Review: Welling and the RNO-G Collaboration; Precision measurement of the index of refraction of deep glacial ice at radio frequencies at Summit Station, Greenland

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I was happy to be provided with the opportunity to review a manuscript that leverages measurements of ice conductivity and radio-wave englacial reflections to determine a specific index of refraction for glacial ice at the Radio Neutrino Observatory Greenland, Summit Station, on the Greenland Ice Sheet. I have limited expertise to understand the specifics of the radar hardware used, and I hope that a more qualified reviewer is able to confirm that the instrument setup was appropriate for the experiment. My suggestions to address comments below are my own personal opinion, and the authors are free to take alternative approaches so long as it is justified. Please consider my comments and suggestions below, and I apologise if I may have missed or misconstrued elements of your manuscript.

TJ Young (University of St Andrews)
31 July 2023

General comments

Overall—a succinct and clearly-written manuscript and I have several comments, of which all are relatively minor.

(a) Further clarity on radio wave properties

Please provide the signal frequencies/wavelengths generated. Even within the radio frequency band, most of the equations that the manuscript results employ rely on assumptions, which may or may not be negligible depending on the nature of the radio wave properties used by the instrument. Frequency affects the permittivity variations, which in turn relates to the index of refraction. Hence, for example, your assumption of negligible polarisation dependence on your calculations (L175) can only be justified if the frequencies used are the same or within a threshold to those used in Aguilar et al. (2022c). Separately, though not affecting the actual calculations, frequency will also affect the strength of observed conductivity-induced englacial reflections (Fujita & Mae 1994).

(b) Explicit statement needed that this method assumes additional invariance in several parameters

Given that the study calculates a bulk index of refraction, there is then an implicit assumption of a constant permittivity in and density of ice, following Looyenga (1965). At this point, the framework needs to assume that reflections detected by the radio wave is from abrupt contrasts in conductivity and not from permittivity (Fujita & Mae 1994). Note also that englacial reflections can also be caused by changes in density and crystal orientation fabric.

Additionally, the speed of the radar wave when travelling through ice also is dependent on density, temperature, and crystal orientation fabric (the last of which is already mentioned in (a)). Density is addressed for the most part (I think) by absorbing it into the ΔT free parameter (via the offset in time by firn properties). Within the depth ranges that you are working at, the effects of temperature should be negligible. However, if you extend your analyses to shallower or deeper sections of the ice column, it should be taken into consideration, or at least shown to (still) be negligible.

I would then suggest to make explicit that the method used in this manuscript assumes invariance in these factors (permittivity, temperature) for both radio-wave transmission and reflection. A good citation for this would be Fujita et al. (2000).

(c) Consideration of the "echo-free zone"

The manuscript presents confident claims that the method can be applied "to greater depths relatively easily". There is however a common occurrence of an 'echo-free zone' (e.g. Drews et al. 2009) in which, for reasons still largely unknown, radars are unable to consistently receive coherent englacial reflections. I would suggest to take this caveat into consideration.

(d) Suggestions to consider employing ice-penetrating data to strengthen the argument

The suggestion that the differences between reflectors at the two different radio-echo sounding sites, as well as their comparison to the GISP2 borehole, can perhaps be verified through visual interpretation of ice-penetrating radar profiles done around the site, depending on exactly where and which directions the measurements were taken relative to the surrounding landmarks. See if the radargrams provided in Jacobel & Hodge (1995) may help towards this suggestion. There may be other radargrams that exist at resolutions that may be too coarse for beneficial use (e.g. the CReSIS datasets).

(e) Formatting

I have not commented on issues with formatting, but the authors should give the manuscript a thorough proofreading to correct typos and formatting issues, especially with citations (`\citep` v. `\citet` in LATEX).

Specific comments (by line L)

10	"Cosmic rays have been of interest to physicists for over a hundred years" ← why? The journal has a wide readership so providing more basis will strengthen your motivation for research.
16-17	Spell out Eev (exa-electronvolts?) It would also perhaps help those not familiar with neutrino physics if you can also mention that the energy produced by cosmic neutrinos can be in this range. Does the detection of high-energy particles then scale proportionally with size, such that the detectors have to be proportionally large?
70	How "near" was the first measurements to the GISP2 borehole?
86-92	To just check, were the same antennas used in these two additional measurements and were they also positioned 106m apart? Was the antenna plane aligned in the same direction as the first measurement?
86	Which direction were the measurements (here I am assuming the 2nd and 3rd) taken from the GISP2 hole?
100	Note also, though, that there is considerable variation between conductivity measurements between adjacent ice cores (Wolff et al. 2005, Gautier et al. 2016).
105	Suggest taking this first sentence out, this is your opinion.
Eq. 4	From this equation it is now evident that z_0 is the vertical distance that also takes into account planar distance, and z is the vertical distance without this deviation. However Eq. 3 implies the opposite (that z_0 is instead the vertical distance with no horizontal deviation).
124	Quantify how "negligible" is this effect.

125 A statement that firn variations around the GISP2 site is negligible would support your case here, if there is a study that exists.

Fig. 3 I'm not quite sure where the values for the bottom plot are coming from. Are these max correlation values for a given index of refraction regardless of which time offset they represent, or for the specific time offset that gives the maximum correlation value of 1.778?

157 Same argument as my comment for L125: this statement is true only if there is no areal variation in firn density if you want to include measurements taken from different locations.

Figs. 4, 5 This is my personal opinion, but I can get all the information that I need from Figure 5, which renders Figure 4 unnecessary.

165 Please give the citation that provides the 0.5m uncertainty measurement.

168 650 ~~unit~~m

170 I am not certain that simply adding the uncertainty measurements on Δz and Δt is the correct way to produce a corresponding uncertainty for n especially given their placement in Eq. 1.

174 Give units for 1.6 ± 3.3

176 As far as I understand, there are three measurements, one taken "near the GISP2 borehole" (L70-71) and two taken "550m away from the GISP2 borehole" (L86) – which of these are the "two measurements" that you are referring to?

183 "… and radio reflections *should* hold…" ← given that you have not shown this evidence yet.

References

Drews, R., Eisen, O., Weikusat, I., Kipfstuhl, S., Lambrecht, A., Steinhage, D., ... & Miller, H. (2009). Layer disturbances and the radio-echo free zone in ice sheets. *The Cryosphere*, *3*(2), 195-203.

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Gautier, E., Savarino, J., Erbland, J., Lanciki, A., & Possenti, P. (2016). Variability of sulfate signal in ice core records based on five replicate cores. *Climate of the Past*, *12*(1), 103-113.

Jacobel, R. W., & Hodge, S. M. (1995). Radar internal layers from the Greenland summit. *Geophysical Research Letters*, *22*(5), 587-590.

Looyenga, H. (1965). Dielectric constants of heterogeneous mixtures. *Physica*, *31*(3), 401-406.

Wolff, E. W., Cook, E., Barnes, P. R., & Mulvaney, R. (2005). Signal variability in replicate ice cores. *Journal of Glaciology*, *51*(174), 462-468.