYI requires investigation. Previous studies used a single-frequency approach (Ka- (Lytle & Ackley, 1995), Ku- (Onstott et al., 1979; Livingstone et al., 1987), X- (Livingstone et al., 1987; Dierking, 2010), C-band (Dierking, 2010; Komarov et al., 2015), and L-band frequencies (Eltoft et al., 2013)), linking snow-covered FYI electro-thermo-physical properties to microwave parameters. Studies using Ku-band (Livingstone et al., 1987) on smooth FYI with/without snow cover, showed fluctuations in backscatter at different incidence angles, owing to saline/non-saline snow layers. Studies using X-band (Dierking, 2010) showed strong dependence of backscatter on snow grain radius, and exhibited high backscatter from brine-wetted snow cover on FYI. Recent studies (Komarov et al., 2015; Gill et al., 2015; Fuller et al., 2014) using C-band revealed ambiguities in snow thickness estimation on Arctic FYI due to the presence of high salinity especially at the top most layers of the snow pack. Furthermore, no studies have been carried out in a polar environment such as the Arctic, which combine multi-frequency observations to better understand the sensitivity of microwave scattering to snow thermodynamics and geophysical properties on Arctic FYI.

Owing to their pixel spacing, correlating space-borne active microwave backscatter from synthetic aperture radar (SAR) (e.g., Cosmo-SkyMed, TerraSAR-X, RADARSAT-2 and ALOS-2 PALSAR-2) to geophysical and thermodynamic properties of snow covered FYI has inherent sampling ambiguity (Geldsetzer et al., 2007). This adds significant uncertainty for direct geophysical interpretation, due to a possible mixture of signatures in the SAR data. Moreover, all of the above mentioned satellite data operate over a wide range of varying spatial resolutions (1–1000 m at swath widths of 30–500 km) and revisit times, swath widths and polarization combinations. For e.g. TerraSAR-X and Cosmo-SkyMed (X-band), have revisit times of 11 and 16 days respectively, while RADARSAT-2 (C-band) has a revisit time of 24 days. Therefore, it is currently potentially difficult to carry out a study using multi-frequency satellite data since: a) neither grid resolutions nor revisit times of these satellite sensors match, b) the SAR signals acquired at Ku-, X- and C-bands might temporally de-correlate, due to dynamic temporal variability of snow/sea ice electro-thermo-physical properties, and c) since sea ice moves, temporal coverage of SAR scenes over one specific spot requires high-resolution sea ice motion product for a correction of the spatial offset between the SAR scenes. In order to avoid this, unambiguous in-situ measurements of snow/sea ice geophysical properties must be sampled coincident with homogeneous in-situ microwave backscatter measurements (Geldsetzer et al., 2007), at high spatial and temporal resolution. Although a number of studies (e.g. Onstott et al., 1979; Yueh et al., 2009; Werner et al., 2010) have already evaluated sensitivities of different microwave frequencies to snow properties using surface-based and air-borne multi-frequency and multi-polarization microwave measurements, no previous studies have been conducted using quasi-coincident multi-frequency microwave observations for a highly saline snow cover on FYI.

Various quantitative first- and second-order physical models (e.g. Ulaby et al., 1984; Kim et al., 1984; Drinkwater, 1989; Kendra et al., 1998; Winebrenner et al., 1992; Du et al., 2010) have been developed to estimate microwave backscatter and penetration depth for snow-covered FYI. In conjunction with in-situ microwave backscatter measurements, these models provide additional capability towards an enhanced understanding of microwave scattering mechanisms, and microwave penetration depth at multiple frequencies. These models act as a tool to better understand snow/sea ice electrical and geophysical properties with microwave backscatter (σ^0_{VV} and σ^0_{HH}, where σ^0 is the normalized measure of the radar return from a distributed target called sigma-nought, and VV or HH represents co-polarized backscatter in vertical and horizontal polarizations) at multiple frequencies. Therefore, this study employs the multilayer snow and ice microwave backscatter model (MSIB model) (see Section 3.6).

2. Research objectives

This study presents in-situ snow geophysical data collected quasi-coincident with surface-based microwave backscatter (scatterometer) measurements acquired at Ku-(17.25 GHz), X- (9.65 GHz) and C-band (5.52 GHz) frequencies from a 14 cm highly saline snow cover on smooth FYI. We employ these particular frequencies since they correspond closely to the center frequencies of recent and currently operating space-borne SAR and space-borne scatterometer systems (i.e. ASCAT, QuikSCAT, TerraSAR-X, COSMO-SkyMed, and RADARSAT-2). Utilizing modeled and in-situ measured microwave backscatter measurements (σ^0_{VV} and σ^0_{HH}), this study employs a combined theoretical and experimental approach to understand microwave scattering interactions and penetration under two different snow temperature conditions. To help achieve our research objectives, we address the following questions:

1) What are the differences between Ku-, X- and C-band measured and modeled σ^0_{VV} and σ^0_{HH} from snow covered (14 cm) smooth first-year sea ice?

2) How do Ku-, X- and C-band surface and volume scattering contributions vary in a saline snow cover, for different snow volume temperature cases?

3) What are the differences in the Ku-, X- and C-band modeled penetration depths between different/changing saline snow volume temperature scenarios?

3. Methods

3.1. Study area

The in-situ snow geophysical property measurements and quasi-coincident surface-based Ku-, X- and C-band polarimetric microwave backscatter measurements were acquired from a homogeneous highly saline 14 cm snow cover located on smooth land-fast FYI (74.70435°N, 95.63381°W), near Resolute Bay, Nunavut, Canada (Fig. 1). All measurements acquired for this study were collected on 18th and 19th May 2012, sampled at approximately eight hour intervals throughout the