"Ground-penetrating radar reveals ice thickness and undisturbed englacial layers at Kilimanjaro's Northern Ice Field" by Pascal Bohleber et al.

- Response to reviews and revised manuscript -

**General Remarks:** All line numbers in "Changes to manuscript" refer to the revised version. Changes in the corresponding pdf of the revised manuscript are highlighted in red.

Author's responses to the referee's comments are in blue.

All new references used in this text here can be found in the revised manuscript.

**Response to anonymous referee #2 posted on Sept. 19th 2016**

This manuscript presents the GPR data collected on Kilimanjaro's Northern Ice Field for the first time and estimate the total ice volume as of September 2015. Also, the integrity of internal reflecting horizons for the majority of the NIF is clearly established here, opening possibilities for future studies such as extending the depth-age relationship obtained from ice cores to reconstruct the historical change of the NIF. The manuscript is well structured and concise. I have only a few minor comments on uncertainty analysis, discussion of results in light of previous studies, editorial comments to clarify the writing, and the size of figures and some text embedded in them. I recommend this manuscript for publication in The Cryosphere after a minor revision.

Thank you very much for your review and helpful suggestions!

**Specific comments**

**Referee comment**

Section 2.3: There is no discussion about the horizontal uncertainty that could arise from the determination of from where the pulse is returned, for example. Please add some discussion of the horizontal uncertainty.
This point was noted by both referees and we took care to add information regarding the horizontal resolution in section 2.3 "uncertainty considerations".

Changes to manuscript:

- Page 5, Line 6 ff.: "Shot distances in data acquisition..." 

Referee comment

P4, L27-28: I’m not totally clear on how you calculated the combined uncertainties here. These uncertainty components are independent of each other so I think the proper way to combine the uncertainties in this case is by the root sum of squares. So for the IRH and the bedrock reflection at 200 MHz, they would be $\sqrt{2.5^2+4^2}=4.7$ ns and $\sqrt{2.5^2+8^2}=8.4$ ns, respectively.

Thank you for pointing this out. The values of 6 and 9 ns were erroneously reported for 200 MHz but belong to 100 MHz. We have corrected the text accordingly and changed the values where needed (we rounded to full ns and m, respectively).

Changes to manuscript:

- Page 4, Lines 25-26: Changed values and explicitly noted that the root sum of squares was used.

Referee comment

P5, L4-5: The total uncertainties for the IRH and bedrock depths would change depending on how you combine different uncertainty components as per the comment above. Please check the final number and change as needed.

Thank you, we have corrected the values, see comment above.
Changes to manuscript:

- Page 5, Lines 2-3: Changed values accordingly.

Referee comment

P5, L12-13: It is difficult to assess if 0.3 m is appropriate for the uncertainty of the rope length because there is no explanation as to how knots would lead to this number. In addition, I would expect some stretching of the rope unless you specifically chose a static rope with minimal stretching.

We made an effort to estimate at first order how much the length of the rope changes based on the knots. We agree that some rope stretching can be expected and have now clarified that we regard our estimate as a lower limit of uncertainty only.

Changes to manuscript:

- Page 5, Lines 17 ff.: "To derive a lower estimate of uncertainty..."

Referee comment

P5, L13-14: Why could you neglect potential effects from the image stitching and deskewing routines? Are there any references to justify this?

We thank the referee for pointing this out and have now included discussing the uncertainty of image stitching and deskewing routines. Although we are unable to come up with a quantified estimate we believe this contribution is negligible and have add references to justify this.

Changes to manuscript:

- Page 5, Line 17 ff.: "To derive a lower estimate of uncertainty, we assumed 0.3 m uncertainty in the length of the rope at 16 m (resulting from knots tied into the rope) and neglected stretching of the rope. This translates to
Further uncertainty is introduced by the image stitching and deskewing routines. The software estimates the internal and external camera orientation from the image data alone. Hence, the quality of the results strongly depends on the camera positions, image overlap and the object shape (Agisoft2016). In comparable applications, related errors in the millimeter and low centimeter range were found (e.g., Thoeni 2014, Robleda 2015). In our case they cannot be quantified and were assumed to be negligible."

