

Reviewer Recommendation and Comments for Manuscript Number egosphere-2023-671  
**SPECTRAL INDUCED POLARIZATION IMAGING TO MONITOR SEASONAL AND ANNUAL DYNAMICS OF FROZEN GROUND AT A MOUNTAIN PERMAFROST SITE IN THE ITALIAN ALPS**  
Theresa Maierhofer et al.

### **Summary**

The authors present an improved version of their interesting and relevant manuscript. They addressed all my general and specific comments on the original version of the manuscript. Specifically, they removed redundancies, included a detailed discussion of the expected broadband response of ice-containing sediment and rock, which improves the understanding of the mechanism underlying the new “phase frequency effect”, and provided some additional discussion on the risk of misinterpreting the effect of electromagnetic coupling in terms of ice content.

However, as detailed in my general comments below, there are still parts of the discussion section that remain hard to follow for the reader. More clearly structuring the manuscript (introductory considerations in the introduction section, results in the results section,... ) would improve the clarity and readability of these parts of the manuscript. In addition, the authors might overestimate the scope of the newly added electric circuit experiments, which – from my point of view may only represent a lower bound of the coupling effects to be expected. These issues together with a number of specific comments and technical corrections listed below, should be straightforward to address. Therefore, I recommend accepting the revised manuscript after an additional minor revision.

We thank you very much for the detailed and really helpful comments! We appreciate and considered your suggestions carefully and address them in the following in detail.

We admit that our Discussion Section in the revised manuscript is still too long and tried to structure the manuscript following your recommendations.

Additionally, we agree and decided to move the circuit experiment to the supplementary material and only keep a small section, where we discuss implications to our field monitoring measurements.

### **General comments**

#### **Structure and clarity of the discussion section**

Mainly in the discussion section, there are still some parts of the manuscript, which are hard to follow as they mix literature reviews (introduction), data processing (methods), presentation of data (results) and discussions. In my specific comments below, I provide some suggestions on how these passages could be improved by more clearly structuring the manuscript.

We agree and followed the suggestions of the reviewer.

#### **Reference circuit experiment (section 4.1.1)**

The new electric circuit experiment provides interesting extra information on the performance of the field equipment in a high-resistance environment. However, strongly suggest moving the entire section to the supplementary material for two reasons:

**Structure:** An entire experiment should not be presented in the discussion section. In case you decide to leave the study in the manuscript, please consider presenting the experimental method in the methods section, show the results in the results section and discuss the implications in the discussion section.

**Scope of the experiment: I doubt that this experiment carried out under laboratory conditions (perfect coupling of current into the test circuit, no significant spatial extension of the layout, etc.) would be able to assess the full error due to the various coupling effects occurring in a real field measurement. It should rather be taken as a lower bound of the expectable error, i.e. the error in the field data might be much higher than this.**

We thank the reviewer for these helpful suggestions and decided to move the circuit experiment to the supplementary material. We only kept a small section, where we discuss implications to our field monitoring measurements. We also agree that this laboratory experiment represents the lower bound of error that we can expect at the field scale. Hence, we tried to make it clear within the discussion section.

