Authors’ response to referee comment #2

RC - Referee’s comment

AR - Authors’ response

RM - Revised manuscript

RC *In light of rapid glacier retreat and degradation of alpine permafrost, reliable observational methods for subsurface liquid water and ice contents are urgently needed. The authors present an interesting case study and a very rare application of surface nuclear magnetic resonance (SNMR) to detect and characterize an englacial channel of Rhonegletscher, Switzerland.*

Although challenged by considerable and yet unknown sources of electromagnetic noise, the authors managed to derive a useable signal as well as plausible 1D models of the englacial hydrological setting by advanced data processing. Results were validated with their own colocated as well as previously acquired ground-penetrating radar measurements.

The manuscript is well structured and written with commendable scientific rigour reflected, among other things, by a discussion of alternative plausible models given the measurement uncertainty as well as a dedicated subsection to discuss the limitations of the approach presented.

I believe that the practical considerations and data processing steps presented here make a valuable contribution for researchers and practitioners applying SNMR in particular in, but not limited to, the emerging field of cryogeophysics.

The authors are kindly asked to consider the comments below in (minor) revisions of their exciting paper and excuse the delay in my review.

Kind regards

Florian Wagner

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AC We thank the referee for taking the time to provide us with such detailed feedback on our manuscript. In the section below, we address each comment individually and highlight the changes in the revised manuscript (underlined and blue).

Main comments

Comment #1

RC *1. State of the art: The authors rightfully state that application of SNMR in cryogeophysical settings is very rare and hence only a few studies are cited in the introduction together with some GPR studies. However, the cryogeophysical community has made substantial progress in recent years in quantifying subsurface liquid water and ice contents with other geophysical methods (e.g., electrical* *resistivity tomography, seismic refraction, spectral induced polarization, etc.) also developing joint inversions to directly estimate water content by a combination of these methods. I feel the paper would benefit from acknowledging a few of these developments and properly placing the potential advantages and limitations of SNMR measurements in the overall effort of quantifying subsurface liquid water content with cryogeophysical methods.*

AR We agree with the reviewer that there exist additional geophysical methods that can be used in cryospheric environments. However, in practice, those methods (ERT, SIP) cannot be meaningfully deployed on pure glacier ice (like Rhonegletscher), since the ground is too resistive. We added a short section on those methods in the reviewed version of the manuscript.

While electrical and electromagnetic methods have been successfully applied in geophysical applications in cryosphere studies in various settings (primarily in permafrost investigations), the investigation of pure temperate glacier ice usually shows resistivities in the MOhm range (Hochstein, 1967 and references of this study), which is too high to be investigated with electrical and electromagnetic techniques. Due to the small vertical velocity gradient in glacier ice, seismic refraction methods would be also unsuitable, but seismic reflection surveys proofed to be useful (Church et al., 2019).

RM In the revised version of the manuscript, we added a sentence on the use of electrical and electromagnetic methods in glacierized environments and why their use on “pure” glacier ice to estimate the water content is limited (Sec. 1, L. 22):

…While GPR and seismics are effective at detecting the boundaries of englacial structures, they do not provide direct information about water content in the ice, which can be of particular interest in the context of hazard management, like in the case of glacier water pocket outburst floods (Ogier et al.; Vincent et al., 2012; Haeberli, 1983). Although electrical and electromagnetic methods have been successfully applied in geophysical applications in cryosphere studies in various settings (primarily in permafrost investigations, e.g. Wagner et al., 2019; Mudler et al., 2022), the investigation of pure temperate glacier ice usually shows resistivities in the MΩ range (Hochstein, 1967), which is too high to be investigated with electrical and electromagnetic techniques.

Comment #2

RC *2. Inversion approaches: The main inversion is based on a grid search for the 1D water content distribution. Prior to this step, a least-squares inversion is conducted to fit the decay curves. I feel that these two inversions need to be separated more clearly. In particular, I find it confusing that for the first inversion a model vector is defined, but not for the actual inversion for layer thicknesses and water contents.*

AR We agree that it makes sense to define two model vectors, one for the least-squares inversion and one for the grid search. We hope this helps to more clearly separate the two.

