Review 2 (02.05.2019)

R: Referee's comment

A: Author's response

C: Change in manuscript

R: SUMMARY
This paper presents data and modelling results for broadband spectral capacitive resistivity experiments performed in cold regions. The experiments appear sound in design, and the data are novel and very interesting from the perspective of electrical/electromagnetic geophysics and cold-regions research.

A: We appreciate the overall positive evaluation and we thank for the constructive comments.

(1)
R: However, the paper has a few shortcomings. The objectives of the paper are not entirely clear at first. Is the focus on SIP or CR? It becomes clear (I think) that the focus is on cold-regions application of broadband spectral CR. If this is the desired focus, the paper would be made more impactful by including: 1) a review of electrical, IP, SIP, and CR applications to cold regions and permafrost; 2) a clear description of the benefits, limitations, and favourable conditions for broadband spectral CCR, and how these relate to cold regions; and 3) a more thorough analysis of the inversion results in terms of cold-regions ground properties of interest such as water content, ice content and temperature.

A: The CCR (in the spectral way we use it) is actually the method of SIP in a higher frequency range, additionally using the capacitive coupling instead of the "normal" galvanical coupling. Without the capacitive coupling, the method would be similar to Grimm & Stillman (2015) who call it "Broadband SIP" or the "HFIP" (high-frequency IP) from Zorin & Ageev (2017). We focus on CCR as we used it in the field with the logistical advantages and in the terms of the discussed electrode height effect.
C: 1) A review of existing methods and studies of ERT, IP, CCR will be provided in the introduction. We will, however, refer back to textbooks instead of a full literature review, because some of the aspects have already been summarized.
2) Our CCR method will be described more precisely.
3) The analysis of the Inversion results will be described and compared with external information in more detail (p13 ff.). We will not be able to provide an extensive ground-truth comparison, however, because ground truth, for example in terms of ice content, is not available for our test sites. Since the focus of the paper is more on methodological aspects, we hope that this issue is not so critical.

(2)
R: Abstract: Lacks focus on objective and results.

A: We agree that the abstract needs to be rewritten.
C: Abstract will be reformulated to describe objective and results more clearly.

(3)
R: p1,L19: Why? High conductivity material exhibit spectral characteristics as well.

A: It is true that high cond. subsurface exhibits spectral characteristics. But for the determination of the permittivity (in addition to resistivity), lower cond. material is more suitable, because we are limited in frequency range. The reason is, that as lower the conductivity is, the transition to displacement currents and therefore the possible extraction of the permittivity, happens for lower frequencies (e.g. Zorin & Ageev (2017)).
C: The relationship between conductivity and determination of permittivity will become clear in a new section explaining the operating range off CCR (see below).

(4)
R: p2,L28: What about Routh et al. (1998), Kemna et al. (2000) and several works thereafter?

A: These inversions of IP data works in the way that they invert single frequency data and the in postprocessing integrate all spectral and spatial data, which is the difference to the work of Günther and Martin (2016) and Maurya et al. (2018), who invert all frequencies at the same time. But we agree, that this works should be mentioned in the manuscript.
C: The works with an explanation will be included in the introduction.

(5)
R: p.2,L30: Introduction is somewhat unclear. It starts out focussed on SIP, then CCR, but then states the objective as investigating the field applicability of [spectral] CCR in cold regions. To support the latter, the intro needs a little more background on electrical geophysics and material properties in permafrost and/or glaciology.

A: We agree.
C: The introduction will be reorganized. There will be a review of existing electrical methods and studies before explaining what is new and what is the goal of our method (see (1)). Additionally, the connection to material properties of ice will be made clearer.

(6)
R: eq.1: Although somewhat semantic, I view the low-frequency CCR experiment as responding to the complex conductivity where the imaginary conductivity has a contribution from the real dielectric. Of course, at higher frequency and in the presence of ice, permittivity may be more relevant. However, I do not think that equation 1 should be referred to as representing the "complex permittivity." Consider "effective permittivity" which has a contribution from the imaginary conductivity. The distinction is important because the true dielectric permittivity is what results in wave propagation in Maxwell's equations, not the imaginary conductivity. Furthermore, to talk only of displacement currents denies the possibility of IP-type currents which may dominate at lower frequency.