#### **Specific comments and technical corrections**

- 1) **Line 34: about -> of**  
We agree with the reviewer and adapted the sentence accordingly.
- 2) **Line 50: ... the interpretation... are... -> ... the interpretation... is...**  
We agree with the reviewer and adapted the sentence accordingly.
- 3) **Line 67: ... the enhanced polarization response at... -> ... the enhanced polarization response of water ice at...**  
We agree with the reviewer and adapted the sentence accordingly.
- 4) **Figure 1: If the shaded map comes from TINITALY, why the credit "Google Maps" in panel 1?**  
Thank you for the indication, we removed it from the figure.
- 5) **Line 137-139: Refer to (Fig. 2b).**  
We agree with the reviewer and adapted the sentence accordingly.
- 6) **Figure 2, caption: Please specify at which point in space the snow height is measured!**  
We agree with the reviewer and adapted the caption accordingly.
- 7) **Line 154: Add a "." after "(not shown)"**  
We agree with the reviewer and adapted the sentence accordingly.
- 8) **Line 158: "sums are" -> "is"**  
We agree with the reviewer and adapted the sentence accordingly.
- 9) **Line 176: "for low frequencies < 1 kHz" -> this limitation is not necessary here, please consider removing!**  
We agree with the reviewer and adapted the sentence accordingly.
- 10) **Line 189: "to fit a" -> "to reliably fit a"**  
We agree with the reviewer and adapted the sentence accordingly.
- 11) **Line 201: "polarization effect... are..." -> "polarization effect... is"**  
We agree with the reviewer and adapted the sentence accordingly.
- 12) **Line 217: Please consider adding a brief explanation of the concept of super cooling!**  
We added a description of supercooling in lines 481-482.
- 13) **Line 237, equation (9): In " $S_w$ " the S should be upper case.**  
We agree with the reviewer and adapted the equation accordingly.
- 14) **Line 242: "at relatively low temperatures" -> "at temperatures below 0 °C"**  
We agree with the reviewer and adapted the equation accordingly.
- 15) **Line 254: Please consider substituting "electronic conduction" by "high electrical conductivity".**  
We agree with the reviewer and adapted the equation accordingly.
- 16) **Line 265: "These MG" -> "The MG"**  
We agree with the reviewer and adapted the sentence accordingly.
- 17) **Line 283-285: In Fig. 3, low current injections are listed as additional filter criterion. Please check and add here or remove from Fig. 3!**  
We removed it from Fig 3, as this was not a criterion in our end-filter-criterion.
- 18) **Line 300: "in the error parameters" -> please consider adding "(i.e.,  $\Delta Z$  and  $\Delta\phi$ )"**  
We agree with the reviewer and adapted the sentence accordingly.

- 19) **Line 301: "...winter and higher..." -> "...winter, which are expected to result in higher..."**  
We agree with the reviewer and adapted the sentence accordingly.
- 20) **Line 315: "the error model" -> "an error model"**  
We agree with the reviewer and adapted the sentence accordingly.
- 21) **Line 315: Please consider introducing the error model and its parameters and explaining how the error model parameters are obtained from the NR misfits of magnitude and phase!**  
We added a short paragraph within lines 303-310, where we define the error model applied within our study.
- 22) **Line 320-322: This explanation of the DOI is not clear. What are  $m_1$  and  $m_2$  for a given inversion result?**  
We agree and added an explanation within lines 333-339.
- 23) **Line 334: "was chosen" -> "were chosen"; "and 2 m" -> "at 2 m"**  
We agree with the reviewer and adapted the sentence accordingly.
- 24) **Line 338: Please define the error model (by stating the equation) – here or further above (see comment on line 315)**  
See comment 22.
- 25) **Line 356-357: "We used a surface conductivity..." -> "We tested inversions with a surface conductivity..."**  
We agree with the reviewer and adapted the sentence accordingly.
- 26) **Line 373: Please also introduce geometry, arrangement and material of the current electrodes!**  
We agree and added 2 sentences about the geometry, arrangement and material of the electrodes.
- 27) **Line 376: From this description of the experimental setup it seems as if no measures were taken to avoid polarization of potential electrodes by the current through the sample. Most experimental setups remove the potential electrodes from the tested sample to avoid this effect. Please add a sentence or two to discuss this aspect and explain why this was not needed/possible!**  
During freezing, we had to ensure a direct contact of the potential electrodes and the measured sample, hence, investigations concerning possible sources of error arising due to the contact between potential electrodes and the tested sample (e.g., Wang and Slater, 2019) and where out of scope of this study. We added a sentence within lines 394-396.
- 28) **Line 399: "no variation" -> "no significant variation"**  
We agree with the reviewer and adapted the sentence accordingly.
- 29) **Figure 5a: Add a blank space between numbers and units (two times "2 m").**  
We agree with the reviewer and adapted the figure accordingly.
- 30) **Line 410: "absolute phase values" consider adding "(only  $\phi_{75}$ )"**  
We agree with the reviewer and adapted the sentence accordingly.
- 31) **Line 414-416: At which (approximate) depth is the bedrock being detected? Please add this information to the sentence!**  
We agree with the reviewer and adapted the sentence accordingly.
- 32) **Line 420, table 2: What do the abbreviations AL and PF mean and where exactly can these materials be found along the profile?**  
We agree with the reviewer that this is misleading and added a description within the table and the description of the table.
- 33) **Line 459: Fig 7a and 7b do not show freezing and thawing cycles, respectively.**  
We agree with the reviewer and adapted the sentence accordingly.
- 34) **Line 461: "and cooling" -> "and during cooling"**  
We agree with the reviewer and adapted the sentence accordingly.
- 35) **Line 464-468: units and "per" should not be type set in italic.**  
We agree with the reviewer and adapted the sentence accordingly.

