Referee #1

The authors present a very coherent and complete literature review on the various applications for detecting IRHs in radagrams, a very challenging and important problem. This is a very useful paper for anyone who wants to study IRHs and develop novel methodologies for automatically identifying them. I really enjoyed reading this review and I believe that the paper contributes to the existing literature and should be published subject to minor corrections.

- We thank the reviewer for their effort to go through our manuscript and provide the feedback.

My comments are given below:

The authors should consider mentioning at the introduction that radio-echo sounding is also often referred to as Ice Penetrating Radar (IPR) or radioglaciology.

- The authors follow the suggestions by Schlegel et al (2022, Ann. Glac.) about radar/RES terminology. But we can add IPR as well for completeness.

Line~ 40: Matlab is referenced as a software for processing radar data and automated mapping of IRHs. Although I am sure there are some Matlab scripts that can do that, Matlab in general is a high-level programming language and should not be referenced as a radar processing tool. The authors should also reference Geolitix, which is a recent commercial software that is used quite extensively by the GPR community nowadays. The unique thing of geolitix is that it is web based. Regarding Matlab, there are some packages for example “GPRlab: A ground penetrating radar data processing and analysis software based on MATLAB”. But I have never used them, so I cannot comment on the quality of these tools.

- Thanks for the point. We will incorporate Geolitix, and correct the mistake with Matlab and name the relevant Toolboxes.

Line~ 60. The authors mention echograms are also known as radagrams. I would also add the term B-Scan, which is also widely used by the community.

- Thanks for this point. In 2.2, we have mentioned A-scope and Z-scope. We will include B-scan (B-scope) as well.

Line ~ 80. I would suggest the reviewers to add the well-known book of David Daniels “Ground Penetrating Radar” as a reference.

- We will add this reference.

Line ~ 85. The authors refer to radioglaciology as a remote sensing methodology. This term might exclude the ground-based in-situ systems.

- It is mentioned there as a remote sensing method to emphasize its main difference to satellite imagery. But we will make sure to clarify that ground-based systems are also RES systems.

Line ~ 85: The authors mention that the waves are reflected by changes in the "complex permittivity" of ice. I believe it would be better to use the term “dielectric properties” instead of

“complex permittivity”. Dielectric properties are more inclusive and hold as special cases the complex permittivity, conductivity and magnetic permeability. It would be better also to explain the term “dielectric properties” because in paragraph 95 it is said that the main source of reflections of IRH are changes in conductivity while in previous paragraph you mention complex permittivity as the main source of reflections.

- Thank you for your meticulous point. We acknowledge that different terminologies for radioglaciology have been used throughout the decades, but we have decided to use the most conventionally-accepted ones for this review article. We will use the broader term dielectric properties.

Line ~ 90. The authors refer to similar references as they refer them on paragraph 80 for the same context. I think there is a repetition here that can be avoided.

- This is indeed a repetition, we will remove and refer to the line ~80 (2. background) section.

Line ~ 95. The abbreviation IRH is previously already defined.

- This is a repetition, we will remove that.

Line ~ 95. The authors mention that the main source of reflections of IRS is the change in conductivity, while at Line~85 they mention that reflections occur due to complex permittivity.

- The complex permittivity is more general so we change this to complex permittivity.

Line ~ 100. The authors mention that crystal orientation fabric can also result in reflections. How does this translate to dielectric properties? In the reference given by the authors (Eisen 2003) it is stated that there are evidence that suggests that changes in permittivity and not conductivity give rise to reflections in IRHs.

- The reference should be Eisen et al. 2007 (https://doi.org/10.5194/tc-1-1-2007), where it has been discussed that COF-related IRHs stem from conductivity. Changes in COF can occur along IRHs (together with conductivity) but also independently of conductivity. We will clarify this.

Line ~ 105. I would suggest the authors to use the term B-Scan as well as echogram and radargram.

- As previously stated, we will note that.

Line ~ 105. Along A-scope I would also suggest the term A-Scan.

- This will be added in parentheses.

Line ~ 115. The authors discuss Figure 1, where an example of old traces is illustrated, where traces needed to be differentiated. I think it would be better to show more recent radagrams that don't need to be differentiated.

- As this review aims to be comprehensive, we have decided to include this example to include also older systems. Not including those system would mean to exclude a lot of data.

Line 127. Typo “…. a simplified schematic of a …”

- We will correct that.

Line ~ 130. The authors state “The red lines in the radargram indicate IRHs. In an ice sheet, these represent the interfaces between the neighbouring ice layers of different properties, such as layers with different density or crystal orientation fabric, or they can be caused by thin individual horizons with higher conductivity, thus forming IRHs”. From the above I understand that interfaces caused by changes in conductivity (and not permittivity) are IRHs?

- Conductivity is mentioned as an example for some of the properties. As mentioned in Line ~85, IRHs are caused by complex-valued permittivity, which includes both conductivity and permittivity. In the first part of this mentioned text, the density is mentioned which is caused by change in permittivity, but only in the top few hundred meters, only not mentioned.

Line ~ 170. Reference is needed there to support this statement.

