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# *Interactive comment on* "On the Green's function emergence from interferometry of seismic wavefields generated in high-melt glaciers: implications for passive imaging and monitoring" *by* Amandine Sergeant et al.

**Amandine Sergeant et al.**

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Sergeant et al. presents multiple approaches to extract Green's functions from the seismic record on the surface of glaciers. Such an effort is challenging and this study looks technically correct, but the manuscript needs several revisions. One potential major problem is the length of the paper. I found many paragraphs are not necessary after spending time to read through the article. Considering that this is not a dissertation nor textbook, reducing unnecessary texts makes the points of this study clearer. In addition to this, I provide specific comments below.

Thank you for your careful reading and comments. We improved the discussions you were referring to in the comments below. We shortened some parts, revised our writing and used fewer technical terms to smoothen the reading.

**Introduction:**

L36–37: The "crustal" and "local scales" do not look contrary. Probably "local to regional" or "regional to global"?

We modified to "from regional to local". Line 36

L39: What are the original observations? Please rephrase.

We now give additional details on the original observations: "Ambient noise studies have so far led to original observations such as thermal variations of the subsoil, spatio-temporal evolution of the water content, stress changes along fault zones with applications to geomechanics, hydrology and natural hazard". Lines 39-40

L60: Rather than theoretically, experimentally? If authors want to claim the condition is met THEORETICALLY, please explain which theory.

We rephrased the entire paragraph (Lines 65-68) being more precise on theoretical conditions (i.e. equipartitioned source wavefield) and the limitations of their applicability to the Earth which then ends up with the simplified assumption of a diffuse wavefield in practice. We replaced the specific statement you are referring to by: "The latter condition (ii) is sufficiently met only at high- frequency (> 0.5 Hz) in the inhomogeneous Earth's crust. Even if the noise wavefield is not generally diffuse (Mulargia, 2012), the presence of scatterers in the Earth's crust and the generation of oceanic ambient noise all around Earth make ambient noise interferometry applications generally successful."

L64: The statement looks the opposite. Considering that the next sentence is mentioning the source distribution, it sounds better to say: the condition (i) can compensate for the lack of condition (ii).

Thank you for reporting this. Indeed, the statement was incorrect and has been modified.

L80–81: Brief explanation is expected for "virtual reflector" if authors want to mention it here.

Instead of speaking of "virtual reflector seismology", we specifically refer to the process that was used in the referred study as "multidimensional deconvolution on a contour of receivers" and refer to section 6.2. for additional explanation.

**Section 2: Material and data**

L102: waves that => whose seismic waves

We modified as suggested.

L116: Moment magnitude? Local magnitude? Surface-wave magnitude?

We specified local magnitude.

Figure 1: Please label all panels: one panel below b and above d.

We changed the label accordingly.

L123: brief => short

We modified as suggested.

L151: Please explain why the authors use only the vertical component, while the sensor is three-component?

We add a paragraph to explain that using horizontal components from on-ice recordings require additional processing step to reorient the sensors (Lines 158-162).

L164: How long was the experiment? It should be explained beforehand.

The experiment was 5 week-long as stated in Line 164.

L166: Please make the sentence complete. GPS stations were deployed, and the DEM is used for later analyses?

Thank you for reporting this. We rephrased the sentence. Line 174-175

L167: What "GPR" stands for?

We modified GPR to Ground-Penetrating Radar.

L170: Insert space before: from

Space added

**Section 3: Glacier d'Argentière dense array**

L187–188: because of instrumental sensitivity => because of low instrumental sensitivity

We modified as suggested.

Figure3: ranging from 150 m to 250 m => either 150 or 250 m

We modified as suggested.

L213: anticausal => acausal. Please use the same word consistently throughout the Manuscript

Modified to "acausal". We checked for the whole manuscript.

L223: Why is it claimed to be correct?

