# tc-2021-149
# Retrieval and parametrisation of sea-ice bulk density from airborne multi-sensor measurements

## An item-by-item response to referees' comments

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In the following, you can find the *referee comments in italic bullet points* and our responses in regular font in an item-by-item fashion.

## Referee #2: Dmitry Divine

### Overall:

- *In this manuscript the authors present the approach to bulk sea ice density retrievals from parallel airborne measurements of total thickness, snow thickness and surface freeboard. For their study the authors use the data retrieved during airborne IceBird campaigns over the Beaufort/Chukchi Sea and Canadian Arctic in the spring seasons of 2017 and 2019.*

  *The authors provide new, generally higher than was used before, estimates for the bulk densities for different types of sea ice. They further propose a new nonlinear parameterization linking observable ice freeboard with sea ice density to be potentially used in satellite based retrievals of sea ice thickness/volume.*

  *The paper is clearly written and results, including figures, are well presented. I therefore consider the manuscript deserves to be published after some moderate modifications according to the comments provided below.*

On behalf of all authors, I would like to thank referee Dmitry Divine for his time and effort in reviewing our manuscript and for the constructive feedback, which we have considered carefully. We are very grateful for the very positive evaluation by the referee, and we are confident that with the referee's help the manuscript will improve. I am hopeful that we are able to meet his expectations and eliminate all his concerns.

### Major comment:

- *My only major comment concerns a new freeboard to density model proposed by the authors. The model is based on exponential fit to the data collected by the authors and offers at the moment RMSE values for the fit itself (model calibration error). However, since the model has a potentially high applicability in the algorithms for ice thickness/ice volume retrievals from satellite-based sensors, it makes sense to have its predictive skills to be tested properly.*

*Generally, a good agreement with data can be achieved via applying a data model complex enough and hence overfitting; it will not guarantee nevertheless any decent predictive skills for such model.*

*Since the authors have aggregated a significant volume of measurements for this study, a bootstrapping aproach (or block bootstrapping in case if autocorrelation in the series is substantial) can be used to test the model predicted vs measured values. This routine will provide a more realistic value for the RMSE to be used in future potential uncertainty estimates – RMSE for prediction.*

We have evaluated the RMSE value of our exponential parametrisation using the suggested bootstrapping approach with $10^4$ random samples of the measurements, which resulted in an average RMSE of 15.2 kg $m^{-3}$ with a 95 % confidence band of 14.8–15.7 kg $m^{-3}$. The average RMSE is equal to previously reported RMSE, but we will report the increased accuracy of the RMSE and include the confidence band in the revised manuscript.

## Other (minor) comments:

- *Sec 2.5: "... a sporadically observed by the ALS at fractures (leads) of the seaice cover and we manually selected the corresponding elevations". Is the ALS used onboard receives returns from open water areas too, or the authors refer to refrozen leads only? Would it be possible to use the measured surface temperatures to support the detection of leads? Or this is actually already a part of the procedure for these z-control points identification?*

Yes, the ALS receives returns also from open water close to the nadir. Open water targets away from the centre line tend to reflect the laser beam away. The sea-surface height tie points are selected from both open water and newly refrozen leads with negligible sea-ice freeboard, preferably from the centre line beam with the strongest laser returns. Because the tie points are selected manually, utilising surface temperature data has not been necessary at this point. Perhaps an automatic lead detection scheme using surface temperature data can be developed in future.

- *Line 167: Please consider adding a most recent reference to Rosel et al., https://doi.org/10.5194/tc-15-2819-2021; where this effect is also considered.*

Thank you for the suggestion. Rösel et al. (2021) was published after the submission of our manuscript and will be added for the revised version. However, it must be noted that Rösel et al. as well as Kurtz and Farrell (2011) and Kurtz et al. (2013) use radar versions and retrieval algorithms different to ours which may limit the direct applicability of their results.

- *Line 180: Please clarify the formulation/ application of the level ice criterion. I find it to be not too informative; it is nearly a copypaste from Rabenstein et al which suffice from the same issue.*

We thank the referee for asking for details. We will extend the description of the level ice criterion in the revised manuscript as follows: "We started with identifying level and deformed ice following the approach of Rabenstein et al. (2010). The filter is based on the observation that level ice is mostly flat and extends over long distances. We identified data points that fulfilled those characteristics using two criteria. First, we calculated the along-track total thickness gradient using a three-point Lagrangian interpolator. We applied a threshold gradient of 4 cm/1 m below which the ice was classified as level following Rabenstein et al. (2010). Second, this condition must be met continuously for at least 100 m of the profile length. Choosing the value of 100 m, which represents approximately twice the footprint size of the EM-bird, makes sure that the conditions were met over two completely independent EM total thickness measurements."

- *Lines 185-188: Discussion on age assignment to sea ice along the flight track is somewhat unclear: do the authors refer to an average thickness estimated for level ice only, or for all* *(level+deformed) ice along a specified transect/transect segment?? If this is the latter, how long the transect segment length used for the age assignment?*

The sea-ice age (years) is assigned by collocating the EM-Bird measurement locations at the nominal resolution of 5-6 m sample spacing with the NSIDC product or Canadian Ice Service charts. This does not depend on ice deformation. To take into account the spatial (12.5 km grid) and temporal (weekly) resolution of the sea-ice age products and possible sea-ice drift, we finally define sea-ice type (FYI/SYI/MYI) according to sea-ice age and thickness together. This way we aim to avoid some of the potentially erroneous classifications. For example, assigned age of 1 year but level thickness of 3 m indicates thermodynamically grown MYI and not FYI as the sea-ice age would simply first suggest. Similarly, all individual measurements with sea-ice thickness less than 2 m are classified as FYI. When considering the data that has been along-track averaged over a length scale, we consider the mean sea-ice thickness including both level and deformed ice within each length scale (800 m or 25 km).