- We will add Winter et al. 2019 (cited also in the paper) for the sentence “ The IRHs in snow and firn... “. However, for the subsequent statement “This is the foremost reason …” is an observation by the authors.

Line ~ 135. This statement has been repeated many times in the text so far, and I believe that could be omitted.

- That is correct, we will remove that.

Line ~ 190. It would be good to outline the limitations and advantages for each type of methods.

- This has been mentioned for some of the methods (in section 4), however, we will add this to the methods as much as it can be relevant. This is because each method can be implemented differently and could alter in terms of limitations. We will add general remarks on the limitations, advantages and weaknesses.

Line ~ 210. “..avoidance of having discontinuities”, I would add “..avoidance of having discontinuities between splines”.

- Thank you for the suggestion, we will incorporate that.

Line ~ 225. Both Level Set Function and Snake are part of the Active Contour methodologies. The authors should consider adding them as subsections in the same section “Active Contour”.

- Thank you for the suggestion, we will merge them into one “Active contour section”.

Line ~ 250. The Radon and Hough transform are very similar. To my understanding the Hough transform is a discreet version of the Radon transform.

- Thank you for the suggestion. This is implicit in the text, but we will explicitly mention that.

Line ~ 290. This is a very generic definition of support vector machines (SVM). The original support vector machines fit hyper-planes, but with the Kernel trick SVM can deal with non-linear boundaries. Also SVM can deal with multi-class problems using strategies such as one vs one, or one vs all.

- Thank you for the suggestion. This is a detail but correct observation. We will add the note about SVMs ability to deal with multi-class problems.
  Section 3’s short description of each method are meant to be to some extent generic, as the

aim is to explain the methods in general and not necessarily how they can be used for IRH tracing.

Many of the sections that define the methodologies 3.1-3.12 are flagged as AI-generated text, which often results to read very generic and definitional.

- The authors have checked with a couple of AI-detector softwares and sections 3.7 to 3.11 seem to show that some of the sentences are AI-generated. However, as clearly stated at the end, no sentence or clause were AI-generated or AI-refined. As the AI-detector are not reliable, they can detect erroneously.

Section 3.12. Flagged as AI generated. This is a very detailed and out of scope explanation of deep learning. I believe that this paragraph is not necessary. Otherwise another paragraph is needed to define what is machine learning prior to describing Support Vector Machines.

- We have considered to summarize and simplify the text in some of the subsections of section 3 to facilitate readability.
  At the time that this referee's comments were out, the authors checked LuCun et al. 2015 (oi.org/10.1038/nature14539) paper with AI-detector websites and some of that text was also flagged as AI-generated. This is an indication of the immaturity of the AI-detector tools. Also, the authors checked section 3.12 with some AI-detector tools and it was not flagged as AI-generated.

Line ~ 345. The authors state that U-net is a type of autoencoder. An autoencoder outputs the same inputs i.e. is an un-supervised learning method that has the same inputs as outputs. U-net can be an auto-encoder if the inputs and outputs are the same, but U-nets can also use different inputs and outputs. The paper cited by the authors (Ronneberger et al., 2015) is the first introduction to U-net, used as a segmentation tool, therefore not as an autoencoder.

- Thank you for highlighting this important point. This is correct. U-net, although is similar to autoencoders because of its encoder-decoder structure and can be used like one, it is not an autoencoder. It differs in terms of input-output, purpose, and skip connections. We will correct the text accordingly.

Line ~ 395. The authors state "Over the last decade, various studies have put forth the use of pattern recognition methodologies in the examination of ground-penetrating radar (GPR) signals (e.g. Delbo et al., 2000)." The reference is from 2000 so it cannot support this statement.

- We will use more recent references.

Line ~ 435. Typo "….a semi-automatic picking routine…"

- We will correct that.

Line ~ 436. Typo " …the maximum amplitude of each…"

- We will correct that.

Chapter ~ 4.1. It is not clear why some references are in bold font while others are not.

- Throughout section 4, bold references are the ones that are included in Table 1, as they are the references which have performed the similar task of tracing IRHs or segmenting

radargrams. We have decided to bold those references (in their first mention) to indicate that the summary following belongs to that publication, for the interested readers to refer to for further information.

Line ~ 785. This is a very big paragraph that needs to be divided into smaller ones.

- Section 4 paragraphs are meant to be similar publications bundled to each other. However, we will consider this and make necessary changes in order to facilitate readability, such as shortening paragraphs.

In Figure 7, would it be easy to include machine learning (not deep learning) related papers as well?

- We assume the referee means to separate SVM and similar methods as Machine learning methods. We will consider that, although this will be only few papers, it might be a better categorization to separate them. Thank you for pointing it out.

The authors should use some figures from the most important cited papers to illustrate the results of the methods discussed in chapter 4. It would be good to showcase with some visual examples how these methods work.

- Including figures from some of the papers is potentially a good idea. However, considering the current length of the paper, it would not make sense to extend it even more. We hope that the description of each paper suffices to encourage the readers to check out the papers that are interesting to them. We will consider to add more figures during the revision where those might really provide added values without lengthening the manuscript too much.