Review 1 (04.04.2019)

R: Referee's comment

A: Author's response

C: Change in manuscript

(1)
R: The manuscript describes the new development in the capacitively coupled method which was developed for low-frequency measurements. Authors modified the method by including Cole to Cole parameterization. However, for someone not deeply familiar with these methods it hard to follow the manuscript. It was very unclear from reading an abstract: Why is it important to modify low frequency method in first place? What do low frequency methods provide? Why it is important to extend them to wider frequency range? Which additional rate of frequencies does this new modification cover? What type of information do we get by inverting CCR data?

A: We can measure with our method from 1Hz up to 240 kHz, IP works usually in the range of mHz up to 1kHz. The higher frequencies in combination with the high resistivity conditions enable to estimate the resistivity as well as the permittivity of the subsurface. Ice (and snow) has a characteristic relaxation process within our frequency range at around 10kHz, which is what makes the extension in frequency range so important. The Cole-Cole model gives a possibility to fit the spectra of these data. We can determine the 5 Cole-Cole parameters and thereby characterize the subsurface. The modification of the inversion algorithm is necessary because compared to existing IP inversions we need one more parameter.

C: The abstract will be rewritten such that the aim of the study and the issues mentioned above become clearer. Also, sections of the introduction will be rewritten to describe better what information can be provided by other methods, and what is new here what we try to obtain out from our method.

(2)
R: Similarly, in the introduction, authors jump on explaining how by having electrical resistivity and dielectric permittivity is not enough. I suggest to start with explaining why doing ERT measurements is important in the first place? What type of subsurface information do we obtain by using these ERT? Then move to explaining why it is not enough and that having permittivity provides and additional information that is useful for interpretation of subsurface conditions. It is not clear, which subsurface conditions authors are referring to?

A: We agree with the idea of starting from the ERT and then explain the benefits of our method. The subsurface conditions we are focusing on are periglacial areas. The main reason is that the method is sensitive to the presence of water ice, due to the characteristic frequency dependence of electrical permittivity.
However, in this paper we focus on methodological aspects, such as the questions: Is it possible to measure the CCR with our unique equipment in areas of (possible) occurrence of ice/permafrost? How strongly are the data affected by the electrode height? Can we invert our data with the new spectral 2D inversion and are results consistent with the subsurface structure and literature values?

The quantitative estimation of ice content is an ultimate goal of future developments, for which we lay the foundation with this work.

C: We will rewrite several sections of the introduction. First we focus more on the existing studies and methods, starting from ERT and then explaining the role of spectral induced polarization (SIP). We will explain the characteristic relaxation of ice and make clear why our measurement uses these aspects to obtain specific additional information.

(3)
R: First paragraph ends with statement that determination of the ice content is possible with ERT. Is that the overall goal of this work?

A: This might be subject of future work. The statement was intended to point out what could be possible (and was already discussed by several authors). It is not the focus of this work.
C: The focus of the work will be explained more clearly. The introduction will be changed accordingly (see (2)).

(4)
R: P2L10 Why is it usable on the extremely hard surface? Need to better explain it. From the description, I not sure what type subsurface information CCR provides.

A: On hard surface the capacitive coupling gives an advantage over the “normal” coupling with skewers (no drilling or watering of electrodes needed). This is explained in P2 L10-13.
The information are resistivity, permittivity and the characteristic relaxation information given by the other CC parameters (tau, low-frequency permittivity).
C: see (1) (2)

(5)
R: P2L30. OK, the aim of the study is test the application of the newly developed method on the identification of the ground ice.

A: Yes.
C: See above. We will try to make this clear from the beginning.

(6)
R: Shilthorn From the description of the subsurface I conclude that it is a rock. What type of ground ice can exist in the solid rock? Does that rock has fractures that filled with ice? What about ice that might be formed at the ground surface? Does that ice layer is important and was taken into account?

A: The surface under the snow is a layer of limestone (described in the text). Unfortunately, we do not know details, like if its fractured. We do not have a high investigation depth, so just Ice in very shallow depth would influence the measurements. But main focus lies on the structural aspects.
C: Will formulate this more precisely and add information.

(7)
R: Lake site Lake was frozen. Is there any information of the ground subsurface? Is it frozen? How deep is the seasonal frost layer? Any information on the percentage of ice within the ground?

A: Unfortunately, there is no further information of the ground subsurface. The measurements were made with the idea to test whether the transition between lake and land is visible in our data. A correlation with geology, or quantitative estimation of ice content, was not a primary goal. Therefore, we can make an assessment of the data only in a qualitative sense.
C: We will modify the corresponding sections such that it is clear from the beginning that we are not aiming at a quantitative correlation with ground properties, but that we consider the qualitative assessment sufficient at this stage.

(8)
R: P6. L10. There some GRP measurements in permafrost regions that estimate ALT (active layer thickness) and soil moisture, and could be used to calculate ice content (e.g. Chen et al., 2016 and Jafarov et al., 2017).

A: The role and possibilities of GPR will discussed a little more.
C: This will be included in the text.

(9)
R: P6.L15 What is relatively high? Do you mean ice lenses wise or massive ice?

