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Freshwater lake ice thickness derived using surface-based X- and Ku-band FMCW scatterometers

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ABSTRACT

Time series of ground-based X- and Ku-band frequency-modulated continuous-wave (FMCW) radar data are used to derive ice thickness for bubbled freshwater lake ice with heterogeneous snow cover under the assumption of interactions in range occurring at the ice–snow and ice–water interface. Once adjusted for the refractive index of ice and slant range, the distance between peak returns agrees with in-situ ice thickness observations. Ice thicknesses are derived from the distance of peak returns in range acquired in the off-nadir incidence angle range 21°–60°. Derived ice thicknesses are compared to in-situ measurements, an upward-looking acoustic sonar (Shallow Water Ice-Profiler (SWIP)), and a one-dimensional thermodynamic lake ice model (Canadian Lake Ice Model (CLIMo)). Median ice thicknesses derived with University of Waterloo X- and Ku-band scatterometers (UW-Scat) agreed well with in-situ measurements ($R^2 = 0.953$ and 0.964), SWIP ($R^2 = 0.842$ and 0.893), and Canadian Lake Ice Model (CLIMo) simulations using 25% of terrestrial snowpack scenario, respectively. UW-Scat derived ice thicknesses produced root mean square error (RMSE) values of 0.053 and 0.088 m for X- and Ku-band, respectively, relative to in-situ ice thickness measurements. This study is the first FMCW X- and Ku-band off-nadir approach to observe interactions at the snow–ice and ice–water interface to derive ice thickness.

1. Introduction

The presence of freshwater lake ice constitutes an important component of the biological, chemical, and physical processes of the cold regions freshwater cycle. Lakes cover approximately 2% of the Earth's land surface, with the majority located in the Northern Hemisphere (Brown and Duguay, 2010). In the Arctic and sub-Arctic, lakes can occupy up to 40% of the land surface. The presence or absence of freshwater lake ice affects local and regional weather and climate, influencing evaporative and sensible heat fluxes to the atmosphere as well as weather events (e.g. thermal moderation or lake-effect snow) (Brown and Duguay, 2010; Rouse et al., 2008). Knowledge of the status of ice-covered lakes is crucial for numerical weather prediction and regional climate modeling in regions where a significant fraction of land cover is composed of lakes (Kheyrollah Pour et al., 2012; Martynov et al., 2012). Freshwater lake ice phenology and thickness also has many economic implications ranging from hydroelectricity to winter ice road transportation used to supply remote northern settlements (Prowse et al., 2009). In addition to its significant influence on weather, climate, and socio-economic systems, freshwater ice is also an important indicator of climate change. Increasingly warm temperatures (Overland et al., 2014), increased snow precipitation (Arp et al., 2012), and Arctic sea ice thickness/extent reductions (Serreze et al., 2007) have become enhanced in recent years (Walsh et al., 2011). The response of lakes to changes in climate may vary due to variations in areal extent, depth, volume, and latitudinal position.

Historically, the observation of lake ice properties such as ice phenology (freeze-up, break-up, and duration) and thickness was collected through manual measurements in conjunction with weather observation; the network of which has drastically reduced over the last two decades (Lenormand et al., 2002; Prowse et al., 2011). Recent studies identify and demonstrate the use of remote sensing to produce observation of ice parameters, including lake ice phenology (Geldsetzer and van der Sanden, 2013; Geldsetzer et al., 2010; Howell et al., 2009; Latifovic and Pouliot, 2007; Tian et al., 2015) and ice thickness (directly or indirectly) (Arcone et al., 1997; Jeffries et al., 1996; Kang et al., 2010, 2012; Surdu et al., 2014). The previous studies indicate that the use of microwave observations is suitable for lake ice observation as a result

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of the ability to acquire observations independent of incoming solar radiation or cloud cover. The high spatial resolution of active microwave sensors compared to passive microwave instruments (metres vs kilometres) are able to resolve small ponds and lakes, permitting the observation of ice cover variability.

Spaceborne C-band synthetic aperture radar (SAR) (Cook and Bradley, 2010; Mueller et al., 2009; Surdu et al., 2014), X-band SAR (Sobiech and Dierking, 2013), and Ku-band scatterometer (Howell et al., 2009) measurements have been used for tracking ice phenology, focusing largely on the observation of freeze-up and break-up dates. Active microwave observations of ice thickness have been restricted to shallow lakes, where ice thickness values have been inferred when a floating ice cover thickens sufficiently to become grounded, subsequently resulting in a drop in backscatter ($\sigma°$) (Hirose et al., 2008; Sellmann et al., 1975; Weeks et al., 1978). Mellor (1982) tracked X-band $\sigma°$ departures using multi-temporal airborne acquisitions and referencing previously produced bathymetric charts, successfully mapping bathymetry for multiple lakes on the Alaskan North Slope. The method was repeated using C-band ERS-1 SAR acquisitions with the successful mapping of bathymetric elevations (Mellor, 1994). Jeffries et al. (1996) extended this methodology by applying predicted ice thickness values derived from a one-dimensional thermodynamic lake ice model to areas that were identified as frozen to bed from ERS-1 SAR acquisitions. Jeffries et al. (2005) repeated this methodology, assigning ice thickness values to pixels at the edge of the floating ice and interpolating bathymetry at increments of 0.25 m. While independent of bathymetric charts, the method presented by Kozlenko and Jeffries (2000) could only predict a maximum ice thickness of areas that are frozen to bed, restricting the application to shallow lakes. Duguay and Lafleur (2003) remotely observed lake depth using Landsat Band-2 (0.52–0.6 μm) and determined ice thickness by tracking backscatter over a time series of ERS-1 acquisitions. Surdu et al. (2014) inferred the thinning of ice cover in Arctic lakes through the classification of a time series of C-band ERS-1/2 acquisitions identifying areas of ice that froze to bed versus remained floating, whereby a the grounded ice fraction reduced by 22%.

