Multi-sensor, multi-frequency remote sensing of snow for improved sea ice thickness retrievals

Recent Progress

Here, I describe my progress, relative to each of my most recent NSERC Discovery Grant objectives. I have published 27 peer-reviewed journal papers in high impact journals with 2 additional manuscripts either accepted or in revision over the past 6 years (see CCCV). Considerable progress has been made towards demonstrating that both surface-based multi-frequency (Ku-, X- and C-band) polarimetric microwave scatterometry and spaceborne synthetic aperture radar (SAR) can be used for estimating Essential Climate Variables (ECV's) of the marine cryosphere, and in particular, snow and sea ice geophysical properties and thermodynamic state, including snow thickness on first-year sea ice (FYI). Furthermore, my program has increasingly been evaluating the integration of passive microwave radiometry with scatterometry to estimate these ECV's. I have published 20 papers and 8 conference papers pertaining to this objective. A salient finding is that saline snow on seasonal sea ice masks penetration of high-to-mid-frequency (Ka to C-band) radar signals first observed using surface-based polarimetric microwave scatterometry. This finding was then exploited as an important diagnostic to improve Ku-band satellite radar altimetry-derived radar freeboard and sea ice thickness, now recognized, along with sea ice roughness, in operational thickness retrieval algorithms from satellite radar altimetry (Landy et al., 2020). As such, dual-frequency (Ka- and Ku-band) altimetry has become a central theme of my research program to be evaluated for its role on improving pan-Arctic scale snow thickness estimates on seasonal sea ice. I have also made progress on developing methods for ECV measurement from analysis of time series, multi-frequency (Ku, X-, C- and L-band) polarimetric microwave backscatter data/parameters from both surface and satellite-based scatterometer/SAR systems to infer and constrain the snow thickness distribution on FYI within certain thermodynamic regimes of its annual cycle. Here, I am principally interested in how each of these sensor parameters (polarimetry, frequency, and incidence angle) can provide information on the thermophysical state of the snow-covered sea ice system throughout its evolution. Furthermore, my research colleagues and I have also come to understand how snow thickness distributions, controlled by thermal diffusivity, play an important role in the seasonal transition of sea ice surface albedo, melt pond onset timing and eventual pond fraction as a function of ice type and surface roughness. Over the course of this most recent NSERC cycle I contributed 7 papers and 6 conference papers towards these inter-related objectives.

Objectives

The primary goal of my research program is to understand how the complex nature of atmospheric and thermodynamic processes responsible for the annual growth and decay of snow-covered sea ice over a continuum of space and time scales can be inferred using surface and spaceborne polarimetric microwave scatterometry, altimetry and synthetic aperture radar (SAR). Improved understanding in recent years has enabled snow and sea ice physical property estimates that are less ambiguous (more accurate), especially to account for uncertainties in satellite estimates made by the science community. Towards this goal, my program will integrate a combination of ground- and satellite based scatterometry, altimetry and SAR data, supported by surface validation data, mathematical modeling, including data science (GeoAI and machine learning). Salient to accomplishing this goal is further understanding the relationship between the physical and electrical properties (as a function of frequency) of the snow cover on sea ice during the various thermodynamic regimes spanning the winter to summer seasons. The following summarizes my research objectives within the time frame of this granting period (1-2) and of a longer duration (3).

Obj.1 Collect coincident geophysical property measurements of snow along with micro-scale ice surface roughness (described in Methodology) for input into advanced radiative transfer models for comparison of the simulated co-polarized radar waveforms (Ka- and Ku- band) and backscatter (all frequencies) with scatterometer observations acquired at nadir (Ka- and Ku-bands) and between 15- and 55-degrees incidence angles (all frequencies).

Obj.2 Identify the primary Ka- and Ku-band scattering horizons/surfaces near-to the air/snow and snow/sea ice interfaces at unique stages (which are often event-driven) of the thermodynamic evolution of the snow/ice system using knowledge gained from Obj 1.