Referee comment

P7, L1: What is the significance of the “large bedrock inclination”? Is this related to one of the components of the uncertainty, namely losing track of coherent phase? Otherwise, this whole sentence seems to imply that there was in fact a component of uncertainty other than the two you discussed in section 2.3 but you got away with considering only the two by chance. Please clarify.

Keeping track of a coherent phase can be more difficult over an inclined bed. Although most regions over NIF feature an almost planar bed (except over the crater rim) based on the referee's comment we feel it is necessary to explicitly refer to an additional effect: In regions with a large bed slope, a full 3-dimensional migration is superior but requires a sophisticated survey setup. With a 2-dimensional conventional migration ice thickness uncertainty is ~16% if the bed is strongly inclined (Moran and others, 2000). We thank the referee for pointing this out and have added specific reference to the above fact in section 2.3 and also changed the wording regarding P7 L1.

Changes to manuscript:

- Page 5, Lines 3-5: "In addition, in case of a strong..."
• Page 7, Lines 11-13: "Since neither NIF2 nor NIF3 feature large surface/bed inclination (migration issues) nor pronounced presence of meltwater (Figure 4) the uncertainty in GPR ice thickness seems to be well represented by our previous considerations."

• We also decided against using the word "bedrock" to refer to the subglacial substrate, which at NIF consists to a large degree of sand. Accordingly we have replaced "bedrock" with simply "bed".

**Referee comment**

P7, L14-16: I don’t agree that the observed mismatch could be attributed to the combined uncertainty. My interpretation of this statement is that your analysis of the combined uncertainty is wrong, which would require you to revise section 2.3. I don’t think that is the case. It seems as though the mismatch could be largely due to the spatial and possibly the temporal variability (?) of the bottom melting caused by fumarole activities, which are not well documented so you are not able to quantify it, and a potential uncertainty in the core length.

Based on the referee’s comment we realize that a different term should have been used than "observed mismatch", since there is no actual mismatch because the difference between ice loss values based on the GPR-ice core comparison and ablation stake measurements is in fact within the estimated range of uncertainties. Hence we agree with the referee that this is not an issue of uncertainty considerations here. In fact, what we intend to discuss is the systematic offset (although within uncertainty) to larger ice loss derived from the GPR-ice core comparison. In this context, basal melting and uncertainty in ice core length could contribute to this offset but we are unable to quantify them. What we have tried to say is that, in view of the uncertainties involved, we cannot go as far as interpreting this result as evidence for basal melting. We have modified the wording of the respective paragraph to clarify.
Changes to manuscript:

- Page 7, Lines 24-27: "In the absence of GPR evidence for basal fumarole activity and lacking quantitative information on basal melting, it seems more likely to attribute the observed systematic difference in the two ice loss estimates to the uncertainties involved in GPR and ablation stake measurements, combined with spatial variability of ablation rate and, to a minor extent, a potential discrepancy in the ice core length."

Referee comment

P8, L29-30: The discrepancy between your finding and the interpretation of Thompson et al. is significant. This warrants further discussions, at least further explain what Thompson et al.’s interpretation is and more details on how your result questions their interpretation.

We have now added additional text in the discussion to clarify on the significance of our findings with respect to the study by Thompson et al. (2002). We also decided to move the discussion of the large dust layer in the NIF3 core from Page 8 Lines 27-29 to this section, since it illustrates the point being made here.

Changes to manuscript:

- Changed paragraph starting on page 9, line 27: "With respect to the two ice core drilling sites..."

Technical corrections

These are very helpful and we have integrated all of the suggested corrections in the revised manuscript if not noted otherwise.
The use of the word “employed” is awkward. Change to “GPR has also been used...”

Add “e.g.,” to the references because these might not be the only studies that used GPR on tropical glaciers.

“To our knowledge the study presented here...” should be “to our knowledge this is the first time a GPR was used at Kilimanjaro’s NIF.”

The sentence “Although not further discussed...” seems unnecessary if not discussed at all in this manuscript. We feel it is appropriate to keep this sentence, since it refers to the main reason why we extended our GPR profiles to precisely this position at the vertical wall. We also come back to this in the Conclusions.