Ground-based frequency-modulated continuous-wave (FMCW) radars operating at C- and X-band have been utilized to observe the snow–ice and ice–water interface with the sensor normally angled at nadir incidence angle (0°), resulting in a coherent reflection from the horizontal interfaces (Arcone et al., 1997; Leconte et al., 2009; Yankielun et al., 1992). Leconte et al. (2009) utilized a FMCW radar with a linear chirp over a bandwidth of 2 GHz (4–6 GHz) in laboratory observations of artificially grown bubble-free freshwater ice and obtained a coefficient of determination (R^2) of 0.989 for ice thicknesses <0.26 m. This study utilizes two ground-based FMCW radar systems with center frequencies at X- (9.6 GHz) and Ku-band (17.2 GHz) (UW-Scat) with a smaller bandwidth of 500 MHz to extend the framework of the laboratory experiments of Leconte et al. (2009) using field-based scatterometer observations of snow-covered freshwater lake ice, near Churchill, Manitoba. The goal of this study is to identify the ability of X- and Ku-band scatterometers to derive ice thicknesses of floating freshwater lake ice that exhibits heterogeneous snow depth and surface ice types. Verification of snow and ice thicknesses are provided by in-situ snow and ice measurements adjacent to scatterometer scans, an upward facing SONAR on the lake bed, and a one-dimensional thermodynamic lake ice model; the Canadian Lake Ice Model (CLIMo) (Duguay et al., 2003). The use of two frequencies also provides potential for increased information of targets within range, as the difference in wavelengths may potentially interact with discrete scatterers within the snow and ice volume.

2. Study site

Scatterometer observations were acquired at four undisturbed sites with repeated observations (dubbed “static sites”) and 12 sites where sampling occurred within the scatterometer-observed footprint immediately after the completion of the scan (dubbed “roving sites”). Observations were collected from 28/11/2010 to 6/3/2011 on Malcolm Ramsay Lake (formerly known as Lake 58) within the Canadian Snow and Ice Experiment (CASIX). Malcolm Ramsay Lake is situated 20 km east of Churchill, Manitoba (58.7221°N, 93.7845°W) in the Hudson Bay Lowlands region (Fig. 1). The lake bed is composed of sediment and organics with a mean depth of 2.4 m and maximum of 3.2 m (Duguay and Lafleur, 2003).

The Hudson Bay Lowlands region is typified by the intersection of three ecological zones: tundra, tundra–boreal forest transition, and boreal forest, the separation of which runs parallel to the coast (Scott et al., 1987). The relief of the region surrounding Malcolm Ramsay Lake is relatively flat with a high lake fraction (32% of surface area), with formations of overburden the result of glacial deposits (Lafleur et al., 1997).

According to the 1981–2010 climate average obtained from Environment Canada, the mean annual temperature recorded at the Churchill airport (58.7392°N. 94.0664°W) is −6.9 °C, with negative monthly average temperatures occurring from October to May. During the observation period, the average observed temperature was −20.9 °C. The normal water equivalent precipitation is 452.5 mm, with 2010 mm falling as snow. Churchill is situated on the south-western shoreline of Hudson Bay, contributing to its high annual sustained average wind speeds of 20.7 km/h, influencing ice stratigraphy and is requisite for the formation of the tundra-lake snow classification, as discussed in Sturm and Liston (2003).

3. Data and methods

3.1. UW-Scat

The University of Waterloo Scatterometer (UW-Scat) is composed of two frequency-modulated continuous-wave (FMCW) radars that are operated at a bandwidth of 500 MHz with center frequencies of 9.6 and 17.2 GHz (X- and Ku-band, respectively) (manufactured by ProSensing Inc.). UW-Scat functions in a switched transmit and receive mode, obtaining fully polarimetric data (VV, HH, HV, VH). Scans are conducted by mounting the radar units to supports, which are maneuvered using a Kipp and Zonen 2ap Suntracker positioning instrument. Each scan is composed of 60° azimuth sweep across and incidence angle range of 21°–60° at 3° intervals (incidence angles >60° exhibited marked reduction in overall SNR). The height of the radar unit ranged between 1.94 and 2.26 m above the snow surface depending on the incidence angle observed, producing an ellipsoidal ground footprint of approximately 30 cm. Additional relevant UW-Scat sensor parameters are provided in Table 1, with an extended sensor properties and description of the calculation of normalized radar cross-section (NRCS) provided in King et al. (2013).

Raw data blocks observed by the scatterometer are converted to range domain using a fast Fourier transform. Range-dependent transmit leakage was estimated within–scene by acquiring an average of sky observations and coherently subtracting them from the target range bin. The range profiles for each incidence angle are then averaged in azimuth (Geldsetzer et al., 2007).

Fig. 2 shows an average range profile for observed polarizations at X- and Ku-band at 45° for floating lake ice at the beginning and end of the observation period. The profiles are binned to steps of 0.16 m and fitted to highlight peak returns within range. The minimum distance in range r_{min} that can be resolved by an FMCW is influenced by the refractive index of the media ($n_{ice} = 1.78$) and the bandwidth (BW) in Hz (Marshall et al., 2007; Yankielun et al., 1992) where:

$$r_{min} = \frac{c}{(2n_{ice})(BW)} \qquad (1)$$