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

Anonymous Referee #1
Received and published: 23 July 2015

We appreciate the extensive review by Referee #1, in particular as he points towards several relevant studies which were not included in the paper. We also followed the advice of the Referee to better structure and increase readability of the paper by rephrasing "density per layer/ traditional stratigraphy" to "cylinder cutter" and referring in the results section better to the methods section. However, we want to clarify here that this paper focuses solely on snow, and not on firn or ice.

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

Comments on the discussion paper by M. Proksch et al “Intercomparison of snow density measurements: bias, precision and spatial resolution

General comments: The paper presents the results of an intercomparison of different density measurement methods. Compared methods are density cutters (3) with Micro- Computed-Tomography. Compared are 1. Box cutter to CT in the lab, 2. all cutters to CT in the field, 3. all methods to a layer mean (obtained by averaging over all methods). Statistical results of the comparison are provided.

A comparison of the different methods to obtain density of snow is a valuable approach to improve the quality of all applications where the measured density is used. The study compares three gravimetric methods (density cutters) with a high-resolution method (CT). The density cutter methods have been compared in earlier studies, the CT method, as it has a much higher resolution has been compared to other high resolution methods in earlier studies (which is not mentioned or discussed by the authors).

We thank the Referee for his valuable advice regarding the earlier studies, which have been indeed not addressed in the current version. We included them in the manuscript, as detailed below.

In general the results presented here are interesting for a broader community. However, the study as its current stage lacks a larger scientific background. What is the advantage, the gain or benefit to recent scientific discussions? What is the take-home message for people using these measurement data in model applications or any other application? What is the implication of presented variations in density measurements (how much would that effect for example the calculation of swe, or the computation of metamorphism in models etc).

This study, as well as the whole "Intercomparison of snow grain size measurements methods workshop", which is an outcome of the IACS working group MicroSnow, aimed to provide an estimate how much the state of the art methods differ from each other. We see the advantage for the recent scientific discussion exactly there: to raise awareness about the differences between different measurement methods, and moreover to quantify these differences. With respect to the density paper, the take home message is that density derived from CT agrees in general within 9% with the density derived from density cutters.
As no "true" snow density measurement is existing, we limited ourselves to an intercomparison of methods. Users, i.e. microwave modelers, which are driving their models with density measurements from one or the other instrument, now do have an estimate how much variation they have to expect solely from the differences in density measurement. Depending on the model, users

are now able to estimate how this difference may propagate through their model and affect their results. It is, however, beyond our abilities to track these kind of error propagation. Nevertheless, we provided some simple estimates for thermal conductivity and the critical cut length (a measure of snow instability):

Assume a density of 300 kgm3 and a variation of 10% or 30 kgm3. The error in thermal conductivity based on Callonne2011 would equal 0.045 Wk-1m-1, which is on the order of the thermal conductivity for snow with a density of 150 kgm-3. The critical cut length, a measure for snow instability, increases from 0.53 cm to 0.59 cm (increase of 9 \%), if the density of the snow slab on top of the weak layer is increased by 10 \% from 300 kmg-3 to 330 kgm3 following the procedure described in Reuter2015 (slab height 60 cm, weak layer fracture energy 0.5Jm-2, elastic modulus of the snow slab derived from Scapozza2004, slope angle 0°).

The data are presented, beyond that a profound presentation or discussion for example on the indeed interesting problem of different layering seen by different instruments and the intra-layer variability is missing.

We tried to address the issue of different layering (section 5.2.1 " Representation of the stratigraphy by the density measurements", Fig. 3 and 8) and intra layer variability (section 5.2.3 "Unresolved variation", Fig. 6 and 7):

- For the different layering, Fig 3 shows the all the density profiles of the different methods, and section 5.2.1 e.g. states on page 3594 ll. 16ff: "…the wedge cutter did not represent the variations measured by the box cutter, and the box cutter did not represent the variations measured by the CT." or l. 18ff: "on the one hand, layer boundaries which were defined following the traditional stratigraphic approach (Fierz et al., 2009) appeared less distinct in the CT, and on the other hand, the higher resolution methods resolved a high degree of variability within a layer." A detailed illustration of the stratigraphies for the lower part of the snow profile revealed by different methods is shown in Figure 8.
- The intra-layer variation is discussed in section 5.2.3. and quantified in section 4.3

It is obvious, that more instruments cannot be taken into account, since they were not involved in the measurement campaign, from which the presented data origin. However, it would have been much more interesting to include more high-resolution methods, since they represent the state of the art and are also widely used in the field. At least in the discussion part, published results of previous comparisons of high-resolution measurement methods (their known precision and bias) could be compared to the results obtained in this study. Overall, there have been earlier studies with a similar approach (comparing traditional gravimetric methods to high-resolution methods and stratigraphy). With regard to these publications the presented study does not provide new results.

We agree with the reviewer and tried to add the results of the previous studies, see comment below " General comment to that section: "

Specific comments:

Title: Spatial resolution is not addressed at all in the paper
We agree to the reviewer and changed the wording in the title to: *"vertical resolution"*

Abstract Line 4-5: This is not true. Examples: Freitag et al. 2004, comparing CT density measurements with gamma-absorption method Kawamura, 1990, comparing CT to hydrostatical method (which is comparable gravimetric), ice Lundy et al., 2002, comparing CT to traditional method, snow

We agree with the reviewer, however, Lundy et al, 2002, reported only qualitative results (derived from weighing a snow sample, but without using a density cutter), and the other studies did not focus on alpine snow. Therefore we changed to: *"No study has yet quantitatively considered the recent advances in snow measurement methods such as micro-computed tomography (CT) in alpine snow"*

Line 18: what is meant by "introduced by the observer" ? Check Phrasing
The observer decides on the layering of the snowpack, and as such "introduces" layers into the snowpack, as described in section 2.1. Layers are not an a-priori property of the snowpack, but layers represent a stratigraphic arrangement of the snowpack, which was classified by an observer. Different observes will observe different stratigraphic realities and different layers in consequence. The code of practice for classifying the layers in an alpine snowpack is given in Fierz et al., 2009.

Introduction Page 3583, Line: 20ff: This part could be improved a lot: Take for example Hawley et al., 2008, or Harper and Bradford, 2003, who take very different methods and compare them and already discuss the issue of different resolutions; Kendra et al., 1994, comparing gravimetric methods with snow probe
We agree and included the relevant studies:
Page 3583, l.20: Despite its relevance, few studies quantified so far the differences between the methods to measure snow density. Indeed several studies focused on firn and ice density, but those were mostly limited to firn and ice, i.e. density ranges (>500) larger than the one typically found in alpine snow (50 - 400).
Page 3583, l.28:
Page 3584, l.3: …micro-computed tomography (CT, Schneebeli and Sokratov, 2004, Lundy, 2002)…
Page 3584, l.10: Dielectric devices… (Denoth et al., 1984; Tiuri and Sihvola, 1986; Kendra, 1994; Mätzler, 1996). Neutron absorption (Kane 1969,Morris2003) was in particular used to measure density inside a firn or ice bore hole.
Page 3584, l.17ff: The impact of measurement resolution was in particular demonstrated by Harper and Bradford 2003, who showed that the identification of stratigraphy is a function of a tool's sensitivity to vertical contrast. Hawley 2008 in addition highlighted the smoothing of the density profile of an ice core for instruments with larger measurement/sensor length. In terms of measurement time, the SMP is more time efficient as excavation of a snow pit is not necessary. Vertical profiles of snow density through repeated measurements with the SMP allow the investigation of the spatial variability of snow density.

Page 3583,Line 24 ff: What is then the new approach of your study, the three cutter methods already compared elsewhere?
All three cutter have never been compared to the CT (and Lundy reports only qualitative results and did not use a density cutter.)

Page 3584, Lines 1-13: there is more around, not all need to be included, but currently the presented selection is quite narrow (DEP: S. Fujita or F. Wilhelms; Neutron-scattering, R. Hawley and Liz Morris etc).
See comment Introduction Page 3583, Line: 20ff.

Page 3584, Line 23: why keeping 'spatial variability' in the title?
The title does not contain "spatial variability". However, we changed to *"vertical resolution"*, see comment above.

General comment to that section: Introducing other methods and comparisons is good, unfortunately the presented study only uses gravimetric methods (3) and CT – What is the sense of the introduced methods here, if not picking up on them in the discussion? Maybe the authors could

use the results of previous publications and comparisons by discussing their findings with results found by others (i.e. is the difference between the gravimetric methods and CT comparable to the difference between CT and other high-resolution methods etc – to get a feeling, were the main uncertainties are).
We appreciate the suggestion of the reviewer to discuss results of other studies:
Several studies have compared different methods to measure density, but were mostly limited on firn and ice, i.e. density ranges (>500) larger than the one typically found in alpine snow (50 - 350). Freitag 2004 compared firn densities measured by CT with those measured by gamma-absorption for three sections of a firn core, each approx. 60 cm long. The authors report an deviations of less than 1 \% for both the methods in the density range from 640 - 733 kgm-3, but also qualitatively higher values for the CT in the range 460 - 550 kgm-3 and lower values for the CT in for densities above 733 kgm-3. However, no results are reported for densities below 460 kgm-3, which were in evidence at the workshop. Kawamura reported good agreement between CT and the hydrostatical method to determine the density of ice cores. Hawley 2008 compared neutron probing, dielectric profiling, optical stratigraphy of the core and gravimetric measurements on an 11 m firn/ice core from Kongsvegen, Svalbard. The authors reported a smoothing of thin ice layer in particular for the neutron probe due too its large detector size of 13.5 cm, but also for the dielectric device due too its finite sampling volume, where the authors estimated a sensing length of approx 4 cm. Other problems related to the gravimetric and dielectric measurements were mentioned with respect to collecting cores (accurate measurement of borehole diameter, depth registration, core breaks, poor core quality or melting of cores during shipping) or loose snow at the surface of the bore hole.

Studies which quantitatively focus on snow rather than firn or ice are rarely available. A study which compared density measured by Ct and by weighing samples of sieved was presented by Lundy 2002. The authors reported qualitatively a good agreement between both methods for their 4 investigated samples, however, none of the three density cutter used in this study was used. Dielectric devices were also compared to gravimetric measurements. Kendra 1994 found an RMSE of their snow probe of \pm 50 kgm-3 compared to gravimetric measurements only in a qualitative way, whereas a RMSE of maximum 9 \% (29.7 kgm-3; lab data, box cutter to CT) was found for our data.

