Authors Response to Review 2 (from 05.08.2021)

R: Referee's comment

A: Author's response

R: Mudler et al. present a case study using high frequency spectral induced polarization (HFIP) data to detect the frozen/unfrozen layer and estimate the ice content in a permafrost environment. The spectral IP data were fitted using an empirical model to extract the complex dielectric permittivity and DC resistivity parameters. These parameters were interpreted to characterize the frozen/unfrozen layer of the subsurface. The parameters were further used to estimate the ice content. While this manuscript matches the scope of the Cryosphere, it contains a few technical issues in terms of the methodologies and data interpretation.

Major comments

(1)

Measurement accuracy of HFIP

R: This study collected SIP data from 2 Hz to 115 kHz. Particularly, high frequency (HF) data in kHz were mainly discussed as it was stated that polarization of ice occurs in this frequency range. However, the measurement accuracy of HFIP was not evaluated quantitatively. It is well known to the IP community that the four-electrode method results in huge errors at high frequencies. It is very challenging and requires extensive procedures to remove HF errors at the laboratory scale measurements. It is even more difficult to collect high-quality HFIP data at field-scale, especially in a high resistivity environment like this study. This manuscript does discuss the HF error topic (only qualitatively) in Section 4, whereas it does not provide any information concerning instrument accuracy.

A: The accuracy of field scale measurements in comparison with lab measurements is a complicated issue, in particular when EM coupling is involved. We tend to disagree with the general statement that it is more difficult at the field scale, as we are not aware of any studies supporting the statement.
The potential problems of data acquisition for HFIP data are caused by the interference from electromagnetic effects. However, the reduction of these effects is taken into account by the measurement device (Chameleon-II), designed to be used in high resistive areas (Radic et al., 2018). Thus, inductive and capacitive cable couplings are minimized by the used hardware. Capacitive coupling between current cables and the subsurface is reduced by integrated cable-earth compensation (CEC) from the instrument side and the software according to Radic & Klitzsch (2012). Inductive coupling effects between current cables and the subsurface can be estimated, for example by the induction number and suggest that over resistive subsurface, such as permafrost, those effects can be neglected in the used range of the measurements.
To give a quantitative estimation of these effects, we will provide and illustrate statistical errors of the measurements for exemplary data with and without the CE compensation. Furthermore, we will provide a simple estimation of the influence of inductive coupling effects.

(2)
The models

R: I found it difficult to follow the SIP models used in this study. Generally, there are four parameters describing the electrical conduction and displacement/polarization: real conductivity, imaginary conductivity, real permittivity, and imaginary permittivity. It is not clear how these parameters were treated, for example, were the conductivity parameters related to the permittivity parameters? Was any parameter neglected?

A: Concerning the choice of permittivity instead of imaginary conductivity, we will add the following explanation in the section below eq. (2):
"In general, there is a choice whether the data interpretation is based on imaginary conductivity, or on the real part of permittivity, because the two are mathematically equivalent. Whereas for low-frequency (<100Hz) SIP measurements, imaginary conductivity is often preferred (Loewer et al. 2017), for high-frequency SIP covering the relaxation of ice, permittivity is generally considered (Bittelli et al., 2004)"

R: Specific questions are:
In eq. (1), are ρ and ε_r complex quantities? If so, is ε_r the same as ε_{r^*}. If not, is ε_r the same as ε_r'?

A: In principle ρ and ε_r in eq. (1) are real values. We reconsidered eq. (1) and decided that it is not necessary for the following explanations. Therefore, we will take out eq. (1) and instead we will integrate the explanation of the real and imaginary part of ε_r into eq. (2).

R: The description of Eq. (2) is a bit confusing as a Cole-Cole form model does not have the third term. It is reasonable, though, to have the third term to describe the DC conduction, but again the discussion of these parameters is mixed up. It seems that imaginary conductivity was never mentioned, although it is very important for SIP. Besides, as eq. (2) is the key equation for fitting the data, more information is needed to clarify how complex impedance was converted to a complex permittivity.

