Dear Anonymous Referee #2,

Thank you for your insightful and stimulating review comments. Modifications based on these comments will significantly improve the quality of this research paper.

General Comments:

1. *Regarding the availability of two co-polarized (HH and VV) channels.*

   The key here is 'at present'. By demonstrating the approach and suggesting it may offer a means of providing wide-scale melt pond fraction mapping, this work draws attention to current limitations in mission designs and highlights how improved sensing technologies (HH and VV multipolarisation SAR in this case) can enhance sea ice information retrievals and scientific understanding from next generation missions. As mentioned by the reviewer, wide swath dual-polarisation data available to most operational users is in co- and cross-polarisation combinations (HH + HV or VV+VH), e.g. from Radarsat-2 operating in ScanSAR mode. Similarly, the ESA Sentinel-1 mission will only provide dual-polarisation data in co- cross-polarisation combinations. These current/past mission designs have been primarily motivated by objectives aimed at utilizing mature applications while meeting demands for continued operational applications. For sea ice this is consistent with work which points to the utility of HH and HV channels for discrimination between ice types, ice/water discrimination, and identification of deformation features (review in Scheuchl et al., 2004). It does follow that HH and VV data supplied together is less common (especially now with the loss of Envisat-ASAR), which for Radarsat-2 requires the collection of quad-polarisation scenes (25 by 25 km) as used in this study. However the SAR mission design limitation outlined here does not impact the merit of this work as a developing scientific application which will benefit from future SAR missions which offer dual polarisation VV + HH in a ScanSAR mode similar to what is widely available in HH + HV, or from design solutions which facilitate the capture of full polarimetric data over wider swaths. The reviewer comment that the approach, to be widely applicable, will have to wait until full polarimetric data becomes widely available should be clarified. Full polarimetry is not a requirement, instead dual-polarisation linear VV and HH data or hybrid (compact) polarimetric data such as will be available from RCM. The compact mode will provide channels RV = VV and RH = HH, with R being the right-circular transmitted pulse. There is also a current C-band SAR, RISAT-1, capable of acquiring RH and RV together in ScanSAR mode (223 km swath), though it is noteworthy that the nominal NESZ of -18 dB represents a challenge to low-intensity targets such as analysed in this study (Misra et al., 2013).

2. *Regarding the incidence angle requirement.*

   The incidence angle requirement is another technical limitation which currently constrains the use of wide swath imagery for this approach. This paper (Part 2) verifies the approach for SAR image data with incidence angles 44-49°; measurements of ice and ponds using an in-situ C-band scatterometer (Part 1) suggest the VV/HH ratio approach may be applicable down to ~ 35°. Assuming the latter, the current Radarsat-2 operating in Fine Quad-Pol mode will image a point location at 75°N ~ 25 times over a one month period. This is based on the

Radarsat-2 mission acquisition planning tool and searching beams FQ15 to FQ31 (34.6° to 49.5°) for the period May 1 to 31, 2014. Using the 40° or greater constraint and running the same test reduces the number of possible acquisitions to 16. This serves to illustrate that, while under current C-band SAR technical limitations the wide scale application of this approach is not attainable, it is still possible to monitor melt pond evolution at a single site (small area) in support of, for e.g., process studies conducted at the local scale. The noted RCM, beginning around 2018, will provide higher revisit frequencies (approx. 4 passes per day at > 75°N) by employing three platforms operating in constellation mode. Greater revisit frequency means wide spread coverage within the incidence angle constraints of this approach, and its extension to the regional scale. The Abstract now indicates the tested incidence angle range (44-49°) and the suggested range of applicability which takes into consideration the results from Part 1 of this study (about 35° and above). Further testing with SAR data is needed to determine the actual range of applicability.

Regarding the title of the paper.

The reviewer's assertion that the title of the paper is misleading may be a reflection of their operational mapping viewpoint and stated assumption that the paper refers to large volumes of wide swath data in the common co- and cross-pol combination (HH + HV or VV + VH). That large volumes of wide-swath data are currently available only in dual cross-polarization format is a limitation which does not impact the scientific relevance of this paper. Instead of altering the title we have carefully re-written the Abstract so that a potential reader can quickly identify key findings from the article pertaining to either dual polarisation combination (article content unchanged). One can gleam that a statistically significant portion of the variability in pond fraction can be explained by the cross-pol ratio (ponding Stages II and III); the association between cross-pol ratio and pond fraction is strongest when ponds are frozen; and, despite not being a problem concerning the experimental data used here, the utility of the cross-pol ratio will be limited given low signal strength relative to the noise performance of the SAR. I.e. instead of outlining the VV/HH algorithms and their performance, the significant cross-polarisation ratio association with pond fraction is given relative to pond fraction . Instances of the terms “large-scale” and “wide swath” have been removed.

Regarding how representative are the ice conditions.

Test data were limited to undeformed, landfast, first-year sea (FY) ice located in the Canadian Arctic Archipelago. Strictly, the data represent a small proportion of sea ice in the Arctic which is limited to Arctic coastal environments and the Canadian Archipelago. This is compared to mobile and rougher first-year and multiyear pack ice. However Meyer et al. (2011), who address the mapping of landfast ice by operational agencies who compile ice charts from satellite remote sensing data sources (and introduce an L-band SAR interferometric technique for its identification), highlight the difficulty in separating landfast ice from first-year pack ice on the basis of no clear edge or morphological difference. They note that, for Radarsat imagery, a time interval is required in order to effectively separate landfast ice from mobile ice. More importantly this raises the possibility that the results here are likely extendable to first-year pack ice, provided the ridged or deformed ice zones such as at floe edges are excluded due to secondary-scale scattering effects (VV and HH approach unity). Their exclusion would not be expected to have a major impact on the total fraction of ponds on the floe as ridged/deformed ice are less likely to be ponded (Eicken et al., 2004). The large-scale morphology of multiyear ice is likely to limit the applicability of the technique. In light of this issue we will add “First-year” to the title and address this concern in the discussion.