Obj.3 Develop an expert system, using a combination of physically and empirically based microwave scattering models, whereby altimetry, SAR and machine learning are integrated to retrieve snow/sea ice variables over local- to regional- and hemispheric scales. This long-term objective will use advanced snow models, such as SMRT, SNOWPACK and MEMLS-A for forward modeling, simulate waveforms and conduct model inversion to retrieve snow/sea ice geophysical properties.

Literature Review

Earth's climate is experiencing unprecedented change and monitoring and predicting the nature of this change is an ongoing global scientific endeavor. Inclusion of sea ice in global climate models is paramount due to its control on heat transfer between the atmosphere and ocean. For example, with less sea ice, more ocean heat can transfer to the atmosphere, leading to further warming and less sea ice, a particularly damaging positive feedback loop. Arctic sea ice extent has declined by 13% and thinned by nearly 40% over the past four decades as estimated from satellites, with the Arctic Ocean predicted to become ice free in summer for the first time before 2050. Considerable uncertainty remains as to how these changes will influence the Arctic marine ecosystem, Arctic and mid-latitude climates and ecosystems, socio-economic issues such as pan-Arctic shipping and cruise tourism, and the livelihood of indigenous communities including those in northern Canada.

Sea ice is an important indicator of climate change, playing a fundamental role in the Arctic energy and freshwater balance. Furthermore, because of complex physical and biogeochemical interactions and feedbacks, sea ice is also a key component of the marine ecosystem. Over the last several decades of continuous observations from multi-frequency satellite passive microwave imagers, there has been a nearly 50% decline in Arctic sea ice extent at the time of the annual summer minimum (Stroeve and Notz, 2018; Stroeve et al., 2012; Parkinson and Cavalieri, 2002). This loss of sea ice area has been accompanied by a transition from an Arctic Ocean dominated by older and thicker multiyear ice (MYI) to one dominated by younger and thinner FYI (Maslanik et al., 2011; Kwok, 2018; Kwok et al., 2020). While younger ice tends to be more dynamic, much less is known about how thickness and volume are changing. Accurate ice thickness monitoring is essential for heat and momentum budgets, ocean properties, and the timing of sea ice algae and phytoplankton blooms (Bluhm et al., 2017; Mundy et al., 2014). Salient to sea ice thermodynamic processes is the overlying snow cover (Webster et al., 2018) owing to its control on thermal diffusivity. The snow cover on sea ice is changing (Webster et al., 2014) and quantifying its distribution across a continuum of space and time scales is paramount. Research has also shown that it is possible to combine CryoSat-2 (Ku-band) and Alti-Ka (Ka-band) to simultaneously to more accurately retrieve both ice thickness and snow depth during winter (Lawrence et al., 2018; Guerreiro et al., 2016; Garnier et al., 2021; Tilling et al., 2018; Hendricks et al., 2016; Kurtz and Harbeck, 2017; Armitage and Ridout, 2015) and it the impetuous of the Copernicus CRISTAL mission (Kern et al., 2020) of which I have been an Advisory Group member since 2019.

Several studies have assessed combining CS-2 with snow freeboard observations from laser altimetry (e.g., ICESat-2), in a joint ESA and NASA orbital track adjustment (Cryo2Ice), to map coincidently spaced pan-Arctic snow depth and sea ice thickness during the cold season (Fons et al., 2021). The accuracy of pan-Arctic sea ice thickness estimates from satellite remote sensing depends on the performance of statistical thresholding methods using radar altimetry to distinguish sea ice floes from sea ice leads and open water. However, these simple methods do not fully account for seasonally and spatially varying complex geophysical processes in the snow cover on sea ice, which affect radar propagation and add considerable error and uncertainty to estimates.