Methods General: The definition, use and presentation of the 'stratigraphic method' is unclear. Reading the first part of the method section one expects later two profiles of each method – the continuous profile and the profile with samples from each layer. However, this is not the case. Later the authors refer to the stratigraphy method, but it is not clear, how it is determined and which line in the graphs actually shows this method.
We agree that the term " stratigraphic method" or "density per layer" is misleading and changed it to "cylinder cutter", to be in line with the legend of the figures.

The stratigraphic method is the only method which determines the density per layer, and was solely performed using the cylinder cutter. All other methods were used to determine the density per sample, and not per layer (section 2.1.). We clarified this in the methods section and added the following phrase:

Page 3585 l. 26:"In this study, the cylinder cutter was used to measure the density per layer, after the layers were determined following Fierz 2009. All other method were used to measure the density per sample. As such, the cylinder cutter provided a density profile with varying vertical resolution, based on the thickness of the layers, contrasted by box and wedge cutter, as well as CT, which were operated with constant vertical resolution."

Page 3587 l. 28: "The density per layer or traditional stratigraphy is termed "cylinder cutter" hereafter, as only by the cylinder cutter was used in this study to determine the density per layer. All other devices (box and wedge cutter, CT) were operated without considering layering or stratigraphy of the snowpack, i.e. with constant vertical resolution (see also Section 2.1)."

Page 3586, Lines 8-15: sample size and resolution are missing here (there are included in the sections dealing with the other methods below) General: CT samples are extremely small compared to the others. A discussion on the difference of the samples size and its effect on the comparison is missing. As the snow is not homogeneous in space and over different scales some words or even numbers / references need to be included.
We agree and added the following sentence in the discussions:

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. As the measurement volume of the CT was sufficiently large to be representative (1.25^3 mm^3 = 1.95 mm^3 found by Kaepfer2005, section 3.1.), these high frequency density fluctuations are not an artefact of a small measurement volume.

(Is there a possibility to have many samples from the same layer /depth interval etc to look at the variability of a number of CT samples within the same 'bulk sample' captured by the other methods, and compare this variability then to the variability of different methods?) At least this issue needs to be discussed and an estimation of the value of the variability introduced by this compared to the method-induced variability should be given.
We agree that an estimate of CT density variability would be beneficial. However, due to time and cost constrains, only a single profile was samples and we can't provide any numbers on the variability.

Page 3587, Lines 5-28: Where in paper are the profiles shown? Might be overseen, but a plot, where the profile (layer) is compared to the continuously sampled profile is missing.
Figure 3.

Page 3588, Lines 1 - 23: General Structure: Three different methods of comparison are introduced here (a-c). For the reader it is hard to find them in the following text. It would be more convenient to structure the results in the same way. Another option could be to add a link/reference to the sub chapter/ figure/table, where the relevant results of this method is described/shown here, so that the reader can find the results of this method (i.e. method a (see chapter x.y and figure x.y)
We agree and structured the results section better:
Page 3590 l.24: Three types of comparisons (Sect. 2.3) were performed, all excluding ice layers. For comparison a), the bulk densities derived from each method were compared. In addition a cylinder of inner diameter 9.44cm and length 55 cm (Sect 2.2.3). was used.

Page 3591 l.6: "For comparison b), all methods were compared to the CT density profile. For this reason, the high resolution CT profile was averaged…."

Page 3591 l.16: "For comparison c) and to facilitate a more objective comparison, all measurements were averaged to the same vertical resolution, i.e. to match the traditional stratigraphic layers. The mean density per layer of all instruments was then set as reference. With respect to this reference, the different methods agreed within 2 to 5% (Fig. 5, Table 6), the bias was between -1 and 1 % and R2 = 0.99 for all instruments, significant at the 1% level. When ice layers…"

Meaning of approach a: Reading section on page 3588 lines 4-7 (not quite straightforward to understand – What is meant by 'it' in line 5?) one understands the following: The whole measured profile is taken and converted into one swe value - that gives one value for each profile. This value obtained by one method is compared with the value obtained by another method. What is the meaning of such an approach? Where are the results of this comparison?
This approach shows whether the means of all methods were consistent with each other. It is basically the first check to see if the methods agree or not, and if they are biased towards lower or higher values.

Approach c: One has to search and read twice in order to find the results of this comparison. It would be interesting to have a sketch of the observed traditional stratigraphy and the measured densities together.
See comment above on Page 3588, Lines 1 - 23. We also modified Figure 3 for better illustration of the different profiles:

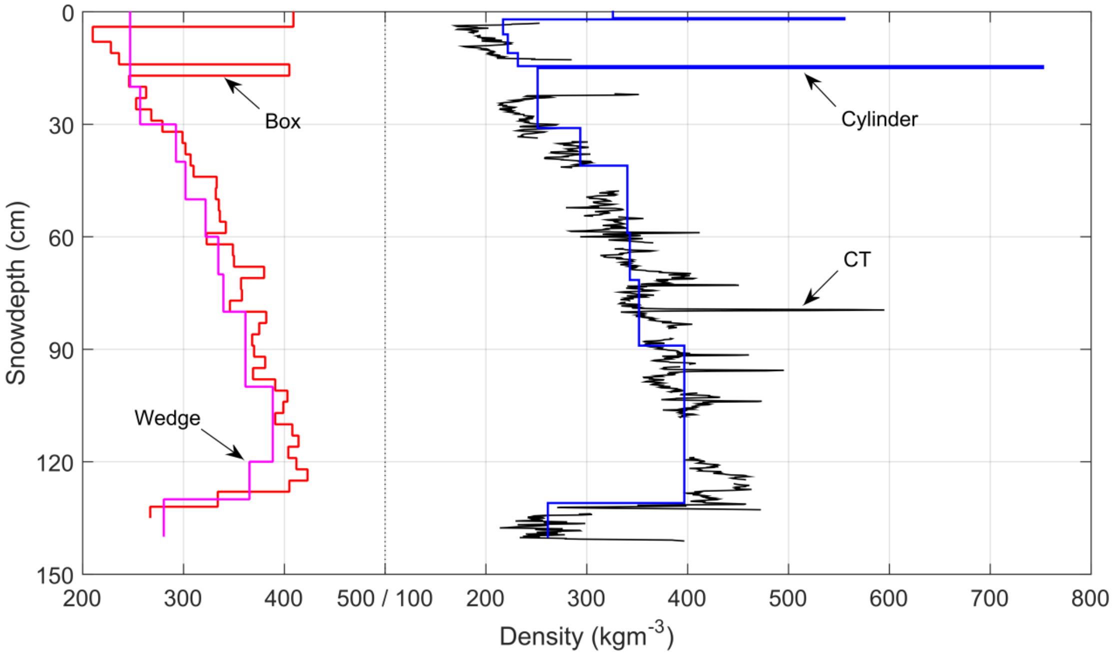

Abbildung 1: Density profile measured by different methods. Two methods each are displayed separately for better visibility. Note that the cylinder profile shows the density with respect to the stratigraphic layers.

Data collection Page 3589, Lines 1-18: Maybe this part should be moved to the methods-part, where the CT is introduced, the same for the following lines on page 3590.
We agree and moved this section to the methods part.

Results Page 3590, Line25 ff: General: Suggestion to structure this chapter according to the methods – that makes it a lot easier for the reader to follow Line 25:Is this the result belonging to method a (Page 3588) ?
See comment above on Page 3588, Lines 1 - 23.

Probably this is a problem of wording: What is meant by reference value? How is the swe calculated – some words on that could be included in the methods part. How does the ratio of swe to snow depth look like? What can one learn from that? Where are the values presented? As mentioned above, this needs some explanation.
We agree with the reviewer and changed the wording of reference value to: "An additional density measurement…." The calculation of this value is explained in the same paragraph (Page 3591, l.1-

3) and not in the methods, as this is the only time were this method is used, solely to increase the amount of mean density values and to better illustrate the comparison of these values.
The comparison of the mean values (reported on Page 3591 l.3-5) shows that wedge cutter gives the lowest mean density and box cutter the highest density. In terms of SWE, box cutter would give the highest SWE. We could not, however, perform the calculation of SWE, as the CT profile was sampled without overlap, i.e. no continuous measurement needed to calculate SWE could be achieved.
However, we believe the mean density of the whole snow profile is a valuable information (i.e. for single layer microwave models) and its comparison reasonable.

Page 3591, Line 6: Again, taking it right – here starts the method b part? Or is this the comparison to the layer density (as it reads “density per layer”)? It reads like the mixture of both... Same Page, Line 13: Why these thresholds?
We changed the term density per layer to *cylinder cutter*.
The thresholds are for over/undersampling of the cutters with respect to the Ct density (Fig. 4). Their calculation is explained in the methods section 2.3, Page 3588, l. 12-15.

Same Page, Line 16: Is this method c? What is the difference to the lines above (10 – 13).
Method c allows a more objective comparison without setting one instrument as reference (see section 2.3), as done in lines 10-13.

Same Page, Lines 23 – 28: A definition /introduction of the phrasing ’unresolved variation’ is missing and how it is estimated and why. For here and the discussion part it would be interesting to discuss this with regard to the variability within a ’layer’, variability due to thin layers, which are not considered or the variability ’lost’ by merging layers (section 2.2.3) with adjacent layers or variability due to ice crusts. Otherwise these values do hardly have any meaning.
We agree that the definition of the unresolved variation was too short and included the following sentence: *"The unresolved variation is the density variation within a layer. It was calculated as standard deviation of the CT density within a certain vertical distance. For instance, for the 100cm3 box cutter which had a vertical resolution of 3 cm, the CT profile was averaged to 3 cm vertical resolution and the standard deviation for each 3 cm window was derived. The mean of all these standard deviations was then defined as unresolved variance (in this case for the 100 cm3 box cutter with respect to the CT density)."*
As such, the unresolved variance also included the effect of merging layers, as the CT profile was subsequently averaged to coarser resolution, i.e. subsequently two adjacent layers were merged. The unresolved variance is discussed in section 5.2.3.
Thin layers are discussed also within the unresolved variance section 5.2.3. on Page 3596 l.10ff, where thin density variations are mentioned to be critical for several properties. Thin layers are illustrated in Fig. 8, where a close-up of the high resolution CT profile (as well as a 3D reconstruction) is compared to the methods with coarser resolution.
The variability due to ice crusts is discussed in section 5.2.2., statistics are given in Table 6.

