

## **Sea ice melt pond fraction estimation from dual-polarisation C-band SAR – Part 2: Scaling in situ to Radarsat-2**

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### **General comments**

The authors have studied retrieval of sea ice melt pond fraction over first-year ice (FYI) in the Canadian Arctic Archipelago (CAA) using Radarsat-2 (RS-2) dual-polarization (HH/VV) imagery. Melt pond fraction data are needed for e.g. sea ice process studies and parameterization of albedo in numerical weather prediction (NWP) models. The retrieval of the melt pond fraction is based on the difference between sea ice and melt pond (liquid state) backscattering coefficient co-polarization ratio ( $PR=VV/HH$ ) signatures at incidence angles higher than  $40^\circ$ . In the retrieval three experimental methods are used based on surface based scatterometer data, Bragg scattering model and RS-2 and airborne imagery (sub-sample of the data to construct a predictive model). At best a RMSE of 0.07 is achieved in the RS-2 based melt pond fraction estimation. Poor pond fraction estimation accuracy were attributed to wet snow and freezing of melt ponds (this was not, to my understanding, verified with in-situ observations, but rather based on weather and pond water temperature data) which are plausible explanations based on previous studies and sea ice backscattering models. It seems that more work are needed before accurate automatic melt pond fraction retrieval from SAR images is possible.

In general, the paper is well written, and the data acquisition, processing and analysis methods are scientifically sound and discussed in needed detail. The paper gives some new insight on SAR based melt pond fraction estimation methods, and also on problems imposed by varying sea ice conditions when retrieving melt pond fraction from SAR images. Unfortunately, dual-polarisation HH+VV SAR images are needed, these are not currently available with large temporal and spatial coverage, but this is technical limitation, not scientific in the author's method.

The Introduction Section discusses very nicely why estimation of melt pond fraction is needed and previous studies conducted. In page 850 it is said “RS-2 backscatter statistics over undeformed FY ice ...”, so sea ice in your study was thermodynamically grown level ice, without any deformations? Give overview of sea ice conditions (snow and ice thickness etc.) in your study area somewhere in the paper.

The melt pond fraction retrieval is studied using five RS-2 images acquired at different stages of the seasonal pond evolutionary cycle in May-June 2012. The study would benefit from larger number of images, e.g. error statistics would be more reliable, and images acquired over multiple summer melting periods, e.g. two-three summers, would allow better to see the retrieval performance in different sea ice conditions. Is addition of more RS-2 images (or SAR images from any other sensor, like ENVISAT APP images from Scharien et al. 2007, see below) to the study possible, even without accompanying in-situ data?

Yackel and Barber (2000) speculated that backscattering coefficient ( $\sigma^\circ$ ) 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  $\sigma^\circ$ . What's the authors' view on this; would it be better to investigate the relationship between PR and albedo than PR and melt pond fraction? Discuss this in Introduction Section.

The paper would benefit using the IEM scattering model instead of the Bragg model as it has larger range of validity, see comment below.

## **Specific comments**

Page and line numbers refer here to the printer-friendly version of the article.

### **Introduction**

Page 848, line 20: Data from these sensors have been used to identify pond formation (Comiso and Kwok, 1996; Howell et al., 2006), though their low resolution (several kilometres) and vulnerability to signal contamination by land and open water (Heygster et al., 2012) make quantitative melt pond retrievals problematic.

Yes, signal is contaminated by land and open water, but the areas of contamination can be estimated with landmask and sea ice concentration data. Thus, the major problem is low spatial resolution.

In a previous study with the same first author as here it was demonstrated that albedo of melt-pond-covered landfast FYI can be estimated with better accuracy using C-band SAR derived co-polarization ratio than using only co-polarized  $\sigma^\circ$  at larger incidence angles. This is likely the first study where the usability of PR in albedo/melt pond fraction retrieval is discussed, and it should be mentioned in the Introduction.

Why in Scharien et al. (2007) you studied PR vs. albedo relationship, but now switched to PR vs. melt pond fraction?

R. K. Scharien, J. J. Yackel, M. A. Granskog, and B. G. T. Else, “Coincident high resolution optical-SAR image analysis for surface albedo estimation of first-year sea ice during summer melt,” *Remote Sens. Environ.*, vol. 111, no. 2-3, pp. 160-171, 2007.

### **2.2 Bragg scattering model**

Equation (2) is valid under single scattering assumption in backscattering, i.e. cross-pols are zero. This could be mentioned in the text.

Give references for values sea ice and sea water (melt pond)  $\epsilon_{\text{psr}}$ .

