CGU HS Committee on River Ice Processes and the Environment
14th Workshop on the Hydraulics of Ice Covered Rivers
Quebec City, June 19 - 22, 2007

A controlled experiment to retrieve river ice characteristics from an FMCW radar system

by

R. Leconte[1], S. Daly[2], Y. Gauthier[3], N. Yankielun[2], F. Bérubé[3] and M. Bernier[3]

1: École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, CAN, H3C 1K3
2 : US Army Research and Development Center, Cold Regions Research and Engineering Laboratory, 72 Lyme Road., Hanover, NH, USA, 03779
3: Institut national de la recherche scientifique, Centre Eau, Terre et Environnement, 490 de la Couronne, Québec, QC, CAN, G1K 9A9

Abstract

A controlled experiment was conducted at the Cold Region Research and Engineering Laboratory (CRREL) facilities for retrieving freshwater ice characteristics using a Frequency Modulated Continuous Wave (FM-CW) radar system. The objectives of the experiment are 1) to try to unravel the complex interactions between a backscattered radar signal and ice cover characteristics such as thickness and air bubble content; and 2) to provide a comprehensive data set for testing a theoretical radar backscattering model currently under development at INRS-ETE in collaboration with ÉTS. The experiment was held from October 16 to 27 2006 in an indoor test basin (36.5m X 9.4m X 2.5m), where an ice sheet was grown from 0 to 24 cm thickness and monitored with a series of radar and geophysical measurements. At every 1.5 cm of ice growth, backscattering of the ice cover using an in-house FM-CW C-band radar was measured at incidence angles varying from 0 to 50 degrees for four polarisation combinations, HH, VV, HV, and VH. For each series of measurements, ground penetrating radar (GPR) profiles were obtained at 400, 900 and 1500 MHz, as well as Time Domain Reflectometry (TDR) measurements using horizontal probes installed at 7 cm and 18 cm below the ice surface and a 0-30 cm vertical probe. Ice thickness was measured by extracting small ice samples and snow resulting from air moisture condensation was characterized for depth, snow water equivalent and crystal size. Ice cores were also extracted to characterize their air bubbles content.

Pre-processing of some of the radar data (filtering, fast Fourier transforms, etc.) has been made to 'clean' the data for further processing to extract ice cover characteristics. Preliminary analysis of the data indicates that the radar backscattered signal is notably affected by ice thickness. For example, the HH/HV ratio of power signals correlates with ice thickness between 8 and 24 cm with an R^2 value of 0,95. Using Maxwell's equations, it was shown that the lack of correlation at lower thicknesses (0-8 cm) may be due to

multiple reflections causing interference patterns. As expected, the power of the backscattered signal decreases with increasing incidence angle for all polarization combinations, with HH signal displaying the sensitivity with incidence angle changes. The presence of snow at the ice surface marginally altered the backscattered signal. Preliminary investigations confirm previous findings that ice characteristics can be extracted from the spectral content of backscattered signal.

Introduction

Monitoring of freshwater ice is important for hydropower generation, flood forecasts and mitigation, navigation in inland waters and the construction of winter roads. However, the precise monitoring of river ice development throughout the freeze-up is made difficult to accomplish in northern rivers because of site accessibility. Moreover, ice conditions at the onset of ice break-up, which are particularly important to evaluate in order to properly forecast the incipient flood, are often unsafe to those who take measurements. Under such circumstances Earth Observation technologies, especially Synthetic Aperture Radar (SAR), are seen as potential viable means for river ice monitoring. However, radar signal interact with river ice in a number of ways which depend on the physical properties of the ice cover itself relative to the parameters of the imaging radar. A number of research initiatives were devoted to a conceptual interpretation of the SAR interactions with river ice cover (e.g. Pelletier et al, 2005), however a comprehensive quantitative understanding of these interactions has been the subject of very few studies. One of the reasons relates to the challenge of gathering detailed, representative in-situ information of stable, heterogeneous river ice covers, for a variety of radar configurations. Controlled laboratory experiments are able to control the many parameters which influence radar returns from an ice surface, thereby allowing investigating the radar-ice interactions through careful theoretical modelling.

A controlled experiment was recently conducted at the Cold Regions Research and Engineering Laboratory (CRREL) facilities for retrieving freshwater ice characteristics using a Frequency Modulated Continuous Wave (FMCW) radar system. The objectives of the experiment were: to try to unravel the complex interactions between the backscattered signal and ice cover characteristics such as ice thickness and air bubble contents; and to provide a comprehensive data set for testing a theoretical radar backscatter model currently under development at the Institut National de la Recherche Scientifique, Eau, Terre et Environnement (INRS-ETE) (Gherboudj et al., 2007); and to develop an expertise which will be valuable for setting up and conducting follow-up experiments over more diversified ice cover characteristics.