Discussion Page 3592, Lines 6-11: What is the authors conclusion from the results then?
Conclusion are given in section 6. For the lab data, the conclusion is that it resembles the field data, i.e. that all methods agree within 5 to 9%. However, for the discussion here we wanted to point out that our results (oversampling of the box cutter) are in agreement with Carroll 1977, even so neither of the snow blocks used in the lab consisted of the snow type for which Carroll1977 in particular reported the oversampling (light snow, depth hoar).

Page 3592,Lines 13: Again, it would be very helpful for the reader , if this chapter was structured according to the methods(a-c). It is done bit in the following lines, by adding the related method in brackets, but this could be made much clearer, by having separated paragraphs and the first sentence related to each method.

We excluded an extra sentence repeating the method a b or c in the beginning of each paragraph for better readability and in order to keep the paper short. summarizing each method in one sentence is a bit too short, and we therefore preferred referring to the methods in brackets, where the precise description can be found.

Page 3592, Line 17: In the method/results part – it is explained, that the measurement methods (3 cutter plus CT) are compared to the mean value. What is meant here by “traditional stratigraphy” then? Why is this profile not shown somewhere?
We changed the term "traditional stratigraphy" to *"cylinder cutter"* in the whole manuscript. This profile is shown in Figure 3.

What can one learn from this approach (related to the question concerning the results part) and what is the authors conclusion from the results?
Please refer to the answer to comment Page 3590, Line25 ff, second part.

Page 3593. Line 12: Repetition of lines 8-10 of previous page?
Yes, as it applies for both field and lab results.

Page 3594 Lines 4 – 10: What is meant by ’traditional stratigraphy’ here and where can one see it in figure 8 (as the reference is give to figure 8)?
See answer on comment on Page 3592, Line 17.

No line shown in figure 8 follows the description given here (’highly detailed representation of specific types of density variations....contrasted by a very coarse representation in the lower part..’). What is meant by ’specific types of density variations’?
In the manuscript it is written " Traditional stratigraphy showed a highly detailed representation of specific types of density variations such as ice layers….". As such, the specific density variations are ice layers.

Line 14ff: same problem as above, what is meant by ’traditional stratigraphy’ and where is it shown? One could assume at one point, that the box cutter measurements are named as ’traditional stratigraphy’, however in lines 14-15 the box cutter is compared to ’traditional stratigraphy’... Because of this, it is hard to follow the argumentation given in this chapter.
See answer on comment Page 3592, Line 17.

Line 21ff: What is meant by ’introduced by the observer’?
See answer on comment on Abstract Line 18.

Line 24: Why not? At least this would improve the study and add some new aspects to this topic.
We agree and discuss the results of previous studies:

Page 3594 l.24: The effect of different stratigraphic representations on microwave emission modeling was unambiguously demonstrated. Durand 2011 estimated the error in retrieved snow depth from PM simulations up to 50\% due to neglecting stratigraphy. Rutter2014 showed that the bias of a three layer representation of a tundra snowpack with respect to microwave emission was half of the bias for a single layer representation. For the validation of snow cover models Monti et al., 2012 mentioned the higher number of simulated layers than observed ones to be critical.

Page 3595: Lines 5-7: strange sentence Lines 8-10: unclear sentence Line 17: What about sample 9 shown in figure 8; at 104 cm depth there seems to be an ice crust? With the resolution of the CT an ice layer should be detectable and with some image processing the density of this layer should be possible to estimate.

Unfortunately, the CT samples did not contain any ice crusts, as mentioned in line 17. The 3D reconstruction shows that the layer at 104 cm depth is not an ice crust but only a layer with higher density.

Page 3596 General: same comment on this issue as given above: “Please define /introduce somewhere your meaning of ’unresolved’ variation and how it is estimated why. For here and the discussion part it would be interesting to discuss this with regard to the variability within a ’layer’, variability due to thin layers you do not consider or the variability you ’loose’ by merging layers (section 2.2.3) with adjacent layers or variability due to ice crusts.”
See answer on comment Page 3591 Lines 23 – 28.

Table 1: chose a more common currency, why is this value added anyway, as it is not discussed in the paper?
We changed the currency to Euro. The paper focused only on the performance of the instruments independent of their costs. However, the cost can become a major practical limitation when it comes buy instrumentation, so that we decided to included it for informational reasons in the table.

Table 2: What is the depth of ’bottom’
"Bottom" refers to the snow-ground interface, the bottom of the snowpit.

Figure 3: add what is called ’stratigraghic method’ , ’traditional stratigraphy’ , and/or show the layers and the related ’mean densities’ at least as a scetch
See answer on comment Page 3592, Line 17.

Technical corrections: Page 3582, Line 23-25: redundant Page 3584, Line 21: n missing (known)
Changed

Page 3589, Lines 1-18: you have an extra cubic over each number
15^3 refers to 15x15x15, here 15 denotes the length of a square cube.

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

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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:

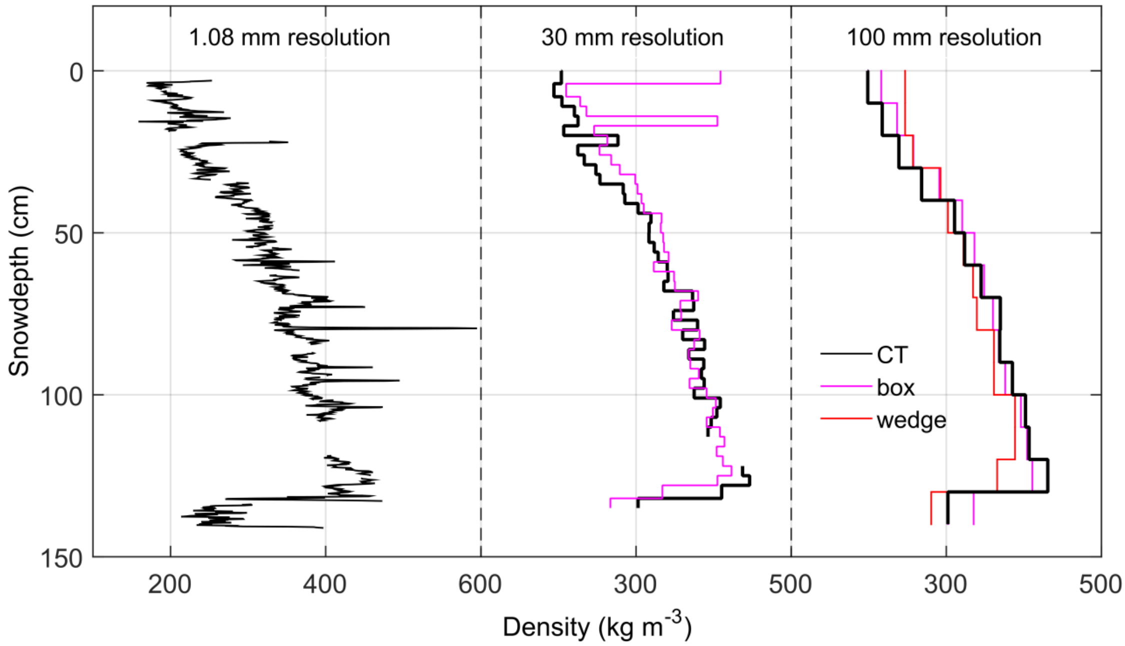

Figure 1: CT derived density (black), subsequently averaged to 30 mm (black, middle) and 100 mm (black, right) vertical resolution. For comparison, the box cutter densities are shown in raw resolution (magenta , middle) and averaged to 100 mm resolution (magenta, right). The wedge cutter density is as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

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

Anonymous Referee #2

Received and published: 23 September 2015

General Comments:
This paper compared the different snow density measurement methods with substantial experimental data (lab and field). It does not only clearly list the overestimation and underestimation of different results, but also explain the reasons of the difference in detail. The precise measurement of snow density is very important to understand the snow physical processes and few studies have focused on comparing the different methods before. This paper will be a very good reference to further investigate snow density measurement.
The paper is well written and is recommended to publish. Below are some minor revisions.

We highly appreciate the valuable comments by Referee #2, which will help to improve the manuscript.

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

Specific Comments:
3583-5: Parametrization of snow properties such as…… are lined to density. Snow mechanics is significantly related to snow density, which should not be ignored [Schneebeli and Johnson, 1998; Wang and Baker, 2013]

We agree and extended the following sentence:
P3583, l.4ff: The biological and photochemical activities of snow are related to snow density (Domine et al., 2008). Further, snow mechanical parameters are linked to density, (Schneebeli and Johnson, 1998; Wang and Baker, 2013) and the snowpack stability depends on vertical density variations (Schweizer et al., 2011).

3585-15: A stragraphic layer is a certain stratum with similar properties in snow layer. It is better to list several properties used to define a stragraphic layer. Is there any special calibration method to define the layer in the field?

We agree and added the relevant layer properties in brackets:
P3585, l.17ff.: A stratigraphic layer is a certain stratum with similar properties (e.g. microstructure, density, snow hardness, liquid water content, snow temperature, impurities) in the snowpack as defined in Fierz et al. (2009)

An objective calibration method to define a layer in the field cannot exist, as the determination of layer is subject to each field observer. However, the standard procedure for observers to define a layer (which is not a calibration method) is given in Fierz, 2009.

3586-10: For Gaussian filter used in CT measurement, how to define support and sigma, how do those parameters influence the measurement?

The Gaussian filter is used to smooth the image in order to get rid of noise before segmentation. The values of support and sigma are chosen by a trained operator, and are in line with the values used in other studies, e.g. Kerbrat, 2008. These parameters were kept constant for all measurements.

However, Hagnmuller2014 showed that for sigma in the range [0, 20] μm, density varies in the range [-8, +2]% with respect to the value obtained without smoothing (sigma = 0). Details of the CT processing will be provided in separate article, see also comment below.

3589-10: Different samples size was set with different scan resolution. The different resolution will influence the measured ice volume to some extent. Could you explain how the difference of 18 um and 10 um affect or not affect the results?

The resolution was sufficiently small in both cases that no significant influence on the measured densities has to be expected. This is supported by the fact that the variation for the different CT densities is very small (see error bars in figure 2).
In this paper, we focused just on the mean of the measurements – an in-depth analysis of the CT measured parameters with respect to scan resolution, segmentation, filtering, ect is planned as separate paper, which will be presented as well within this special section.

