Response to review by reviewer #1

We thank the reviewer for a constructive review, allowing us to improve our manuscript. Most of the reviewer's requests have been met. Below follow our answers and comments, highlighted in blue after each of the reviewer's comments. Blue page (P) and line(L) numbers refer to the manuscript published in TCD and red numbers refers to the marked-up revised document.

Interactive comment on **"Signature of Arctic first-year ice melt pond fraction in X-band SAR imagery"** ***by*** **A. S. Fors et al.**

Anonymous Referee #1

Received and published: 3 September 2016

The manuscript is dedicated to the melt pond fraction estimation from X band of polarimetric SAR. This sensor is not dependent on cloud cover or presence of daylight, which is an advantage over radiometers like MODIS and MERIS. Currently, melt ponds are poorly represented in the climate models, and the melt pond research is therefore an important topic which fits well into the scope of the journal. The paper is well written and the text extensively referenced. However, the manuscript still has some potential for improvement in the points listed below.

1)The study is limited to the drifting first year ice and to the X band only; in the Introduction, the authors give a very extensive literature review which reveals a massive amount of work already published regarding SAR X and C bands for melt ponds on many ice types for many locations, among which the landfast FYI and MYI. What is the motivation for this additional study for drifting ice and X band? Drifting FYI is a widespread ice type indeed, but it features a variety of subclasses which calls for a robust method. What is the advantage of X band over other SAR bands for this challenging task?

As the reviewer highlights, many studies have already been exploring melt pond fraction retrieval from SAR. However, a majority of these studies are *single polarimetric* studies, mostly reaching vague results when it comes to melt pond fraction estimation from SAR. Only a few studies have investigated the *multi polarimetric* SAR signature of melt ponds. Among these, only one study (Han et. al 2016) has explored X-band opportunities. Han et al. (2016) focuses on one single satellite scene with known melt pond fractions, the study is performed on MYI, and very important factors like SAR incidence angle, noise floor and wind speed are not discussed. Hence, we believe there is need for more studies polarimetric X-band SAR signatures of melt ponds. To make this clearer in our manuscript, the following changes have been made:

- The following paragraph was added (Introduction, P3L90, P3L93): "In summary, the main achievements on f_{MP} retrieval with SAR come from dual polarimetric C-band studies on land-fast FYI. The potential of f_{MP} retrieval with polarimetric X-band SAR has only been explored in one single study by Han et al. (2016), focusing on MYI. Hence, there is a need for more studies on the influence of f_{MP} on polarimetric X-band SAR imagery. As MYI and land-fast FYI have been the main focus in previous studies, there is also a need to expand to other sea ice types. Drifting FYI is becoming more prominent in the Arctic with the recent shift to a thinner, more seasonal, and more mobile sea ice cover (Perovich et al., 2015), and the polarimetric SAR signature of f_{MP} in drifting FYI needs more attention."
- He following sentence was added (Introduction, P3L69, P3L71-72): "… underestimation of f_{MP}. All in all, retrieval of f_{MP} from single polarimetric SAR has proven to be difficult."

TerraSAR-X offers higher resolution than Radarsat-2, which is expected to be an advantage, due to the small size of melt ponds. X-band is also offering sensitivity to smaller surface roughnesses than C-band, which will could potentially affect the polarimetric signature beneficially. In general, it is also important to study the effect of melt pond fractions in all operational SAR frequencies, both because they can supplement each other, and because melt pond signatures will appear differently at different wavelengths. Knowledge of melt ponds polarimetric signatures is also important for classification of sea ice in X-band scenes. To highlight these points, the following changes have been introduced in the manuscript:

- The following sentence was added (Introduction, P3L93, P4L104-107): "TerraSAR-X offers very high resolution multi-polarimetric data, with a strong sensitivity to micro-scale surface roughness due to the high frequency. Both the high resolution and sensitivity to surface roughness can be advantages in f_{MP} investigations."
- The following sentence was added (Discussion, P15L478, P18L580-581): "This is also an important result, implying useful knowledge for instance in classification of summer sea ice based on X-band imagery."

