Comment on tc-2022-174
Anonymous Referee #1

Referee comment on "In-situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory" by Rasha Abbasi et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2022-174-RC1, 2022

Review of the manuscript entitled, “In-situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory” submitted to The Cryosphere

This study discusses propagation patterns of the ~400 ns wavelength light wave (or photons) within a thick ice sheet at South Pole, Antarctica, with a local condition of the crystal preferred orientation (CPO), grain shape and size of polycrystalline ice. The authors (a team of very many people) used ~5000 photomultipliers installed within the ice sheet, as IceCube Neutrino Observatory instruments. Through procedures for calibration of the light emitters and the receivers, the authors discovered unexpected light propagation effect within the ice sheet. The authors described it as “an anisotropic attenuation”. It is orientation-dependent variations of the received light, which has directional dependence of wave propagation along the flow direction of the ice sheet. The authors examined birefringence of ice crystal grains, that is, anisotropic properties of reflections and refractions at ice grain boundaries, birefringent propagation within each crystal grains, as well as additional effects from grain shapes and sizes as possible main causes for the observed effect. The authors examined both orientation dependent scattering effects due to impurity-related inclusions and various effects related optical birefringence of ice. They claimed that they made a model that is quantitatively accurate for optical properties of the IceCube glacial ice. They found an explanation as to why curved light trajectories occur resulting from asymmetric diffusion. To harmonize between simulated effects using their model and the observational data in the field laboratory, the authors raised a possibility that ice crystal may have anisotropic absorption properties and stress-strain induced changes in optical properties, which is still unknown in the research field of ice physics.

General comments
I put number to each section of comment.

[G1] This is an interesting and informative paper in which the authors examined propagation of light wave (photons) within the thick polar ice sheet, using a local area (~1 km$^3$) of the ice sheet as a field laboratory. Ice has special crystal orientation fabric and undulation of internal layers in the vicinity. To my knowledge, there seems no prior studies who found or explained propagation of light wave within a condition of a particular crystal orientation fabric. Basic investigations that the authors performed seem sound, such as CPO, grain shape and size, and propagation of light wave within polycrystalline ice.

I must confess that for a few sub-sections of the manuscript, I found difficulty to understand.

The study also clarified that there were still many major unknowns, such as anisotropy in imaginary part of the refractive index of ice single crystals (in crystal lattice) or stress/strain induced properties. I must note that there is major uncertainty in the discussions. Possibilities that the authors raised – ice crystal lattice should have both anisotropic absorption properties and stress-strain induced changes in optical properties – may be either correct or incorrect. If it is correct, we must find yet-unexplored physical properties of ice. If the hypothesis is incorrect, there can be major points to reconsider, repair or modify in their models. Questions are open now. My concern is that in this study there are accumulated errors in model simulations, and then possibly false reasons are examined attempting to explain them, without knowing they are errors.

[G2] This paper is useful and important for people who analyze Cherenkov light in the IceCube project. They need to know accurately how light wave have nature of light propagation in glacial ice. In terms of cryospheric sciences, it may provide insights into crystal properties in the ice sheet. What seems robust and new is light propagation within preferred orientation of ice lattice, grain shape and size and grain boundary network. In terms of cryospheric sciences, immediately useful practical applications are not clear at least for me.

[G3] In this paper, many factors that can affect propagation of light wave were discussed. However, I felt that they are not well listed or summarized to be understood comprehensively. The authors tend to list them one by one in different sections within the manuscript. Sometimes they were mentioned only conceptually and vaguely such as “the first-order principles”. I suggest that the authors should provide a table (or tables) as supplementary information, listing items, shape and size of the items, state of presence (or distribution), possible effects in terms of light wave propagation, reference papers, and notes (such as unknown, hypothesized by this work, and so on). Such tables will help better understanding. Possible items that are useful for readers are, for example, as follows.
I. Ice matrix items that can cause effects of reflection, refraction, scattering or absorption.

Anisotropic refractive index (real part) of ice in each crystal grain

Crystal Preferred Orientation

Grain shape and size

Distribution network of grain boundaries in terms of ice fabric, grain shape and size

Distribution of triple junctions of grains in terms of ice fabric, grain shape and size*

*The authors did not mention it. But it is one of major locations for presence of impurities. See Stoll et al. (2021) given in [D19] below.

Anisotropic refractive index (imaginary part) of ice in each crystal grain

II. Clathrate hydrate inclusions

Number density, size distribution and possible localization within ice matrix.

III. Various inclusions

Dust (Number density, size distribution and possible localization within ice matrix).
Salt particles (Number density, size distribution and possible localization within ice matrix).

