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Interactive comment on "Empirical sea ice thickness retrieval during the freeze up period from SMOS high incident angle observations" *by* M. Huntemann et al.

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Here are our answers to the reviewers, we want to thank ltp Pedersen and the Anonymous reviewer for their fruitful comments and suggestions which helped to improve our manuscript.

Answers to ltp Pedersen:

P4380L1: Done

P4380L19: Done

P4380L22: Done

P4380L23: Done

P4380L24: cited Kaleschke et al. (2010).

P4380L24: changed to "into ice of less saline waters"

P4381L6-9: changed sentence to address penetration depth: "The high penetration depth at L-band and the high brightness temperature contrast of over 100K between ice and open water encourages us to investigate the sea ice growth process with SMOS."

P4381L10: Done

P4381L20: Changed to "measures"

P4382L2: Done

P4382L3: changed sentence to: "The griding introduces positional errors of no more than a few kilometers, which are not critical since the SMOS footprint is at nadir about 30x30 km, increasing with incident angle up to 90x33 km at about 65 degree."

P4382L4: Inserted sentence: "In this paper we work with incidence angles of 40 to 50 degree where the footprint size is about 50x31km."

P4382L10: Done

P4382L21: Done

P4382L22: The threshold of 300K was considered as useful value within the SMOSice project. This filter is to filter out RFI which, due to the fourier transform, otherwise would induce ringing in the whole snapshot. A RFI which has an intensity at L-band of less than 300K would not induce such ringing, so that there is no need to lower the threshold. Changed C4382L19 to indicate that strong RFI can influence a whole snapshot.

P4383L7-10: We find these details worth to be documented even though this is a small detail but needed to understand the paragraph.

P4383L22: Done

P4384: Stated TOPAZ V3 and NCEP NCAR surface temperature, ECMWF data is removed.

P4384L15-18: ECMWF is removed since it was not beneficial for the manuscript.

P4384L23: The formula for CFDD used here had directly the ocean water freezing temperature as input. See also: http://nsidc.org/cryosphere/seaice/processes/thermodynamic_growth.html

P4384L25: Done

P4385L1-2: changed sentence to:

In this region the sea ice drift is of the order of 8 km/day on average according to the low resolution ice drift product of the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) (Lavergne et al. 2010). This is about a half of the size of the 15 km grid cell used here (Section 2) so that the influence of sea ice drift from one day to the next may be neglected. There- fore, 1D-models like HIGHTSI or the CFDD can be applied without introducing too large er- rors from the 1D assumption. The training areas are in a sufficient distance from each other so that the CFDD based SITs are not obtained from the same grid cell of the NCEP grid.

P4385L5: added "... from the 1D assumption." at the end of the sentence. (see above)

P4385L6: changed sentence to:

"The training areas are in a sufficient distance from each other so that the CFDD based SITs are not obtained from the same grid cell of the NCEP grid." In a resolution of 1.5 of ECMWF and 2.5 degree of ncep data, no regions have a common closest grid point center. Geophysical correlation stays, but SIT from CFDDs within these regions will not be exactly the same.

P4385L16: Not yet applied. Due to the radiative properties of sea ice and simplicity we

investigate in freeze up and ice growth of thin ice only. To our knowledge no relation of CMDD to sea ice thickness is published yet.

P4385L23: See new Figure 5 and time series in Figure 4. Especially in Area 6 (middle) one can see that the ice concentration does not increase from Day 30 but the SMOS brightness temperatures do.

P4386L1: added:

R. Kwok, J. C. Comiso, S. Martin, and R. Drucker, "Ross Sea polynyas: response of ice concentration retrievals to large areas of thin ice," J. Geophys. Res., vol. 112, p. C03S21, 2007.

and

Stefan Kern et al. 2007, Annals of Glaciology, "Polynya Signature Simulation Method polynya area in comparison to AMSR-E 89 GHz sea-ice concentrations in the Ross Sea and off the Ade′lie Coast, Antarctica, for 2002–05: first results"

P4386L4: removed "wind induced" in sentence.

P4386L6: It was intended to have an exemplary discussion to give the reader an impression of what is done exactly to train the algorithm. All used traning regions are shown now in updated Figure 4.

P4386L13-15: introduced requested plot (Fig. 5) of Intensity and polarisation difference versus ice thickness. Including the function fit.

P4386L23-28: rephrased to: The uncertainty of the instrument is about 2 to 3 K for a single measurement (Brown et al., 2008). The error budget of daily averages within one grid cell is reduced by the averaging over the incidence angle range of 40âŮę to 50âŮę , but increased by the emissivity variations with incidence angle (Fig. 1(left))

P4386L27: Done

P4387L15: Done

P4387L16: Done

P4387L18-19: It was meant that the deviations can be larger in reality than stated in the Table for SIT close to 50cm. Changed for clarification to "...it might yield larger deviation than stated close to the 50 cm border"

P4387L19: changed to "RMSD values"

P4387L21: Done

P4388L4-5: Done

P4388L6: Done

P4388L6-8: Done

P4388L14-15: Done

P4388L23-24: Example just shown for illustrating the problem of comparing the two data sets and how it is done. Added data of 70 additional MODIS scenes to the scatterplot. And changed to hexagonal binning for density information. New Figure 4 includes all data used for training. Plot 6 shows already all data points.