2)The study is dedicated to the comparison of helicopter-borne imagery to the dual polarisation X band SAR data. Overall, 4 SAR scenes have been taken, to which the helicopter data were possibly accurately collocated. Nevertheless, the comparison data shows considerable scatter, the Spearman correlation was used instead of Pearson (could you please justify this), and the noise equivalent was subtracted. The authors are struggling to collect all the available signal which is over the noise floor and compare it to the airborne data. However, even with this cumbersome approach, the correlation coefficients of the developed empirical relationships are Rˆ2=0.15 and 0.21, which is a very weak to weak correlation for Spearman. The authors state the surface deformation as a reason for the scatter and claim the correlation "significant" and enough to give a starting point to MPF evaluation, but the reviewer fails to see how it could work. Under these circumstances, the quality of the developed method when applied to a variety of different X-SAR images of drifting ice (even with known wind speed) is very hard to estimate, even when the one smoothes out or grids the retrieved pond fractions to coarser resolutions.

This point addresses several parts of the manuscript, and the reply is divided into 8 individual bulletpoints (a)-h)) found below.

a) Spearman's correlation coefficient was used instead of Pearson's correlation coefficient as it allows for non-linear relationships, broadening the range of detectable correlations. It is also less sensitive to outliers, which can be a problem in SAR scenes due to speckle. We have now clarified this in the manuscript:

- The following sentence was extended (Method, P9L287, P12L330-332): "A negative sign indicates an inverse relationship. Spearman's correlation coefficient assumes a monotonic relationship. It is used instead of Pearson's linear correlation coefficient, to allow for non-linear correlations. It is also less sensitive to outliers than Pearson's correlation coefficient."

We would like to note that Spearman's correlation in this study was used as a simple metric to identify SAR features potentially useful for further f_{MP} reconstruction. In the latter procedure, however, an ordinary linear regression technique was used (see point d)). We consider that in the future studies when a sufficient information on the SAR f_{MP} signature for a broad range of controlling factors have been accumulated, an application of more sophisticated multivariate techniques will be required to elaborate the model(s) robust enough for operational products. This is reflected in the manuscript:

- The following sentence was added (Discussion, P12L365, P16L508-511) "These correlations are not strong enough for the results to be used directly in operational models. However, with improved methods and more satellite data added, our results imply a future potential in retrieving f_{MP} from X-band SAR."

b) "Significant" or "statistical significant" are used several times in the manuscript, referring to correlations that are significant within a 95% confidence interval. This is clearly stated in the Results-section in the version of the manuscript published in TCD (Results, P11L351, P12L375).

c) We see that working with the signal both with and without NESZ-subtraction can be confusing for the reader. We have therefor decided to use the NESZ-subtracted signal in the manuscript, and only include values without NESZ subtraction in parentheses in Table 4. This imply the following changes:

- The following sentences were rephrased (Method, P8L230, P9L270): "All scenes were converted to ground range and radiometrically calibrated to σ^0. The noise equivalent σ^0 (NESZ) was then subtracted."
- The following sentences were rephrased (Results, P11L326-334, P12L374-385): "Values significant within a 95% confidence interval are highlighted in bold, and values in parentheses show results before NESZ subtraction of the signal. In scene T3, $R_{VV/HH}$ shows the strongest correlation to f_{MP}. In addition, the mean of α_1 is significantly correlated to f_{MP}. None of the other investigated SAR features are significantly correlated to f_{MP} in scene T3. In scene T4, the mean values of σ^0_{HH}, σ^0_{VV} and $R_{VV/HH}$ are significantly correlated to f_{MP}, the strongest correlation is found for, σ^0_{VV}. Some of the standard deviation values are also correlated to f_{MP}. Without NESZ subtraction in the calibration, however, almost all features are correlated to f_{MP}. The large difference before and after NESZ subtraction indicates that the signal is close to, or reaching the noise floor."
- The following sentence was rewritten (Discussion, P15L477, P18L579-581): In addition to $R_{VV/HH}$, five other dual-polarimetric SAR features were included in our study, after NESZ subtraction most of these showed no statistical significant relationship to f_{MP} in our data set.
- The figure caption of Table 5 was updated: "Spearman's correlation coefficient (*r*) between f_{MP} retrieved from the helicopter images at the investigated floe, and mean and standard deviation of the polarimetric SAR features from the corresponding area in T3 and T4. Bold indicate significant values within a 95 % confidence interval, and values in parentheses are retrieved before NESZ subtraction in the calibration process."
- Figures and Table 6 were updated, now presenting results after NESZ subtraction.