3589-25: The field measurement has any temperature record during the sample collection? It will be good to compare with lab measurements temperature (-10 OC) and also be useful to analyze the different density results among different methods.

The temperature range of the snow in the field was [-14; 0] °C. Snow temperature has no influence on gravimetric measurements.

3610-figure2: The figure is not very straightforward. What does the length of red line and blue line represent? Could you explain more about those details of the graph?

The red and blue lines are error bars indicating +- one standard deviation for the box cutter (red) and CT (blue) measurements. This is explained in the caption of the figure: "Error bars are +- one standard deviation, resulting from the three cutter measurements (red) and the three CT samples per block (blue)."

References:

Hagenmuller, P.: Modélisation du comportement mécanique de la neige à partir d'images microtomographiques, PHD Thesis, *University of Grenoble,* **2014**

Kerbrat, M.; Pinzer, B.; Huthwelker, T.; Gäggeler, H. W.; Ammann, M. & Schneebeli, M. Measuring the specific surface area of snow with X-ray tomography and gas adsorption: comparison and implications for surface smoothness *Atmospheric Chemistry and Physics,* **2008**, *8*, 1261-1275

Manuscript prepared for The Cryosphere Discuss.
with version 2014/07/29 7.12 Copernicus papers of the LATEX class copernicus.cls.
Date: 12 November 2015

Intercomparison of snow density measurements: bias, precision and ~~spatial~~ vertical resolution

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Abstract

Density is a fundamental property of porous media such as snow. A wide range of snow properties and physical processes are linked to density, but few studies have addressed the uncertainty in snow density measurements. No study has yet quantitatively considered the recent advances in snow measurement methods such as micro-computed tomography (~~CT)~~μCT) in alpine snow. During the MicroSnow Davos 2014 workshop different approaches to measure snow density were applied in a controlled laboratory environment and in the field. Overall, the agreement between μCT and gravimetric methods (density cutters) was 5 to 9 %, with a bias of -5 to 2 %, expressed as percentage of the mean μCT density. In the field, the density cutters tend to overestimate (1 to 6 %) densities below and underestimate (1 to 6 %) densities above a cutter-type dependent threshold that fell between 296 to 350 $\mathrm{kg\,m^{-3}}$, respectively~~, depending on the cutter type~~. Using the mean per layer of all measurement methods applied in the field (μCT, box, wedge and cylinder cutter) and ignoring ice layers, the variation of layer density between the methods was 2 to 5 % with a bias of -1 to 1 %. In general, our result suggests that snow densities measured by different methods agree within 9 %. However, the density profiles resolved by the measurement methods differed considerably. In particular, the millimeter scale density variations revealed by the high resolution μCT contrasted the thick layers with sharp boundaries introduced by the observer. In this respect, the unresolved variation, i.e. the density variation within a layer, which is lost by sampling with lower resolution or layer aggregation, is critical when snow density measurements are used as boundary or initial conditions in numerical simulations.

1 Introduction

Density is a fundamental property of porous media (**?**) such as snow. It plays a key role for a wide range of applications and almost all of them require density values. Snow hydrology (**?**) and climatology (**?**) based on microwave remote sensing require snow density, as it is directly linked to the relative permittivity of dry snow (**??**). Light transmission and the extinction coefficient of snow depend on density, and as such density affects the optical properties of snow (**??**). The biological and photochemical activities of snow are related to snow density (**?**)~~, and the~~. Further, snow mechanical parameters are linked to density (**??**)and snowpack stability depends on vertical density variations (**?**).

In addition, parametrization of snow physical properties such as permeability (**???**), thermal conductivity (**???**) are linked to density. Snow models like SNTHERM (**?**), CROCUS (**?**) and SNOWPACK (**?**) adopted density for the parametrizations of such properties as well, and models describing ventilation and air flow (**?**), isotopic content in polar snow (**??**) or drifting snow (**?**) also require density.

As important as density is, there are many properties, notably albedo (**??**), where higher order geometric descriptors like specific surface area (SSA) or anisotropy are necessary, as **?** showed for thermal conductivity. As such, a precise measurement of snow density and its variation in horizontal and vertical direction is of major importance to better understand and model a wide range of snow physical processes. Despite its relevance, few studies ~~focused so far on different~~ quantified so far the differences between the methods to measure snow density. Indeed several studies focused on firn and ice density, but those were mostly limited to firn and ice, i.e. density ranges (> 500 kg m^{-3}) larger than the one typically found in alpine snow (50 - 400 kg m^{-3}). **?** compared tube and box type density cutters and reported no significant difference between the two cutter types (~~even so he found a tendency that inexperienced users would~~ although there was a tendency for inexperienced users to overestimate the density of light snow and depth hoar by 6 and 4 %, respectively). **?** compared box, wedge and cylinder type density cutters and reported a variation of up to 11 % ~~within~~ between the three cutter types. Both studies compared only measurement methods of the same type, the direct gravimetric ~~measurements~~ measurement of snow samples with a well defined volume.

However, there are more methods available to measure snow density besides the gravimetric approach: stereology (**?**) determines density on the millimeter scale in vertical sections; micro-computed tomography (~~CT,~~ μCT, (**??**)) allows the reconstruction of the complete 3-D microstructure of small (centimeter) snow samples and calculation of the snow density with a resolution of up to 1 mm. In addition, high resolution penetrometry (SMP, **?**) was recently shown to be suited to derive snow density (**?**). Dielectric devices were developed to measure snow density, as the dielectric permittivity of dry snow is not strongly affected by other structural properties at certain frequencies (**????**). Neutron absorption (**??**) was in particular used to measure density inside a firn or ice bore hole. Another method in development is diffuse near-infrared transmission (NIT, **?**) that allows to derive the density of snow in macroscopic vertical sections with millimeter resolution in the horizontal and vertical direction.

Advantages of these approaches are substantial compared to the gravimetric measurement systems. The vertical resolution of the μCT, SMP and NIT in the millimeter range is clearly a significant improvement to the centimeter resolution of the gravimetric systems. The impact of measurement resolution was in particular demonstrated by **?**, who showed that the identification of stratigraphy is a function of a tool's sensitivity to vertical contrast. **?** in addition highlighted the smoothing of the density profile of an ice core for instruments with larger vertical measurement length. In terms of measurement time, the SMP is more time efficient as excavation of a snow pit is not necessary~~, therefore vertical~~. Vertical profiles of snow density through repeated measurements ~~allow~~ with the SMP allow the investigation of the ~~measurement of~~ spatial variability of snow density. **?** demonstrated the use of the SMP to reveal spatial density variations in an Antarctic snow profile. Although spatially varying density is a ~~know~~ known problem for a broad range of applications (e.g. **?**), an intercomparison of the ability of the different methods to resolve ~~spatial~~ vertical density variations was beyond the scope of ~~the Microsnow 2014 workshop.~~ this study.

Several studies have compared different methods to measure density, but were mostly limited to firn and ice, i.e. a density range ($>$ 500 kg m^{-3}) larger than the one typically found in alpine snow (50 - 350 kg m^{-3}). **?** compared firn densities measured by μCT with those measured by gamma-absorption for three sections of a firn core, each approx. 60 cm long. The authors report a deviation of less than 1 % for both methods in the density range from 640 - 733 kg m^{-3}, but also qualitatively higher values for the μCT in the range 460 - 550 kg m^{-3} and lower values for the μCT for densities above 733 kg m^{-3}. However, no results are reported for densities below 460 kg m^{-3}, which were in evidence at the workshop. **?** reported good agreement between CT and the hydrostatical method to determine the density of ice cores. **?** compared neutron probing, dielectric profiling, optical stratigraphy of the core and gravimetric measurements on an 11 m firn and ice core from Kongsvegen, Svalbard. The authors reported a smoothing of thin ice layers in particular for the neutron probe due too its large detector size of 13.5 cm, but also for the dielectric device due too its finite sampling volume, where the authors estimated a sensing length of approx. 4 cm. Other problems related to the gravimetric and dielectric measurements were mentioned with respect to collecting cores (accurate measurement of borehole diameter, depth registration, core breaks, poor core quality or melting of cores during shipping) or loose snow at the surface of the bore hole.

Studies which quantitatively focus on snow rather than firn or ice are rarely available. A study which compared density measured by CT and by weighing samples of sieved was presented by **?**. The authors reported qualitatively a good agreement between both methods for their 4 investigated samples, however, none of the three density cutters used in our study was used. Dielectric devices were also compared to gravimetric measurements. **?** found an RMSE of their snow probe of $\pm$ 50 kg m^{-3} compared to gravimetric measurements only in a qualitative way, whereas a RMSE of maximum 9 % (29.7 kg m^{-3}; lab data, box cutter to μCT) was found for our data.

Although the non-gravimetric approaches have advantages compared to the simple density cutters, there are major drawbacks to be mentioned. Besides cost and evaluation time, the technical simplicity, robustness, portability and ease of use of the density cutters remain attractive characteristics. However, for a wide range of applications, users need the higher resolution and efficiency of technologically more sophisticated measurement methods.

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.

This paper focuses on density data measured during the MicroSnow Davos workshop held in March 2014, i.e. ~~traditional stratigraphy,~~ different types of density cutters as well as μCT measurements. 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. SMP derived densities were discarded due to the use of a new version of the instrument, for which the calibration of **?** was not applicable. The main objective of this paper is to intercompare the available measurement methods (box cutter, wedge cutter, density per layer and μCT) and to assess the error and the variability between methods as well as their respective measurement resolution. The paper is organized as follows: Sect. 2 introduces the measurement methods and Sect. 2.1 the available data from the field and the laboratory. Section 3 summarizes the results, which are discussed in Sect. 4. Section 5 concludes our findings.

2 Methods

2.1 Samples and stratigraphic layers

All instruments provided density profiles with different vertical resolution. For clarity, we discriminate between *layer* and *sample*. A stratigraphic *layer* is a certain stratum with similar properties (e.g. microstructure, density, snow hardness, liquid water content, snow temperature, impurities) in the snowpack as defined in **?**. Layers thus represent a stratigraphic arrangement of the snowpack, as classified by an observer, with heights ranging from a few millimeters to several decimeters. However, the determination of layer boundaries in the snowpack ~~depend~~ depends on the observer and different observers will identify different layering. In addition to layers, a *sample* is a specific volume extracted from the snowpack in order to measure a certain property. Sampling can be performed independently of the stratigraphic layering and results in a constant vertical resolution, which is given by the vertical size of the sample; the resolution can be both enhanced or reduced by overlapping or spacing samples, respectively.