We want to highlight here the differences in ICC and NCC arising from different source contributions. When compared to NCC, ICC quality is very much less sensitive to the orientation of the station pair because we control the icequake source distribution. We then obtain "correct" GF estimates for ICC, in the sense that spurious arrivals vanish when controlling the icequake source aperture. On the contrary, NCC yield to poor Green's function estimates at some station paths which are not aligned with the most abundant noise sources down/upstream of the array. We rephrased the sentence as: "The control of the icequake source aperture enables to minimize the spurious arrivals which are observed on some NCC (Fig. 3b) and obtain more accurate Rayleigh wave traveltimes at most station paths (Fig. B2b) " Lines 230-231.

L236: Fig. 3b => 3c?

We modified to Fig 3c

L240–241: ICC has limited energy at low frequencies just because spectral whitening is not applied?

ICC and NCC are both computed on spectrally whitened seismograms (for same frequency corners). The difference in ICC and NCC spectral energy mainly result from the spectral content of icequake seismograms. Indeed, icequakes have short duration of about 0.2 s and then do not carry much energy below 5 Hz. We specify this: "Reconstruction of Rayleigh waves and resolution of their phase velocities using f-k processing are differently sensitive for NCC and ICC at frequencies below 5 Hz (Fig. 3c versus Fig. B2c) as ICC have limited energy at low frequency (Fig. 4a) due to the short and impulsive nature of icequake seismograms (Fig. 1d-e)." Lines 245-247

Figure 5: What is "all" generated misfit values? Isn't it 2500, as explained in the main text? To calculate deviation around each node line, how long horizontal distance did authors consider?

Yes, it is right and we modified the text in the caption accordingly to the main text. Ice thickness uncertainty comes from inversion results reached for misfit values that are below one standard deviation of the 2500 best misfit values. This consideration generally gives a misfit value threshold of 0.02. We added in the main text additional details on how is calculated the misfit (normalized RMS error), Lines 266-267. A maximum misfit value of 0.02 corresponds to ground models which reproduce the data dispersion curve with an approximate error of 2%. The normalizing term for the misfit function is the standard deviation of the uncertainties of the data dispersion curve measured at each frequency. These uncertainties are larger at lower frequencies below 5 Hz because we have less redundant measurements at these wavelengths considering 450m-long profiles. We specify this in Line 273-274.

L282: What is "thickness absolute values"? Probably no need to say "absolute values" here.

"absolute" was removed.

L284: Why errors and uncertainties are linked to bedrock velocities? Is there any theory ? or is it just implied based on the result? Please explain.

Errors and then uncertainties in ice thickness (as derived here from the deviation of best-fitting ground models) are linked to bedrock velocities as stated few lines before (Lines 270-272: "Walter et al. (2015) explored the sensitivity of the basal layer depth to the other model parameters and report a trade-off leading to an increase in inverted ice thickness when increasing both ice and bedrock velocities."). Indeed, using the Greenland ice-sheet array, Walter at al (2015) find a best match for the ice-thickness of 540 m by fitting the Rayleigh wave dispersion curve obtained from match-field processing. They test the sensitivity of the result to the values of S-wave velocities when fixing them in the ice and in the bedrock. However, in our case, the velocities in the ice are very well constrained as all misfit values generally lower than 5% yield to Vs around 1700m/s. We did not perform any further tests like Walter et al, 2015 to assess the ice thickness dependency on the bedrock velocity solely. But from our inversions, we see that the ice thickness estimate slightly depends on the rock S-velocity (Fig 5b). We say on Lines 272-273: "Here the ice thickness estimation is most influenced by the rock velocities as we notice that a 100 m/s increase of basal S-velocity results in an increase in ice thickness up to 15 m" So our statement purely comes from observations and refers to the analysis of Walter et al, 2015. We add additional details Lines 273-374 about the errors and constraints on the bedrock velocities that also related to 3D effects and larger uncertainties on the dispersion curves at lower frequenciesÂă(see also answer above): "These results are moreover influenced by larger errors at lower frequencies (Fig. 5a) which comes from less redundant measurements at great distances."

Walter, F., Roux, P., Röösli, C., Lecointre, A., Kilb, D., and Roux, P.: Using glacier seismicity for phase velocity measurements and Green's function retrieval, Geophysical Journal International, 201, 1722–1737, 2015.