- *Line 238: It can be useful to mention directly (though this is also apparent from eq. 4) that uncertainty in \sigma_rho_i includes spatially variable uncertainty in measured \sigma_rho_s, and hence both uncertainties vary along the track.*

The uncertainty of snow density $\sigma_{\rho_s}$ was not measured but taken as constant (Table 2), so we assume that the referee really means the uncertainty of snow depth $\sigma_{h_s}$ in his comment. However, as the referee points out, the factors influencing the uncertainty of sea-ice density are already apparent in Eq. (4).

- *Table 3: Table 3 shows numerous numbers with redundant precision in FYI density/density uncertainty estimates. Decimals can be eliminated throughout the table (and the text too in many places) by rounding to the nearest integer to leave significant figures only. E.G. 929.7\pm17.9 -> 930\pm18.*

We prefer to keep the precision in FYI density estimates and their standard deviation values in Table 3 to ease the direct comparison with the values in Alexandrov et al. (2010). In the final data product, the density values are released with corresponding uncertainty values that inform the potential user of the precision.

- *Line 263: typo? "... combined they results... "*

We disagree with the referee's suggestion for two reasons. First, the subject and the verb must agree in number, i.e., either both singular or plural. Second, results are generally written in past tense, because they refer to completed work. Here, we meant that measurements over FYI in both 2017 and 2019 put together resulted in an average density of $928.5 \pm 16.4$ kg m$^{-3}$. Therefore, we will keep the expression "...combined they resulted in..." and refrain from any modifications.

- *Line 289: "... ice due to air incorporated in the pore spaces and to an increasing degree in MYI." Please consider rewriting the sentence. The meaning is clear it only appears awkward.*

We will split the sentence into two parts: "Above the waterline, the density is lower than that of pure ice due to air incorporated in the pore spaces. This feature is more pronounced in MYI."

- *Line 291: "Despite the indirect measurement method, we are able to detect a difference in FYI bulk density between 2017 and 2019 that can be linked to the high sea-ice deformation in 2017". Please consider referring to Figure 8 here, provided that my comment to figure 8 below is justified."*

Please see our comment below.

- *Figure 8: From the figure it appears that there is a tendency towards higher uncertainties for lower values of density. This is especially clear for FYI where the data may form two groups* *clusters one below and one smaller group above the fit line. I wonder if these two groups of data points originate from different campaigns? Or could this be only the artefact of the data visualization? This is not to be ruled out (at least for me) as this figure is quite busy. I see no similar tendency for the MYI densities.*

The points raised by the referee are indeed artefacts in the data visualisation. Admittedly, Figure 8 is busy, that is the unfortunate downside of the significant data volume (more than 2000 data points). There is no tendency toward higher uncertainty for lower density values but there is for lower sea-ice freeboard. That is related to all measurements (total thickness, snow depth, and snow freeboard) having relatively small values and thus, large relative uncertainties. The FYI data points from the campaigns in 2017 and 2019 overlap with each other and do not form distinct clusters on either side of the fit line.

# Additional corrections by authors

In the abstract, we will add a description of the study area to complement the study period: "Our sea-ice density measurements are based on over 3000 km of high-resolution collocated airborne sea-ice and snow thickness and freeboard measurements **in the western Arctic Ocean** in 2017 and 2019."

## Data availability

The data products related to this paper have been prepared by PANGAEA and they are ready to be published together with the paper. Corresponding DOIs will be updated to the revised manuscript.

- Jutila, A., Hendricks, S., Ricker, R., von Albedyll, L., Haas, C.: Airborne sea ice parameters during the PAMARCMIP2017 campaign in the Arctic Ocean, Version 1, *PANGAEA*, https://doi.pangaea.de/10.1594/PANGAEA.933883, in review, 2021.
- Jutila, A., Hendricks, S., Ricker, R., von Albedyll, L., Haas, C.: Airborne sea ice parameters during the IceBird Winter 2019 campaign in the Arctic Ocean, Version 1, *PANGAEA*, https://doi.pangaea.de/10.1594/PANGAEA.933912, in review, 2021.

# References


Alexandrov, V., Sandven, S., Wahlin, J., and Johannessen, O. M.: The relation between sea ice thickness and freeboard in the Arctic, The Cryosphere, 4, 373–380, https://doi.org/10.5194/tc-4-373-2010, 2010.

Kurtz, N. T. and Farrell, S. L.: Large-scale surveys of snow depth on Arctic sea ice from Operation IceBridge, Geophysical Research Letters, 38, L20 505, https://doi.org/10.1029/2011GL049216, 2011.

Kurtz, N. T., Farrell, S. L., Studinger, M., Galin, N., Harbeck, J. P., Lindsay, R., Onana, V. D., Panzer, B., and Sonntag, J. G.: Sea ice thickness, freeboard, and snow depth products from Operation IceBridge airborne data, The Cryosphere, 7, 1035–1056, https://doi.org/10.5194/tc-7-1035-2013, 2013.

Rabenstein, L., Hendricks, S., Martin, T., Pfaffhuber, A., and Haas, C.: Thickness and surface-properties of different sea-ice regimes within the Arctic Trans Polar Drift: Data from summers 2001, 2004 and 2007, Journal of Geophysical Research, 115, C12 059, https://doi.org/10.1029/2009JC005846, 2010.

Rösel, A., Farrell, S. L., Nandan, V., Richter-Menge, J., Spreen, G., Divine, D. V., Steer, A., Gallet, J.-C., and Gerland, S.: Implications of surface flooding on airborne estimates of snow depth on sea ice, The Cryosphere, 15, 2819–2833, https://doi.org/10.5194/tc-15-2819-2021, 2021.