The Cryosphere Discuss., 6, C3131–C3140, 2013
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The Cryosphere Discussions

Interactive comment on "Sea ice thickness, freeboard, and snow depth products from Operation IceBridge airborne data" *by* N. T. Kurtz et al.

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We thank the reviewer for the thorough reading of the manuscript and attention to the presentation of the subject matter. We have added in a number of new figures to the text to better illustrate the procedures used in the retrieval of the sea ice properties. Most significantly, we have included figures illustrating example waveforms from the snow radar data set with visual displays of the terminology referred to in the text. We hope these additional figures provide insight into the nature of the retrieval methods and complement the text to provide a more clear understanding of the IceBridge data set.

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The specific comments outlined below are also addressed. A number of sections have been clarified in the manuscript to address the reviewers questions. Again, we thank the reviewer for these comments, the manuscript has certainly been much improved by addressing them.

Specific comments

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Comment

Introduction P. 4774, l.19: Please define freeboard from the outset.

Freeboard is now defined at first usage in the introduction.

2.1 Laser altimetry data P. 4777, l. 12: What is the range of signal strength values? How much would they exceed 950? Show an example to illustrate nature and application of regression equation?

Statistics on the mean and standard deviation of the signal values have been added into the manuscript, and a figure showing the distribution of signal strength values has also been added in (see below). For the 2009 campaign, the signal values exceed 950 44% of the time (varying from 15% to 67% for each flight).

A figure demonstrating the nature and application of the regression equation has been added in (see below).

2.2 Snow radar P. 4778, l. 9-11: Please explain what pre-sums are? L. 13-27ff: I am not sure this paragraph is easily understandable if one has never heard of the FMCW principle and instrument. How is snow depth determined from radargrams?

Presumming (also called coherent averaging or stacking) of the received waveforms is done in-flight to reduce the data rate to the recording hard drive (∼20 MB/s). Additional coherent averaging are done in post-processing to increase the signal-to-noise ratio and further reduce the data volume. The text has been updated to better explain this term.

In order to make the paragraph more understandable we have added in less technical text to describe the snow depth retrieval principle. The statement reads “The snow radar system measures the return power as a function of time which is scattered from the area illuminated beneath the aircraft. Snow depth is determined by detecting the snow-air and snow-ice interfaces within the radar waveform and multiplying the time separation between the interfaces by the speed of light within the snow pack. Details of the snow depth retrieval process are provided in Section 4.”

2.3 Visible imagery P. 4779, l18: Are images overlapping or not? L. 22 ff: what are typical roll, pitch, and yaw angles?

The CAMBOT images were not overlapping (the DMS images are, however). For the nominal flight altitude of 460 m and flight speed of 460 km/hr, there is ∼300 m of track which is not covered between each image. This statement has been added to the text. Pitch and roll angles are recorded and provided as data files, a typical pitch value is 2 degrees (standard deviation of 0.25 degrees for the 2009 campaign) and roll value is ∼0 (standard deviation of 2.6 degrees).

3. Sea ice freeboard retrievals P. 4780, l. 23: resolve resolution?

Corrected the grammar mistake.

P. 4781, l. 21ff: mention spatial scale of these waves; this may be another reason that they don’t matter in this context.

The polar tide varies less than 1 mm over length scales of 100 km which is negligible. This has been added to the text.

P. 4782: Here too it would be interesting to mention the characteristic length scales of these corrections.

The length scales of these corrections is highly variable, as they depend on day-to-day weather patterns, locations of the survey, tidal cycles, etc. Thus, there isn't necessarily a single characteristic length scale which can be listed for these corrections.

P. 4785 and 4786 top: are these criteria applied for each lead individually? Or for a larger number of leads at the same time?

These criteria are applied for segments of the flight which span +-250 meters from the a point on the flight track. Thus, it can span a single lead, or multiple leads, depending on the size of an individual lead. This is stated on P. 4784, L20-21 "A value of $\pm$ 250 m has been chosen to span the width of an individual DMS or CAMBOT image."

P. 4787, l. 13: how is L determined?

L is determining by computing the autocorrelation of the sea surface height measurements and selecting the distance at which the autocorrelation sequence falls below 1/e (0.37). This has been added to the text.

