Interactive comment on “Intercomparison of snow density measurements: bias, precision and spatial resolution” by M. Proksch et al.

C. Derksen
chris.derksen@ec.gc.ca
Received and published: 24 August 2015

General Comments
Snow density is a fundamental and commonly measured snow parameter to which little attention has been paid to measurement accuracy. This paper quantifies spread and uncertainty in snow density profiles using a very carefully collected set of measurements in both laboratory and natural environments. Micro CT measurements provide the means to compare traditional gravimetric sampling with a state of the art technique. The results are clearly presented, and provide clear baseline information to guide the acquisition and interpretation of density measurements. I have some relatively minor comments which will hopefully improve the final version of the manuscript (note page numbers refer to the ‘print-friendly’ pdf version:

We highly appreciate the valuable comments by C. Derksen which will help to improve the manuscript. We included in particular the comments 1. and 10., which broadens the scope of the manuscript with respect to applications that do not require high vertical resolution measurements.

Please find our answers to the comments below in blue, *and the text changed in the manuscript in green.*

1. In no way do I disagree with the statement on page 3585 that “for a wide range of applications, users need the higher resolution and efficiency of technologically more sophisticated measurement methods.” But there are also many applications for which detailed SMP or CT derived density profiles provide far too much vertical resolution (i.e. microwave remote sensing applications where 1 or 2 layer snow models are used in operational retrievals). So another contribution of this paper is in showing how the high resolution measurements, simplified to coarser vertical resolution, compare to traditional gravimetric profiles. I think it’s worth adding a statement that the value in these comparisons is not just to understand what vertical resolution is lost with traditional sampling, but to quantify how sub mm scale profiles aggregate back to coarser vertical resolutions.

We agree and included the following sentences in the introduction:

p. 3585, l.2: Besides this, many applications exist that (to date) do not require high resolution profiles. For instance, microwave remote sensing applications often use 1 or 2 layer snow models in operational retrievals. Consequently, the scope of this paper is to show how high resolution measurements, simplified to coarser vertical resolution, compare to traditional profiles, i.e. to quantify how millimeter scale profiles aggregate back to coarser vertical resolutions.

2. Section 2.2.2. The wedge cutter has 10x the volume of the box and cylinder cutters. While this influences the vertical resolution, it may also play a role in the measurement error and uncertainty. There are wedges (and boxes and cylinders) available with different volumes. Can any comment be made on the sensitivity of the results to cutter volume?

This point was as well addressed by referee1 (we added a sentence about the wedge cutter here):

Page 3594, l.26.: The fact that the higher resolution methods resolved a higher degree of density variability is closely related to the measurement volume of the different instruments. For instance, the measurement volume of the CT (15^3 mm-3 = 3375 mm^3 = 3.375 cm^3) is around 3 % the measurement volume of the 100 cm^3 box density cutter. A larger measurement volume is immutably connected to a smoothing of the measured density profile, as very thin layers are averaged within the measurement volume. This explains the lower variability of the box cutter density profile, compared to the high frequency density variations resolved by the CT, and is also true for the lower variability of the 1000cm^3 wedge cutter compared to the box cutter. As the measurement volume of the CT was sufficiently large to be representative (1.25^3 mm^3 = 1.95 mm^3 found by Kaepfer 2005, section 3.1.), these high frequency density fluctuations are not an artefact of a small measurement volume.

3. This is more of a lament than a comment, but it's very disappointing that the SMP measurements are not usable. The CT was essentially used as reference, but no estimate of uncertainty is provided in section 2.3. The SMP measurements would have no doubt helped in this regard, but can information be added on the potential error in the CT derived density?

We agree and added a paragraph in the discussion related to CT segmentation:

p.3594, l.3: The main uncertainty of the CT density lies in the segmentation of grey-scale images into binary images. In this study, the threshold for image segmentation was visually determined by a trained operator. Both visual and automated threshold determination (e.g.Kerbrat 2008) are based on the same principle, finding the minimum between the ice and air peak in the grey scale histogram, but a trained operator is able to compensate for the disadvantages of automated threshold selection e.g. at uni-modal histograms for snow samples with high SSA. However, no error estimate is available for the visual technique, but Hagenmuller 2013 reported similar density values for an automated threshold segmentation, gravimetric measurements and an energy based segmentation developed by these authors. The authors further noted that both segmentation techniques produce basically identical results, which gives also confidence for the visual threshold based segmentation used in this study, as the physical principle behind both techniques are the same. For the sensitivity of the threshold selection, Hagenmuller 2013 reported that the density of a snow sample (gravimetric density of 280 kg m-3, CT determined SSA of 8.0 mm-1) the dilation of a pixel would increase the density from 278 kg m^{-3} to 294 kg m^{-3} which on the order of 5\%. In general, the strength of the CT derived density is the precise information of the density evolution enabled by the sub-millimeter scale resolution of the CT; the absolute density is more sensitive to the segmentation process. As such, the analysis of field data presented in this study, which focused on density evolution with depth, is expected to be fairly insensitive on the CT segmentation process, whereas the bias values are more sensitive to the segmentation. Providing CT error values would, however, require extensive re-segmentation of CT samples, which is beyond the scope of this study.