P4388L26: Kept original, The retrieval uncertainty for the MODIS retrieved SIT is 40 to 50 percent most of the time. Added more details to the text, for further information see Mäkynen2013.

P4389L7: The instrument where the data stem from is a different one, especially designed to be carried by helicopter or plane.

P4389L9: Refined explanation as "The method employs the contrast in electrical conductivity between sea water and sea ice for determining the distance to the ice-water interface, and from a laser altimeter the distance to the ice top. The difference yields the ice thickness (Haas et al. 2009)." (see also

http://www.awi.de/de/forschung/fachbereiche/klimawissenschaften/meereisphysik/methoden

P4389L11: Added reference, (Haas et al, 2009)

P4389L15: changed to: "The uncertainty of the EM bird results of about 10$\sim$cm makes it suitable for validating SMOS SIT retrievals which are expected to have a clearly higher uncertainty, especially in the upper thickness range."

P4389L20: Original L1C grid spacing is about 15km with overlap in an ISEA grid as described before. To be able to show a regular grid with square tiles, we regridded into the 12.5km NSIDC grid for visualization purposes. However, comparison is done as described in the native SMOS L1C equal area grid.

P4389L20: Swath data is used to have more accurate and stable values on the brightness temperature in daily averages which are the input for the retrieval. The day to day difference now is taken for October to December 2010. The deltaSIT(FDD)/deltaT analysis will be part of the further analysis described in the outlook.

P4389L27-28: Reworked EM bird section to include histograms and discussion of em bird measurements within every closest SMOS footprint to the EM bird track.

P4389L28: Inserted size of SMOS footprint as about 50 km.

P4390L5-10: Median is used to put less weight on the higher thicknesses from EM bird.SMOS retrieves SIT up to 50cm while EM bird can retrieve easily 5m. It is assumed that a median SIT is a more speaking comparison to the SMOS retrieved value. See reworked EM bird section.

P4390L19-20: changed sentence

P4390L24: Done

P4390L28: Region was declared in P4389L13, reworked complete section. Better highlighting of area now.

P4391L1: Changed according to suggestion

P4391L5: Done

P4391L5-6: Changed sentence

P4391L14: Done

P4390L21: Done

P4391L22: Changed “reliable” into “accurate”.

P4392L12-13: Changed according to suggestion.

P4395L21: Done (p35-40)

P4399: Done

P4400: Not applicable in the Mercator projection as scale varies with place. Distances may be estimated from lat/lon values.

P4401: Replaced ECMWF CFDD ice thicknesses with NCEP near surface temperature data, added 2 more regions and made visual improvements.

P4403: Reworked scatter plot to show all available MODIS data from 24.11.2010 to 14.04.2011 (71 days in total now)

P4404: The histograms of the EM bird thickness distributions of the analyzed regions are now included in the figure. They give an impression about the width of the distribution. As the histograms are clearly non-Gaussian, description by standard deviation does not appear appropriate to us.

Answers to Anonymous reviewer:

1.

As Figure 4 shows, the NCEP/CFDD derived thicknesses deviate in the thickness range up to 65 cm from those from HIGHTSI not more than 10 cm while ECMWF/CFDD

and TOPAZ show higher discrepancies at higher thicknesses. All shown model thicknesses are used to demonstrate the range of variability of the sea ice thickness retrievals. HIGHTSI, ECMWF and TOPAZ are not used at other places in this study. ECMWF is removed and replaced by air temperature close to surface from NCEP in new Figure 4 since it brought no new insights for the discussion. For the relation between CFDD and sea ice thickness, five analytical forms have been suggested by Maykut (1986). As they have been obtained under different conditions, the standard deviation of the ensemble has been used as an estimate for the thickness uncertainty by Kaleschke et al. (2013). The results are 2, 5 and 12 cm uncertainty for the thickness ranges of 0-10, 30-40 and 40-50 cm, respectively. The algorithm parameters have turned out to be quite stable if the learning data set is varied. Except for TOPAZ, all ice thicknesses from CFDDs and HIGHTSI agree quite good as seen in Figure 4. However, the training with the TOPAZ model resulted in about 30% lower ice thickness retrievals. In addition the RMS of the I and Q from training with TOPAZ were high compared to HIGHTSI, NCEP CFDD or ECMWF CFDD training, which suggest that TOPAZ does not reflect the surface condition we see with SMOS.

2.