P. 4789, l 25ff: how large is the difference between fb_mean and fb_adj in general (value?).

The difference varies, on average it is small (typically less than 1 cm) over a flight. But on local regions it has been observed to vary up to $\sim$5 cm. This has more of an impact on estimates of the ice thickness distribution because the thinnest ice types are under-sampled by the ATM instrument. Additionally, in the Antarctic where thin ice is prevalent this will be more important.

4. Snow depth retrievals P. 4792, l20: what is the vertical direction? The direction of travel time?

This sentence was perhaps confusing as originally written. N_echo refers to the number of points in an individual radar waveform (which is constant across each echogram file).

L. 22: what does incoherently mean in this sense? Does this require a smooth snow surface to be successful (i.e. constructive stacking?).

Incoherent averaging does not use the phase information, only the absolute values of the complex data are used (phase information was not originally provided for the 2009 data set). A smooth surface is not required for the stacking to be successful, but the impact of surface roughness on the stacking procedure is an area of study which could be explored through comparisons to detailed in-situ surveys to determine the full effect.

P. 4793, l. 17: is 5 m above before or after the maximum peak?

This is before the maximum peak, assumed to be in the air above the snow pack.

L24 ff: Show an example! This section really needs some illustrative examples.

Two example radar waveforms illustrating cases with a distinct peak and a case without a peak are now included (see below). The different radar parameters defined here, as well as the picked snow-air and snow-ice interfaces are defined in the figures to better explain the concepts introduced in the text. Additionally, a radar waveform over a ridge has also been included.

P. 4795, l1: is this two-way delay time?

For the 2009 and 2010 campaigns, this is the one-way delay time. So snow depth is determined by: snow_depth = delta_t * c_snow delta_t is found by multiplying the number of range bins between the snow_air and snow_ice interfaces by the time parameter found in the radar data file.

L 10-14: So does this snow depth represent mean snow depth then? Or some arbitrary snow depth? Unfortunately snow depth varies on much shorted length scales.

The snow depth is assumed to represent the mean snow depth. Yes, it is unfortunate that snow depth does indeed vary on much shorter length scales, but the length-scale is set by the current technological limits of the instrument. However, if the mean snow depth is retrieved, it should provide valuable information for snow studies at this length-scale and larger.

Eqs 9 and 10: unclear. What are m and b? Is power (in dB) generally negative? Show an example.

m and b are defined on P 4793, lines 10 and 11. These equations have now been numbered and inserted into the text of this section.

Power (in dB) is generally negative for the snow-air interface and positive for the snow-ice interface. However, given the lack of radiometric calibration the use of positive and negative numbers here is arbitrary.

An example radar waveform for a ridged location is now shown (see below).

P. 4797, l1: power is near the system noise level?

For the 2009 campaign, the mean power for the snow-air interface was indeed near the system noise level at 2.8 dB above the system noise level.

For the 2010 campaign, the mean power for the snow-air interface was higher than the system noise level at 6.4 dB above the system noise level. This is due to the increased signal-to-noise ratio of the 2010 campaign described earlier in the section.

Table 5: How useful is it to list mean results if there must be some strong, regional variations along those long flight tracks?

Indeed there are strong regional variations along some of the long flight tracks. The table is meant to supplement Figures 9 and 10 by providing more specific information which isn't necessarily easily discernible from the maps. Thus, the table is meant to provide the reader with quantitative numbers with which to further evaluate and understand the results.

Figure 5: It would be nice to show two corresponding aerial photos for the two exam-

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ples.

These two examples were taken from randomly selected data areas to illustrate the fitting technique, the locations of the fits were thus not recorded for determination of the corresponding aerial photos. However, Figure 4 illustrates the selection of lead points from the coincident ATM and aerial imagery.

More importantly, in 5b, why does the original Gaussian fit only encompass the right peak? I would have imagined that it encompassed the two big peaks, for example, and of course initially not providing a good fit at all?

