Anonymous Referee #1

Received and published: 5 March 2019

Referee: This paper proposes an improvement to the method of Green's function retrieval from ambient noise by cross-correlation. A specific stacking method is proposed which discards partial correlation results that are not coherent with the average correlation result. After applying an iterative procedure, a correlation function is obtained with a higher signal-to-noise ratio than the ones obtained by other stacking methods. The method is illustrated with two preliminary field data examples. The authors discuss the advantages and limitations of the method.

This reviewer is familiar with the theory of Green's function retrieval but does not have a broad overview of the many processing methods that have been developed. Therefore it is difficult to judge the originality of the proposed method. I recommend that the paper be reviewed at least by one additional reviewer, who is more experienced with the practical aspects of Green's function retrieval. Assuming the proposed method is original, I recommend publication after moderate revision, taking the following comments into account:

- I wonder why the authors call their method "signal-to-noise ratio (SNR) stacking". Aren't all stacking methods aiming to improve the SNR? The proposed method stands out because it discards incoherent correlation results. Please consider a new name, which better matches the specific aspects of the proposed method. For example: "Coherent stacking"? "Coherent cross-correlation stacking"?

Authors: We agree that all stacking methods aim to increase SNR of evaluated EGF. Nevertheless, we call the method "SNR-stacking", because of using "signal-to-noise ratio" as a parameter that is optimized in our suggested algorithm. The methods performs global optimization search by retrieving EGF with highest SNR. Using other terms like "coherence", in our opinion, may mislead readers, because we use this term only in order to shorten the description of the method. Our definition of the term "coherence" is defined in Introduction part of the manuscript.

Referee: • On page 2 the authors mention that they want to use high-frequency surface waves to extract information about deep structures. This sounds as a contradiction. Surface waves do not penetrate deep into the subsurface, and using high frequencies makes it even more difficult to reach deep structures. Please be quantitative about the depths that need to be reached.

Authors: The sentence with the description of depth of investigation has been corrected as proposed by Referee.

Referee: • Page 3, line 2. The introduction of _te via the inequality is confusing. Is _te the time-lag interval, or is the inequality □tds < _te < tds the time-lag interval (as actually stated in line 2)? If _te is the time-lag interval (as stated in line 7), what does it mean that it can take a negative value (as stated in line 2)? Please explain.

Authors: This was a mistake in definition. The _te is time lag, not time lag interval. Additional explanation has been added to the text. Our algorithm is based on global optimization trying to optimize the SNR and we are calculating the SNR as a function of time lag that is variable and also other variables such as initial function number etc.) with the expected signal. In most cases, we do not know azimuthal distribution of noise sources. That is why we need to consider both casual (positive time lags) and acasual (negative time lags) parts of crosscorrelation functions. In this case, we use the time interval with zero point at _te with width of two periods of expected signal.

Referee: • Explain abbreviations, such as MEMS and BB sensors.

Authors: MEMS – microelectromechanical system. BB – broadband. Explanation has been added to the text.

Referee: • Mention the area of the experiments in all figure captions (Fig1: Pyhäsalmi mine area, Fig2: Kuusamo Greenstone Belt area, etc.).

Authors: Figure captions are corrected as proposed.

Referee: • Figure 6a: I am surprised that the time-shift of the peak appears almost at t=0. Why don't you show a more representative example with a time-shifted peak, corresponding to well-separated receivers?

Authors: On figure 6 we show differences in signal-to-noise ratio for EGFs, obtained by different methods of stacking. In this case, the time lag, which corresponds to signal, is small compared to the length of noise wavetrain, and on the figure it looks like zero-lag. Nevertheless, for illustration of quality of EGF obtained, it is necessary to show the whole time interval that was used for calculation of noise level. It seems for us, that for visualisation of signal-to-noise ratio improvement it is better to use a large time window, in which the difference between noise and signal is seen better.

Referee: • Figures 6b and 6c: I think these figures (or the corresponding captions) should be interchanged: the SNR in 6b looks better than that in 6c, but the captions say the opposite.

Authors: This was a typo and it has been corrected.

Referee: • Figure 7. The SNR of the proposed method converges to 40. However, according to the caption of fig 6a the SNR equals 71. Please explain. Are these different experiments?

Authors: This was a typo and it has been corrected.

Referee: • Figs 9 and 10 show only some preliminary results of the method for both regions. These figures show that Green's functions can be retrieved and the derived velocities seem to be in agreement with earlier derived results. I would have liked to see more discussion on what can be done with these results (or do we need more data before useful inferences about the area of investigation can drawn?)

Authors: Extracted empirical Greens functions can be processed by the same techniques as a signal from controlled source. Further processing of the signal (EGF in our case) is simpler if the signal-to-noise ratio is relatively higher. The goal of our paper is to describe a method for improving of EGFs quality and its possibilities. We plan to use the method with the data of other experiments, with larger number of sensors.

Referee: • Last but not least, the paper needs significant language editing!

Authors: We are very thankful to the reviewer for this comment and additional text editing was done.

