

The Cryosphere Discuss., referee comment RC2  
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## Comment on tc-2021-154

Anonymous Referee #2

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Referee comment on "Broadband spectral induced polarization for the detection of Permafrost and an approach to ice content estimation – a case study from Yakutia, Russia" by Jan Mudler et al., The Cryosphere Discuss.,  
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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

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.

### 2. The models

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? Specific questions are:

In eq. (1), are  $\rho$  and  $\epsilon_r$  complex quantities? If so, is  $\epsilon_r$  the same as  $\epsilon_r^*$ . If not, is  $\epsilon_r$  the same as  $\epsilon_r'$ ?

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.

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  $\tau$  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  $k$ .

### 3. Data interpretation

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. 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?

According to Bittelli et al., 2004, the  $\epsilon_{r,DC}$  of ice is around 100, and  $\epsilon_{r,HF}$  is around 3. Figure 7 shows that  $\epsilon_{r,DC}$  is as high as 600 in the frozen layer even though the ice content is less than 100%. Figure 7 also shows high  $\epsilon_{r,DC}$  values ( $\sim 200$ ) even in the thawed layer without ice. It may indicate that the applied complex permittivity model is a good choice as the fitted  $\epsilon_{r,DC}$  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  $\epsilon_{r,DC}$  and  $\epsilon_{r,HF}$ . This is contradictory to Eq.(4), which states that the permittivity of the ice-free matrix is constant.

4. 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.

Some suggestions:

Page 5 line 24.  $\tau_E$  should be  $\tau_i$ .

Page 8 line 17. Suggest indicating the river on the map in Figure 2.

Page 8 line 22. What are the 'separate measurements'?

Page 8 lines 11-12. Phrases 'right half' and 'first half' are ambiguous.

Page 13, line 11. Caution with the word 'same' as resistivity from SIP only shows similar patterns to the ERT results. The resistivity values differ between the two measurements. Also, maybe remove 'electromagnetic methods' as no EM data were presented.