In Figure 5b, the original Gaussian fit only encompasses the right peak since the fitting algorithm looks for the highest discrete peak with a Gaussian shape to fit the curve. Since there are two distinguishable distributions in this example, the algorithm only fit the case with the highest peak. If the two peaks were closer together the fitting algorithm would indeed fit a Gaussian function over the entirety of the distribution. In both cases the chi square goodness of fit test would show a bad fit to the data.

Fig 7: Provide better figure quality? Fig 9: Add flight numbers to figure to provide better link to table 5.

We have converted Figure 7 to a PDF image which should improve the figure quality. Flight numbers have been added to the figure to better link with Table 5.

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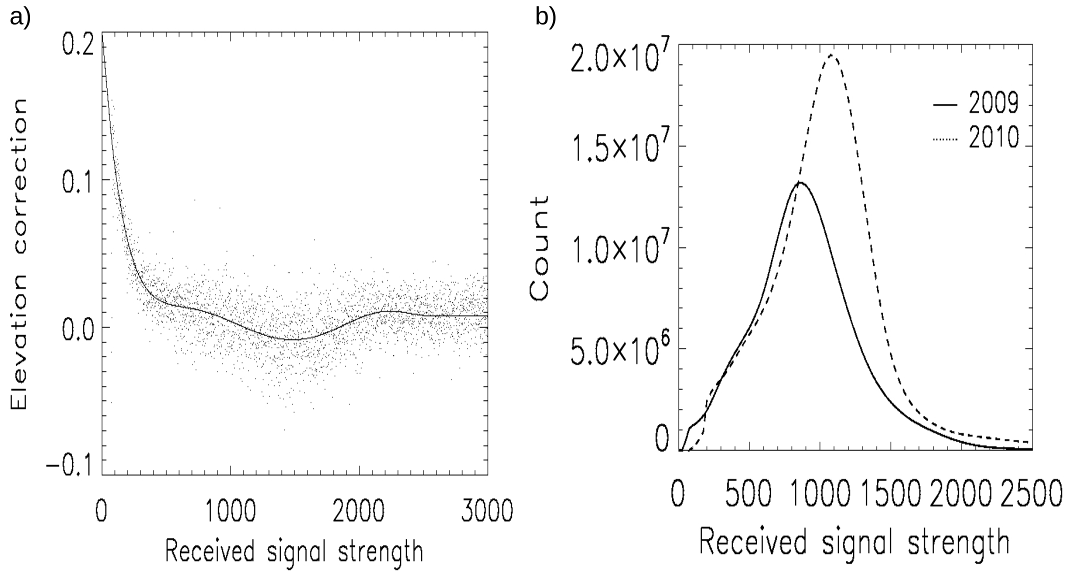

Fig. 1. a) Dependence of received signal strength on measured range to a fixed target for the 2010 ATM instrument. b) Histogram of ATM received signal strength values