**36) Line 472-474: “Additionally, we observe a lowering of the freezing point of water due to ions being excluded from ice formation and accumulating in the liquid phase”. Which specific observation supports this interpretation? Please provide a short explanation/justification for this statement!**

We added a description of the supporting observation within lines 492-493.

**37) Figure 7: Add labels “a)” and “b)” to the panels of the figure! Add unit “(-)” to the phase frequency effect in 7b.**

We agree with the reviewer and adapted the figure accordingly.

**38) Line 490 and caption to Figure 8: How are the “vertical 1D logs” obtained (extraction from 2D sections or borehole log)? Please provide a brief explanation!**

We agree and clarified the statement within the text and the caption of Figure 8.

**39) Figure 9: Please consider using the same colors for both the variations of temperature and electrical parameters at the identical depths. This would reduce the legend and make it easier to compare the various time series amongst each other.**

We considered all suggestion of the reviewer and adapted the color of the first subplot of Figure 9.

**40) Line 616: “and unfrozen” -> “and the unfrozen”**

We agree with the reviewer and adapted the sentence accordingly.

**41) Line 621-622: “Supercooling... at the same temperatures...” This is discussed in the context of Figure 12, which does not contain temperature information. Please detail!**

We agree with the reviewer and adapted the sentence accordingly.

**42) Line 634-654: This section is quite confusing: It introduces complicated concepts and approaches used by other authors (which do not directly link to the section title “Temporal variability of the phase-frequency effect and unfrozen water content”) but finally reaches the conclusion that these concepts and approaches cannot be applied to the present data set. In order to improve the clarity of the (still lengthy) manuscript, I strongly suggest removing this section.**

We can understand the point made by the reviewer and drastically shortened the paragraph.

**43) Figure 12:**

- c) Add unit “(-)” to UWC on vertical axis
- c) What is “S”? Please explain in the caption or remove from vertical axis!
- Please consider stretching the legend over the entire width of the figure to reduce the large white space.
- Legend: “20m” -> “20 m”

We agree with the reviewer and adapted the figure accordingly.

**44) Line 671: Figure 12 does not show ice-content data. Please check and eventually rephrase!**

We agree with the reviewer and adapted the sentence accordingly.

**45) Line 671: Actually, only Figure 8d shows a clear relation between  $\phi_{FE}$  and the PJI ice content. Figures 8a and 8c do not show a clear relation between these two parameters.**

We agree with the reviewer and adapted the sentence accordingly.

**46) Line 672: “the proposed parameter” -> “ $\phi_{FE}$ ”**

We agree with the reviewer and adapted the sentence accordingly.

**47) Line 691-692: Fig. 13a and 13d show  $\phi_{FE}$ , not Fig. 13b and 13c. Please check!**

We agree with the reviewer and adapted the sentence accordingly.

**48) Figure 13:**

- Add labels “z (m)” to all vertical axes.

- a) Add unit “(-)” to phase frequency effect on horizontal axis.
- b) Add unit “(-)” to phase frequency effect difference on horizontal axis.
- c) Make sure the legend does not mask the data!
- **Caption: “difference”, “Aug22” and Aug20” should not be set in italic.**

We agree with the reviewer and adapted the figure accordingly.