Freshwater ice monitoring using SAR

A number of studies have demonstrated that SAR signal returns are affected by the SAR properties such as incidence angle, radar polarisation and frequency, as well as the river ice cover characteristics, which includes roughness, air bubble content and impurities found in the ice cover. The roughness at the ice-water interface has been identified as a potentially strong contributor to the overall radar return because of the very high dielectric contrast between liquid water (dielectric constant $\varepsilon \cong 80$ at centimeter-wavelength) and solid ice ($\varepsilon \cong 3.2$) at Ghz microwave frequencies. However, the complexities of the interactions make difficult the interpretation of the radar signal and resulting imagery, which so far has impeded on an operational use of SARs for freshwater ice monitoring. For example, Pelletier et al. (2005) in a monitoring study of the 2003 break-up of the Athabasca River, noted a decreasing trend in the radar backscatter coefficient at the onset of break-up. They attributed this decline to the presence of liquid water on the ice surface which reduced the penetrating depth of the radar signal and the domination of surface scattering by the relatively smooth surface. However, the exact opposing behaviour was observed on another image collected over the same areas and for similar environmental conditions. The most likely explanation for this apparent anomaly was the use of a different, steeper imaging configuration for this particular image. These qualitative assessments, albeit reasonable and probably correct, need to be substantiated with theoretical modelling experiments.

The remotely sensed mapping of freshwater ice thickness has been attempted with good success using high-resolution airborne FM-CW radars in the millimetre-wavelengths (Yankielun, 1992; Yankielun et al., 1993). Using a prototype FM-CW radar system, Yankielun (1992) was capable of resolving a minimum ice thickness of 3 cm over a freshwater lake. Ice thickness was calibrated from the separation of two difference frequencies obtained using spectral analysis techniques, one frequency attributable to the air-ice interface reflection and the other attributable to the ice-water reflection. Radar profiling data on a river ice cover with ice thickness varying from 5 to 50 cm, open leads and massive ice accumulations showed good agreement with in-situ observations.

Estimation of lake or river ice thickness from SARs has so far not been demonstrated conclusively. Leconte and Klassen (1991) noticed a change in radar backscattering coefficients of lakes depending whether the ice was frozen to the bottom or not. This opens up the possibility of monitoring lake thickness indirectly from lake bathymetric maps. The major challenge in directly estimating lake or river ice thickness is to evaluate the volume scattering component of the total radar signal which should be related to ice thickness given the heterogeneity of the ice cover. Change detection techniques may provide some information, however additional difficulties arise if the water/ice interface is rough and significantly contributes to the overall signal. Other difficulties relate to the radiometric sensitivity of the radar as compared to the volumetric scattering component of the radar return. Gauthier et al. (2006) and Jasek et al. (2003) obtained a positive linear relationship between average radar backscattering coefficients over 100 to 500-meter reaches of the Peace River (Alberta) and average ice thickness measurements measured on four test sites. Many ice types were identified in the studied reaches, from juxtaposed ice to consolidated ice cover to heavy consolidated ice cover, precluding any physical explanations to the reported behaviour between radar return and ice characteristics.

The difficulties associated with understanding the physical causes behind the observed SAR signal and river ice covers prompted us to conduct a laboratory experiment by which it would be possible to investigate linkages between radar parameters and ice thickness in a controlled environment. The experiment is described in the following section.

Experimental set-up

The radar-ice experiment was conducted in October 2006 at CRREL's Test Basin facility. The test basin is used mainly to conduct large-scale studies of ice forces on structures such as dams and piers. The basin has dimensions of 36.5 m x 9 m x 2.4 m which is housed in a cold room that can be refrigerated to -28^{o}C (-20^{o}F). At that temperature, a 2 mm per hour ice growth rate can be achieved. Two carriages are installed on top of the basin. One carriage has a heated room inside which instruments, computers, electronic equipment, etc. can be deployed and manipulated. A second carriage can be used to access any location above the basin to make various measurements.

A custom-made C-band (4-6 GHz) FM-CW radar was used for the experiment (Figure 1). The radar is capable of taking measurements in the following polarisation modes: HH, VV, HV and VH. It is also possible to set up the radar at various incidence angles from 0^o (vertical) to 50^o by 5^o increments. This allowed radar measurements at incidence angles and polarisation modes directly compatible with the future Radarsat 2 satellite (C-band, 4 polarisation modes, 20-49^o at standard beam mode), and also with the current Envisat and Radarsat 1 satellites. In this experiment, the radar was mounted at the end of a truss that was attached horizontally and perpendicularly to the main carriage (Figure 2). The radar data acquisition and digital signal processing computer system was installed inside the heated cabin. The system is controlled directly by a lap-top computer. The data acquisition process can be monitored in real-time by visualizing the time series samples transformed into a power spectrum via a FFT. Each radar scan provided a minimum of 1000 time series samples, and each series comprised 1024 bins (data points). The raw, digital signal was also stored in the computer hard disk for later processing and analysis. The second carriage was used to reach the radar and adjust its incidence angle positions and polarisation modes when the ice cover was too thin to allow walking on the surface. A step ladder was later used when ice thickness allowed it, as it proved to faster than the carriage to reach the radar.