RM In the revised version of the manuscript, we added the definition of the water-model vector used in the grid search (Sec. 3.2.2, L. 228) and adapted the manuscript accordingly. We also changed the notation of the first model vector from m to m_1.:

….We perform a grid search within the parameter space spanned by $m_2 = (x_{ice}, h_{aq}, d_{aq}, x_{aq}, h_{surf}, x_{surf})$ to identify the most likely water distributions f (z) explaining the measured e0(q). For all possible combinations of $m_2 = (x_{ice}, h_{aq}, d_{aq}, x_{aq}, h_{surf}, x_{surf})$, we repeat the following three steps (cf. Fig. 2):...

Comment #3

RC *3. Noise discussion: The authors are very transparent about the poor data quality. However, the reader is kept left wondering where this noise comes from and how much is attributed to the (too close?) placing of the loops. Is it possible that the site is actually not that noisy, but the approach to estimate noise is not ideal?*

AR We are unsure if we understand this comment correctly. Typical anthropogenic noise sources in SNMR surveys include power lines, electric fences, and other electric infrastructure. On Rhonegletscher, we were not able to identify distinct sources of noise. Thus, we do not know the distance between the loops and the potential sources. We assume that the infrastructure in the larger area emitted electromagnetic waves that we recorded as noise. Presumably, in the highly resistive environment of crystalline rock and ice in the Rhonegletscher area, remote sources could have a stronger impact due to negligible electromagnetic attenuation. Possible sources are mentioned in more detail in Sec. 5.3, L. 376 - 380. Note that knowledge of noise sources and propagation is still missing in the field of SNMR.

RM We added a sentence on the possible effect of the highly resistive environment in Sec. 5.3., L379:

Since no thunderstorms were recorded in the larger area during the survey either, we remain puzzled by the noise's origin. Presumably, in the highly resistive environment of crystalline rock and ice in the Rhonegletscher area, remote sources could have a stronger impact due to negligible electromagnetic attenuation. While the data exhibits some signatures of spikes and higher harmonics of 16.6 and 50\,Hz, the predominant noise is probably a superposition of multiple sources.

Comment #4

RC *Also, care should be taken when comparing noise to other studies. For example, a link is made to a study in Denmark (Larsen and Behroozmand, 2016) where the magnitude of noise is compared on the basis of the RMS data misfit. To my understanding, the RMS misfit is a poor indicator for observational noise, as it can be dependent (and thus "tweaked") by the noise estimates, the quality of the forward model, the complexity of the subsurface parameterization, the inversion approach with its settings, and many other settings. In short, a "good" RMS misfit can also be obtained for a data set of poor quality or am I missing something here?*

AR The “RMS misfit” we mention on P.18, L. 372 is not the same as the RMS misfit defined in Eq. 7 on P. 11, otherwise, it would be a poor indicator indeed. The “RMS misfit” mentioned in the context of the study in Denmark has nothing to do with inversion fitting. Instead, it refers to the standard deviation of a time series with a mean value of zero (i.e. the predicted value for each time sample is zero).

Therefore, their “RMS misfit” is equivalent to the standard deviation we use to quantify the noise level. We understand that the wording is very misleading and will change that.

RM In the revised version of the manuscript, we change the wording “RMS misfit” to “noise level” (P.18, L. 372):

… For example, Larsen and Behroozmand (2016) studied the noise properties of multiple sites in Denmark. They investigated "sites with high-noise levels" showing noise levels of 0.25 and 0.3 nV m−2, which is almost one order of magnitude lower than the noise we recorded….

