Signature of Arctic first-year ice melt pond fraction in X-band SAR imagery

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General comments

The authors have studied melt pond fraction (MPF) estimation using TerraSAR-X dual-polarization SAR imagery acquired over drift ice north of Svalbard, and presented empirical models for MPF estimation in two different wind speed conditions (low speed and intermediate speed).

In the Introduction Section authors give good overview on importance of melt ponds on the Arctic sea ice heat budget and in the Arctic climate system, and on previous studies on melt pond fraction estimation with optical and SAR imagery. The number of previous SAR studies on melt pond detection and fraction estimation is quite large, and so far a generic method for the estimation has not been presented/developed. There has been some success for the melt pond fraction (MPF) estimation over smooth landfast ice using C-band co-polarization ratio (HH and VV pol SAR images needed) or HH-pol backscattering coefficient ($\sigma°$). For MPF estimation over drift ice only few studies has been conducted. At least it seems that MPF estimation over drift ice with C-band single pol imagery is not possible. Over drift ice sea ice deformation features like ice ridges and make MPF estimation in theory much more difficult than over smooth landfast ice. Other frequencies than C-band have been used only in few case studies. Likely (to my opinion) accurate MPF estimation is only possible with high resolution (<5-10 m) SAR imagery. So far time series of MPF maps over the Arctic have been produced only with optical imagery (MODIS, MERIS). These charts are limited by accuracy of automatic cloud masking and persistent cloud cover during the Arctic summer. Accurate MPF charts from SAR imagery would supplement greatly the MPF charts from optical imagery.

Section 2 discusses nicely about melt pond signatures in SAR imagery, but it could also include overview of observed $\sigma°$ behavior during melt ponding season (ponding, drainage etc.), see e.g. D. G. Barber, J. J. Yackel, and J. M. Hanesiak, "Sea ice, RADARSAT-1 and arctic climate processes: A review and update," Can. J. Remote Sens., vol. 27, no. 1, pp. 51–61, 2001.

Dual-polarization TerraSAR-X imagery acquired over drift ice for MPF estimation have been previously studied by Kim et al. (2013) and Han et al. (2016). Kim et al. (2013) used only one TSX image acquired in Aug 2011 over East Siberian Sea, but they have large amount of co-incident airborne very fine resolution X-band (single pol) images. Comparison MPF data was from airborne photography. Han et al. (2016) used the same datasets and also one additional TSX image acquired in July 2011 over the Chukchi Sea. Kim et al. (2013) estimated MPF with "We first delineate the ice and melt pond features using image processing software (ENVIA EX), based on the combination of multiscale segmentation and aggregation methods."; not discussed in more details, but Han et al. (2016) studied various polarimetric parameters and their textural features in MPF estimation by machine learning approaches.

The authors have used here four TSX dual-polarized StripMap images acquired during ICE2012 campaign in north of Svalbard. Comparison MPF data was from helicopter-borne optical imagery. In addition, surface roughness data was calculated from stereo camera imagery, and weather data was measured by R/V Lance at the ICE2012 campaign site. They have studied MPF estimation with different polarimetric parameters calculated from the dual-pol TSX imagery, as was done also by Han et al. (2016). The main questions now are: 1) Does this study give new scientific results/information compared to Kim et al. (2013) and Han et al. (2016)? 2) In what ways it is different to them, data and/or methods?

My answers: Study area is different (Chukchi Sea vs. Svalbard) which could have influence on the results if sea ice conditions (FYI vs. MYI) where different; authors should discuss this in the paper. Wind speed is taken into account here unlike in Kim et al. (2013) and Han et al. (2016). Wind speed has large effect on the backscattering from melt ponds (not frozen). Somewhat more SAR images have used, four here compared to two in Han et al. (2016), making the results here more reliable. The developed MPF algorithms are linear functions between MPF and one polarimetric parameter. I favor this kind of simple approach as the results can be related easily to theoretical backscattering models. Han et al. (2016) utilized machine learning approaches where relations between polarimetric parameters (and scattering theory) and an estimated parameter may not be very clear. However, I think that the paper in its current form gives quite little new information/findings compared to previous studies on the MPF estimation with SAR. The statistical reliability of the developed empirical MPF estimation models seems quite low, r2 was at best only 0.21 and RMSE is high. The value of the paper could be improved by following changes and additions:

The empirical models for the MPF estimation were developed using datasets over a large ice floe. Why were not all co-incident SAR imagery vs. airborne photography used? How results would change if they were?