d) The correlation coefficients of R^2=0.15 and 0.21 represent the least square regression fits of Eqs. 16 and 17 and Figs. 4 and 7, and are presented in addition to Spearman's correlation coefficient (corresponding values of -0.53 an 0.45). To clarify this in the manuscript, the regression fit correlations are renamed R_{fit}^2 (changed in Results, P12L362, P13L398, P13L421, P15L477), while Spearman's correlation coefficient is kept as *r*. For clarification, the following change was introduced:

- The following sentence was changed (Abstract, P1L7, P1L7): Co-polarisation ratio was found to be the most promising SAR feature for melt pond fraction estimation at intermediate wind speeds (6.2 m/s), with a Spearman's correlation coefficient of 0.46."

e) Due to the reviewer's comments, we revised the regression fits, and managed to improve Eq. 17 by not log-transforming σ^0_{VV}, returning a new correlation coefficient of R_{fit}^2=0.26 (previously 0.15).

- Eq. 18 was changed in the text (Results, P13L397, P15L474): "$f_{MP}(\sigma^0_{VV})=-52.83\ \sigma^0_{VV}+1.89$"
- The following sentences were updated (Results, P13L398, P15L475): "Note σ^0_{VV} is not in dB. Again, the goodness of fit of the regression is reflecting large sample variation, with R_{fit}^2=0.26 and RMSE=0.0039.
- Figures 7, 8 and 9 were updated according to the new regression fit equation.

f) We agree with the reviewer that these correlation values are weak, and not yet suitable as a basis for operational models. It is however worth noting that the operational method used for extraction of f_{MP} from MODIS has R^2_{fit} values ranging between 0.28 and 0.45, not too far from our values of 0.21 and 0.26. We also emphasize that we do not intend to develop an operational model based on a single SAR scene. To differentiate this we have changed the wording "model" to "regression", "regression fit", or ''estimation" in the manuscript. This modification is implemented several places in the manuscript. Hence, with improved co-location (see point g) below) and more satellite data, X-band SAR can potentially be used for f_{MP} estimation. The following changes have been made in the manuscript to stress these points:

- The following sentences were added (Results, P12L363, P13L422): "This implies a weak correlation, corresponding well to Spearman's correlation of 0.45."
- The following sentence was added (Discussion, P13L417, P16L506-512): "The results of this study show that f_{MP} influences the signature of several X-band polarimetric features. The strongest correlations were found for $R_{VV/HH}$ and σ^0_{VV}, where linear regression fits gave R^2_{fit} values of 0.21 and 0.26, respectively. These correlations are not strong enough for the results to be used directly in operational models. However, with improved methods and more satellite data added, our results imply a future potential in retrieving f_{MP} from X-band SAR. For comparison, the method developed for retrieval of f_{MP} from MODIS has R^2_{fit} values ranging from 0.28 to 0.45 (Rösel et al. 2012)."
- The following paragraph was rephrased (Results, P11L247-351, P13L398-403): "The melt ponds affect the polarimetric signatures in scene T3 and T4 differently (Table 4 and Fig. 4 and 5), mainly due to different wind conditions, but also due to different incidence angles and noise floors. In the following, we look closer into the feature displaying the strongest correlation to f_{MP} in each of the scenes, $R_{VV/HH}$ in T3 and σ^0_{VV} in T4."
- The following sentence was rephrased (Results, P12L360, P15L471-474): "As for the intermediate wind case, a robust least square linear fit was applied to the data to describe the relationship between σ^0_{VV} and $f_{MP:"}$

g) From the reviewers comment, we find that the large scatter observed in the scatter plots, reflected in weak correlations values should be discussed in more detail in the manuscript. Deformation (and volume scattering in the sea ice) may contribute to the low correlation values, but another source is probably equally important. Substantial efforts were made in co-locating the helicopter photos and the floe's position. As stated in the Method-section we estimate a possible areal offset between the helicopter images and the compared corresponding SAR pixels of up to 27%. Even a small positional offset of a few percentages would introduce random noise in the regression, lowering the correlation values. Viewed against this background, we find it acceptable to explore the effect of the regression fit on the floe and the full scenes in the data set, even if the R_{fit}^2 values are low. The following changes have been implemented in the manuscript:

- The following sentence was added (Results, P12L363, P13L423-425): "However, the co-location between the helicopter images and the sea ice floe contain some uncertainty (a maximum areal offset of 27%) possibly introducing a random error to the regression, resulting in an artificially low R_{fit}^2."
- The following paragraph was added (Discussion P15L490, P18L605-614): "The correlations found in our study are not very strong. The weak to moderate correlations might suggest a limited sensitivity to f_{MP} in X-band SAR imagery, but they could also reflect limitations in the data set. The co-location between the helicopter images and the SAR imagery is estimated to have a possible offset of at most 27% potentially introducing a large random error into our investigation, lowering the correlation values. A larger degree of smoothing than the area covered by the helicopter images allows for might also be needed to improve the results. The absolute radiometric accuracy of TSX scenes could also influence the results of our study, but this influence is expected to be very small compared to other uncertainties. All the above-mentioned issues should be addressed in future studies."
- The following sentence was rewritten (Conclusion, P16L515, P19L640-645): "Challenges in co-location of airborne observations and SAR imagery limited coordinated use of existing

data in our study and introduced uncertainties in our results, possibly causing artificially low correlation values."

h) We agree that the quality of the method when applied to the full satellite scenes can be hard to evaluate. To improve this, we have included the figures suggested in the reviewers point 3). We have also moderated the way we present and discuss our results in the Abstract, Discussion and Conclusion sections. Hence, the following changes are introduced:

- The following sentence was moderated (Abstract, P1L18, P1L20) "Despite this, our findings suggest new possibilities in melt pond fraction estimation from SAR, opening for expanded monitoring of melt ponds during melt season."
- The following paragraph was moderated (Discussion, P13L417-419, P16L506-607): "The results of this study show that f_{MP} influences the signature of several X-band polarimetric features."
- The following sentence was moderated (Discussion, P14L435, P16L532-534): "In our study we found a significant correlation between $R_{VV/HH}$ and f_{MP} at an incidence angle of 29° (T3), demonstrating that f_{MP} has an impact on polarimetric X-band SAR signatures also at lower incidence angles."
- The following sentence was added (Discussion, P14L444, P17L542-543): "However, the different acquisition geometry observed in Fig. 1 could also play a role."
- The following sentence was rewritten (Discussion, P15L468, 17L568-569):"A larger window size reduces the amount of speckle in the SAR scenes, which possibly explains the improvement."
- The following sentence was rewritten (Discussion, P15L475, P17L574-576)"The large sample variability observed in Fig.4 might therefore be negligible, as long as the $R_{VV/HH}$-based regression fit produces a good estimate of the mean f_{MP} for a larger area."
- The following sentence was moderated (Conclusion, P15L495, P19L618-620): "In this study we demonstrate statistically significant relations between f_{MP} and several polarimetric SAR features on drifting FYI in X-band, based on helicopter-borne images of the sea ice surface combined with four dual polarimetric SAR scenes."
- The following sentences were moderated (Conclusion, P16L497, P19L621-625): "The study reveals a prospective potential for f_{MP} estimation from X-band SAR, but also stresses the importance of including wind speed and incidence angle in a future robust f_{MP} retrieval algorithm. Such an algorithm could supplement optical methods, and be used as a tool in climate applications, both as input in climate models and in studies of melt pond evolution mechanisms."
- The following paragraph was moderated (Conclusion, P16L505-512, P19L627-636): "The theoretical range of suitable wind speeds (<5 m/s) and sea ice surface roughnesses (s_{RMS}<1.4 mm) for f_{MP} extraction based on $R_{VV/HH}$ are slightly more limited in X-band than in C-band but our results show that f_{MP} also influences the X-band SAR signature when these criteria are partly exceeded. The high noise floor of TerraSAR-X also restricted use of scenes with incidence angles above 40°, while an incidence angle of 29° gave better results. At very low wind speeds (0.6 m/s), the backscatter signal from the melt ponds became too low for f_{MP} retrieval based on polarimetric features. In that case, σ^0_{VV} was found suitable for f_{MP} estimation. In the future, use of X-band scenes can possibly increase the total amount of SAR data accessible for f_{MP} retrieval, despite their limitations compared to C-band scenes."
- The following sentence was added (Conclusion, P16L525, P20L651-653): "For development of a robust operational method, 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."