L315: Taking derivatives should not increase the number of cycles of sinusoids in the theory of math. Please rephrase the sentence.

This is a misleading from the terms we used. We modified "derivation" to "the formulation of equation 1 also gives rise to (...)"

L319: It should be explained earlier that they calculate "within 250 m of the target point".

We moved this sentence earlier to line 327.

L323: Please add explain "transversal crevasses" as "perpendicular to flow" here.

We now specify "transversal crevasses, i.e. perpendicular to the ice flow"

L331–332: The sentence of "However we do not exclude ..." is unclear. It sounds like some excuse for something but needs modifications to make it logical, definitely.

We rephrased the entire paragraph. What we want to point out is that our anisotropy measurements are not punctual but are averaged over the ice column given the consistency of the align-flow fast-axis pattern with frequency. At frequencies 10-15 Hz, the sensitivity kernels are not zero near the base of the glacier (Fig 4b). We then attribute the along-flow fast axis pattern to features at depth, likely a water conduit. We rewrote the paragraph as: "Alignment of the fast-axis directions with that of ice flow appears along the central lines of the glacier (receiver lines 4-5) with anisotropy degrees of 0.5% to 1.5%. This feature is only observed along the deepest part of the glacier where it flows over a basal depression. Results are here computed for seismic measurements at 25 Hz and maps of anisotropy do not change significantly with frequency over the 15-30 Hz range. If we extend our analysis down to 7 Hz, we notice that the aligned-flow fast-axis pattern starts to become visible at 10 Hz. At frequencies lower than 10 Hz, the fast-axis generally tend to align perpendicular to the glacier flow because lateral topographic gradients introduce 3D effects and non-physical anisotropy. The results presented here are not punctual measurements but are rather averaged over the entire ice column. The vertical sensitivity kernels for Rayleigh waves (Fig. 4b) are not zero in the basal ice layers at the considered frequencies. The align-flow anisotropic pattern is likely attributed to a thin water-filled conduit as also suggested by locations of seismic hydraulic tremors at the study site (Nanni et al, 2019)." Lines 335-340

L333: aligned-flow => flow-parallel

We did not modify the wording.

**Section 4: MFP at the Greenland ice-sheet**

L350: Short explanation of MFP is needed here. Especially, providing the direct purpose of the processing helps readers. Here, "to locate specific localize sources" would be appropriate.

We added the following short explanation: "One of the approaches we apply here is Matched-Field Processing (MFP) (Kuperman and Turek, 1997), which is an array processing technique allowing to locate low-amplitude sources. MFP is similar to a traditional beamforming that is based on phase-delay measurements" Lines 356

L361: "localized" is better than just dominant.

We removed "dominant" from the title of the subsection: L̈ocation of noise sources at the GIS via matched-field processing"

L380: frequency band of => frequency band between

Modified

Figure 7: frequency band of => frequency band between

Modified

L403: SVD itself is not a process to decrease the number of information, and therefore it is inappropriate to mention "as few coefficients as possible" in this sentence.

We corrected the sentence to: "SVD is a decomposition of the CSDM that projects the maximum signal energy into independent coefficients (. . .)."

L408: Are eigenvectors normalized to be unit?

U and V are unitary matrices, so their columns (eigenvectors) are unit vectors (e.g., |eigenvector| = 1) forming an orthonormal basis. We replace "orthogonal matrices" with "unitary matrices".

L409: Please choose either "singular value" or "eigenvalues" to be consistent throughout the manuscript.

We choose "eigenvalues" and modified the text accordingly.

L414: threshold in "singular values / eigenvalues"?

As above.

L415: Eigenvector is not a scalar, so it is inappropriate to say "eigenvector" above the threshold.

We changed the phrase to "the index of eigenvectors".

L426–427: Why it is thought to be related to frequency content differences? Different eigenvector does not necessarily mean they consist of different frequency contents.