The following data was collected during the experiment:

- Radar signals at HH, VV, HV and VH polarisations and at incidence angles of 0, 20, 30, 40 and 50^o;
- Ice depths measurements by driving a manual ice auger through the ice cover;
- Time domain reflectometry (TDR) measurements of the water and ice using three probes installed in the basin next to the main carriage, from which values of the ice and water dielectric constants were retrieved. One probe was set up vertically to monitor the change in the dielectric constant with increasing ice thickness, while two other probes were installed horizontally at 7 and 18 cm below the water surface to detect the moment the ice thickness would reach these values;
- Snow depth and snow water measurements. Running the cold room at – 28^oC during 10 days resulted in the formation of surface hoar that reached 1-2 cm thickness, consecutive to the releasing of moisture in the air as part of the cold room refrigeration cycle;
- Ground penetrating radar measurements to further provide another data set of ice thickness measurements;
- Water and air temperature (recorded continuously);
- Ice samples were collected using a manual saw and also using an ice corer. Core samples were stored in a freezer to later perform thin section analyses for retrieving information on air bubble content.

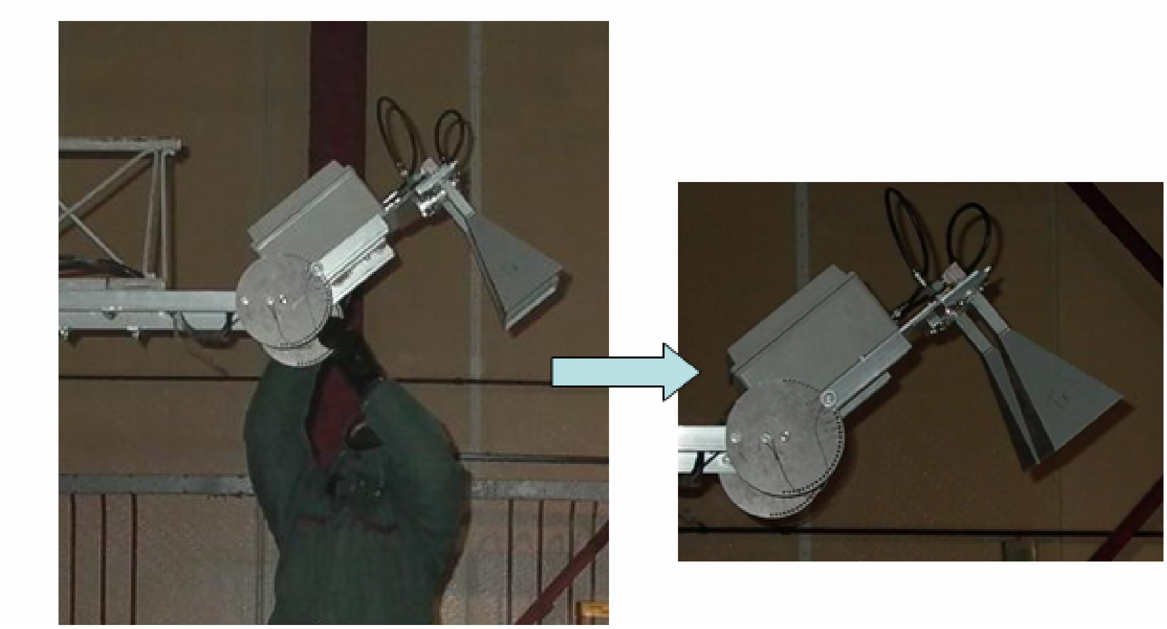


Figure 1. C-band FM-CW used for the experiment

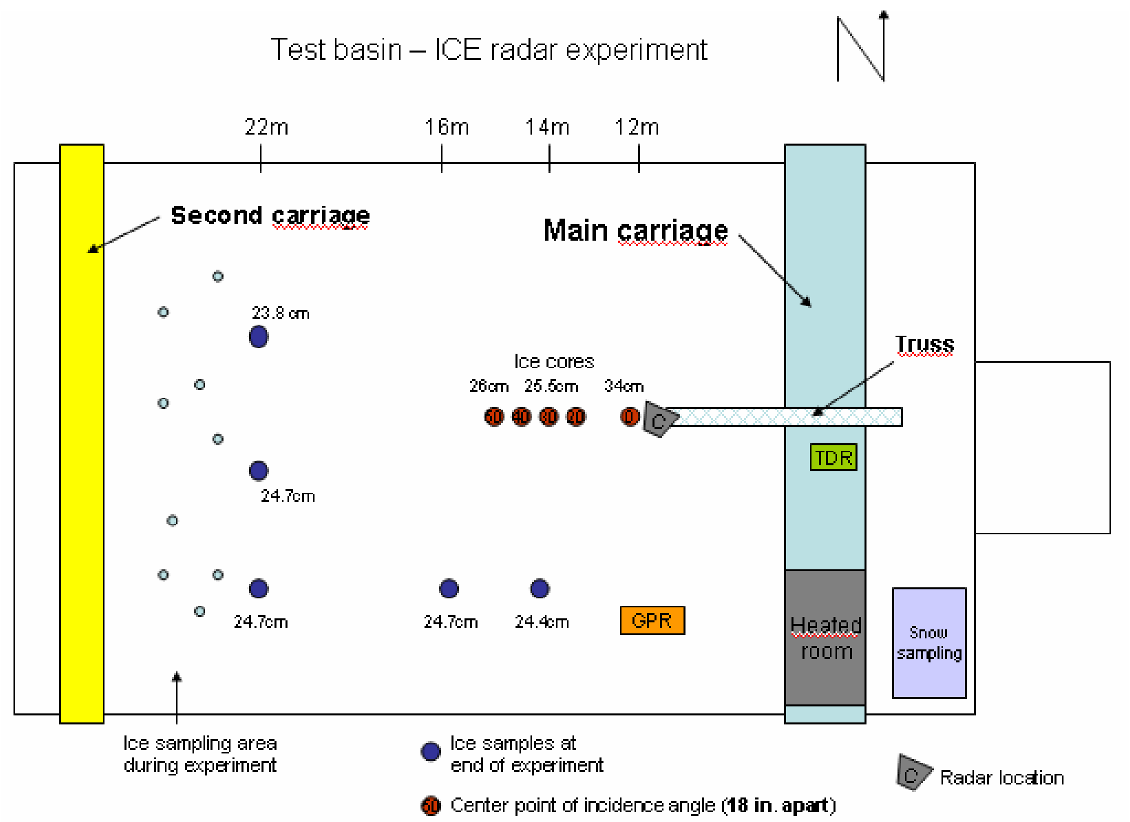


Figure 2. Test Basin layout. Maximum ice thickness values and sampling locations are indicated on the figure. The main carriage was fixed for the duration of the experiment, while the second carriage could be moved to reach the radar.

The ice cover was sampled and corresponding radar and ancillary data were collected 18 times during the experiment, which ran from October 17th to October 27th. An initial thin ice sheet was seeded by spraying a mist over the basin while the temperature was well below the freezing point. The sheet was grown by thermal conduction as the air temperature was lowered to -28°C. This resulted in an ice cover with smooth ice/air and ice/water interfaces at all times. The ice cover reached an average thickness of 24 cm at the end of the experiment. The thickness increased approximately linearly during the first 2 days of the experiment, which was followed by a diminishing rate of increase as thicker ice and the presence of surface hoar increased the insulating capacity of the cover (Figure 3).