Acids (State of presence and possible localization at triple junctions)

Soot (Number density, size distribution and possible localization within ice matrix)

Volcanic ash (Number density, size distribution and possible localization within ice matrix)

Possible alignment of these items along some orientations

Possible effects from stress/strains or pressures

Also, the authors cited an old textbook by Hobbs published in 1960s. Rather than citing such old very thick textbook, I suggest the authors to cite responsible original papers which really addressed points. For readers it is hard to find out points of discussions in thick textbooks. Also, similar situation occurs when citation is PhD thesis.

[G4] As for citations for the glaciology-based information, there are points that seems necessary to be updated, or more proper papers should be cited. In detailed comments, I will comment one by one.

[G5] My concern as for the structure of the paper is sequential order of Section 4.3 and Section 5. Section 4.3 discusses early empirical modelling, given just after the observational results (Sections 4.1 and 4.2). When we think about glacial ice as a media of light propagation, it seems natural that light diffusion in birefringent polycrystals should be taken as one of substantial bases. This phenomenon should have priority to be discussed. And then, empirical modelling related to absorption should be provided as the item with secondary priority because in this aspect modelling attempt does not seem very successful to explain observations. In addition, assumptions for directional dependence for absorption seem to be suffered from lack of observational evidence.

For readers, they need to be informed, with an order of importance. Present order will tend to confuse readers, as I felt so.
Main text alone has 14,000 words. The paper is very long. For a better readability, this can be more concise, by sending some parts to supplementary information.

**Detailed comments**

[D1] Abstract, Lines 4-5:

I suggest that “Birefringent light propagation has been examined” can be modified as “Birefringent light propagation through networks of ice grain boundaries has been examined” (or something like this) to stress substantial points, medium of propagation, in this study. It seems that birefringence is one of components in the model. But it seems that grain boundary network closely related to ice fabric is also one of essential conditions. The authors termed as “birefringence model”. My concern is adequacy of this vague wording. Please choose more concrete terms.

[D2] Abstract in general:

Readers of this paper will wonder if this paper discusses polycrystalline properties, ice lattice properties within single crystal, or both. Indeed, this paper discusses both. Please consider a possibility that the authors already mention these key points in the abstract. It seems fairer then.

[D3] Abstract, Lines 6-8:
Only polycrystalline properties are given. How about lattice properties?

[D4] Citations in general:

It seems to me that several citations require "e.g.," because they are not unique choice of possible citations. In the introduction, Cuffey, McConnel, Faria, and Alley papers (books) are such examples. Cuffey citation is a textbook where established knowledge is reviewed. McConnel is a very old paper. Anisotropy in plastic deformation of ice was reviewed in many textbooks of ice, such as Hobbs, Petrenko&Whitworth etc. Rather than giving only one, the most original paper, it is beneficial for readers to find recent textbooks as well. Alley 1988 is one of papers in which the measurement method was applied. I suggest that useful method papers for readers include, as follows.


[D5] Lines 20-21:

The authors mention only a case of growth of vertical girdle fabric here. At this stage of this paper, the authors should assume that readers do not know how special the cases of the vertical girdle fabric are. The authors need to specify type of strain, compression, extension, or shear. If the authors express c-axes orthogonal to the strain, it is response to the extensional strain or convergent ice flow.

[D6] Lines 22-23
This statement is wrong: vertical girdle fabric is typical only at ice divides and in convergent flow. They are rather limited zone in the ice sheet. It will not occur in divergent flow or simple laminar flow.

[D7] Line 23 “aforementioned scenario”

Despite these words, it was not mentioned before in this manuscript. It seems that this manuscript takes the girdle fabric as a basis. Please inform non-specialist readers of more general aspects, such as relations between type of strains and consequent preferred orientations of the c axes.

[D8] Lines 29-30, citation of Linow

Linow et al. (2012) discuss a very special case of firn, and not ice-depths below pore close-off. In ordinary ice cores using X-ray CT, we will not observe presence of grain boundaries, grain volume or grain elongation. Please rewrite and repair this part of description. Please do not mislead readers. In addition, X-ray CT is available even for whole cylinder of ice cores. Please look at Freitag 2013 paper indicated below for example. Thus, "these techniques further restrict the sampling volume" is not correct as a general statement.


[D9] Lines 30-31:

It is sudden that the authors mention thin slices here. It is nothing to do with previous sentences.
I suggest that a method described in papers below is available for detection of ice fabric using thick volume of ice core using radio-wave birefringent nature of polycrystalline glacial ice. Because your context is on limitations of earlier methods, these seem necessary citations.


I did not understand a relation between "can not only be imaged in ice cores" and the rest of this sentence. As for meaning, I did not find good link.

Optical anisotropy

Term is vague. Please specify as optical anisotropy of polycrystalline glacial ice, single crystal, or both.
The effect was originally modelled as a direction-dependent modification to Mie scattering quantities, either through a modification of the scattering function as proposed by Chirkin (2013d) or through the introduction of a direction-dependent absorption as introduced by Rongen (2019). As also shown by Rongen (2019), both parameterizations lack a thorough theoretical justification and resulted in an incomplete description of the IceCube data.