We think that the dominant source (the moulin) is located either in the first eigenvector or the second eigenvector depending on the frequency. This can be related to the seismic signature of the tremor and the distinctive frequency bands of either elevated or suppressed seismic energy that can be also noted on the spectrogram of the hydraulic tremor (Figure 1c). We changed the following sentence: "This might be related to the change in the distribution of the dominant sources depending on the frequency related to the seismic signature of the hydraulic tremor and the distinctive frequency bands generated by the moulin activity (Figure 1c)."

L427: SVD => eigenvalue?

We mean the "eigenvalue distribution". We corrected the phrase to: "Moreover, the eigenvalue distribution decays steadily (. . .)."

L427–428: I do not understand why the number of ambient noise sources is more than the number of receivers based on this observation. Please explain this more logically.

We do not claim that the number of noise sources is higher than the number of receivers, but that the number of degrees of freedom (number of parameters that can be used to describe the seismic wavefield, ax explained earlier in the manuscript L:400-405) is higher than the number of receivers, as defined in Seydoux, 2017. This confirms that the wavefield is undersampled by the seismic array (see Seydoux et al, 2017 for details). We changed the phrase into the following: "The latter confirms that the wavefield is undersampled by the seimic array (see Seydoux et al., 2017) for details)."

L429: reconstructed => decomposed

Here we mean "reconstructed", as we talked about the reconstruction of the CSDM by using individual eigenvectors.

L430: Please use a different symbol for $K_i$, which is different from the previous $K_i$.

Thank you for this comment, we now use the symbol for the reconstructed CSDM.

L444–446: This explanation is too redundant: i.e., L431–432.

We removed the last two repeating phrases.

L461: wavenumber vectors are normalized => wavenumber is normalized We change the phrase to the following: "The wavenumbers $k_x$ and $k_y$ are normalized by the wavenumber $k_0$ corresponding to Rayleigh wave slowness s=1/1680 s/m."

L481: Why only one-day used in this study?

Please see our reply below.

L483: Again, it is too straightforward to apply the same analyses to the other day, but why authors are not interested in doing so as a part of this study?

We agree that it is straightforward to apply the same analysis to another day. For example, Figure R1 shows the same analysis for the 28th of July (the following day after the day presented in our study). Moreover, we can take it even further, and stack the Green's function estimates for these two days (Figure R2). However, one can see that the moulin seismic signature is located in the second eigenvector for the 27th of July and the first eigenvector for the 28th of July. Therefore, in order to extend this analysis to other days, one should find an automatic criterion to find the index of eigenvectors that corresponds to the moulin. Selecting the eigenvectors manually in order to extend the study to more days would be a tedious task and it would not change the interpretation of the current results. We added the following paragraph in the manuscript, although we do not think that adding the Figures R1, and R2 would enhance the manuscript scientific impact. However, if the Reviewer thinks that this is important, we can add the Figures R1, and R2 in the Appendix. "For example, a similar procedure could be performed on other days and the eigenormalized NCF could be stack over a few days to increase the SNR. However, we verified that the index of eigenvectors corresponding to the moulin changes over days (the moulin can be located in the first, second, third etc. eigenvector). This is the reason why it would be useful to find an automatic criterion of the eigenvalue selection based on the MFP output. However, this is beyond of the scope of this paper."

Figure R1: (a) Location of the dominant noise sources using MFP in the frequency band of 2.5 Hz and 6 Hz (the MFP output is averaged over 30 discrete frequencies). (b), (c) Reconstruction of the CSDM for the 28th of July by using first (in (b)) and second (in (c)) eigenvectors that are related to different noise sources. Each figure represents the MFP gridsearch output calculate for the corresponding eigenvectors. (e) Stacked sections of NCC in the frequency band 2.5-6 Hz. The red line shows the propagation of the Rayleigh waves with velocity of 1680 m/s (also in f). (f) Stacked sections of NCC reconstructed in the frequency band 2.5-6 Hz from the CSDM eigenspectrum equalization.