Regarding the Radarsat-2 image acquisition plan (new acquisitions and RS-2 archive).

The acquisition of scenes over the field site at 17 different times would have facilitated a more robust temporal evaluation of the technique. However the experimental design was driven by the need to take full advantage of aerial photography missions. By acquiring aerial photographs coincident to adjacent 25km by 25km scenes a much greater spatial distribution of pond fractions over the Parry Channel at each of the time intervals was made possible. Logistical constraints, namely flying conditions, would have made the acquisition of the aerial photos, essential for evaluating the technique, difficult. Similarly, though we agree that the inclusion of data from different years and locations (including the CIS archive) would increase the reliability of the results, validation requires accurate melt pond fraction measurements as provided here by aerial photographs. A cross-comparison of melt pond fraction retrieval techniques using archived data, for example comparing the technique as applied to archived RS-2 images and the method of Rösel et al. (2012) as applied to co-located optical data from MODIS, would be very interesting and provide insights into the robustness of this technique. However such a study would still require high-resolution image data capable of discriminating melt ponds and providing ‘verification’ of melt pond fraction (e.g. aerial or tethered balloon photos).

Specific Comments

<u>Abstract</u>

P846/L14: The algorithm was developed from data acquired at 4 intervals during the ponding season. The first scene (R1) was acquired prior to ponding and is included to provide context from which to evaluate changes in backscatter that occur within the same radar-target configuration once ponds have formed.

P846/L17: Changed

<u>Introduction</u>

P848/L20: Changed to correctly communicate the potential of passive microwave and scatterometer data for synoptic scale estimations and SAR for regional (not synoptic) scale.

<u>2.2 Bragg scattering model</u>

P852/L5: A sea ice type classification filter would be possible but not currently given the lack of ponding season surface roughness data related to ice type. This is a developing area of research made increasingly possible with advances in LiDAR and photogrammetry. That is unless the reviewer means to derive the rms height from the polarimetric response (eigenvalues and eigenvectors of the polarimetric coherency matrix as in Hajnsek et al., 2003) and apply a threshold where the ks criterion is exceeded? Some clarification is needed.

3.2 Data processing

P858/L3 and P858/L6: Dimensions given in metres.

3.3 Pond fraction retrieval

P859/L8: "Full resolution" is used here to discriminate the disaggregated data (collocated SAR PR and AP derived pond fraction data pairs described in P858/L1-10) from the aggregated data pairs (collocated SAR and AP derived pond fraction estimates within 7.5km grid cells). The use of "full resolution" isn't clear, so it has been removed and the text changed to clarify aggregated from disaggregated data.

4.1 Seasonal evolution

P859/L23: This was also specified by anonymous reviewer #1. Estimating variation due to incidence angle is difficult during ponding since the target parameters cannot be held constant; i.e. an equivalent pond fraction measured at two instances (incidence angles) are likely to include variations in backscatter caused by roughness and dielectric permittivity differences. For the final version of the manuscript an estimate using a suitable scattering model (likely IEM not the Bragg as per reviewer #1) will be included.

4.2 Spatially distributed

P861-P862: Correct that slight freezing means that pond fraction estimates would not be possible using PR. However the fact the freezing is detectable by PR suggests that it can be used as a proxy for the freezing state (e.g. PR falls below certain threshold) without the need for meteorological or optical satellite data. Interestingly the PR_x holds potential as a for pond fraction when freezing occurs (see R4 panel in Fig. 4) though this requires a SAR with very low noise floor to detect (as used here). Determining the robustness of either of these approaches requires more work; the final version of the manuscript will include these points.

4.3 Pond fraction retrievals

P863/L9: Corrected.

P864/L18: Yes, this is an abbreviation. It's now correctly defined in Section 3.3. The same was done for the Bragg and cross-validation models for consistency.

5 Discussion

P865/L10: Agreed that HH+VV does not apply to Sentinel-1; however the paragraph discusses the need to further advance the use of SAR for sea ice process and modeling studies regardless of the polarisation specific information addressed in the paper. That said it is appropriate to include the relevant mission characteristics in the final version of the paper.

6 Conclusions

P867/L23: Agreed that level ice areas will be difficult to find outside of fast ice zones around the Canadian Arctic Archipelago incl. the Northwest Passage (this study), as well as northern Greenland and Russian shelf seas as indicated by anonymous reviewer #2. The extension of this approach to other ice types (e.g. seasonal pack ice) or other regions requires further study and possibly the creation of site specific models. As such we do not aim to present this approach as a means for Arctic-wide mapping of pond fraction, rather an approach to further our understanding of satellite derived measurements of the thermodynamic conditions of melting ice which can be used in to understand timings and spatial variations in related processes (e.g. evolution of under-ice primary production). Fast ice provides a suitable platform for such studies. We will be sure to include undeformed FY ice here only.

Technical Corrections

P856/L23: Changed

P883/L23: Modified as suggested.

Literature cited this document

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