Please specify, at least, how these authors assumed sources of scattering or absorption. Otherwise, readers do not easily understand what kinds of studies they have done before unless they visit these papers and read closely. Also, it is hard for readers to explore someone’s PhD thesis.

grain size

Please specify size range, to provide not only concept but also range of quantity.

grain boundary properties

What kind of properties? Please specify to readers, to provide not only concept but also concrete physical basis.

Please explain to readers about physical mechanisms responsible for the scenario of the diffusion. Things are explained rather conceptually around this part of the paper.
Bubble – clathrate hydrate transition occurs as a thick zone ranging several hundred meters. Please let readers know it.

When you express as “ice”, please specify whether it is polycrystalline glacial ice or intrinsic nature of single crystal of ice. Otherwise, it will be one of sources of confusion for readers. When you discuss nature of absorption or scattering, we need to know, if nature under discussion is polycrystalline ice with grain boundary network or not. Also, we need to know if nature is for ice that include various kinds of impurities/inclusions or not. Please be careful on this point throughout this manuscript.

Specifically at lines 137-138, please clarify if Warren and Brandt assessed nature of ice sheet ice or not.

The impurity constituents are believed by He and Price (1998) to be dominated by mineral dust, marine salt and acid droplets as well as (volcanic) soot.

I understand that He and Price (1998) paper summarized possible materials that can interact with light, with their knowledge in 1998. However, there are advancement of science in cryospheric sciences.

I suggest that the authors to consider providing updated knowledge, rather than drawing attentions of readers to old belief of 24 years ago.

Just as an example, I provide one of possible statements.

The impurity constituents are dominated by insoluble mineral dust, salt components, liquid
Phase acids, soot and volcanic glass (e.g., Arienzo et al., 2017; Barnes et al., 2003; Narcisi et al., 2005; Sakurai et al., 2011; Stoll et al., 2021).

Points: Belief by He and Price seems old to cite here now in 2022. Chemical reactions related to salts are much more understood nowadays. Various chemical reactions occur in the atmosphere during transport of aerosols and in snow and firn to general salts and acids in ice. In addition, soot is not related to volcanic eruptions (though there may be exceptions). Droplet does not seem proper wording. Acids sometimes exist at grain boundaries as liquid depending on components, temperature, and chemical reactions. Particles that come from volcano is glass shards.

Here, possible citations are as follows. There are much more choices.


In addition, as for clathrate hydrate crystals, a paper below seems informative for examination of light wave propagation, even if the authors evaluate possible effects are negligibly small. In the present paper, you are discussing weak changes in refractive index. There is huge amount of clathrate hydrate crystals in the ice sheet. Thus, readers need to know this presence is properly assessed by the authors.


[D20] Line 145:

I suggest that “climatological conditions” can be “climatological conditions such as dusts and aerosols in the atmosphere in the past” to be more concrete.

[D21] Lines 170-171:

The authors wrote as “The limited volume of the ice cores does thus not allow for a direct measurement of optical properties, even though they are able to inform on the impurity constituents and their size distributions.”

It seems a vague and subjective statement. There should be many methods to directly measure “optical properties” of ice. You state generally as optical properties; it seems impossible to provide a statement like this. You mention propagation through distance of 100-400m. If we can prepare proper experimental setting, we may be able to detect it.

Later at lines ~290, you showed directional dependence of the signal was double for propagation of 125 m. If assume that directional dependence of the signal was 3dB / 100m as approximation, for diameter of an ice core (0.1m), it is 0.0003dB/0.1m. It is far better if the authors provide size of numbers that is necessary for a scale of ice core measurements.
Please clarify meaning of “ice realizations” to the readers of TC. I did not understand what was meant. My concern is that the same problem happens to many readers of TC.

$c_{\text{ice}}$ is not defined anywhere. I imagine it is speed of light in ice. I wonder if it is an expression commonly used in physics.

I did not find definition of scattering coefficient in the equation. Did you simply rephrase “diffusion coefficient” as “scattering coefficient”? If it is so, please make it clear to readers.

I was confused at multiple points. Please let us understand why this is inaccurate. Please let us know why an assumption of clear and layered ice causes problem? What do you mean with a word “layered”? Do you mean layers caused by deposition layering? Alternatively, do you assume presence of layered propagation paths?
From here, please note that my understanding after section 3.2 was bad, even after reading the paper many times. I ask the editor to find a reviewer who can fairly evaluate these sections.

[D26] Section 3.2 in general

I did not understand how your Photon Propagation Code (PPC) was used. Please let readers know how you assumed many physical properties of ice and inclusions, in your PPC calculations.