In this study, the cylinder cutter was used to measure the density per layer, after the layers were determined following **?**. All other method were used to measure the density per sample. As such, the cylinder cutter provided a density profile with varying vertical resolution, based on the thickness of the layers, contrasted by box and wedge cutter, as well as μCT, which were operated with constant vertical resolution. The high resolution μCT also belongs to the sample category, as it is operated with a constant vertical resolution.

2.2 Instruments

The following section gives, together with Table 1, an overview of the instruments and methods which were used to measure snow density during MicroSnow Davos workshop in 2014.

2.2.1 Micro-Computed Tomography

Micro-Computed Tomography (μCT) (**?**) allows the full 3-D microstructure of snow to be reconstructed. μCT measurements of snow result in a gray scale, which was filtered using a Gaussian filter ($\sigma = 1$ voxel, support $= 1$ voxel, following (**?**)) and then segmented into a binary image. The threshold for segmentation was constant for each sample and determined visually. After segmentation, the binary image contains the full microstructure and allows to derive the volume fraction ϕ_i of the snow sample, which is then related to the mass density ρ of snow by $\rho = \rho_\mathrm{ice}\,\phi_\mathrm{i}$ in terms of the density $\rho_\mathrm{ice} = 917\,\mathrm{kg m^{-3}}$ of ice.

2.2.2 Density cutters

Density cutters provide a gravimetric measurement, where the density is calculated by weighing a defined snow volume, which is extracted from the snow by using a cylinder, wedge or box type cutter. Figure 1 shows the three different types of cutters which were used during the workshop: (a) a $100\,\mathrm{cm^3}$ box cutter, $6\,\mathrm{cm} \times 3\,\mathrm{cm} \times 5.5\,\mathrm{cm}$ originating from the Institute of Low Temperature Science, Japan, now known as Taylor-LaChapelle density cutter, manufactured by snowhydro (http://www.snowhydro.com/products/column4.html) and WSL-SLF, (b) a $100\,\mathrm{cm^3}$ cylinder cutter, $3.72\,\mathrm{cm}$ inner diameter and $9.2\,\mathrm{cm}$ in height, constructed from an aluminum cylinder with one end sharpened to cut cleanly through the snow and (c) a 1000 cm^3 wedge cutter, 20 cm $\times$ 10 cm $\times$ 10 cm manufactured by snowmetrics (http://snowmetrics.com/shop/rip-1-cutter-1000-cc/). In addition, a cylinder of inner diameter 9.44 cm and length 55 cm (also vertically inserted into the snow) was used to determine the bulk density~~, but, due to its coarse resolution, was not further considered in this intercomparison~~.

2.2.3 Traditional stratigraphy and density per layer

After the stratigraphic arrangement of the snowpack was identified (see Sect. 2.1), density measurements were made within each layer. ~~A~~ The 100 cm^3 cylinder cutter inserted vertically down through the snow to a pre-placed crystal screen (see also **?**) was used to extract snow samples within stratigraphically defined layers. Samples were weighed using an ACCULAB Pocket Pro 250-B with a resolution and nominal accuracy of ± 0.1 g. Each density measurement is repeated twice and the average of both samples taken as either layer or sub-layer density. The density of layers, the height of which are less than the cylinder length, can be calculated using the ratio of the layer height and the cylinder length. However, in general layers thinner than about 2 cm are aggregated to adjacent upper or lower layers and cannot be resolved with ~~regards~~ regard to density except when the hardness of the layer itself or of an adjacent layer is greater than a hand hardness index of 3 (i.e. 1 finger, see **?**). In that case, a sample may be cut out of the snow and by measuring its dimensions and weight its density can be estimated. If the sample contains two layers, the softer one may then be gently scrapped away to allow for determining the density of the harder layer. Using both measurements yields the density of the softer layer. Such measurements are prone to large errors (≥ 10 %) even by a skilled observer. Three melt-freeze crusts or ice lenses were determined in this manner.

Conversely, where vertical layer thickness was larger than the cylinder length, seamless sampling down the layer was required to determine its mean density. In that case, densities at sub-layer scale may be obtained within a layer. Finally, depth averaging the layer densities over the full profile yields the Snow Water Equivalent (SWE) of the snowpack.

The density per layer or traditional stratigraphy is termed "cylinder cutter" hereafter, as only the cylinder cutter was used in this study to determine the density per layer. All other devices (box and wedge cutter, μCT) were operated without considering layering or stratigraphy of the snowpack, i.e. with constant vertical resolution (see also Section 2.1).

2.3 Comparing measurements with different vertical resolutions

Intercomparison of measurements with different vertical resolutions followed three different approaches:

a. The mean density over the full depth of a profile is related to the snow water equivalent (SWE) of the snowpack. However, unlike SWE, it can be compared independently of the actual snow depth. The comparison of this value showed whether the means of all methods were consistent with each other.

b. The high resolution μCT profile was averaged to match the vertical resolution of the three different cutters, as solely the μCT provided a high enough resolution (1.08 mm) to be averaged to the resolution of all other gravimetric methods. This allowed comparison of each method with its original resolution, without any averaging (besides the μCT which was used as a reference). A linear regression was then calculated for each comparison. The point of intersection between the linear regression line and the 1 : 1 line was defined as threshold between over- and under-estimation with respect to the μCT density.

c. To facilitate a more objective comparison where none of the instruments was set as reference, all measurements were depth-averaged to the same coarse vertical layer resolution of ~~traditional stratigraphy~~the cylinder cutter. Similar to **?**, the mean density per layer of all instruments was assumed to be the accepted reference value of the layer density, and all instruments were compared against this reference value. As the vertical resolution of the box and wedge type cutters did not ~~fit to~~ match the traditional layers, a depth weighted layer average was applied.

3 ~~Data collection~~

2.1 Data collection

2.2 ~~Lab measurements~~

2.1.1 Lab measurements

Thirteen snow blocks of ~~40 cm × 40~~40 cm x 40 cm in area and between 10 and 36 cm in height were ~~measured by the~~ 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 **?**. All blocks were measured using the μCT and the 100 cm^3 box type density cutter in the laboratory, at a constant air temperature of $-10\,^{\circ}\mathrm{C}$. μCT samples were taken from depths between 2.9 and 6.8 cm from the surface of the block. Up to three samples were taken per block~~:~~; two samples were extracted using a 35 mm diameter sample holder, and one using a 20 mm diameter sample holder. The samples in the 35 mm sample holder were scanned with a resolution of 0.018 mm, within the scanned volume of $15^3\ \mathrm{mm}^3$, whereas the samples in the 20 mm sample holder were scanned with a resolution of 0.010 mm within the scanned volume of $10^3\ \mathrm{mm}^3$; the representative cubic volume to derive density from μCT measurements is around $1.25^3\ \mathrm{mm}^3$ (**?**).

Continuous box cutter measurements were performed from the snow surface to the bottom of the snow block with a vertical resolution of 3 cm leading to a maximum of 8 measurements per block. For comparison with μCT densities, the upper most ~~3~~ three cutter measurements (0–9 cm snow depth) were analyzed, to avoid any misalignment with the location of the μCT measurements. An overview of the lab measurements is given in Table 2.

2.2 ~~Field measurements~~

2.1.1 Field measurements

The field site of the workshop was a tennis court in St. Moritz (46.4757° N, 9.8224° E) surrounded by forest, fenced, wind sheltered and flat, and as such showed a very homogeneous natural snowpack. For instance, wedge cutter measurements, where two profiles were performed within 20 cm horizontal distance, showed a mean difference of 7 $\mathrm{kg\,m^{-3}}$ or 2 % of the mean wedge cutter density. All density measurements were performed within less than 3 m horizontal distance. Field measurements were made on 11 and 12 March 2014 (Table 3). Warm temperatures caused surface melt after the measurements during the first day, leading to densification of the upper-most layers and to more pronounced crust and ice layers on the second day. Measurements were made between ~~05:00–10~~04:00–09:00 each day, while the snowpack was still dry.

To analyze a profile completely from top to bottom by means of μCT, five blocks of $20\,\mathrm{cm} \times 20\,\mathrm{cm} \times 30\,\mathrm{cm}$ were extracted from the snowpack on 11 March 2014. Snow blocks were quickly transported to the lab and each block was sampled using 35 mm diameter sample holders, leading to a total of 18 μCT samples for the whole vertical profile. Each sample was scanned with a resolution of 0.018 mm within a scanned volume of $10.8\,\mathrm{mm} \times 10.8\,\mathrm{mm} \times 2.16\,\mathrm{mm}$. Scans were performed with a vertical overlap of 50 %. The density was then resampled in a window of 1.08 mm depth. Field μCT samples were evaluated using the classic segmentation approach (Sect. 2.2.1). Three types of density cutters (Sect. 2.2.2) were used in the field. Measurements using the cylinder cutter (densities per layer) and wedge cutter were made on 11 March and box cutter measurements were made on 12 March. All measurements were performed within two meters horizontal distance.

3 Results

3.1 Lab results

Box cutter and μCT measurements agreed within 8 % (Fig. 2, Table 4). The box cutter measurements showed slightly higher densities, with a bias of 5 %, expressed as percentage of the mean of μCT density. The coefficient of determination R^2 was 0.90, significant at the 1 % level.

3.2 Field results

The density profiles of all instruments are shown in Fig. 3. Three types of comparisons (Sect. 2.3) were performed, all excluding ice layers~~, starting with the bulk density and the ratio of SWE to snow depth of each profile. The reference value was obtained~~ . For comparison a), the bulk densities derived from each method were compared. In addition a cylinder of inner diameter 9.44 cm and length 55 cm (Sect 2.2.3) was used, where the sampling was performed similarly to the mean density of a thick layer (see Sect. 2.2.3)~~but with a cylinder of inner diameter 9.44and length 55. Three sub-layers were sampled twice each~~ , yielding a ~~reference~~ bulk density of 325 kg m^{-3}. The bulk density calculated from the ~~traditional stratigraphy~~ cylinder cutter was 332 kg m^{-3}, from the box cutter 344 kg m^{-3}, from the wedge cutter 316 kg m^{-3}, and from the μCT 323 kg m^{-3}.