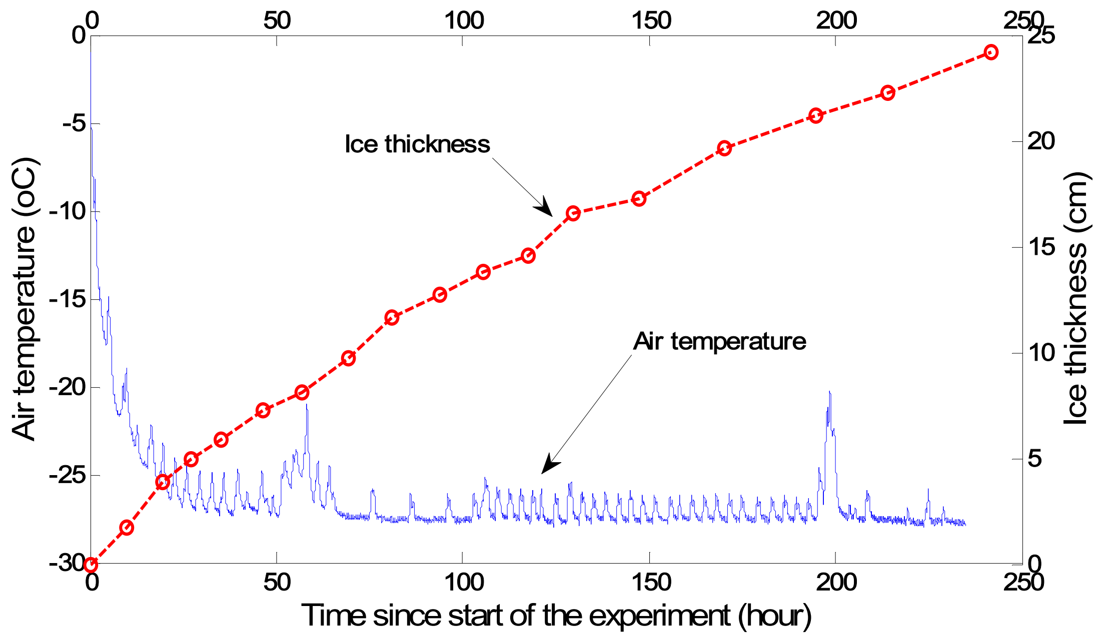
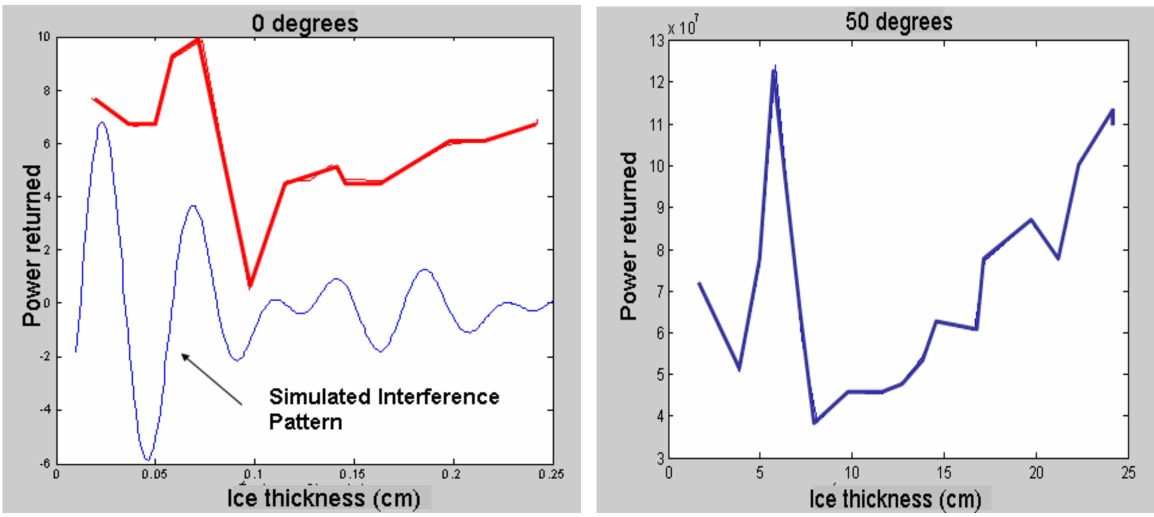


Figure 3. Ice thickness growth and corresponding air temperature during the radar experiment

Results

It is hypothesized that volumetric scattering will be an important component to the radar signal returned as the smooth air/ice and ice/water interfaces would mainly result in specular reflections. Figures 4a and b show an example of the variation of the maximum power returned as a function of ice thickness at incidence angles of 0° and 50°. Both figures show a similar behaviour, characterized by significant fluctuations of the power returned for ice thicknesses below 8 cm, followed by a steady increase of the radar return with increasing ice thicknesses up to 24 cm. The increase was somewhat more significant as the incidence angle increased. This was anticipated since the oblique radar signal would penetrate through more ice and interact with more scatterers. It was also assumed that the fluctuating signal at small ice thicknesses was the result of multiple reflections between the air/water and ice/water interfaces causing interference patterns. This hypothesis was validated by simulating the interference patterns of an electric field interacting with a thin ice layer using the Maxwell equations (Figure 4a). It can be seen that the FM-CW radar is capable of inferring freshwater ice thickness of uniform homogeneous ice covers from the intensity of the backscattered signal.



(a) (b)

Figure 4 Variation of backscattered intensity with ice thickness at incidence angles of 0^o (a) and 50^o (b). Notice the oscillatory patterns at lower thickness values. These patterns can be explained by multiple reflections at the air-ice and ice-water interfaces causing interferences in the return signal.