A: We agree, and actually tried to express this by using the term "effective value" on p5., l.11.
C: We will now explicitly call eq. (1) "effective permittivity", and will also add a few lines on conduction and displacement currents, refering to the overview given by Loewer et al. (2017).

(7)
R: p.6,L4: You say the "conduction current" is in-phase, but then you say that IP is concerned with the conduction current part of the impedance. You need to be clearer on the distinction between the real conductivity (conduction current), the imaginary

conductivity (IP current), and the real permittivity (displacement current).
eq.4: Again, consider noting that any IP effect will be wrapped up in here as εeff = εR + σI/ω.

A: see (6)
C: We will introduce that in a short paragraph (see (6)).

(8)
R: p.7,L8: The height effect is also discussed by Wang et al. (2016) but in a shady pseudojournal. The authors could decide if it warrants consideration.

A: Thank you for pointing this out to us. We agree that it is relevant for our work.
C: The reference will be included.

(9)
R: p.8,L3: You say the inversion is frequency dependent, but then go on to say that the system response is controlled by geometry, not frequency. Clarify.

A: The statement refers to the fact that we work in the range of "geometric sounding" (same as ERT) and so we do not have a frequency sounding (as e.g. RMT); See (10)
C: see (10)

(10)
R: p.8,L5: You need to thoroughly describe the "operating range" of CCR with respect to treatment of the data for the single site inversion and the 2D inversion. Application of a 2D resistivity inversion (with geometry-based sensitivity) requires low-induction number conditions (which actually appears to be violated for some of your lower frequency-resistivity combinations). Does the single-site inversion require LIN conditions? What about wave effects? For some of the high frequency-resistivity pairs encountered, quasistatic conditions are violated and a true permittivity will result in wave propagation. This should not(?) affect CC model fits, but it should(?) affect the 2D inversions using a resistivity-type sensitivity function.

A: The method of CCR operates in the physical range of "geometric sounding" (GS), which indeed requires LIN conditions to be fulfilled. We do not agree, however, that these are violated for some of our data (see more detailed explanation below). Quasistatic conditions, however, are not necessary, because it is the wavenumber that determines which physical process dominates. The detailed explanation is as follows:

The physical boundaries are given by the effects of electromagnetic induction (EMI) and wave propagation (WP). This consideration of the three processes is described in Weidelt (1997) and the "parameter range" refers to the frequency f, the spatial scale a (i.e. distance between transmitter and receiver), electrical conductivity and permittivity.
The equation that allows to compare the processes is: $\gamma^2 = \frac{4\pi}{a^2} + \frac{2i}{\delta^2} + \frac{4\pi}{\lambda^2} = GS + EMI + WP$, where the process corresponding to the largest term will dominate, and the other terms may be negligible, depending on their magnitude.
Skin depth: $\delta = \frac{1}{\sqrt{\pi\, f\, \mu \frac{1}{\rho}}}$; wave length $\lambda = \frac{2\pi}{\omega\,\sqrt{\varepsilon\mu}}$

If we calculate this as a worst-case for our maximum frequency 240 kHz, a smallest resistivity (lowest conductivity) of 100 Ohmm and a spatial length of 10 m, we are still clearly in the range of GS. (GS=4; EMI = 0.02; WP=8e-5)
So we think that there is no violation neither to induction effects nor to wave propagation. For the presented measurements, we always have low-induction numbers and therefore can neglect possible resulting problems in terms of the inversion.
Anyway, we agree that this point has to made clearer in the manuscript.

C: We will describe the operating range and the topic of GS, EMI and WP in a new section within chapter 3.

(11)
R: p8,L6: "Induction effects" would typically be understood to mean inductive source effects of current-carrying cables. You don't have these. So, do you mean magnetic coupling as described by McNeill?