~~The high resolution~~ For comparison b), all methods were compared to the μCT density profile. For this reason, the high resolution μCT profile was averaged to match the vertical resolutions of the box and wedge type density cutters, as well as the layer heights of the traditional stratigraphic profile. Box and wedge cutter and densities per layer agreed with the μCT within 7, 9 and 5 % with a bias of -1, 2 and -1 %, respectively, expressed as percentage of the mean μCT density (Fig. 4, Table 4). Box cutter, wedge cutter and densities per layer (Sect. 2.2.3) overestimated low densities (4, 6 and 1 %, respectively) and underestimated high densities (2, 6 and 1 %, respectively) with respect to the μCT densities. The threshold to discriminate between low and high densities, and over- and under-estimation, was 350, 310 and 296 kg m^{-3} for box cutter, wedge cutter and densities by layer, respectively. Further details are given in Table 5.

~~Finally~~For comparison c) and to facilitate a more objective comparison, all measurements were averaged to ~~match the layer height of the traditional profile. The~~ the same vertical resolution, i.e. to match the traditional stratigraphic layers. The mean density per layer of all instruments was then set as reference. With respect to this reference, the different methods agreed within 2 to 5 ~~for the mean of all aggregated densities per layer~~ % (Fig. 5, Table 6)~~.~~ ~~The~~ , the bias was between ~~−1~~ -1 and 1 ~~, and $R^2 = 0.99$~~ % and R^2 = 0.99 for all instruments, significant at the 1 % level. When ice layers were not excluded, the different instruments agreed within 12 to 35 % with the mean layer density, with a bias of −10 to 12 % (Table 6).

3.3 Unresolved variation: density variation within a layer

Figure 6 shows the μCT density which was subsequently averaged to a comparable vertical resolution as the cutters. The high degree of detail in the μCT density profile vanishes in this case. Figure 7 shows the unresolved variation, i.e. the density variation ~~that is lost compared to the CT by sampling with coarser resolution~~ within a layer. It was calculated as standard deviation of the μCT density within a certain vertical distance. For instance, for the 100 cm^3 box cutter which had a vertical resolution of 3 cm, the μCT profile was averaged to 3 cm vertical resolution and the standard deviation for each 3 cm window was derived. The mean of all these standard deviations was then defined as unresolved variance (in this case for the 100 cm^3 box cutter with respect to the μCT density). The arrows in Figure 7 indicate the density variation which is lost when sampling with the box and wedge cutter (3 and 10 cm height, respectively). For the 100 cm^3 box cutter the unresolved variation is 17 ± 13 kg m^{-3} and for the 1000 cm^3 wedge cutter 23 ± 11 kg m^{-3}. If the μCT profile is averaged to match the layers of the traditional profile, the unresolved variation increases to 25 ± 16 kg m^{-3}.

4 Discussion

4.1 Laboratory results

The higher density values from the 100 cm^3 box cutter compared to the μCT (Fig. 2) corroborate the overestimation reported by **?** for this cutter type. However, **?** found this for light snow (i.e. where the snow was compacted) or depth hoar (i.e. where single crystals broke at the edge of the cutter and filled the void space around the cutter). Neither type of snow was very prominently present in the snow blocks used in the laboratory.

4.2 Field results

The bulk densities (Sect. 2.3, comparison a) ranged from 316 to 344 $kg\,m^{-3}$, with a coefficient of variation of 3 %. Assuming the mean of all bulk densities, which was 328 $kg\,m^{-3}$, as accepted reference bulk density value, the wedge cutter, the μCT and the bulk density from the 55 cm cylinder (as described in Sect. 3.2) underestimated the mean bulk density by 4, 3 and 1 %, respectively. The ~~traditional stratigraphy~~ cylinder cutter and the box cutter overestimated the mean bulk density by 2 and 5 %, respectively. The oversampling of the box cutter is partly attributed to the fact that the box cutter measurements were made on the second day, after melt occurred in the upper layers during the first day and a slight settling of the snowpack, with a decrease in snow height from 140 cm on the first day to 136 cm on the second day. Underestimation by the wedge cutter was already observed by **?**, due to displacement of the cutter as the cutting plate neared the thin leading edge of the wedge.

The intercomparison (Sect. 2.3, comparison b) shows similar results for the blocks in the laboratory as the measurements in the field. The cutter and μCT measurements agreed within 5 to 9 % (8 % in the lab) and showed a bias of -1 to 2 % (-4 % in the lab). However, the three measurement methods overestimated low densities (1 to 6 %) and underestimated high densities (1 to 6 %) with respect to the μCT density (Fig. 4 and Table 5). In contrast, lab data showed slightly higher cutter densities in general (Sect. 3.1) and no underestimation for the higher densities was found in the lab. This was caused by storing the blocks up to eight weeks at constant temperature. During the isothermal storage the thickness of the ice matrix increased at nearly constant pore space (**?**). The snow blocks were therefore less fragile, and it was easier to take intact, unbroken samples in the lab.

? also reported an overestimation of light snow densities by 6 % using different density cutters. The authors found this overestimation occurred with inexperienced users, which was not the case at the Davos workshop, where each instrument was operated by the same expert user. Thus the overestimation was attributed to the device itself, in particular to the compaction of light snow while inserting the cutter into the snowpack. The largest bias was found for the wedge cutter (6 %), which was attributed to the design of the cutter: because 75 % of the measured volume of the wedge cutter is in the lower half of the cutter (**?**), the increasing density with depth causes a systematic oversampling of denser snow. For higher densities, **?** reported also an overestimation. In contrast, higher densities were underestimated at the workshop, caused by loosing parts of the sample in very fragile facets and depth hoar, which appear in the lower part of the snowpack in the field. This underestimation is largest for the wedge cutter, due to the displacement of the cutter while closing it with the cutting plate (**?**).

The comparison of all instruments with the stratigraphic layers (Sect. 2.3, comparison c) compares the aggregated mean and variation. Ignoring ice lenses, the variation between μCT and cutter densities was within 2 to 5 % with a bias of -1 to 1 % (Table 5) with respect to the mean layer density. Those values are ~~naturally~~ lower than comparison (b), setting the μCT as reference. A higher variation ~~naturally~~ occurs in a comparison of single instruments with each other than with the mean of all instruments.

The effect of density variation in the range presented above is illustrated with respect to the calculation of thermal conductivity and snow stability. Assuming a density of 300 kg m^{-3} and a variation of 10% or 30 kg m^{-3}. The uncertainty in thermal conductivity based on the parametrization by **?** would be 21% (thermal conductivity at 300 kg m-3: 0.212 W $k^{-1}m^{-1}$; error 0.045 W $k^{-1}m^{-1}$), due to the almost quadratic dependence between thermal conductivity and density. However, the critical cut length, a measure for snow instability, has an almost linear dependence. It increases increases only by 9% (from 0.53 cm to 0.59 cm), if the density of the snow slab on top of the weak layer is increased by 10 % from 300 kg m^{-3} to 330 kg m^{-3} following the procedure described in **?** (slab height 60 cm, weak layer fracture energy 0.5 J m^{-2}, elastic modulus of the snow slab derived from **?**, slope angle 0°).

In addition possible uncertainties introduced by the μCT should be addressed. The main uncertainty of the μCT 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. **?**) 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 **?** 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 principle behind both techniques is the same. For the sensitivity of the threshold selection, **?** reported that the density of a snow sample (gravimetric density of 280 kg m^{-3}, μCT 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 is on the order of 5 %. In general, the strength of the μCT derived density is the precise information of the density evolution enabled by the sub-millimeter scale resolution of the μCT; 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 μCT segmentation process, whereas the bias values are more sensitive to the segmentation. Providing μCT error values would, however, require extensive re-segmentation of μCT samples, which is beyond the scope of this study.

4.2.1 Representation of the stratigraphy by the density measurements

As the stratigraphy is defined by several properties, density alone is always an insufficient parameter for the traditional stratigraphy. Here we demonstrate that the traditional stratigraphy often shows much sharper boundaries than the density measurements would indicate (Fig. 3). Traditional stratigraphy showed a highly detailed representation of specific types of density variations such as ice layers in the upper part of the profile, contrasted by a very coarse representation in the lower part; only one single layer was determined from 90 to 130 cm depth (Fig. 8). Nevertheless, three sub-layers could be identified within this layer, the density difference of which could not be explained by inter-sample variability (4.2 $\mathrm{kg\,m^{-3}}$ or 1.1 %). While the sub-layer densities of 382, 400, and 418 $\mathrm{kg\,m^{-3}}$ from top to bottom reproduced the trend of both box and wedge cutter measurements, the ~~traditional stratigraphy~~ cylinder cutter did not represent ~~the density variationsmeasured by the box cutter and the wedge cutter within this layer~~these variations. Further, the wedge cutter did not represent the variations measured by the box cutter, and the box cutter did not represent the variations measured by the μCT. Figure 8 illustrates this fact: on the one hand, layer boundaries, which were defined following the traditional stratigraphic approach (**?**), appeared less distinct in the μCT, and on the other hand, the higher resolution methods resolved a high degree of variability within a layer. We would like to point out here that sharp boundaries, as introduced by the observer, compared to the very smooth ~~course~~ development of the high resolution measurements, may introduce a significant bias in numerical simulations, when observed snow profiles are used as initial conditions. The effect of different stratigraphic representations on microwave emission modeling ~~and validation of snow cover models~~ was unambiguously demonstrated. ~~Although we can not quantify this problem here in more detail, we think that more weight should be given to this problem in the measurements and simulation of snowpacks~~**?** estimated the error in retrieved snow depth from passive microwave simulations up to 50 % due to neglecting stratigraphy. **?** showed that the bias of a three layer representation of a tundra snowpack with respect to microwave emission was half of the bias for a single layer representation. For the validation of snow cover models, ? mentioned the higher number of simulated layers than observed ones to be critical.

The fact that the higher resolution methods resolved a higher degree of density variation is closely related to the measurement volume of the different instruments. For instance, the measurement volume of the μCT (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 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 μCT, and is also true for the lower variability of the 1000 cm^3 wedge cutter compared to the box cutter. As the measurement volume of the μCT was sufficiently large to be representative (1.25^3 mm^3 = 1.95 mm^3, ?, Section 2.1.1), these high frequency density fluctuations are not an artefact of a small measurement volume.

4.2.2 Ice layers

The spatially discontinuous near-surface ice layers decreased the agreement between different field measurements (Table 5)~~; this applies only for the field results)~~. Box and wedge cutters did not fully resolve the ice layers in the field, in contrast to the stratigraphic method.