**49) Line 719-721: Please consider breaking down this confusing sentence into clear sentences.**

We agree and adapted the sentence accordingly.

**50) Line 721-733: Please consider moving this part to (or merging this part with the corresponding part of) the introduction! There is no direct link with the section title “Comparison of the phase frequency effect and PJI ice and water content estimations”.**

We agree and incorporated this part within the Introduction section.

**51) Lines 733-738: These practical considerations do also not have any direct link to the section title but rather describe the research gap addressed by this study (move to introduction?).**

We agree and incorporated this part within the Introduction section.

**52) Line 747-765: These are rather considerations regarding the inversion approach. Please consider discussion these inversion-related aspects in a separate subsection to help improving the clarity of the manuscript!**

We prefer to keep these lines within this part of the discussion, as we do not want to open a new chapter.

**53) Line 760: “int” -> “in”**

We agree with the reviewer and adapted the sentence accordingly.

**54) Line 766: Which particular observation in Figure 14 “evidences an over-estimation of the ice-content in the active layer through the PJI”? Please detail!**

We added a description within line 766.

**55) Line 787: “... due to changes in porosity such as fractures at depth...” As this manuscript does not present any data on fractures etc., this statement remains completely unsupported/speculative. Please check and eventually rephrase!**

We agree with the reviewer and adapted the sentence accordingly.

**56) Figure 14:**

- **Upper panel: To which date does the resented phase frequency effect data correspond?**
- **Lower panels: The legends should not mask any of the data points**
- **Lower panels: What does the symbol size indicate?**

We agree and changed Figure 14 accordingly.

**57) Line 800: Empirical petrophysical models linking SIP response and ice content have been proposed earlier (e.g., Zorin and Ageev, 2017).**

We agree and added the reference to line 800.

**58) Line 815: As discussed in the respective general comment, I strongly suggest not to consider the error level observed in the electric circuit experiment as “the accuracy” but rather a lower bound of the error level to be expected in the field.**

We agree with the reviewer and adapted the sentence accordingly.

**59) Line 828: “Cole-Cole” -> “Cole-Cole model”**

We agree with the reviewer and adapted the sentence accordingly.

#### **Additional references**

**Zorin, N. and Ageev, D.: Electrical properties of two-component mixtures and their application to high-frequency IP exploration of permafrost, Near Surf Geophys, 15, 603 – 613,**

<https://doi.org/10.3997/1873-0604.2017043>, 2017.

19/04/2024, Matthias Bucker  
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**Dear Authors, thank you for the revised version of the manuscript.**

**I only have 2 comments which I have detailed below.**

**Figure 7: I understand that additional panels were added with combined freezing & thawing for both loose and solid samples.**

**I suggest removing the initial 4 panels (with green and purple plot curves) as they repeat the same data. The final 2 (new) panels give the complete picture.**

Our intension was to delete the old figure and replace it with the new one. We excuse if there was a mistake and make sure that the new version of the manuscript is correct.

**Line 925: Is "less sources of noise" a realistic explanation for the discrepancy between laboratory and field datasets? I ask because noisy data would mean randomness, however, in these results there seems a trend that both app. resistivities and phase shift trend higher.**

**Secondly, only the apparent resistivities and phase shifts are compared, so the justification of contrasting porosities impacting inversion does not fit here. Perhaps I have misunderstood.**

**I agree that shorter field dipole lengths must be used for a more realistic comparison, i.e., comparable to the laboratory sample size. I also agree that more datasets should be collected to check if this trend continues.**

We agree with the reviewer that our answer was misleading and adapted the paragraph concerning contrasting phase values of laboratory and field measurements. In our opinion the explanation for the discrepancy between laboratory and field datasets consists in larger heterogeneities (according to Fig. 5) and variations in the volumes of investigation at the field scale as well as different sources of contamination in the field data such as electromagnetic coupling effects, which we can reduce to a minimum in the laboratory.

**Many thanks and congratulations again for this exciting research output!**

We again would like to thank you for all your helpful suggestions.