a) The authors compare MPF distributions from airborne and retrieved from SAR data. To evaluate the quality of the results even better, it would be good to show also the spatial situation: the MPF retrieved from SAR plotted on a lat-lon map and the airborne reference data overplotted on the same map using same colorscale. Upon checking spatial features or spatial uniformity, the reader can make sure that the retrieved MPFs are not random numbers, but really correspond to the field situation.

We appreciate the suggestion of a spatial plot. We have now included spatial MPF figures in the manuscript. The following text and Figures are introduced to the manuscript:

- The following paragraph was added (Results, P12L382, P13L445-455): "Zooming in to the southern part of the area covered by the helicopter survey on the floe in T3, Fig. 6 *(new)* displays f_{MP} estimated from Eq. 17 with the observed f_{MP} from the helicopter images overlaid. Two different pixels smoothing windows are shown (21 x21 and 51 x 51). Note that the center pixel underlying each helicopter image frame would give the most representative value for comparison to the observed f_{MP}, as pixels closer to the frame contain a larger amount of information from outside the frame. The middle panel displays the mean estimated f_{MP} value for each frame together with the observed f_{MP} values along the track. The maps confirm some overlap between the estimated and observed f_{MP}, but also illustrates that there is room for improvement. The estimation with a 51 x51 pixel smoothing window appears less variegated than the 21 x 21 estimation, and the range of the estimated f_{MP} values also corresponds better to those observed from the helicopter images in the 51 x51 estimation."
- The following paragraph was added (Results, P13L410, P15L488-497): "Figure 10 *(new)* shows f_{MP} estimated from Eq. 18 with the observed f_{MP} from the helicopter images overlaid for two different pixels smoothing windows (21 x 21 and 51 x 51). Note that the center pixel underlying each helicopter image frame would give the most representative value for comparison to the observed f_{MP}. To illustrate this, the middle panel shows the mean estimated f_{MP} value for each frame together with the observed f_{MP} values along the track. In general, a good overlap between the estimated and observed f_{MP} can be seen, even though some scatter exists. As in Fig. 6 the estimation with a 51 x 51 pixel smoothing window appears less variegated than the 21 x 21 estimation, and the range of the estimated f_{MP} values also corresponds better to those observed from the helicopter images in the 51 x 51 estimation than to those in the 21 x 21 estimation."

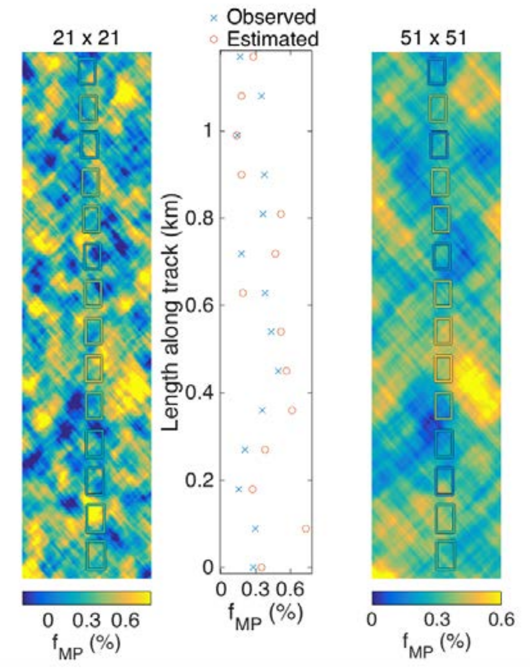

Figure caption: "Figure 6. Melt pond fraction (f_{MP}) estimated from $R_{VV/HH}$, with the observed f_{MP} from the helicopter images overlaid as colored frames. The area displayed is outlined with a frame in Fig. 5. The estimation is performed with 21 x21 (left) and 51 x51 (right) pixels windows. Note that the center pixel underlying each helicopter image frame would give the most representative value for comparison to the observed f_{MP}, as pixels closer to the frame contain a larger amount of information from outside the frame. The middle panel displays the mean estimated f_{MP} value for each frame together with the observed value."