Since as presumed the TBs are a function of SIT, it is not meaningful to our opinion to give complete correlations for the whole variety of thicknesses. The binning of the correlation would, however, reveal the sensitivity to certain SIT ranges. We address this now by introducing and discussing a scatterplot (new Figure 5.) to show the relation and sensitivities between SIT, TB and Q. The investigation period Oct-Dec 2010 was used since for that time HIGHTSI and MODIS data was available in the context of the project to validate the algorithm within the same time and spatial domain as used in the training. As the project is closed now, it is difficult to extend the validation period to more years. Therefore, we decided to stay with an algorithm training for one year (2010) freeze up.

3.

Added more MODIS data from 24 Nov 2010 to 14 Apr 2011 (71 days in total) to the scatter plot and refined discussion: Similar analyses have been performed for all days with a sufficient number of coincident SMOS and MODIS thickness retrievals from 24 November to 14 April 2011 with 71 scenes in total (not shown here). Figure 7 (bottom) shows the combined scatter plot. As the data have been taken under a variety of different conditions, the scatter is pronounced with a correlation of r=0.68 and a RMSD with respect to the regression line of 11 cm. The line has a slope of 1.75, indicating that on average the SMOS retrieval gives 75% higher SIT than the MODIS retrieval. As a consequence, the two retrievals agree best at low thickness.

4.

Probability distributions of the EM bird based thicknesses within the SMOS footprints added (Fig. 8). Section rewritten. Unfortunately EM bird observations of ice with SIT<20cm on average on scales as large as a SMOS footprint are not within this this EM bird flight and are rare in general. Kept scatterplot but addressed explicitly the issue with the limited amount of data points.

5.

We have inserted an additional histogram of daily positive and negative ice thickness changes for the complete freeze up period Oct. to Dec. 2010, (Fig. 10) and discussed. Temperature data have been included in the time series plots of Figure 4. However, a detailed investigation on how different areas show reasonable results throughout the season is beyond the scope of this paper since it requires an analysis of wind speed, direction and temperatures to potentially explain regions of poor consistency.

6.

inserted in Sec 5: The present retrieval and that suggested by Kaleschke et al. (2012) use different, indepen- dently taken data as they use disjoint incidence angle ranges (0âŮę to 40âŮę vs. 40âŮę to 50âŮę). In a future step, both retrievals could be

combined, e.g. by fitting an analytical curve to the observations of all incidence angle within one grid cell and then determining the ice thickness from the parameters of that curve.

Page 4380 line 20: Changed “snow grain size” to “snow cover” to not limit the expression.

Page 4381 line 24: This is a journal specific correction, it was “seconds” in our manuscript. We will watch out for it the next proof.

Page 4382 line 12: changed sentence to: “Even though the frequency band near 1.4$\sim$GHz is not allowed for communication, radio frequency interferences have been strong during the early phase of the SMOS mission They have been reduced since then, but not completely eliminated [Camps2010, Oliva2012].

Page 4384: Added NCEP NCAR near surface level temperature and reference. Removed ECMWF data completely since it was not directly used.

Page 4385 line 12: Done

Page 4385 line 16: Done

Page 4386 line 16: The thermal infrared based MODIS retrieval uses atmospheric forcing data from the HIRLAM model. Added much more details about the MODIS SIT retrieval as: ODIS based ice surface temperature together with HIRLAM atmospheric forcing data was used estimate thin ice thickness over the Barents and Kara Seas through the ice surface heat balance equation (Yu and Rothrock, 1996; Mäkynen, 2011; Mäkynen et al., 2013). The spatial resolution of the MODIS thickness charts is 1 km and they show SIT values from 0 to 99 cm. Only night-time MODIS data was employed. Thus, the uncertainties related to the effects of solar shortwave radiation and surface albedo were excluded. For the cloud masking of the MODIS data, in addition to the different cloud tests (Frey et al., 2008), also manual methods were used in order to improve detection of thin clouds and ice fog. In the SIT chart calculation and average

snow thickness vs. ice thickness relationship was used (Mäkynen et al., 2013). This relationship is based on an empirical relationship between snow and ice thickness by (Doronin, 1971) and the Soviet Union's Sever expeditions data (NSIDC, 2004). The typical maximum reliable SIT (max 50% uncertainty) for the MODIS data was estimated to be 35-50 cm under typical weather conditions (air temperature <-20âŮę C, wind speed 5 m/s). The accuracy is the best for the 15-30 cm thickness range, around 38%. These figures are based on Monte Carlo method using estimated or guessed standard deviations and covariances of the input variables to the SIT retrieval. No in-situ data were available for the MODIS SIT accuracy estimation.

Page 4387 line 14: Done

Page 4387 line 22: Done

Page 4388 line 20: Done, 0.83 was correct. rewritten section, see point 3.

Page 4389 line 4: corrected

Figure 2: Done

References: Kaleschke and 10 others 2013: SMOS Sea Ice Retrieval Study (SMOSIce) Final Report. ESA ESTEC Contract no. 4000101476/10/NLCT. Hamburg 2013, 380 pages.

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