The Bragg scattering model has a nice feature that PR is independent of surface roughness, but its validity limit is small,  $k_s < 0.3$ , as is stated in the Introductory this limit for FY melt ponds can be exceeded. This is somewhat weak point of the paper. How about using the IEM model (Fung 1994)? With the transition model for the Fresnel reflection coefficients (Wu et al. 2001) the restriction for the single scattering IEM model is  $k_s < 2$ . With the IEM model PR is not independent of surface roughness, but as said its valid for more rough surfaces. It should be possible to construct a semi-empirical IEM model where the effects surface roughness and  $\epsilon_{\text{psr}}$  are separate in PR using IEM simulations with measured melt pond surface roughness data, see e.g. Zribi et al. (2006).

Wu, T.D., K.S. Chen, J. Shi, and A.K. Fung. 2001. A transition model for the reflection coefficient in surface scattering. *IEEE Trans. Geosci. Remote Sensing* 39(9), 2040-2049.

Mehrez Zribi, Nicolas Baghdadi, and Christine Guérin 2006. Analysis of Surface Roughness Heterogeneity and Scattering Behavior for Radar Measurements. *IEEE Trans. Geosci. Remote Sensing* 44(9), 2438-2444.

### **3.1 Data collection**

p. 855, l. 20: Each of these scenes has a shallow incidence angle (41 to 44) and, with the exception of R3, falls within 3 h of an AP survey.

The scene R1 (12 May) does not have corresponding AP imagery at all, but is not needed anyway?

### 3.2 Data processing

Estimate using ENL (around 20), the radiometric resolution of PR. This is very important information when you retrieve melt pond fraction from PR, it gives short of noise of the estimated pond fraction ( $\pm$ fraction). With ENL of 20 the radiometric resolution ( $10 \cdot \log_{10}(1 + 1/\sqrt{\text{ENL}})$ ) of single channel  $\sigma^\circ$  is around 0.88 dB. Give absolute calibration accuracy of RS-2.

p. 858, l. 3: A 75 by 75 pixel ...

Give the size of the window also in meters.

### 3.3 Pond fraction retrieval

Based on the radiometric resolution of PR give noise, i.e. inaccuracy ( $\pm$ fraction) of the retrieved PR with all three PR models.

p. 859, l. 8: Full-resolution collocated data corresponding to AP2 and AP4 were used to create a linear model for the estimation of pond fraction (Fp) from PR:

What this full-resolution data here means?

### 4.1 Seasonal evolution of pond coverage and SAR backscatter

p. 859, l. 23: though slight variations due to incidence angle (44–49) must be considered.

Can you estimate how much variation changing incidence angle causes in  $\sigma^\circ$ ?

p. 860, l. 9: Backscatter increases relative to R1 are attributed to stronger surface scattering contributions from wind-wave roughened ponds and wet snow, with the former caused by strong coincident wind forcing ( $U_{10} = 11.9 \text{ ms}^{-1}$ ) from an approaching storm.

What mechanism(s) causes stronger backscattering in wet snow than in dry snow?

p. 860, starting l. 14: R3 and R4 images were acquired under very similar pond fraction and wind speed conditions, but PR shows quite different values, 2.6 vs. 1.3, why is that? Bare ice patches with decreasing moisture and increasing scattering? Explain better in the text. Does air temperature history has any role here? Air temp was smaller for R3.