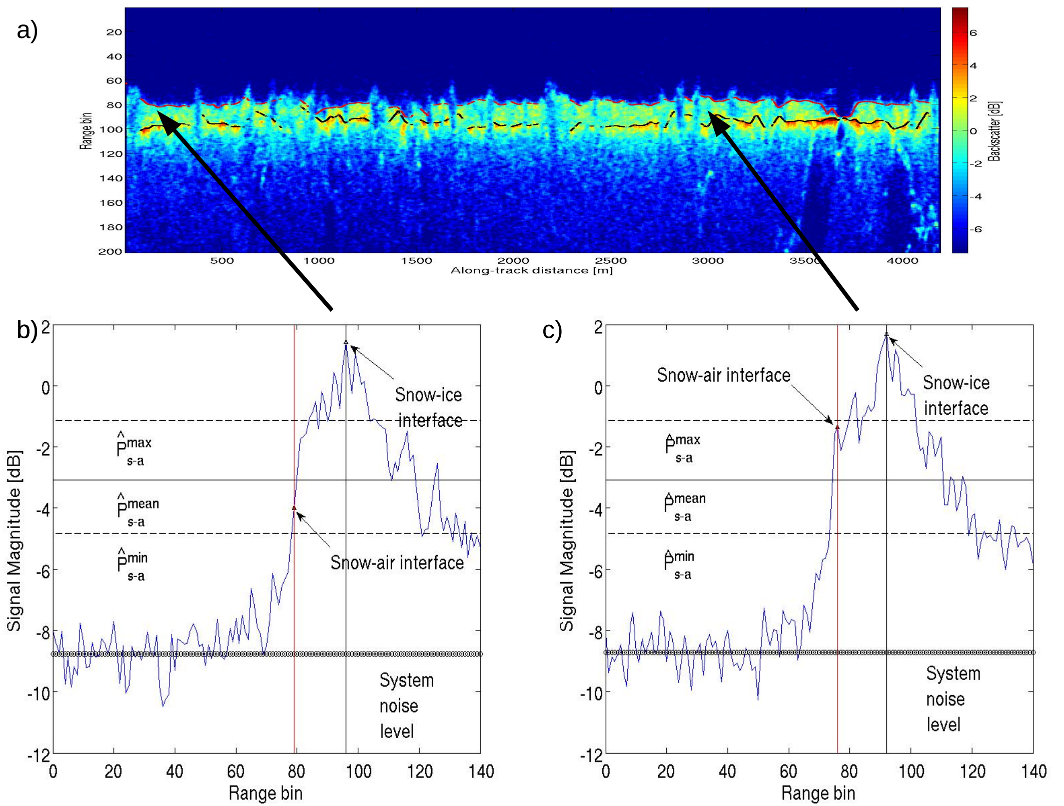

Fig. 2. Example of picked snow-air (red line) and snow-ice (black line) interfaces for a radar file from the 2010 data set.

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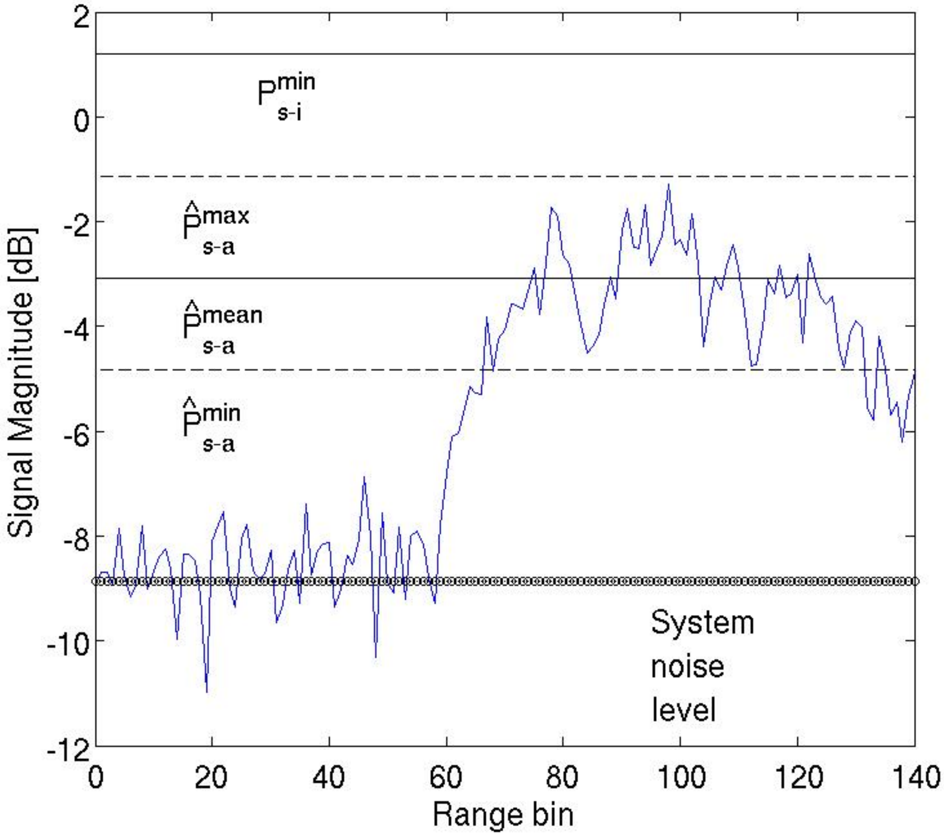

Fig. 3. Example radar waveform over a ridge. The point of maximum power in the radar waveform is within the expected range for the snow-air interface and does not reach the minimum required threshold.