Both wind speed and SAR incidence angle have large effect on the MPF estimation. Wind speed is now taken into account by MPF models for two different wind conditions. I suggest you developed MPF models which include incidence angle or compensate $\sigma°$ incidence angle variation before MPF estimation. The study should include more variable wind speed conditions, but in the current dataset these are not present.

You could study effect of sea ice type in the MPF estimation, e.g. by first segmenting the SAR images to level ice and deformed ice categories (with the help aerial photography if possible). In best case we could have also sea ice type taken into account in the MPF estimation. You have also surface roughness data which could be utilized here.

Show MPF maps from some SAR images and discuss spatial variation present, does it make sense? You have four SAR images, how does estimated MPF behave temporally? Now Table 5 shows MPF averages over the full scenes, but these are not much discussed in the text, and temporal variation does not seem right (36.2->45.7->31.2->53.3).

Can you compare your estimates with those from optical imagery?
See http://icdc.zmaw.de/1/daten/cryosphere/arctic-meltponds.html

The study would benefit greatly from a larger SAR dataset. Are there any co-incident TSX vs. in-situ / airborne data from NICE2015 campaign you could use? You really need more wind speed conditions for the MPF estimation development. Even including more TSX images without corresponding comparison data is possible, you could study spatial and temporal trends. In addition, any fine resolution C-band images available? Comparison between C- and X-band would be nice addition.

In general, the paper is well written and structured, and easy to read and understand. The data processing and analysis methods are scientifically sound and discussed in needed detail. I am afraid in the current form the paper gives quite few new scientific findings compared to previous studies.

From Conclusions: “Future studies should aim to include a larger number of satellite scenes acquired during various sea ice conditions, melt pond evolution stages, wind speeds and incidence angles. The effect and limitations of sea ice surface roughness and dependency on filtering size and scale should also be further investigated.”

You should consider taking some of these topics to this paper!

Finally, Yackel and Barber (2000) speculated that σ° may be more closely related to the albedo than to melt pond fraction due to the fact that albedo results from the integration of all surface types (snow, saturated snow, melt ponds) which contribute to the measured σ°. What's the authors' view on this; would it be better to investigate the relationship between SAR data and albedo than SAR and melt pond fraction? Please, discuss this in Introduction Section.

Specific comments

1. Introduction

page 3, lines 90-92: terms 'dual polarimetric' and 'dual-polarisation' used, confusing…I think it should be 'dual-polarisation' for SAR imagery with two polarizations.

2. Melt ponds in SAR imagery

p. 4, l. 118: "Observed surface roughness increases with increasing frequency, making X-band more sensitive to small-scale surface roughness than C-band."

I think surface roughness is physical property of a surface, and its effect on backscattering depends on radar wavelength.

l. 124: "Six of these features are included in our study and are described in the following subsection."

In Table 4 there are eight features.

3.2 Data set

Give absolute calibration accuracy and equivalent number of looks (ENL) (i.e. effect of radar fading) in TSX images. Do they have any significant effect on your data analysis results?

4.1 Sea ice conditions

Was there any nighttime re-freezing on sea ice and melt pond surfaces which could have influenced backscattering signatures in T1 TSX image acquired at 06:52 UTC on 28 July?

4.3 Intermediate-wind case

p. 12, l. 358: "From visual inspection of the helicopter images, some of the lowest RVV/HH values origin from slightly deformed areas with a surface roughness possibly exceeding the Bragg criterion."

Please discuss how this sea ice condition leads to low RVV/HH.