A: This statement just means that the existence of ground ice, as in periglacial areas, leads to high resistivity without the distinction between massive or ice lenses. The "relatively" might be misleading.
C: The sentence will be formulated more concrete.

(10)
R: P6.L15-22 lit review and can be moved to the introduction.

A: We agree
C: Will be included in the introduction (see (2)).

(11)
R: P7.L25-30 Does that mean that inversion depends on one parameter (c)?

A: No, that is not the case. We just want to say that the other 4 CC-Parameters can directly be related to a physical context and there exist material-specific literature values. There are values for c as well, but just rare.
C: Sentence P7 L28 f. will be changed and formulated more precisely.

(12)
R: P8.L23. Figure 4 inversion done with and without determination of height. Where are those two on the plot? I do not see two curves (one for h0 another for hinv)? The legend should be adjusted correspondingly. X-axis, is f an actual frequency or logarithm?
Figure 6. It is not clear which of the Tromso data correspond to the lake ice and which to the ground ice?

A: As written in the figure caption, the two variants of inversion cannot be distinguished from each other and therefore are shown as one line (see legend).

The x-axis is the actual frequency, but shown in logarithmic steps. Axis and the corresponding label are standard, so we are not sure what causes the confusion. At this stage, in fig. 6 there is no distinction between lake site and land site.
C: Fig.4 (same Fig. 5c and d) will be changed that for h_0 and h_inv separate curves will be shown, but they will lie on each other.
Fig. 6 will be changed, such that there is a distinction between lake site and land site at Tromso data by using two different colors. This will be explained in the text (P11 L7 ff.).
Concerning the frequency axis, we do not see how to change anything, as we follow common standards.

(13)
R: P12.L16 Why authors decided to use AarhusInv code and not BERT for example? How well does AarhusInv compares to other existing codes? Is this code an open source? If it is, then it would nice to provide a link for the modification implemented in the code. Why did authors choose _(CHI-)metric? Is that commonly acceptable fitness metric? Why not RMSE or Taylor diagram?

A: Because two of the authors are developers of AarhusInv, working at Aarhus University. Using BERT would cause the same procedure of extending the code for our aims.
AarhusInv is a freeware for non-commercial purposes (http://hgg.au.dk/software/aarhusinv/). The code is not open source. The complex impedance is modelled in 2-D solving the Poisson's equation, Fourier transformed in the strike direction, without considering EM effects (Fiandaca et al., 2013), as done for instance in the complex resistivity code cR2 developed by Andrew Binley (http://www.es.lancs.ac.uk/people/amb/Freeware/cR2/cR2.htm).
The data misfit values are expressed in terms of chi values, because the objecting function minimized in the inversion process is the sum of the data and regularization chi values (Fiandaca et al., 2013).

C: We will add this information about AarhusInv this in chapter 4.

(14)
R: P20.L17 'reasonably consistent' … Is that possible to quantify it (what is the correlation)?

A: Very difficult to quantify because we do not have exact values for resistivity and permittivity from other methods or even better from laboratory analysis. This statement should mean that the determined values fit in the range of literature values of what we know and what we expect from the subsurface at the test sites.
C: Will be formulated more precisely.

(15)
R: Overall, I have been struggling throughout this paper to understand the purpose of this study. What is an ultimate goal of doing this? Is it to get a better measurement of the ground ice? If yes. Are there any ground truth data? How these inversion can be compared with in-situ data? Suggestions: In this current version of the manuscript, methods, results, and literature review are all mixed up together. Think how you can better organize/separate them. Starting from the bigger picture, like knowing ground ice is extremely important for many reasons... In particular, for better understanding of the permafrost thawing rates and consequences. Then introduce the method. Provide a literature review on the existing methods and models. Justify the usage of the current model and talk about how important the current improvements are in terms of better quantifying of the ground ice. In addition, in the description of the site location, it would be extremely useful to know subsurface characteristics/properties. Are there fractures in the rock? How much do you know about subsurface

ground ice at the lake station? Comparing inversely derived ground ice with actual ground ice will be extremely useful. The current version is a good methodological paper and missing emphasis on how this work is important and how it is contributing the current state of science. Addressing these two missing issues will make this paper suitable for the journal like Cryosphere.

A: We appreciate to positive evaluation as a good methodological paper, and we are thankful for the constructive comments. We will try to address the issues and hope that we can bring the paper into a suitable form.

The purpose of the study is to investigate methodological aspects of a new method that can be useful for the investigation of periglacial environments, and demonstrate its feasibility. Therefore, we make an important step towards quantitative usage, such as the estimation of ice content.
The main purpose is not, however, to actually calculate ice content and compare the results with ground truth data. We admit that this would be desirable to have, but it is difficult to obtain in general, and not available for our test sites. We believe that our results are nevertheless important and interesting for a broad readership.

C: We will restructure the abstract and introduction to better describe the purpose of the study. We will also provide a better context of existing methods and research and explain the potential improvement by our method (see (1)(2)(3)). However, instead of a full literature review, we will prefer to refer to a small selection, as the importance of ground ice, and the usefulness of geophysical methods in general, and electrical methods in particular, have already been discussed in textbooks.
There is not much additional information about the field sites (see (6)(7)), but we will try to give a better explanation of what we know and how we can compare the data with existing information.