

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

3 - Response to reviews and revised manuscript -  
4

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

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

9 *All new references used in this text here can be found in the revised manuscript.*  
10

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

12 This manuscript presents the GPR data collected on Kilimanjaro's Northern Ice Field  
13 for the first time and estimate the total ice volume as of September 2015. Also, the  
14 integrity of internal reflecting horizons for the majority of the NIF is clearly established  
15 here, opening possibilities for future studies such as extending the depth-age  
16 relationship obtained from ice cores to reconstruct the historical change of the NIF. The  
17 manuscript is well structured and concise. I have only a few minor comments on  
18 uncertainty analysis, discussion of results in light of previous studies, editorial  
19 comments to clarify the writing, and the size of figures and some text embedded in  
20 them. I recommend this manuscript for publication in The Cryosphere after a minor  
21 revision.  
22

23 [Thank you very much for your review and helpful suggestions!](#)  
24  
25

26 **Specific comments**  
27

28 **Referee comment**

29 Section 2.3: There is no discussion about the horizontal uncertainty that could arise  
30 from the determination of from where the pulse is returned, for example. Please add  
31 some discussion of the horizontal uncertainty.

32

33 This point was noted by both referees and we took care to add information  
34 regarding the horizontal resolution in section 2.3 "uncertainty considerations".

35

36 **Changes to manuscript:**

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

38

39

40 **Referee comment**

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

46

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

50

51 **Changes to manuscript:**

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

54

55

56 **Referee comment**

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

60

61 Thank you, we have corrected the values, see comment above.

62

63 **Changes to manuscript:**

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

65

66

67 **Referee comment**

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

72

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

76

77 **Changes to manuscript:**

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

79

80

81 **Referee comment**

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

84

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

89

90 **Changes to manuscript:**

- 91 • Page 5, Line 17 ff.: "To derive a lower estimate of uncertainty, we assumed  
92 0.3 m uncertainty in the length of the rope at 16 m (resulting from knots tied  
93 into the rope) and neglected stretching of the rope. This translates to

94 (38.0+/-0.7) m. Further uncertainty is introduced by the image stitching and  
95 deskewing routines. The software estimates the internal and external camera  
96 orientation from the image data alone. Hence, the quality of the results  
97 strongly depends on the camera positions, image overlap and the object  
98 shape (Agisoft2016). In comparable applications, related errors in the  
99 millimeter and low centimeter range were found (e.g., Thoeni 2014, Robleda  
100 2015). In our case they cannot be quantified and were assumed to be  
101 negligible."

102  
103

#### 104 **Referee comment**

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

110

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

120  
121

#### 122 **Changes to manuscript:**

123 

- Page 5, Lines 3-5: "In addition, in case of a strong..."

- 124 • Page 7, Lines 11-13: "Since neither NIF2 nor NIF3 feature large surface/bed  
125 inclination (migration issues) nor pronounced presence of meltwater (Figure 4)  
126 the uncertainty in GPR ice thickness seems to be well represented by our  
127 previous considerations."  
128 • We also decided against using the word "bedrock" to refer to the subglacial  
129 substrate, which at NIF consists to a large degree of sand. Accordingly we  
130 have replaced "bedrock" with simply "bed".

131  
132

133 **Referee comment**

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

141

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

154

155 **Changes to manuscript:**

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

162

163

164 **Referee comment**

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

169

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

174

175 **Changes to manuscript:**

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

178

179

180 **Technical corrections**

181 These are very helpful and we have integrated all of the suggested corrections in the  
182 revised manuscript if not noted otherwise.

183

184

185 P2, L28: The use of the word “employed” is awkward. Change to “GPR has also been  
186 used...”

187

188 P2, L32: Add “e.g.,” to the references because these might not be the only studies that  
189 used GPR on tropical glaciers.

190

191 P2, L32-33: “to our knowledge the study presented here...” should be “to our knowl-  
192 edge this is the first time a GPR was used at Kilimanjaro’s NIF.”

193

194 P3, L3-5: The sentence “Although not further discussed...” seems unnecessary if not  
195 discussed at all in this manuscript.

196 We feel it is appropriate to keep this sentence, since it refers to the main  
197 reason why we extended our GPR profiles to precisely this position at the  
198 vertical wall. We also come back to this in the Conclusions.

199

200 P3, L5-6: The sentence should be changed to “We estimate the total ice volume  
201 presently remaining at NIF by spatially extrapolating the GPR-derived ice thickness.”

202

203 P3, L8: Change “while” to “and”.

204

205 P3, L9-10: You’ve defined the abbreviation already so use “IRH”.

206

207 P3, L14: Change “as well as” to “and”.

208

209 P3, L18: Change “employed” to “used”.

210

211 P3, L18: Change “Technical settings of the setups” to “Details of the technical settings”.

212

213 P3, L23: Change “The spatial coverage that could be achieved was constrained by” to  
214 “The spatial extent of the GPR survey was constrained by ”.

215

216 P3, L24: Change “employ” to “use”.

217

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

220

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

222

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

224

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

228

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

230

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

232

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

234

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

236

237 P4, L29: Delete “relative difference”.

238

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

242

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

244

245 P5, L16: “In order to derive distributed ice thickness” to “To derive the ice-thickness  
246 distribution over the NIF”, and remove the later “over the NIF”.

247



248 P5, L16-17: Change “the previously developed approach by Fischer (2009), in  
249 interpolating” to “the approached previously developed by Fischer (2009), first  
250 interpolating”.  
251

252 P5, L21: “very high resolution” is subjective so remove “very”.  
253

254 P5, L22: No hyphen is needed for surface altitude.  
255

256 P5, L33: Change “We derived an estimate” to “We estimated”.  
257

258 P6, L3: Change “In order to estimate the expected loss on surface area” to “To estimate  
259 the surface area lost”.  
260

261 P6, L14: Change “comprises” to “includes”.  
262

263 P6, L18: Change “reflectors from internal layers” to “internal reflectors”.  
264

265 P6, L19: Remove “very”.  
266

267 P6, L28: You don’t need parentheses around the description of locations.  
268

269 P6, L30: Delete “, however”.  
270

271 P7, L4: Remove “value”.  
272

273 P7, L13: “more or less” is ambiguous so remove.  
274

275 P7, L17: Change “The interpolation of ice thickness” to “The interpolated ice thickness  
276 distribution”.  
277

278 P7, L28: Change “Considering additionally” to “In addition, considering”.  
279

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

282

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

284

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

286

287 P8, L29: Remove “in depth”.

288

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

291

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

293

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

295

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

298 [We have modified the sentence and added an additional reference.](#)

299

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

301

302 P10, L2: Change “can be” to “were”.

303

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

309 [We have taken care of the suggested changes and also generally tried to](#)  
310 [improve the readability of the figures by increasing font size etc.](#)

311

312 Figures 1, 2 and 9: Label the top and bottom rows as (a) and (b), respectively, and  
313 refer to them accordingly in captions  
314  
315