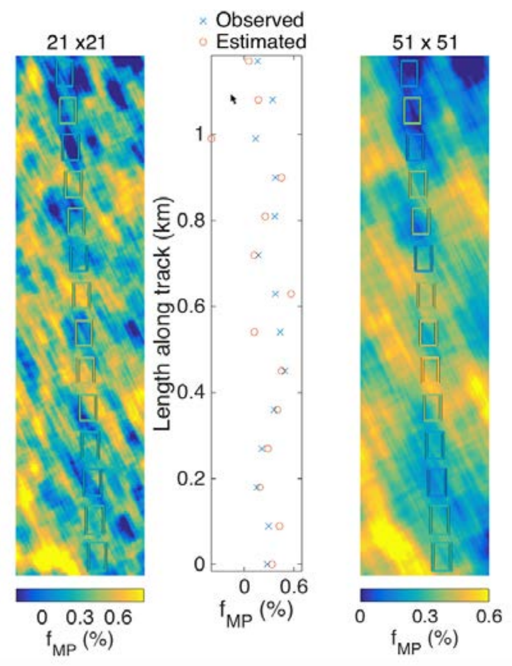

Figure caption: "Figure 10. Melt pond fraction (f_{MP}) estimated from σ_{VV}, with the observed f_{MP} from the helicopter images overlaid as colored frames. The area displayed is outlined with a frame in Fig. 8. The estimation is performed with 21x21 (left) and 51 x 51 (right) pixels windows. Note that the center pixel underlying each helicopter image frame would give the most representative value for comparison to the observed f_{MP} as pixels closer to the frame contain a larger amount of information from outside the frame. The middle panel displays the mean estimated f_{MP} value for each frame together with the observed value."

The authors come to the conclusion that the dual polarimetric SAR data in X band can be used for melt pond estimate given the appropriate wind speed, incidence angle, surface deformation ranges and also upon extensive smoothing or even taking the mean value over the whole scene.

The impact and importance of such a product is not sufficient for advancing our under-standing on melt pond processes and can only serve as complementary data for other studies. Currently, the manuscript serves more as a fundamental study on the SAR features in X band and more displays limitations than advantages of the data.

We agree that the manuscript can be seen as a fundamental study on polarimetric SAR features in X-band, and their relation to melt pond fraction, testing a potential method for melt pond fraction retrieval. Producing an operational product for estimation of melt pond fraction from (X-band) SAR will take more than one single study. To advance in this process, it is very important to focus on possible limitations like surface roughness ranges and wind speed, and optimum SAR parameters like incidence angle and smoothing window size (stated in Conclusion, P15L522-529, P19649-654). This allows for more precise and to the point studies in the future. Hence, we think our study presents important results for future development of melt pond fraction retrieval from X-band SAR.

I recommend to support the shown MPF results with possibly more SAR scenes and definitely show the spatial MPF maps to confirm the quality of the pond retrieval, or refocus the manuscript on signatures of various ice/pond types in X band without the actual MPF retrieval.

SAR-scenes with corresponding ground truth are very rare, being generally a result of coordinated campaigns, and in this data set, we are limited to the presented scenes. As detailed above, we have included the requested MPF maps (new Figs 6 and 10), allowing the reader to confirm the quality of the presented method.

Technical

- Please add the error bar of the empirical fit in Eq. (16) and (17) on the corresponding figures, this helps to estimate the quality of the MPF retrieval.

95% confidence intervals were added in Figure 4 and 7.

- please add the correlation coefficient values into the abstract and into figure captions where you present the empirical fits.

Correlation coefficient values were added into the figure captions of Figure 4 and 7, and into the abstract:

- The following sentence was rephrased (Abstract P1L10, P1L9-13): "To further investigate these relations, regression fits were made both for the intermediate (R^2_{fit} =0.21) and low (R^2_{fit} =0.26) wind case, and the fits were tested on the satellite scenes in the study."

- I suggest to merge the subsection 4.1 Sea ice conditions into the subsection 3.1 Study region. Current section 4.1 logically fits better to 3.1.

The subsections have been merged, and are now united in subsection 3.1 renamed "Study region and sea ice conditions".