Ice layer densities were determined ~~from weighing a carefully~~ by careful measurement of an extracted ice layer~~sample with a known volume, whereas when using both~~. Uncertainties remain in measurements of ice layer densities using this technique, largely due to the triaxial volume measurement of an irregular-shaped ice sample in combination with the precision of the in-situ mass measurement ($\pm$ 0.1g) relative to the mass of the sample. When using box and wedge ~~cutters~~cutter, ice layers represented only a small part of the sampled snow volume. The box cutter showed two distinct density peaks, but with values of 409 and 405 kg m^{-3} these measurements were lower than the layer densities of 567 and 760 kg m^{-3} for the upper and lower ice layers, respectively (Fig. 3). In contrast, the wedge cutter did not show any significant density peak. The perceived lack of ice lenses in the 1000 cm^3 wedge cutter is due to them representing a much smaller proportion of the sampled volume than ~~other measurements~~the other methods. However, uncertainties in measurements of ice layer densities are poorly constrained. Previous measurements have produced a wide range of densities values, such as 630 to 950 $\mathrm{kg\,m^{-3}}$ in the Canadian Arctic (**?**) and 400 to 800 $\mathrm{kg\,m^{-3}}$ in seasonal snow on the Greenland ice sheet (**?**). Unfortunately, no ice layer was present in the ~~sample~~ samples measured by the ~~CT~~μCT. The large variability in ice layer density 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 (**?**).

In addition, ice layers evolved during the two field days. On the first day, the ice layers were very heterogeneous and horizontally discontinuous. After that, warm temperatures and melt in the upper most layers lead to more pronounced and continuous ice layers on the second day. The SMP provided evidence for the thickening of the ice layers. To avoid breaking the sensor, the SMP immediately stops measuring once a force threshold of 41 N is reached, which means that the layer is too hard for the instrument to penetrate. The SMP force threshold of 41 N was reached for 31 % (4 out of 13) and 56 % (13 out of 23) of the measurements on the first and second day, respectively.

For the μCT measurements, the blocks were extracted on the first day when ice layers were less pronounced. No ice layers were contained in those blocks, as the μCT data showed no distinct ice layers. Density peaks, however, were found in the lower part of the profile, e.g. at 80 cm snow depth (Fig. 3). These density peaks correspond to melt-freeze crusts consisting of larger aggregated structures~~.~~.

4.2.3 Unresolved variation

The unresolved variation represents the density variation within a layer. This variation is not captured by the ~~measurements~~ measurement methods with coarser vertical resolution and cannot be reconstructed. The relative unresolved variations were up to 7.7 % (for averaging the μCT densities to match the traditional layers), with a standard deviation of 5.0 %, expressed as percentage of the mean μCT density. On average an unresolved density variation of 7.7 % seems tolerable, but it becomes a critical variable, as the loss of small density variations will propagate through all parametrization which are based on density, such as permeability (e.g. **?**) or thermal conductivity (e.g. **?**). Figure 8b illustrates this: the high resolution density profile of μCT sample No. 9 ~~looses~~ loses all of its detail if measured with the vertical resolution of the box cutter. The temperature gradient inside the snowpack depends on variations of the thermal conductivity caused by variations in density (**???**). ~~Loosing~~ Losing density variation means losing local maxima and minima in temperature gradient, and therefore missing the driver for potential weak layer formation. **?** also mentioned the limited resolution of a traditional snow profile as a major drawback for the characterization of weak layers. Density variations are known to have a large influence on mechanical properties (**?**) and in addition on microwave signatures as they act as interfaces for wave reflection (**?**).

5 Conclusions

This paper compared the snow densities measured by different methods during the MicroSnow Davos 2014 workshop. In general, the agreement between ~~traditional stratigraphy, density cutters , and~~ density cutters and μCT measurements was 5 to 9 %, with a bias of -5 to 2 %, expressed as percentage of the mean μCT density. Box cutter and μCT measurements in the lab agreed within 8 %, where the box cutter showed a slight overestimation of 5 % (Fig. 2, Table 4). In the field, the density cutters tended to overestimate low densities (1 to 6 %) and underestimate high densities (1 to 6 %) with respect to the μCT densities, with a threshold for over- and ~~under-estimation~~ underestimation of 296 and 350 $\mathrm{kg\,m^{-3}}$ depending on the cutter type (Fig. 4, Table 5). Using the mean of all measurement methods applied in the field (μCT, box~~and wedge cutter, density per layer~~, wedge and cylinder cutter) and ignoring ice layers, the variation of layer density between the methods was 2 to 5 % with a bias of -1 to 1 %, expressed as percentage of the mean layer density (Fig. 5, Table 6). 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 μCT.

However, our results are valid if ice layers were not considered, as the methods differed significantly in their ability to resolve the density of thin ice layers. Due to calibration issues, the density derived from the SnowMicroPen (SMP) had to be discarded for now from the intercomparison.

The density profiles revealed by the measurement methods differed considerably (Fig. 8). Traditional layers are defined by an observer with respect to changes in snow properties, whereas the μCT provides a much higher vertical resolution. In particular the millimeter scale density variations revealed by the μCT contrasted the thick layers with sharp boundaries introduced by the observer. This leads to much higher resolved density profiles to initiate or validate snow cover and microwave models. In this regard, the unresolved variation (Fig. 7), i.e. the density variation within a layer lost during the aggregation into thicker layers or during sampling with coarse vertical resolution, is a critical variable, as density variations are of key importance for snow metamorphism, snowpack stability or scattering of electromagnetic waves. In general, our results suggest that snow densities measured by different methods agree within 9 %.

Acknowledgements. The authors want to thank all MicroSnow Davos 2014 organizers and instrument operators. M. Proksch was supported by ESA's Networking/Partnering Initiative NPI No. 235-2012.

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Table 1. Vertical resolution and measurement volume of the different methods. Measurement time in the field is per meter snow depth and includes digging of a snow pit, if necessary.

Method	Vertical resolution (mm)	Volume (cm^3)	Measurement time field	Post processing	Cost/instrument (Euro)
μCT	0.018	0.1	1 h	1 h–1 week	300 k
Wedge cutter	100[a]	1000	1 h	–	50
Box cutter	30[a]	100	1.5 h	–	50
Cylinder cutter	37.2 / 92.0[a]	100	1.5 h	15 min[b]	50

[a] Enhanced/reduced by letting samples overlap or spacing them, Sect. 2.1.
[b] If measurements are taken per layer, Sect. 2.1.

Table 2. Depth below surface and number of measurements/samples per block for the instruments used in the lab.

Method	Depth below surface (cm)	Number of samples per block
μCT	2.9–6.8	2
Box cutter	0–bottom	2–8

Table 3. Date of measurement and number of measurements/samples for the instruments used in the field.

Method	Date	Number of measurements/samples
μCT	11 Mar 2014	18 samples
Box cutter	12 Mar 2014	44 samples
Wedge cutter	11 Mar 2014	28 samples
Cylinder cutter	11 Mar 2014	15 samples

Table 4. Statistics for the comparison of cutter and μCT measurements in the lab (Fig. 2) and in the field (Fig. 4). Bias/RMSE are expressed in % of the mean μCT density. Significant agreement (p val < 0.01) is indicated by bold numbers.

	Lab			Field		
Instrument	Bias (%)	RMSE (%)	R^2 (–)	Bias (%)	RMSE (%)	R^2 (–)
Box cutter	−5	8	**0.90**	−1	7	**0.90**
Wedge cutter				2	9	**0.93**
Cylinder cutter				−1	5	**0.95**

Table 5. Slope, intercept and R^2 for the linear fit of the cutter densities to the μCT densities averaged to the resolutions of the respective cutter shown in Fig. 4. Significance (p val < 0.01) for the slope and the intercept is indicated by bold numbers.

Instrument	Slope (–)	Intercept ($\mathrm{kg\,m^{-3}}$)	R^2 (–)	threshold over-/ underestimation ($\mathrm{kg\,m^{-3}}$)	overestimation low densities (%)	underestimation high densities (%)
Box cutter	**0.79**	**71**	0.89	350	4	2
Wedge cutter	**0.66**	**106**	0.93	310	6	6
Cylinder cutter	0.90	**31**	0.95	296	1	1

Table 6. Statistics for the comparison of the field measurements to the mean layer densities (Fig. 5), expressed in % of the mean layer densities. Significant agreement (p val < 0.01) is indicated by bold numbers.

	No ice layers			With ice layers		
Instrument	Bias (%)	RMSE (%)	R^2 (–)	Bias (%)	RMSE (%)	R^2 (–)
μCT	-1	4	**0.99**	-10	18	0.44
Box cutter	1	2	**0.99**	7	12	**0.76**
Wedge cutter	1	5	**0.99**	-9	20	0.24
Cylinder cutter	-1	3	**0.99**	12	35	**0.71**

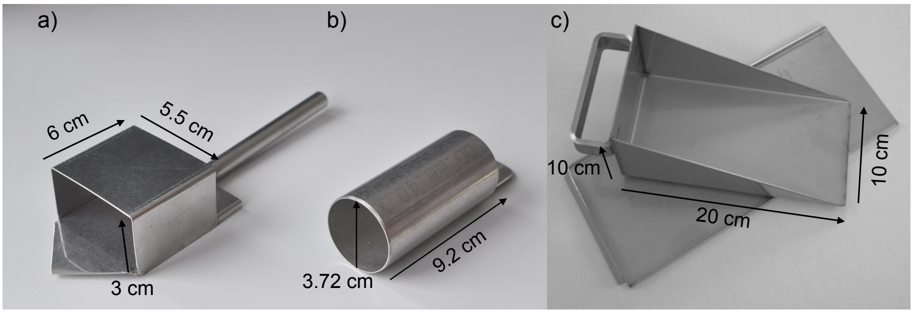

Figure 1. Density cutters used at the MicroSnow workshop: **(a)** box, **(b)** cylinder, and **(c)** wedge (from http://snowmetrics.com/shop/rip-1-cutter-1000-cc/).