Volume scattering is the main interaction which causes the incoming signal to be depolarized. Therefore, one would expect that using cross-polarisation data in conjunction with like-polarisation information would facilitate retrieving ice thickness for smooth ice covers. Figure 5 shows the relationship that was obtained between the power ratio of C-HH over C-HV at a 20^o incidence angle. Data corresponding to ice thickness less than 8 cm were discarded from the analysis because of the above reported oscillatory behaviour. As the figure shows, a strong positive relationship was observed. Although these preliminary findings are encouraging as for the potential of multipolarisation SARs to retrieve freshwater ice thickness values, further research is required to fully evaluate the possibilities and limitations of radar sensors over a range of sensor configurations and river ice characteristics. One potential limitation is the current radiometric resolution of satellite SARs which is of the order of 1 dB, which may limit ice thickness retrieval to thick ice covers.

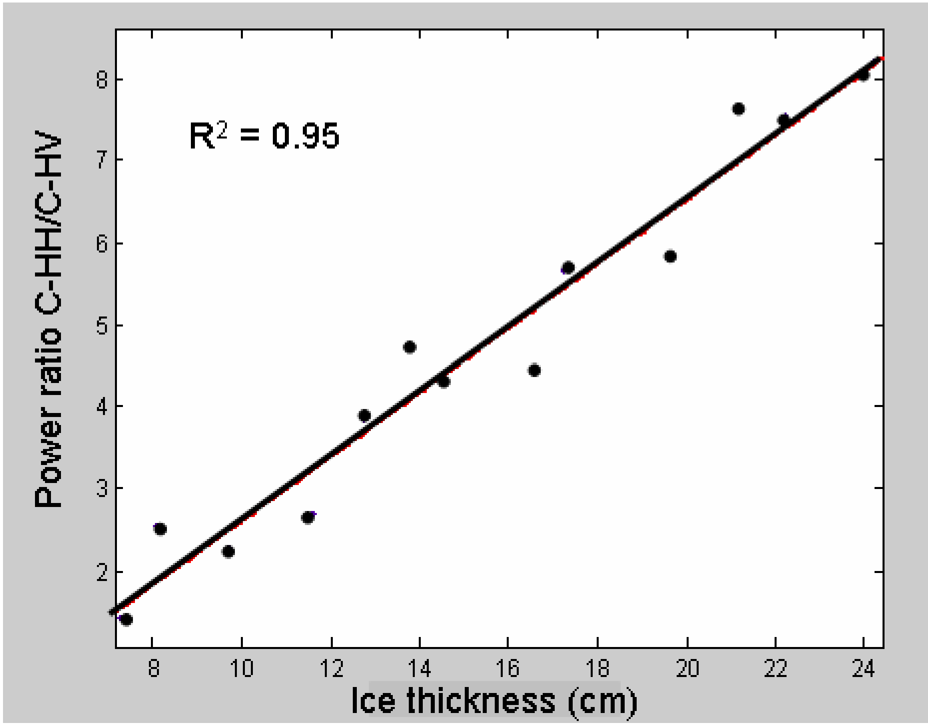


Figure 5. Correlation between the power ratio of C-HH/C-HV with ice thickness at a 20° incidence angle.

The variation of the intensity of the backscattered radar signal with incidence angle was also evaluated. Figure 6 shows an example comparing HH, VV and HV data for the ice cover at maximum thickness (24 cm). The decrease, expressed in dB, is approximately 3 dB for the HH signal over the full range of incidence angles covered. This low value is a further indication that specular reflection at the smooth air/ice and ice/water interfaces is occurring. Duguay et al (2002) obtained differences of 4 to 7 dB using RADARSAT C-HH SAR data for lakes that showed a lesser concentration of bubbles within the ice volume, while small differences in the order of 1 dB were obtained for floating ice covers that contained a greater quantity of bubbles. These observations are in agreement with findings of this study, with very few air bubbles present in the ice cover. Notice that the radar backscatter at a 20° incidence angle appears to be higher than expected, based on the values at incidence angles of 0 and 30°. A possible explanation for this apparent anomaly could have been related to spatial heterogeneities present in the ice cover which were missed by the ice sampling scheme. For instance, it was found that the ice next to the radar was 34 cm thick as compared to 24 cm elsewhere in the basin. A thicker ice cover, resulting from the absence of surface hoar due to walking on the cover, could produce a higher backscattered return than expected. However, its location was not coincident with that of the radar footprint at 20° incidence angle so that this possibility had to be ruled out.