Figure R2: (a) Stacked sections of NCC in the frequency band 2.5-6 Hz averaged over two days (the 27th and the 28th of July 2016). The red line shows the propagation of the Rayleigh waves with velocity of 1680 m/s (also in f). (b) Stacked sections of NCC reconstructed in the frequency band from 2.5 to 6 Hz from the CSDM eigenspectrum equalization averaged over two days (the 27th and the 28th of July 2016).

**Section 4: CWI at Gornergletscher**

L493: Subtitle should represent what is done in each section. In this sense, the study site "Gornergletscher" is not necessary and instead making it confusing.

We removed "using the Gornergletscher array" from the title. To be consistent all through the manuscript, we also removed "using the GIS array" from the title of section 4. We now refer to the study sites in the following first section (i.e. "5.1. Icequake coda waves at Gornergletscher").

L525: Fig 1c => 1d ?

We modified to Fig 1d.

L532: Fig 1c => 1d ?

We modified to Fig 1d.

L540: Do authors see the potential effect of early aftershock in the coda wave?

Yes, we must carefully select event codas to avoid anisotropic fields generated by incident waves from aftershocks. The event selection is a first important step as stated in the manuscript. The window-optimization scheme further helps to reduce their potential effects. Aftershock a-effects and cause of spurious arrivals are explained in Lines 598-599 "(...) spurious arrivals at times 0 or later could result from seismic reflections on the glacier bed beneath the stations, cross-correlations of early aftershocks or other noise sources." and lines 617-620 "the abundance of seismic sources in glaciers often pollutes coda wave seismograms. We often find the situation where ballistic body and surface waves generated by early aftershocks from repetitive and subsequent events (or bed reflections) arrive at the seismic sensor only a few milliseconds after the onset of the first event of interest and therefore fall in its coda window. This typically introduce anisotropic wavefields."

L542: Please show the coda window to be used in the figure 1d as an example.

We indicated the coda window by the gray horizontal bar in Fig 1d.

L542: Fig 1c => 1d

We modified to Fig 1d.

L546: Does it mean the authors are applying spectral whitening and 1-bit normalization together?

The waveforms are first spectrally whitened as stated in Line 534 and then one-bit normalized.

L572–586: Please explain this as a regular paragraph. In addition, many words are redundant (e.g., N or M is already explained).

We rephrase this as a regular paragraph and removed the redundant information.

L613: Indeed, the arrivals could result from the reflection at the bed. Isn't it easy to calculate and validate?

It is not easy to calculate as at the study site, we are very close to the glacier margins. We are sensitive to 3D effects from the lateral margins and also strong basal topographic gradients with about 200 m of depth difference around the array (Walter et al. 2009). Such spurious arrivals may result from the correlation cross-terms from very different reflection arrivals in the coda.

Walter, F., Clinton, J., Deichmann, N., Dreger, D. S., Minson, S., and Funk, M.: Moment tensor inversions of icequakes on Gornergletscher, Switzerland, Bulletin of the Seismological Society of America, 99, 852–870, 2009.

L629: Surprisingly, there are no further analyses of the GF in this section.

We improved the discussion and re-organized it. We already discussed the obtained GF in terms of (1) symmetry, (2) spurious arrivals, (3) (non-)diffuse character of coda waves which arise from single scattering rather than multiply-scattering (medium effect) and non-homogeneously distributed sources and (4) our ability to compute reliable Rayleigh wave dispersion curves. We expose the advantage of CWI to obtain Green's function at seismic arrays where uneven icequake or noise source distributions prevent the Green's function estimation.

**Section 5: Discussion**

L643: allow => allows

Modified

L695: Does SH refer to SH wave?

Yes. Specified

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2019-225/tc-2019-225-AC1-supplement.pdf

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Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-225, 2019.