### 4.2 Spatially distributed polarisation ratios and pond fractions

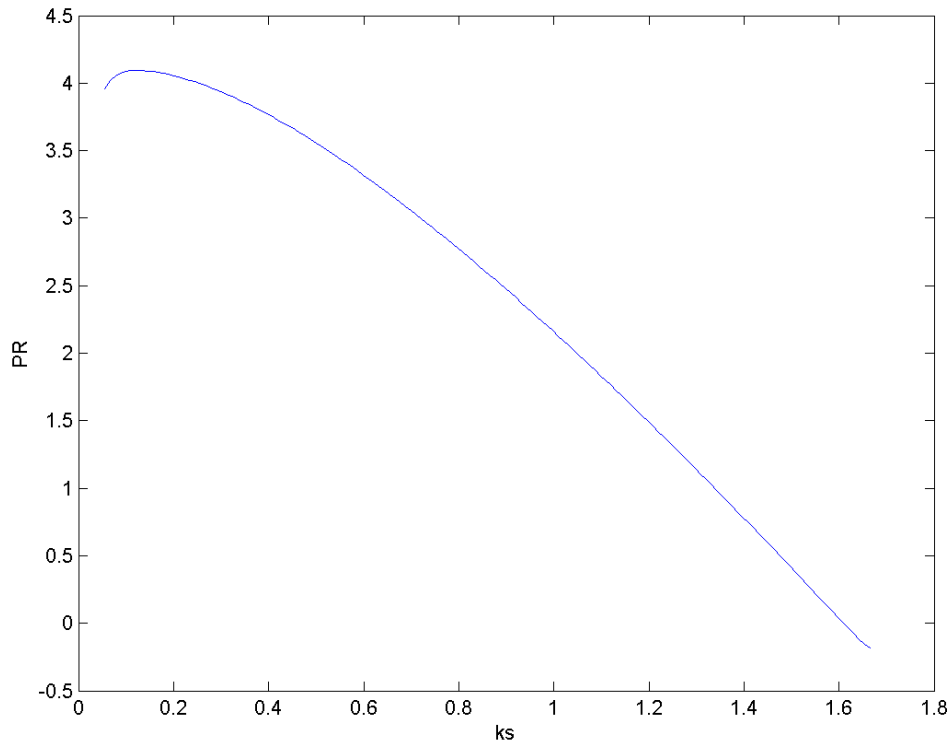
Fig. 4 shows PR, PRx and pond fraction along the survey lines of different RS-2 images. More interesting would be PR/PRx vs. pond fraction scatterplots, especially as linear regression is fitted between these parameters and discussed in the text.

p. 861, l. 18: The PR tends to unity with increasing roughness once the Bragg limit is surpassed.

Yes, with increasing roughness PR typically decreases. With the IEM model you could study this in more detail using your measured roughness data. See example below: ice surface scattering PR with single scattering IEM, 1.5-power autocorrelation function, correlation length 2 cm, ice density 0.9, salinity 5 psu, ice temp -2, frequency 5.3 GHz, incidence angle 44.

Bragg limit  $k_s < 0.3$ , is only 0.27 cm rms roughness at C-band. PR with the Bragg model is 4.2 dB with above data, compare this to the figure. I strongly suggest you to consider the IEM model in your data analysis.

Can you produce the measured PR values in Table 1 with the Bragg model using reasonable sea ice parameters? Discuss this in the text.



Is PRx in any cases contaminated considerably by the closeness of the RS-2 noise floor, -36.5 dB, at HV-polarization? You discuss this in Section 5, but this could be done also shortly here.

#### 4.3 Pond fraction retrievals

p. 863, l. 9: Spatial patterns of retrieved melt pond fractions, created by globally applying Eq. (8) to the PR bands from the RS-2 dataset, are shown in Fig. 6.

Eq. (8) refers to a method based on your surface scatterometer data in Part 1 of your paper (method 1), but Fig. 6 describes that pond fraction is retrieved using the cross-validation retrieval method (method 3?). Did I misunderstood something here?

What you mean by PR bands?

p. 864, l. 15: Model comparison is restricted to scenes R3 and R5 due to low RMSE and bias associated with these acquisitions.

What model you are referring here, Bragg model?

l. 16: The Cscat model generally underestimates pond fractions.

Confusing, the term ‘Cscat mode’ is used first time here, should be named so in Section 3.3.

#### 5 Discussion

Sentinel-1 will not provide HH+VV images in any of its imaging modes. How about RS Constellation Mission? Mention these in the text.

p. 866, l. 2: Co-polarisation (VV and HH) channels for the PR-based retrieval of pond fractions are not subject to noise floor contamination by RS-2, nor should they challenge the NESZ of conventional and future satellite SARs.

In Table 1 the lowest  $\sigma^0$  is -22.5 dB which is quite close to typical noise floor of ScanSAR images, e.g. around -28 dB for RS-2 ScanSAR Wide. How about ENVISAT APP HH/VV

images? These historical APP images are currently the only ones suitable for your melt pond fraction estimation method, in addition to RS-2 Quad-pol which are very scarce over sea ice (or correct me if I am wrong).

l. 14: The high surface permittivity state and strong PR response compared to winter does mean the timing of Ponding Stage I (i.e. pond onset) is identifiable in a seasonal series.

I guess this has been also observed with HH/VV-pol QuikSCAT data by Howell et al., mention this in the text.

You could discuss whether your method can be applied to the much coarser resolution QuikSCAT data. How about for SAR images over pack ice with deformed ice? Do you envisage that ice deformations mask signal by melt pond fraction changes?

## **6 Conclusions**

p. 867, l. 1: Methods applicable to the retrieval of climatologically and biologically significant melt pond fraction on FY ice data using ...

Mention that methods are for undeformed FY ice.

## **Technical corrections**

Fig. 2. The symbol for the field site is hard to see, make it bigger. Outlines of the SAR images are also hard to see.