A: The used model (eq. (2)) is the Cole-Cole model with an additional third term that integrates the low-frequency conductivity mechanisms. This model has been previously used for cryospheric investigations by several publications (e.g., Bittelli et al. 2004, Stillman et al. 2010, Grimm & Stillman 2015). Nevertheless, we agree that the naming of this model as "Cole-Cole model" is misleading and we will change and clarify this in the text.
According the imaginary conductivity, see the above Authors Comment.
The conversion from complex impedance to complex permittivity will be clarified in this section, as it is provided e.g. in Przyklenk et al. (2016).

R: Eq. (3-5). Ice estimation was made based on these equations. On page 5, line 27 states that three parameters are well known and fixed. These parameters should be provided.
I am also curious how the τ_i was selected as it is a temperature-dependent parameter. Also, it would be helpful to describe the meaning of parameter k and present and discuss the variations of fitted k.

A: We will provide the used literature values of the fixed parameters, named on page 5. The polarization of ice does indeed exhibit a temperature dependence, but is approximated here in the first approach as independent and with the values for temperatures immediately below freezing point, which is valid for the discussed field survey. We will discuss the temperature dependence of the parameters in more detail.

Furthermore, we will illustrate the distribution of fitted parameter k and discuss the meaning of k with regard to Zorin & Ageev (2017).

(3)

Data interpretation

R: The whole Section 6 describes the raw data from a 1D sounding. However, those data are apparent IP data and do not represent the true electrical responses of the subsurface. Nowadays, these data mostly only serve as a way to assess the raw data quality. Therefore, it is not proper to relate them to a physical process and interpret them so extensively (accounting for half of the results), especially for a non-layered structure as evident from the zones around 'C' in Figure 7.

A: We agree that the description of raw data from a 1-D sounding is not common for conventional measurements. Here, they are only discussed because there is little research on the method and its application to ice-bearing subsoils, and we find it useful to illustrate the relationship between the models and the raw data. However, we will shorten this section and make it clearer that these are apparent HFIP data that do not allow for physical or geologic interpretation.

R: Besides, there are a few specific questions that need to be addressed:
As the polarization of ice is non-metallic polarization, wouldn't imaginary conductivity be a better parameter to interpret to exclude the effects of variations in water conductivity?

A: We follow the typical parameterization describing the ice polarization in the terms of the complex permittivity (see Authors Comment (2)). Possible effects due to water are not explicitly considered at this stage. It would be an approach for further work to use a combined model from the parameterization of several relaxation processes by the conductivity (low-frequent) and permittivity (high-frequency effects), as proposed for example by Loewer et al. (2017). However, since the number of free parameters would increase significantly, and the application and evaluation of HFIP in the field is quite unexplored, the initial approach was to keep the model as simple as possible and focus only on the known ice relaxation. We will present this aspect more clearly in the paper and likewise revisit it in the outlook.

R: According to Bittelli et al., 2004, the $\varepsilon_{r,DC}$ of ice is around 100, and $\varepsilon_{r,HF}$ is around 3. Figure 7 shows that $\varepsilon_{r,DC}$ is as high as 600 in the frozen layer even though the ice content is less than 100%. Figure 7 also shows high $\varepsilon_{r,DC}$ values (~200) even in the thawed layer without ice. It may indicate that the applied complex permittivity model is a good choice as the fitted $\varepsilon_{r,DC}$ is too high compared to the theoretical value (e.g., 100 for ice). Figure 7 indicates that thawed layer exhibit large relaxation giving the large difference between $\varepsilon_{r,DC}$ and $\varepsilon_{r,HF}$. This is contradictory to Eq.(4), which states that the permittivity of the ice-free matrix is constant.

A: The large values of εr,DC are an artefact of the 2-D inversion code. If the data show no relaxation process, some the 5 parameters become poorly constrained, which may lead to unrealistic values. We will discuss and possibly illustrate this issue in the revised version.

(4)
R: In addition to the above main points, the significance and broad applicability of this manuscript may not be adequate for the Cryosphere journal as the study only has one survey line at one site.

A: Since the HFIP method is not widely used and the approach of determining the ice content at the field scale is new, we initially validated it on only one measurement area with some prior knowledge on ice content. It is logistically quite expansive to gain access to sites where external information on ice content is available and the method can be validated. We hope to generate some interest in our method which will initiate future fieldwork and more case histories.

Some suggestions

A: The authors will adjust all suggestions noted by the reviewer.

Literature

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