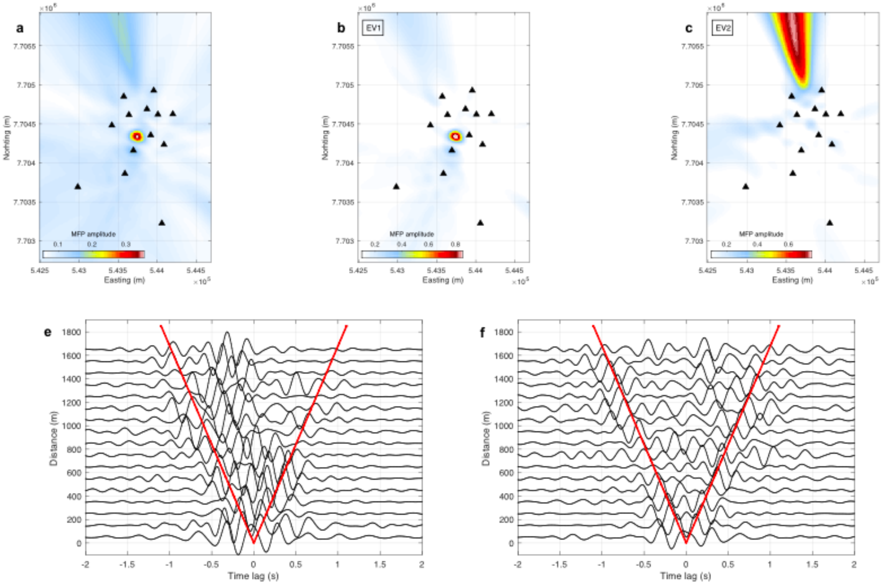


**Figure R1**: (a) Location of the dominant noise sources using MFP in the frequency band of 2.5 Hz and 6 Hz (the MFP output is averaged over 30 discrete frequencies). (b), (c) Reconstruction of the CSDM for the 28th of July by using first (in (b)) and second (in (c)) eigenvectors that are related to different noise sources. Each figure represents the MFP gridsearch output calculate for the corresponding eigenvectors. (e) Stacked sections of NCC in the frequency band 2.5-6 Hz. The red line shows the propagation of the Rayleigh waves with velocity of 1680 m/s (also in f). (f) Stacked sections of NCC reconstructed in the frequency band 2.5-6 Hz from the CSDM eigenspectrum equalization.

**Fig. 1.**

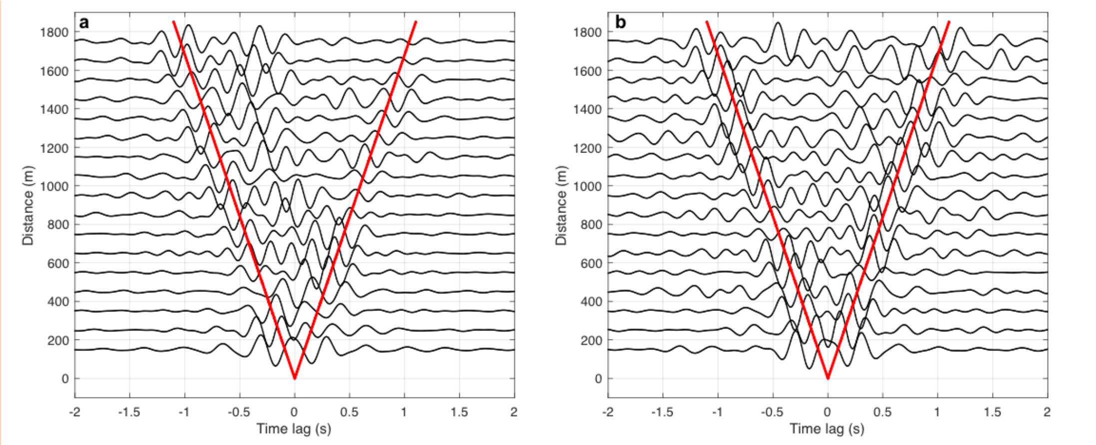


**Figure R2**: (a) Stacked sections of NCC in the frequency band 2.5-6 Hz averaged over two days (the 27th and the 28th of July 2016). The red line shows the propagation of the Rayleigh waves with velocity of 1680 m/s (also in f). (b) Stacked sections of NCC reconstructed in the frequency band from 2.5 to 6 Hz from the CSDM eigenspectrum equalization averaged over two days (the 27th and the 28th of July 2016).

**Fig. 2.**



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Discussion paper