Comment #5

RC *4. Linguistic consistency: The authors currently mix British (e.g., "colours") and American English (e.g., "discretization"). Please choose one consistently throughout the paper. Additionally, I recommend to use the same term if the same thing is meant. For instance, "Earth's magnetic field" vs. "Earth's geomagnetic field" are both used in the paper. Choose one (or use the introduced B_earth symbol).*

AR Thank you for paying attention to the linguistic consistency. We are changing the manuscript accordingly.

RM In the revised version of the manuscript, we consistently use British English and use the same term for the same thing.

Minor comments

Minor comment #1

RC *- L131-133: What is the despiking based on? A bit more information would be helpful here.*

AR This processing step aims at eliminating spikes. MRSmatlab works with the so-called ”TDmean” approach, where a spike in the single traces is identified if the amplitude is larger than a certain threshold. The segment with the spike in the single trace is then replaced by the stacked signal without the spike.

RM *In the revised version of the manuscript, we added a sentence on despiking in Sec. 3.1.1, L. 131:*

…Despiking (DS) removes extreme values (so-called spikes), like the one reaching more than 105 nV in Fig. 3a. A spike is identified if the amplitude is larger than a certain threshold (typically set to five times the standard deviation of the time series, Mueller-Petke et al, 2016). The segment with the spike in the single trace is then replaced by the stacked signal without the spike. Spikes are typically a result of

powerful discharges like lightning. While we identify multiple spikes in the data sets acquired on Rhonegletscher, they do not dominate the overall noise…

Minor comment #2

RC *- L141: Is the closer loop not helpful at all? Or could it be used to estimate the attenuation of the signal and hence the "objectivity" of the noise estimate somehow?*

AR This is difficult to address in great detail. Primarily, the closer loop does not help because of even larger signal distortion, so we don't use it for processing. On the other hand, it also does not help for further noise investigations because it contains noise and signal. One could try to work on the noise-only records and study correlations. However, then we are running into the discussion of time-stability of the noise. So, yes one can think of "playing" with this data, but a discussion of this is beyond the scope of the paper.

RM No changes are made in the revised version of the manuscript.

Minor comment #3

RC *- L148: What exactly is meant by "best results"?*

AR With "best results", we mean the lowest data uncertainty after processing.

RM In the revised version of the manuscript, we properly explain what we replace "best results" with a more precise description (sec. 3.1.1, L. 148):

…In Supplementary Fig. 1a, we compare the noise remaining after different processing sequences and show that the combination "RNC+DS+HNC+DS" is actually the one leading to the lowest remaining data uncertainty after processing.

Minor comment #4

RC *- L380: Could some of these noise sources be listed / discussed here?*

AR See answer to comment #3.

RM No changes are made in the revised version of the manuscript.

The following suggestions are directly implemented in the revised version of the manuscript.

- L10: Maybe reformulate to "... consistent with simultaneously and previously acquired ground-penetrating radar measurements." (also to avoid the not yet introduced GPR abbreviation)

- L26 vs. L31: See general comment #4.

- L70, L91: The SNMR manufacturer is cited twice (with a URL and a not properly formatted

(?) citation in L91), whereas other manufacturers (e.g., Leica or Senors & Software) do not have a reference. I think manufacturers could be simply mentioned without website links, except for the loop recommendation in the manual, which needs to be properly formatted.

- L174: Use square brackets for the model vector here for better readability and consistency with the initial values in L179.

- Caption of Fig. 4 contains a mix of British and American English (see general comment #4)

- L232, L238: I think the introduction of an additional model vector here makes sense to avoid these repititions.

- L263: "provides" -> "provide" because this is referring to the "results", i.e. plural?

- L416 (and elsewhere): No hyphen between model and parameter needed.

- Both "Mueller-Petke" and "Müller-Petke" appear in the reference list.

References

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Wagner, F. M., Mollaret, C., Günther, T., Kemna, A., and Hauck, C.: Quantitative imaging of water, ice and air in permafrost systems through petrophysical joint inversion of seismic refraction and electrical resistivity data, Geophysical Journal International, 219, 1866–1875, https://doi.org/10.1093/gji/ggz402, 2019.