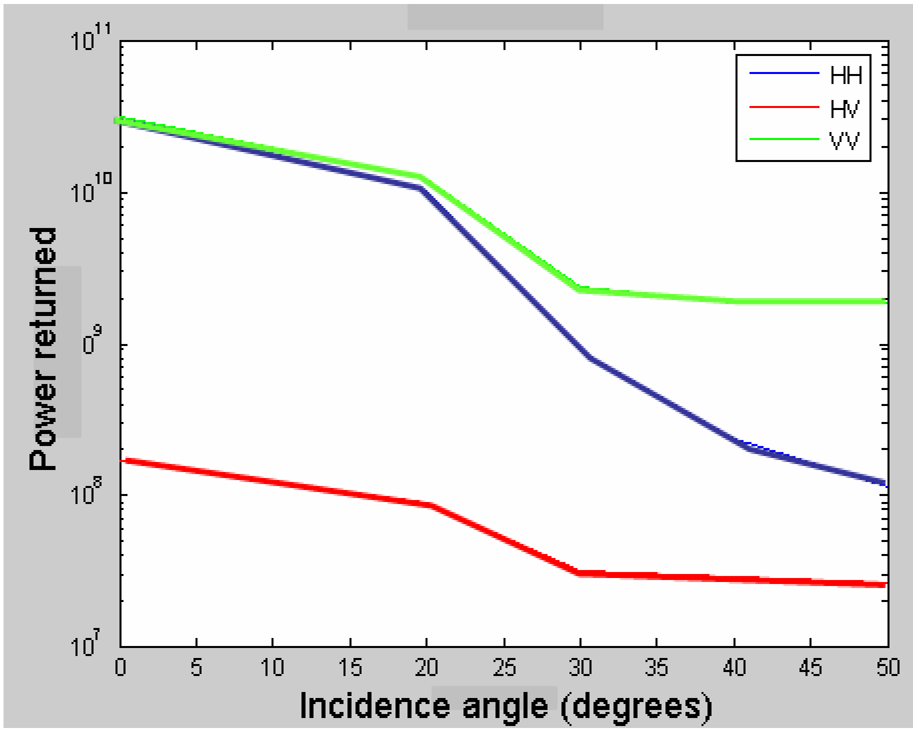


Figure 6 Variation of backscattered power with incidence angle, for an average ice thickness of 24 cm.

The presence of the surface hoar marginally affected the backscattered radar return at all incidence angles and for all polarisation combinations. Although the surface hoar was made of crystal sizes of 2-3 cm, which is of same order as the radar wavelength (5 cm) the thin snow cover (approximately 1-2 cm) along with the very cold temperatures resulted in the snow has being virtually transparent to the radar.

Finally, spectral analysis of the radar return signals was conducted to further assess the performance of an FM-CW radar to detect freshwater ice thickness. The following equation can be used to estimate ice thickness (Yankielun et al., 1993):

$$h = \frac{(F_{r2} - F_{r1})t_{swp}c}{2(BW)n_{ice}} \quad (1)$$

Where F_{r2} and F_{r1} are the difference frequencies attributable to ice-water and air-ice interface reflection (Hz); t_{swp} is the FM-CW sweep time, (s); BW is the FM-CW swept bandwidth (Hz); and n_{ice} is the index of refraction of freshwater ice.

According to this equation, ice thickness is directly proportional to $(F_{r2} - F_{r1})$. The difference frequencies F_{r2} and F_{r1} are proportional to the target range. The strength of the detected frequencies as obtained from a spectral analysis of the signal will depend on the dielectric contrast at these interfaces as well as the radar incidence angle. Note that the real part of the dielectric constant of water dramatically increases from less than 10 to approximately 80 as the microwave frequency goes from the millimetre- to the centimetre-range, while the dielectric constant of pure ice remains approximately constant throughout the millimetre-centimetre spectrum (von Hippel, 1954). One should therefore expect the C-band FM-CW radar used in this experiment to easily recover the F_{r2} and F_{r1} parameters (although to a lesser extent because of the smaller dielectric contrast at the air-ice interface), and to retrieve freshwater ice cover thickness, for ice thickness values larger than the radar wavelength.

In order to enhance the separation between F_{r2} and F_{r1} and therefore to resolve a minimum ice thickness of the order of 5 cm corresponding to the wavelength of the C-band, a spectral analysis of the backscattered radar signals was performed by computing FFTs on 256-bin signal time series extracted from the full 1024-bin traces. A sliding window was used from which FFTs were calculated and the 'best' transform was kept, i.e. the FFT that produced the lowest signal-to-noise ratio. Figure 7 shows the resulting relationship between $\left(F_{r2} - F_{r1}\right)$ and ice thickness obtained during the experiment according to this procedure. A very satisfactory linear relationship was confirmed, confirming that centimetre-wave FM-CW radars are very effective at retrieving accurate freshwater ice thickness values, at least for smooth uniform ice covers.