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Код поля изменен

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Referee: Please see below the comment to the manuscript about method for retrieval of Green's function (GF) with high S/N ratio in selected time window. This post is encouraged by one of the comments of the Anonymous Refree #1 suggesting to focus on the originality of proposed ambient-noise processing technique. In this paper authors propose a method to retrieve improved version of Green's function between receiver pairs and apply it on two different datasets. The paper is enjoyable to read and seems like a great case study. The method is based on rejecting cross-correlation functions which after stacking do not increase the S/N ratio in the time window related to arrivals of the desired phases. The S/N ratio in this method is calculated according to equation 1 (Page 3), and generally is obtained by dividing the maximum amplitude in time interval of expected arrival by the summed amplitudes in the remaining part of CCF. If adding the CCF does not increase the S/N ratio, then it is rejected. Generally all methods basing on S/N criteria are robust and effective, and they are commonly used as part of ambient-noise processing workflows. The main issue of ‘S/N ratio stacking’ proposed here is that the method seems to be not novel. To give some examples please see the papers by Olivier et al. (2015) and Nakata et al. (2015). Both papers describe the process of extracting body-waves form ambient noise and both apply S/N ratio based method as one of the steps in processing workflow. Olivier et al. (2015) designs the selective stacking algorithm for enhancing the S-wave arrivals recorded with array of receivers in the underground mine. In their method the root-mean-square value (RMS) of the signal in the lag-time window of the correlation function around the expected arrival times of the S-waves is divided by the RMS of the signal in the time window of coda waves. It is practically the same method, just instead of maximum amplitude authors use rms. Nakata et al. (2015) as part of his ambient-noise processing designs two different S/N ratio based techniques. First one is more elaborate, so please see the mentioned publication. The second one is (direct citation from paper): “To confirm that we can successfully isolate the traces with strong body wave energy with the second correlation, we compute SNR, which is defined as the average RMS amplitudes between 1.3 and 1.9 s divided by the average RMS amplitudes between 0.0 and 4.5 s.” – again please note the striking similarity of the method. It is important to note that the two above techniques were just one step of the more elaborated processing workflows, and both of the mentioned papers included also extensive synthetic tests and applications of tomography.

Authors: 1) The novelty of our technique compared to the other techniques mentioned by reviewer is that we applied global optimization algorithm to objective function (SNR of EGF in our case) for evaluation of the best solution (EGF of highest quality). In our proposed algorithm, we calculate SNR as a function of several parameters (time lags with expected signal, initial time windows number etc., see the algorithm descriprion). Parametrisation of the global optimization problem is based on the a-priori information and generally, is problem-dependent. After this, algorithm finds the best solution corresponding to the global maximum of SNR function.

2) The other important feature of our algorithm is that the signal-to-noise ratio is estimated in the time-domain and hence the objective function in global optimsation problem is sensitive to variations of not only the RMS, but also to other parameters. For example, changing the azimuth to noise source will shift the position of the signal maximum in the time window considered. In this case, the RMS for this window may be the same as for , but position of the maximum will be shifted. Therefore, our algorithm will reject this function, while algorithms based on RMS would not.

It is true that our method is using the ideas proposed by other authors, and we cited all these studies in our paper. However, we developed original method of signal-to-noise ratio optimisation, which is more sensitive, because we use the maximum of CCF instead of RMS. We compared results obtained by several methods (RMS-based stacking and weight stacking (figure 6)) and found out, that our proposed technique allows to obtain EGFs of better quality. Moreover, we advanced the algorithm of stacking by using of global optimization of SNR, which make results more robust and independent on initial cross-correlation function. Suggested papers has been cited in the text.

Referee: Second part of comment is related to the line 15 (Page 2) in the discussion manuscript where authors provide their definition of ‘coherent’ term. According to this definition the two EGFs are coherent if their maxima fall in the same time window (appear at the same time-lag). While, this definition of coherence is comfortable in terms of improving Green’s function it might not necessarily be correct for the field applications.

Authors: We used the term “coherence” in order to simplify description of the method and we explained in what sense it is used. We think that our definition is close to the standard definition of this term in physics, but in our case, a wave is a cross-correlation function. In our case, increasing of SNR after stacking of two cross-correlation functions is the same as result of interference of two waves which are coherent to each other. There are also some differences from standard physical definition of coherence. For example, we use time lags with maximums instead of phase differences.

Referee: In lines 25-30 (Page 2) Authors argue that stacking only EGFs with which increase S/N ratio given in equation 1, does automatically increase the coherency. This is true, but only for the specific definition of coherency given in this manuscript, which however does not relate to retrieval of correctly estimated Green’s function, which needs source in the stationary phase areas.

Authors: We agree with this comment, but we explained in our paper in what sense we use the term “coherence”. Our proposed technique allows increasing signal-to-noise ratio, but it does not guarantee estimating of the true EGF, because the source may be located outside the stationary phase area. Nevertheless, using of our technique together with the array analysis techniques, which allow estimating azimuth to noise source, makes it possible to evaluate EGF of high quality. The discussion has been added to the Conclusion part of manuscript.