Several key uncertainties limit the accuracy of the microwave or radar-based freeboard retrieval, which then propagate into the freeboard-to-thickness conversion. One important uncertainty pertains to inconsistent knowledge on how far the radar signal penetrates the overlying snow cover (Nandan et al., 2017a; 2020; Tonboe et al., 2021; Willatt et al., 2011). The general assumption is that the radar return originates primarily from the snow–sea ice interface at Ku-band (CS2) and from the air–snow interface at Ka-band (AltiKa). While this may hold true for cold, dry snow in a laboratory (Beaven et al., 1995), scientific evidence from observations and modeling suggests this assumption may be invalid even for a cold, homogeneous snowpack (Nandan et al., 2020; Willatt et al., 2011; Tonboe et al., 2010). Modeling experiments reveal that for every millimeter of snow water equivalent (SWE), the effective scattering surface is raised by 2 mm relative to the freeboard (Tonboe et al., 2021). A further complication is that radar backscattering is sensitive to the presence of liquid water within the snowpack. This means that determining the sea ice freeboard using radar altimeters during the transition phase into Arctic summer was very challenging (Landy et al., 2020) but is now possible with advanced processing of multiple ancillary datasets (Landy et al., 2022). The transition from an MYI-to-FYI-dominated Arctic has resulted in a more saline snowpack (Confer et al., 2023; Domine et al., 2004), which in turn impacts the snow brine volume, thereby affecting snow dielectric permittivity. This vertically shifts the location of the Ku-band radar scattering horizon by several to many centimeters above the snow– sea ice interface (Nandan et al., 2020; Nandan et al., 2017b; Tonboe et al., 2006). Field campaigns have revealed that the dominant radar scattering occurs within the snowpack or at the snow surface rather than at the snow–ice interface (Nandan et al., 2016; Willatt et al., 2011; Giles et al., 2007). Another significant complexity exists in that micro- and macro-scale surface roughness impact the location of the main radar scattering horizon with respect to surface-based Ka- and Ku-band scatterometry and satellite altimetry sub-footprint preferential sampling (Tonboe et al., 2010; Landy et al., 2020; Nandan et al., 2017c). These factors combine to result in significant uncertainty on accurately detecting the location of the dominant frequency-dependent scattering horizon (Landy et al., 2020) and in turn influences the accuracy of sea ice thickness retrievals from satellites. Ultimately, this creates biases in snow depth retrievals obtained from combining dual-frequency radar observations or from combining radar and laser altimeter observations (Kwok et al. 2020).

Methodology

Micro- and macro-scale snow and sea ice surface roughness are undoubtably the most important parameters affecting microwave backscatter (whether from satellite altimeters and scatterometers, SARs or surface-based altimeters and scatterometers) of snow-covered sea ice at Ka, Ku, X and C-band frequencies (Landy et al., 2020; Barber and Nghiem, 1999; Nghiem et al., 1995; 1996). Microscale interface roughness has a long history in terrestrial snow science (Lemmetyinen et al., 2018; Rutter et al., 2019; Sandells et al., 2017). At experimental field locations described below, I will collect coincident geophysical property measurements of snow and sea ice at fixed intervals, adjacent to the scan areas of the Ka-, Ku-, X-, C-, and L-band scatterometer systems. The properties are: 3-cm vertically resolved snow temperature, density, and salinity; snow type classification, thickness, and volumetric moisture content; snow grain specific surface area (SSA); 2 cm vertically resolved sea ice temperature, salinity, thickness, and density; and terrestrial laser scanner (TLS)-derived micro-scale snow surface and sea ice surface roughness represented as RMS height and correlation length (Lemmetyinen et al., 2018; Carlström and Ulander, 1995; Landy et al., 2020) measured at SERF immediately after ice freeze-up and once a thin snow cover accumulates given that significant snow metamorphism undoubtably occurs immediately thereafter. A snow clearing study will attempt to characterize the sea ice surface roughness once snow accumulates but description of such an approach is beyond the scope of this proposal but key terrestrial and sea ice snow scientists (e.g., J. Lemmetyinen, A. Langlois, R. Tonboe, M. Sandells, M. Sturm, N. Rutter, G. Picard, M. Schneebeli, etc) will be consulted. Snow grain specific surface area (SSA) will be measured using both infrared reflectance and a snow micropenetrometer approaches (Lemmetyinen et al., 2018; Langlois et al., 2010; Rutter et al., 2019; Sandells et al., 2017) to characterize snow grain properties towards **Obj's 1 and 2**. These measurements provide the necessary inputs for the SMRT snow/sea ice backscatter model (Soriot et al., 2022; Picard et al., 2018; Sandells et al., 2017) which I will employ throughout the entire seasonal cycle for different snow thickness and roughness conditions and compare the simulated co-polarized radar waveforms (Ka- and Ku-band) and backscatter (all frequencies) with scatterometer observations acquired at nadir (Ka- and Ku-bands) and between 15- and 55-degrees incidence angles (all frequencies).