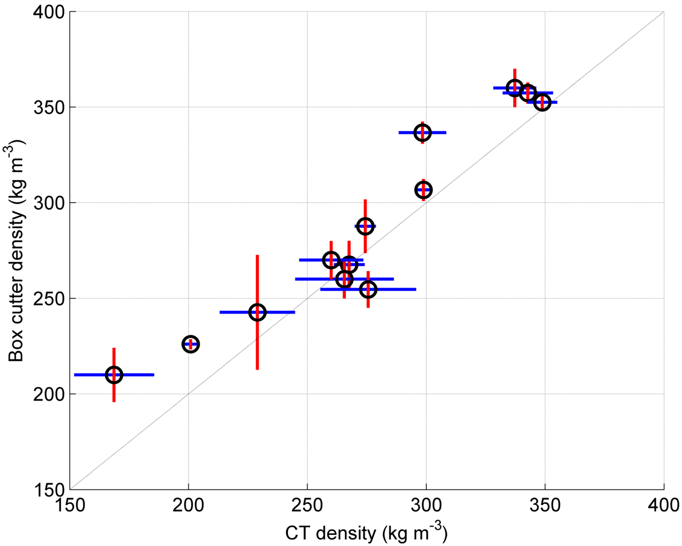

Figure 2. The top three cutter measurements (0–9 cm) in each of 13 blocks were averaged to best match the location of the μCT samples. Error bars are $\pm$ one standard deviation, resulting from these three cutter measurements (red) and the three μCT samples per block (blue).

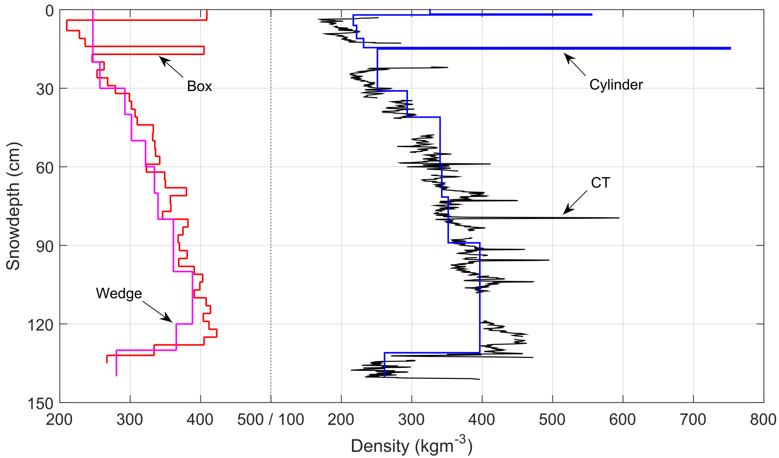

Figure 3. Density profile measured by different ~~measurement~~ methods. Two methods each are displayed separately for better visibility. Note that the cylinder profile shows the density with respect to the stratigraphic layers.

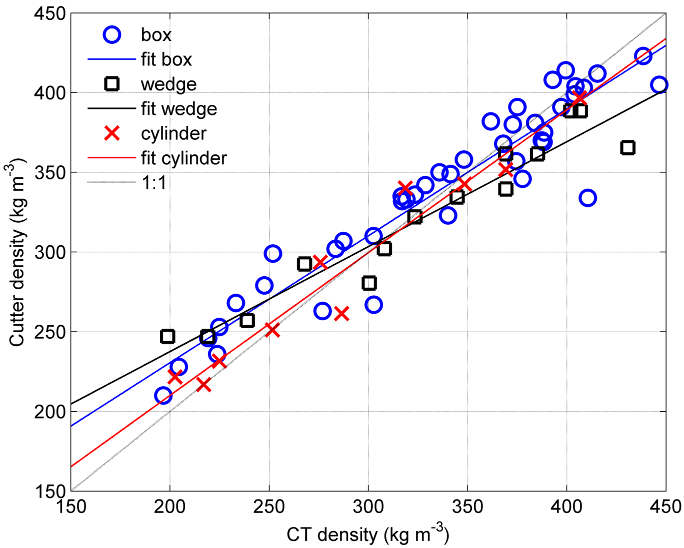

Figure 4. Cutter density vs. μCT density averaged to the resolution of the cutters (symbols). In addition a linear fit for each comparison is shown (lines). Fit statistics are given in Table 5.

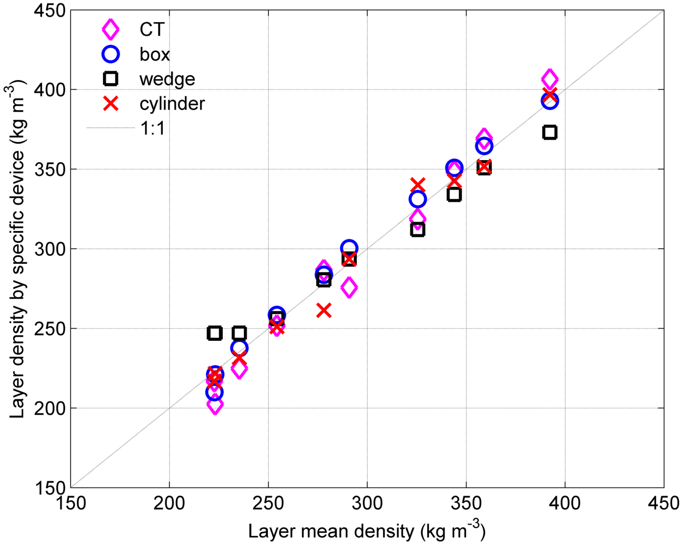

Figure 5. Different measurement methods averaged to match the traditional layers, vs. the mean layer density. Mean layer densities are the average of all layer densities of the different methods. Statistics are given in Table 6.

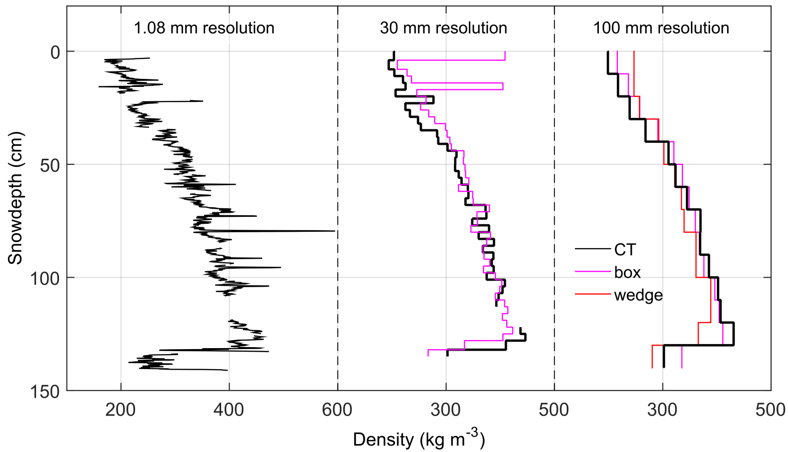

Figure 6. μCT derived density (black), subsequently averaged to ~~the~~ 30 mm (black, middle) and 100 mm (black, right) vertical resolution~~of~~. For comparison, the ~~100~~box cutter densities are shown in raw resolution (~~red~~magenta, middle) and ~~the 1000cutter~~ averaged to 100 mm resolution (magenta, right). The wedge cutter density is as well shown in raw resolution (red, right).

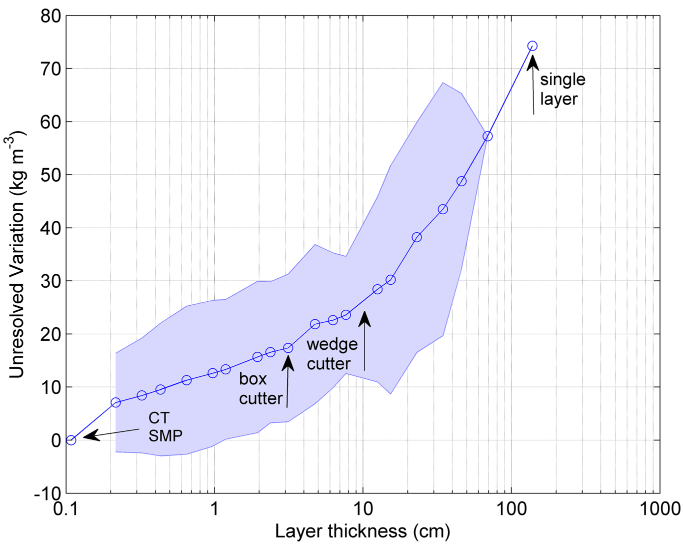

Figure 7. Unresolved variation of μCT profile vertically averaged to larger layer thickness, with the vertical resolution of box cutter (3 cm), wedge cutter (10 cm) and a single layer profile indicated. The shaded area indicates $\pm$ one standard deviation.

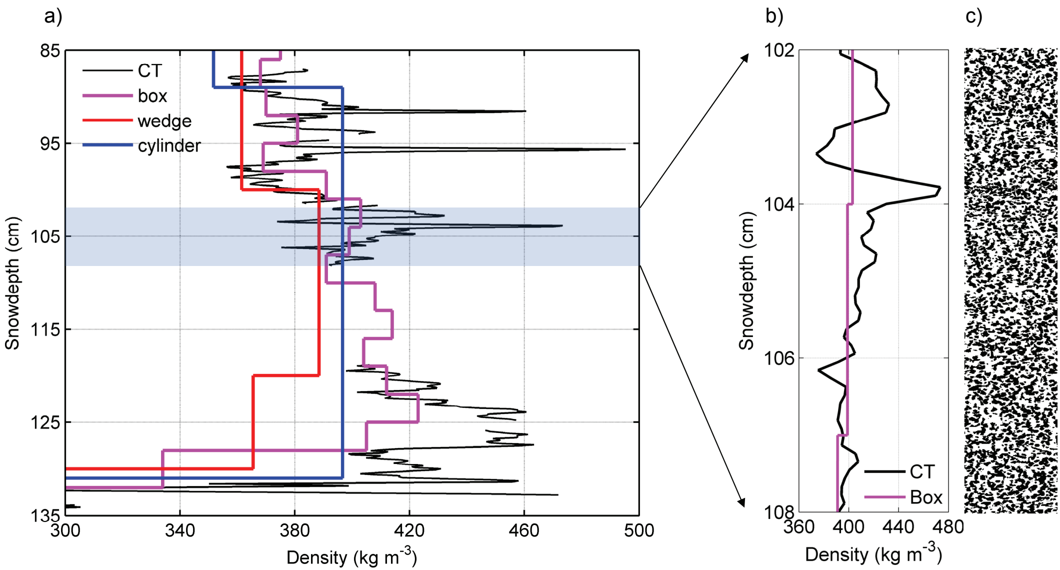

Figure 8. Close-up of the lower part of the density profile measured by the density cutters and μCT **(a)**. The shaded area indicates the location of the μCT sample No. 9. Density profile **(b)** and 2-D reconstruction **(c)** of μCT sample No. 9.