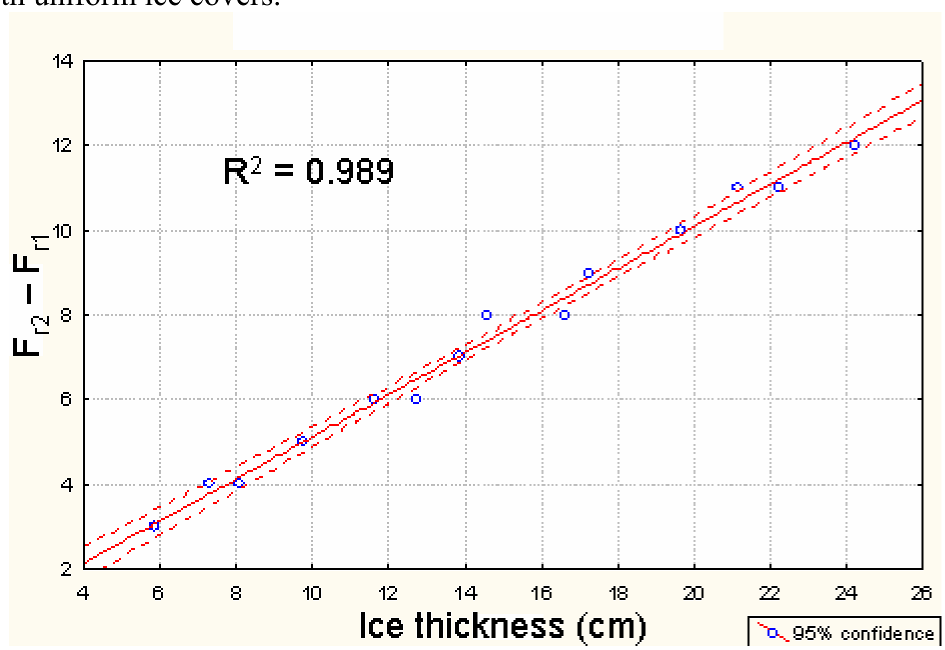


Figure 7 Variation of $\left(F_{r2} - F_{r1}\right)$ with ice thickness

Conclusion

A controlled experiment was conducted in an indoor test basin to assess the potential of C-band radars to retrieve freshwater ice thickness and also to provide a data set for calibrating a theoretical backscatter model applicable to lake and ice. A FM-CW multipolarisation radar, which could be tilted at incidence angles corresponding to those of current satellite SARs was used for the experiment. Radar and ancillary data were collected during the thermal ice growth which achieved 24 cm at the end of the experiment. Preliminary analyses confirm the potential of high radiometric resolution C-band radars to retrieve freshwater ice thickness values from the average power of the backscattered signal over smooth, homogeneous ice covers The reliable extraction of ice thickness values at smaller thicknesses, less than approximately 8 cm for this experiment, was prevented by multiple reflections of the radar signal. As expected, a decline of the radar return was observed with increasing incidence angle, its small magnitude corroborated by small bubble content in the ice matrix. A spectral analysis of the signal further confirms the potential of FM-CW radars to retrieve ice thickness values at various incidence angles. Although encouraging, these results need to be further validated by a more comprehensive evaluation of the data acquired during this experiment, and also with ice covers characterized by rough air-ice and ice-water interfaces. This will be the object of future research and experiments.

References

Duguay, C.R., Pultz, T.J., Lafleur, P.M., Drai, D. 2002. RADARSAT backscastter characteristics of ice growing on shallow sub-Arctic lakes, Churchill, Manitoba, Canada. *Hydrological Processes*, 16:1631-1644.

Gauthier Y, F Weber, S Savary, M Jasek, L-M Paquet & M Bernier, 2006. A combined classification scheme to characterise river ice from SAR data. EARSeL eProceedings, 5(1): 77-88

Gherboudj, I., Bernier, M., Leconte, R. 2007. Validation of a backscatter model of river ice covers using Radarsat-1 images. Proceedings of IGARSS 2007, IEEE, Barcelona, Spain.

Jasek, M., Weber, F., Hurley, J. 2003. Ice thickness and roughness analysis on the Peace River using RADARSAT-1 SAR technology. 12th workshop on the hydraulics of ice covered rivers, Edmonton, Alberta.

Leconte, R. and Klassen, P.D. 1991. Lake and river ice investigations in Northern Manitoba using airborne SAR imagery. *Arctic*, 44, supp.1:153-163.

Pelletier, K.D., van der Sanden, J., Hicks, F.E. 2005. Synthetic aperture radar: current capabilities and limitations for river ice monitoring. 17th Canadian Hydrotechnical Conference, Edmonton, Alberta, April 17-19, 2005.

Yankielun, N.E. 1992. An airborne millimetre-wave FM-CW radar for thickness profiling of freshwater ice. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H., CRREL report CR 92-20.

Yankielun, N.E., Ferrick, M.G., Weyrick P.B. 1993. Development of an airborne millimeter-wave FM-CW radar for mapping river ice. Can. J. Civ. Eng., (20):1057-1064.