Ka- and Ku-band radar waveform and backscatter data acquired at nadir will be used to derive snow depth via radar altimeter waveform differences in co- and cross-polarized channels. This will be used to identify the primary Ka- and Ku-band scattering surfaces at the air/snow and snow/sea ice interfaces, as well as monitor its evolution throughout the seasonal cycle until melt-onset. This method will combine fully-polarimetric Ka- and Ku-band radar waveforms to derive spatially and temporally coincident retrievals of snow depth on sea ice, as a function of different signal responses to surface roughness (derived from TLS scans). Furthermore, I will combine observed and SMRT-simulated non-nadir backscatter from different snow covers to investigate the frequency-and polarization-dependency for different incidence angle ranges. Using SMRT simulations, this analysis will assist in inverting snow depth on sea ice, as a function of frequency, polarization, and incidence angle. I will then conduct sensitivity analyses by varying one property (SMRT model input) at a time (within ranges and at iterative steps to be defined during the implementation phase), while keeping all other properties constant at the baseline values. Although I plan to conduct sensitivity analyses for multiple snow/sea ice model inputs, I will specifically focus on conducting model sensitivity runs at varied surface roughness conditions, to evaluate its impact on multi-frequency backscatter. This will provide me with a better understanding of which snow/sea ice properties have the largest impact on multi-frequency backscatter. This study will provide me with an understanding of how best to exploit SMRT for modelling snow-covered sea ice backscatter for comparison with multi-frequency surface-based scatterometer measurements, and to serve as a basis for conducting model inversion to retrieve snow depth on sea ice. SNOWPACK and MEMLS-A models can then be evaluated against SMRT, but this remains a long-term goal once the latter models mature. Unique to this proposal will be use of dedicated, multi-frequency (Ku- X-, C- and L-band) polarimetric scatterometer systems, being deployed as part of the Canada Foundation for Innovation funded **Churchill Marine Observatory** (CMO). The CMO is a globally unique, highly innovative, multidisciplinary research facility located in

Figure 1. OSIM facility (inset, top-right) at CMO showing the seawater tanks and retractable roof for meteoric snow accumulation on natural grown sea ice from seawater piped in from Hudson Bay (background of inset image).