4. Section 2.2.3 and Section 5.2.2: It's clear the presence of ice crusts have a significant impact on the density uncertainty. How confident are you in the technique of ": : :weighing a carefully extracted ice layer sample with a known volume". How was the known volume determined? Is this method sensitive to a minimum volume or mass? What precision of mass measurement is required? It seems like a better field method for the determination of ice crust density is required.

We agree with the reviewer and tried to better point towards the uncertainties of this method:

p.3595, l.6: "Ice layer densities were determined by careful measurement of an extracted ice layer. Uncertainties remain in measurements of ice layer densities using this technique, largely due to the triaxial measurement of an irregular-shaped ice sample in combination with the precision of the in-situ mass measurement (+-0.1g) relative to the mass of the sample. When using box and wedge cutter…. "

We agree that a better method is needed, as obvious from the large spread in ice layer densities:

p.3595, l17: "The large variability in ice layer densities measured by different instruments in this study suggests that this topic needs further investigation towards the development of a more precise measurement technique, especially due to the significance of this measurement for radiative transfer modeling (Durand et al. 2008).

5. Section 3.1: Based on figure 2, there was a large density range in the lab measurements, and hence the characteristics of the 13 snow blocks. Some additional details would be helpful. What were the characteristic grain types/hardness?

We added the following sentence, as no hand hardness was measured in the lab:

p.3589, l.3. " Thirteen snow blocks of 40 cm x 40 cm in area and between 10 and 36 cm in height were used in this study. The major grain types of the snow blocks were facets (n=7), rounded grains (n=3) and depth hoar (n=3), as classified according to Fierz 2009. All blocks were measured using the CT and the 100 cm^3 box type density cutter in the laboratory…."

6. Page 3591 lines 10-15. The thresholds between density over- and underestimation are stated to be for “box cutter, wedge cutter, and densities by layer” which I believe is referencing Figure 4. The caption to figure 4 shows box, wedge, and cylinder. Please clarify.

We changed the terms " stratigraphic method" and "density per layer" in the whole manuscript to "cylinder cutter", to be in line with the legend of the figures.

7. This is very subtle, but when the measurements are evaluated at the resolution of the cutters (Figure 4) the changing bias with density magnitude is apparent for all three cutters (overestimate for low densities; underestimation for high densities). When the measurement are evaluated at the resolution of the traditional layers (Figure 5) the wedge sample bias with density magnitude is consistent with Figure 4, but the box and cylinder switch to slight underestimation at lower densities and overestimation at higher densities (opposite to Fig 4). Any simple explanation as to why? There seems to be one clear box cutter outlier in Figure 4. Was this one measurement looked at carefully?

In Figure 4 the data of the box cutter without averaging is shown, and the above mentioned point can be found in Fig.3 at around 130 cm snow depth, with a box cutter density of around 330 kgm-3 and CT values in the range of 410 - 420 kgm3.
In Figure 5 the box cutter data was averaged to fit the resolution of the traditional layers, and the point mentioned above with a density of around 330 kgm-3 was averaged into the 90 - 130 cm depth snow layer, which lead to an average density of around 395 kgm-3 for the box cutter at this layer, which was very similar to the mean of all methods for this layer (top most/right points in Fig. 5).
In summary, Fig.4 and Fig.5 present two different comparison, one where the cutter were compared in their native resolution against the CT, and one where cutters and CT were averaged to the layers

of the traditional stratigraphy, and the compared to the mean of all methods, which is why both figures show different results.

8. Figure 6: It would be interesting to see full profiles at the same resolution of all sampling techniques (Fig 3 shows all 4 profiles but at their native vertical resolutions). Perhaps this could be added to Figure 6 for the 3 and/or 10 cm resolution CT panels?

We agree and modified Fig 6 accordingly:

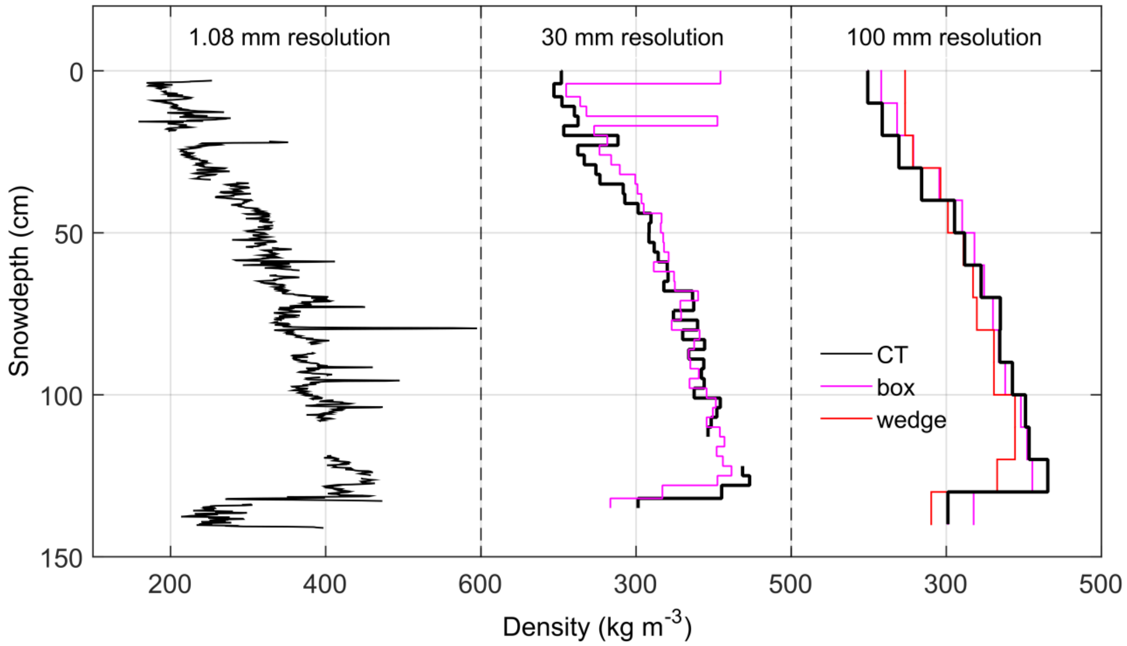

Figure 1: CT derived density (black), subsequently averaged to 30 mm (black, middle) and 100 mm (black, right) vertical resolution. For comparison, the box cutter densities are shown in raw resolution (magenta , middle) and averaged to 100 mm resolution (magenta, right). The wedge cutter density is as well shown in raw resolution (red, right).

9. Figure 7: Nice figure!

10. Despite the issues shown in Figure 8, overall, I would say these results are quite encouraging with respect to the traditional field measurement of snow density, if careful samples are extracted by experienced users. This is particularly true for applications that do not require high vertical resolution, but for which 10 cm density profiles provide more than enough information (i.e. microwave snow modeling), and mean values for 1 or 2 layers are all that is required. Some brief comments in Section 6 with respect to applications that do not require high vertical resolution measurements (i.e. remote sensing; hydrology) would be helpful.

We agree (see also comment 1):

p.3597, l.13. These results are also encouraging for applications where a coarse vertical resolution is sufficient (i.e. microwave snow modeling). For coarse resolutions, the technically simple cutters provide the same information as the more time consuming and cost intensive CT.

Editorial Comments

Abstract: consider rephrasing to ": : :In the field, the density cutters tend to overestimate

(1 to 6%) densities below and underestimate (1 to6 %) densities above a cutter-type dependent threshold that fell between 296 to 350 kgm□3, respectively.”

Agreed and changed.

Page 3583 line 23: change to “: : :although there was a tendency for inexperienced users to overestimate the density of light snow and depth hoar by 6 and 4 %, respectively.”

Agreed and changed.

Page 3583 line 26: Within the cutter types? I think you mean between.

Correct. Changed.

Page 3584 line 23. This is the first mention of the Microsnow 2014 workshop in the body of the paper. Some additional background on the workshop/experiment would be nice here.

We agree, rephrased this sentence and added information on the next page:

p.3584, l.23: the ability of the different methods to resolve spatial density variations was beyond the scope of this study.

p.3585, l.5:The MicroSnow Davos workshop aimed to quantify the differences between available snow measurement methods, motivated by the progress in the development of new measurement methods in the recent years.

Section 2.2.2: information is provided for the commercial availability of the box and wedge cutters but not the cylinders. Can this be added?

Page 3587 line 3: this may be obvious, but I suggest clarifying that the 55 cm cylinder was inserted vertically.

Changed.

Page 3596 line 6: change ‘measurements’ to ‘measurement’
Page 3596 line 14: change ‘looses’ to ‘loses’
Page 3596 line 17: change ‘loosing’ to ‘losing’

All Changed.

References:

Hagenmuller, P.; Chambon, G.; Lesaffre, B.; Flin, F. & Naaim, M. Energy-based binary segmentation of snow microtomographic images *Journal of Glaciology*, **2013**, *59*, 859-873

Durand, M.; Kim, E. & Margulis, S. A. Quantifying Uncertainty in Modeling Snow Microwave Radiance for a Mountain Snowpack at the Point-Scale, Including Stratigraphic Effects *IEEE Transactions on Geoscience and Remote Sensing*, **2008**, *46*, 1753 - 1767