[D27] Sections 3.2 and 3.3 in general

It was hard for me to understand this part of the paper. Possibly, some scientists can understand these sections without difficulties.

[D28] Figure 5:

I did not understand the authors’ purpose of showing this figure. I wonder why mixtures of data from various origins were given here.

[D29] Sections 3.4
I did not understand the model “South Pole Ice Model”. It seems again vague words. What kind of model to analyze what? What are the parameters? If you call it as Ice model, again it seems vague as a term. Can it be ice flow model, light wave propagation model in ice, or ice sheet model related to absorption and scattering? Do you mean profiles in Figure 5 as layering model?

[D30] Line 274:

I did not understand meaning of “footprint of IceCube”. Is it related to footprint of the radar beam pattern in IceCube experiment area? Is it area and depth ranges where you covered by IceCube experiment? If true, why was a term footprint used?

[D31] Line 276 “laminar flow as described by Aartsen et al. (2013a)”

Are you describing flow regime of the ice sheet? Please state more in detail to make it understandable to readers. Also, the vertical girdle fabric should develop under conditions of convergent ice flow. If it is simple laminar flow, presence of the vertical girdle fabric should not be explained. Please provide a brief statement as to how this ice fabric developed within the ice sheet with laminar flow dominated by simple shear strains. Simple shear will give single pole fabric.

[D32] Line 281:

Please word “ice model” (again vague) as ice sheet flow model or something like this to make it understandable. By choices of terms, I was often confused.
“Ice optical anisotropy” does not seem proper term in physics because main topic in this paper is for the polycrystalline ice within the ice sheet. If wording is ice optical anisotropy, it is vague; not a few readers will first think about optical properties of single crystal ice. Wording something like “anisotropy in optical properties within the ice sheet” or “optical anisotropy in polycrystalline glacial ice” seem better. Please consider.

I did not understand statements related to elevation angle. My concern is that not a few readers will experience the same. Similarly, I did not understand a situation why this is a parameter which is hard to accurately obtain from ice core data. Please make it understandable.

I was again confused with reasons below.

- Photon counting perpendicular flow axis is larger than that along flow axis. It does not seem in agreement with Figure 6.
- On the left panel, a peak for the scatter case is at a timing smaller than a peak for the absorption case. I do not understand this timing difference.

I felt that the context became unreliable to read two lines here. If the impurity particles
are aligned due to stress/strain conditions, it should have been observed by ice core scientists. Is it along grain boundaries, along triple junctions, along dislocations or along crystal lattice? What kind of particles do you assume? Rather, how about alignment of triple junctions of grains along the normal axis of the vertical girdle plane (axis of tensile strain and grain elongation)?

[D37] Lines 357-386:

There is no subsection title only in this part of the manuscript. Please define what you would like to let readers know by providing proper subsection title.

[D38] Line 455:

I was not able to find Woodcock parameters in several reference papers given here. Please clarify.

[D39] Line 460:

I visited data set of Voigt (2017). Data are stored separately folder by folder; it was hard to grasp wide view in terms of depth dependence. The same situation will occur for many readers. For a better understanding, it would be nice that you prepare an appendix in which readers can browse crystal fabric pattern. It would be even more nice that Woodcock parameters are given together. Just examples from several depths will help.

[D40] A paragraph from line 462 to 475:
We can observe ice fabric, grain shape and size in Alley et al, 2021. Readers will wonder if your assumption of grain shapes agrees with reality. It is something difficult to evaluate only by reading this manuscript.

[D41] Line 477:

When you denote orientation as “tilt direction”, glacier researchers will be more familiar to a term “transverse direction”.

[D42] Figure 11:

Please explain in more detail what asymmetry of the distribution in the second and the 3rd from the left figures mean.

[D43] Figure 11 and Figure 12 right panel:

I believe that the special case “90 degrees to flow” will attenuate to zero at the end because of scatter at randomly oriented grain boundaries. Perhaps readers should know it if my understanding is correct.

[D44] Figure 13:

It would be useful for readers if you add materials as below.
(i) Elongation 1.0 case, that is, no grain shape effects and only fabric effects

(ii) In (S2/S3) 0.0 case, that is no fabric effects and only grain shape effects

[D45] Figure 13:

Please note to readers that the scales of the ordinate are different depending on rows.

[D46] Lines 583-584:

Elongation fixed to 1.4 does not seem the same as elongation given in Alley et al. (2021). In their slide at page 10, the maximum value is 1.24.

[D47] Lines 596: absorption anisotropy by a factor of 2.45

I find no reason to support or not because there are many items of unknown.

[D48] Line 601:

Cleaner seems a strange word. Even in case you intended to mean “more transparent”, it is not the case in the ice sheet. Degree of transparency depend on inclusions.
In two citations, both indicate much larger grain size. Thus, quantitative much seem questionable.