Churchill, MB, adjacent to Canada's only Arctic deep-water port. The CMO will directly address technological, scientific, and economic issues pertaining to Arctic marine transportation and oil and gas exploration and development through the Arctic. My role in CMO as co-PI is to co-lead the sea ice remote sensing program. Unique to the CMO is the Ocean-Sea Ice Mesocosm (OSIM) (Figure 1) whereby controlled sensitivity studies of snow thickness and its geophysical properties (on sea ice) can be measured via the multi-frequency, multi-incidence angle, polarimetric and altimetric–in stare mode systems. CMO-OSIM has multiple lab spaces, including chemistry, physics and atmospheric lab, a multipurpose meeting room and a data acquisition room. The facility is equipped with an extensive collection of scientific equipment, including additional remote sensing instrumentation (Lidar's and EMI systems) and meteorological instrumentation (wind LiDAR, profiling microwave radiometer, a meteorological station). I will largely address **Obj 1** in April 2024 at OSIM with colleagues J. Stroeve and D. Isleifson and scatterometers. My collaborators from the University of Manitoba (J. Stroeve, T. Papakyriakou, C.J. Mundy, F. Wang, D. Isleifson), will facilitate use of an artificial **S**ea ice **E**nvironmental **R**esearch **F**acility (SERF) for my research program objectives. SERF houses an outdoor sea ice pond equipped with a suite of analytical and mechanical equipment (ie. meteorological instrument tower, retractable roof to allow for partial coverage and exposure to snow accumulation, gantry system to maneuver scatterometer(s) and optical/LiDAR system for microscale snow and sea ice roughness), multi- frequency scatterometer systems at Ku, X and C-band) and an on-site laboratory trailer for in-situ snow and ice geophysical analysis. My collaboration with national and international colleagues on field campaigns where a broad range of surface-based instrumentation can be brought together, including passive microwave radiometers that support related goals of snow thickness inversion during cal/val activities of the ESA Copernicus expansion missions (eg. R. Forsberg, H. Skourup, S. Fleury, S. Farrell, E. Rinne and T. Casal) in partnership with my Canadian collaborators (J. Stroeve, R. Scharien and S. Howell and those colleagues at University of Manitoba, SERF).

Impact

My research program has largely been recognized for using time series C-band SAR and multi- frequency surface-based polarimetric scatterometry to measure sea ice state variables; namely, the thermodynamic state of seasonal sea ice, and for assessing the use of SAR and scatterometers for snow physical properties towards snow thickness estimation. My focus expanded to the use of L-band SAR over the past decade, with Ph.D. students M. Mahmud and R. Scharien, given the sea ice classification improvements observed by various ice services from integration of L-band SAR sensors. Salient research (Nandan et al., 2017b) mandates that considerable effort is now made to plan and acquire detailed measurements of the physical and electrical properties of the snow cover on seasonal sea ice because it is now largely recognized by the international sea ice community. That is, saline snow in the basal layer plays a significant role on the radar scattering horizon and microwave penetration depth (especially at Ka- and Ku-band frequencies) and the ultimate sea ice freeboard to thickness conversion. To address these issues, I am spearheading, through my participation on the CRISTAL MAG, and with European colleagues, the joint **C**opernicus **E**xpansion **M**issions CIMR, CRISTAL, and ROSE-L **S**ea **I**ce **E**xperiment (CEMSIE) to utilize a suite of surface-based scatterometers and radiometers at CHARS in Cambridge Bay, NU in April/May 2025. CEMSIE is designed after MOSAiC *Remote Sensing City* but is focused on snow-covered seasonal ice which is expected to contain appreciable amounts of brine in the basal snow layer. CEMSIE instruments include a surface-based Ka- and Ku-band polarimetric scatterometer (operated in both scan and altimeter mode) via J. Stroeve-CRISTAL, multi-frequency passive microwave radiometers via G. Spreen-CIMR and an L-band polarimetric scatterometer via R. Scharien-ROSE-L and would help fulfil **Obj 1** and work towards **Obj 2**. CEMSIE expects to acquire ESA/European Commission funding through the Sentinel Users Programme. My research program is also making a direct impact on how large, internationally collaborative multi-million-dollar Arctic field programs are being designed to measure the snow geophysical properties. Considerable effort is now made to plan and acquire detailed measurements of the physical and electrical properties of the snow cover on seasonal sea ice because it is now largely recognized by the international community that saline snow in the basal layer of the snow cover on seasonal ice plays a significant role on the radar scattering horizon, microwave penetration depth (especially at Ka- and Ku-band frequencies) and the sea ice freeboard to thickness conversion. For example, processes of saline snow on seasonal sea ice towards defining the radar scattering horizon are now key parameters being investigated in the recently completed UK-British Antarctic Survey (BAS)-led DEFIANT project.