A: Yes, we (as in Fiandaca (2018)) mean the electromagnetic induction effects.
C: Will be described more deeply (see (10), and we will use more precise terminology).

(12)
R: p.13,L25: Well, the dielectric constants for rock and snow are both around 3-5, so...

A: Yes, this is the reason why the values are so close and material is difficult to distinguish.
C: We will include this in the statement (p13 L25).

(13)
R: p.13,L32: Snow cover typically inhibits frozen ground.

A: We agree, the sentence is unclear and actually not necessary for the further discussion.
C: Will change the statement.

(14)
R: Table 1: Add water. More discussion is required in comparing recovered values to expected material properties.

A: The discussion can be done in more detail and by including water in table 1 and the discussion.
C: Will add water in table 1 and deepen the discussion when comparing literature values with the inversion results for the test sites (p15 L4 ff. and p17 L5 ff.).

(15)
R: p.15,L5: In comparing to literature values, what about the observations by Weigand and Kemna (2016) that SIP model parameters obtained from a CC model are biased? Is this alleviated by having c as a free parameter and/or by having 19 points in the spectrum?

A: We thank for pointing this out and agree that this should be included in the text. Yes, we think that the fact of having c as free parameter (see below (18)) and having the high density of 19 frequency measurements in the range of estimated tau alleviate the effect of bad determined CC parameters. The inverted tau-value are in the expected range of relaxation for ice and snow, what strengthen our assumption.
C: Observations of Weigand and Kemna (2016) will be included and discussed in the context of our results.

(16)
R: Fig.8: Use same scales as Fig.7. Are some of the observed differences attributable to height effects or breakdown of LIN conditions?

A: As explained there should be no breakdown of LIN conditions (see (10)). Moreover the height effects in our cases should be too small to influence the 2D inversion, as shown in fig. 6 and discussion. The differences have to be due to the fact that figure 8 is a pseudosection, whereas figure 7 is a 2-D inversion result. We actually had devoted an extra paragraph to this discussion (p. 13, l. 10ff).

C: Since spatial variation in pseudosections is always smoother compared to inversion results, using the same scales would result in loss of information. Therefore, we would prefer to leave the scales as they are. Instead, we try to clarify the discussion of pseudosection and inversion result.

(17)
R: p.18,L5: Why is the DC permittivity so (unreasonably) high?

A: The values are higher than expected comparing with literature values. Nevertheless, LF values of permittivity for natural water, specially with high salinity (as it is in the lake), can be very high (Seshadri et al, 2008). On the other hand an overestimation may be caused by the measured low frequency values (see e.g. Zorin and Ageev (2017)).
C: The role of epsDC and the high inversion results will be discussed in more detail.

(18)
R: p.18,L11: Is there any benefit to setting c constant (i.e., choosing a decomposition for the CC model). Is it reasonable for c to show so much variability? Is it highly sensitive, and if so, is it just absorbing error in the inversion?

A: We did some inversion tests with constant c. It shows that a constant c cannot fit the data of all the different spectra. We think that the different subsurface materials and conditions explain the variability of c and justify the use as free parameter.
C: Will be mentioned in the text.

(19)
R: p.18,L19: Actually, the LF permittivity of water is around 80, but you need to get up to 1010 to 1012 Hz before it drops to around 3.

A: We have to make this clear that the relaxation of water refers to higher frequencies and the value of 80 is the low-frequency value.
C: Will be changed in the text and described in context of adding literature values of water in table 1 (see (14)).

(20)
R: Figure 10: a) Use dash and solid. b) What is the distinction between black and purple lines?

A: b) The distinction is measured (purple) and inverted (black)
C: a) will be changed b) will be added in the figure caption

New References:

M. Loewer, T. Günther, J. Igel, S. Kruschwitz, T. Martin and N. Wagner: Ultra-broad-band electrical spectroscopy of soils and sediments – a combined permittivity and conductivity model; Geophysical Journal International 210, 1360-1373; 2017