The sentence should be changed to “We estimate the total ice volume presently remaining at NIF by spatially extrapolating the GPR-derived ice thickness.”

“We estimate the total ice volume presently remaining at NIF by spatially extrapolating the GPR-derived ice thickness.”

Change “while” to “and”.

You’ve defined the abbreviation already so use “IRH”.

Change “as well as” to “and”.

Change “employed” to “used”.

Change “Technical settings of the setups” to “Details of the technical settings”.

“Technical settings of the setups” to “Details of the technical settings”.

Change “The spatial coverage that could be achieved was constrained by” to “The spatial extent of the GPR survey was constrained by ”.

Change “employ” to “use”.
P3, L27: Change “800 MHz profiles were not found to provide” to “800 MHz profiles did not provide”.

P4, L5: I think “Post-processing of GPR data” reads better as a subsection heading.

P4, L6: “We used the standard routines to process the GPR data including ...”

P4, L9-11: The use of “while” in the sentence “We employed ...” is not appropriate so the sentence should be divided, with the first sentence ending after “5 traces” and the second sentence starting with “For the electromagnetic ...”.

P4, L20: “Major contributions to the uncertainty in depth...”

P4, L21: Change “connected to” to “related to”.

P4, L25: Change “loosing” to “losing”.

P4, L26-27: You don’t need the parenthesis.

P4, L29: Delete “relative difference”.

P5, L8-9: Change “A 200 MHz CO-profile running towards the vertical wall extends to about one meter distance from the cliff” to “The 200 MHz CO-profile running towards the ice cliff ends within one meter from the cliff”.

P5, L9: Change “The cliff height of the wall” to “The height of the ice cliff”.

P5, L16: “In order to derive distributed ice thickness” to “To derive the ice-thickness distribution over the NIF”, and remove the later “over the NIF”.
P5, L16-17: Change “the previously developed approach by Fischer (2009), in interpolating” to “the approached previously developed by Fischer (2009), first interpolating”.

P5, L21: “very high resolution” is subjective so remove “very”.

P5, L22: No hyphen is needed for surface altitude.

P5, L33: Change “We derived an estimate” to “We estimated”.

P6, L3: Change “In order to estimate the expected loss on surface area” to “To estimate the surface area lost”.

P6, L14: Change “comprises” to “includes”.

P6, L18: Change “reflectors from internal layers” to “internal reflectors”.

P6, L19: Remove “very”.

P6, L28: You don’t need parentheses around the description of locations.

P6, L30: Delete “, however”.

P7, L4: Remove “value”.

P7, L13: “more or less” is ambiguous so remove.

P7, L17: Change “The interpolation of ice thickness” to “The interpolated ice thickness distribution”.

P7, L28: Change “Considering additionally” to “In addition, considering”.


P7, L28-29: Change “regard the values derived from this method with caution only” to “interpret the ice thickness derived from this method with caution.”

P8, L27: Change “large layer” to “thick layer”.

P8, L29: Change “interpret” to “interpreted”.

P8, L29: Remove “in depth”.

P8, L30-32: It isn’t totally clear whether “these findings” refer to your findings or those of Thompson et al. (I assume the former). Rewrite to clarify this.

P8, L30: Change “it seems worth” to “it is”.

P9, L7: Change “near-bedrock ice parts” to “ice just above the bedrock”.

P9, L28-29: Briefly explain why this finding is relevant for new ice core drilling and energy and mass balance modeling.

*We have modified the sentence and added an additional reference.*

P9, L31: Change “estimation” to “estimate”.

P10, L2: Change “can be” to “were”.

This is something you could sort out with TC’s but I think figures are a little too small in general. Please pay particular attention to the size of texts embedded in each figures and make sure they are legible without blowing up on a computer screen. Labels of site and profile names in Figure 1, and legends in Figures 5 and 7 are particularly difficult to read.

*We have taken care of the suggested changes and also generally tried to improve the readability of the figures by increasing font size etc.*
Figures 1, 2 and 9: Label the top and bottom rows as (a) and (b), respectively, and refer to them accordingly in captions.