Referee: In line 10 (page 2) authors indeed comment that its important to use systems which allows to estimate the azimuth distribution of noise sources (to increase a chance of capturing the sources in stationary phase areas), yet this comment does not suffice to make a method feasible for improved processing, as usually the exact distribution of sources is not known. In such cases, specific methods can be used for estimation these azimuths (like beamforming etc.), yet when this directional analysis is already done, then it is enough just to stack these sources. After this, any measure of the increase of amplitude in expected time window becomes trivial task.

Authors: In our paper, we consider two cases that are of practical importance for geophysical explorations: the first one is brownfield exploration, in which position of the dominating noise source is relatively well known (e.g. mine) and the second one is greenfield exploration, in which we have no any a-priory information about spatial and temporal distribution of noise sources. In the first case, after directional analysis of noise sources, the EGF evaluation is easy task if one of the following conditions is satisfied: 1) the azimuthal distribution is homogeneous; 2) there are sources located in some limited area and producing noise of high energy. However, if the noise sources are stochastically distributed both in time and in space and are weak, then using simple stacking for extraction of EGF is not a guarantee of a good result, even if one can estimate azimuthal distribution of noise sources, and evaluation of EGF become not trivial task. We demonstrated this by our Kuusamo experiment (see fig. 10).

Referee: Generally, it is reasonable to measure the EGF using coherency because it will, in ideal situation, selectively correct virtual traces, which contribute to the stack. However, using S/N ratio in selected time windows might not be necessarily correct, as the source we are stacking might be located in non-stationary phase areas. In other words, the maximum amplitude we eventually get, may not mean we stack sources related to the stationary phases (which depends on the source-receiver configuration).

Authors: This issue is partially solved by using global optimization of SNR in our proposed algorithm (see also our reply to the comment above).

Referee: Second issue related to possibly biased coherency improvement is related to the division in equation 1. The coherency improvement is theoretically assured if S/N ratio calculated from equation 1 is increasing. This might not be necessarily true, e.g., if coda wave part gets smaller (the denominator in equation 1) the S/N also increases, and again it means that source contributing to desired time-windows might be not related to the stationary region.

Authors: This is one of the possible problems of the method. Correspondent discussion has been added to the text. But in our paper we considered two real data cases that are of practical importance for geophysical exploration, and we demonstrated that method is working.

Thanks for reading and looking forward to your reply.
Kind regards, Michal Chamarczuk

Anonymous Referee #2
Received and published: 2 April 2019

Improving quality of empirical Greens functions, obtained by cross-correlation of high-frequency ambient seismic noise

General overview

A main problem in exploration geophysics applications using anthropogenic sources of seismic ambient noise often is its far from ideal distribution that hinders the extraction of empirical Green's function using methods conventionally used at much larger scales using natural sources, for example, in seismology. The authors introduce a method that seek for a subset of interstation correlations that maximize the signal to-noise ratio (SNR) after stacking to promote converge to the empirical Green's function. Overall the manuscript is interesting but the English usage has to improve and many places need for greater clarity. I just have a few comments.

Main comments

Referee: • Pg. 2: The introduction on the stacking methods is confusing. I would distinguish methods that weight correlations according to the SNR of each correlation (Cheng et al., 2015) or that stack only correlations with high or low coherence (Boué et al., 2014) from methods that weights signal coefficients in a transformed domain after a linear stack, such as the time-frequency phase weighted stack (Baig et al., 2009; Schimmel et al., 2011; Li et al., 2018) or the time-scale phase weighted stack (Ventosa et al., 2017). A clear separation between these methods can help the reader to place your method in its proper context.

Authors: Thanks a lot for more clear formulation of the sentence. Correspondent text in the manuscript has been changed.

Referee: Pg. 2, line 10 and 14: Li et al. (2017) should be Li et al. (2018).

Authors: This work published in 2017:

Li, G., Niu, F., Yang, Y., & Xie, J. (2017). An investigation of time–frequency domain phase-weighted stacking and its application to phase-velocity extraction from ambient noise's empirical Green's functions. Geophysical Journal International, 212(2), 1143-1156.

Referee: •Pg. 2, line 25-26: Can you give detailed information on the pre-processing and the cross-correlation function you apply?

Authors:

There is a number of studies devoted to calculating of EGF from ambient seismic noise. In our study we used the preprocessing routine described in details in Benson et al. (2007), Poli et al. (2012, 2013). These procedures now are the “standard” pre-processing procedures in passive seismic interferometry. That is why we did not concentrate in our paper on these details, but only refer to the papers mentioned above.

Referee: • Pg. 2, line 28-30 and Pg. 3, line 11: These sentences are misleading. Interstation correlation functions do not always give an empirical Green’s function. They converge to an empirical Green’s function when the distribution of source is fairly well distributed. Hence, the importance of the pre-processing, correlation, stacking methods, and potentially the method you introduce, to seek a good balance of sources.

Authors: We put a corrected, more clear explanation into the text.

Referee: • Pg. 3, eq. (1): This estimation of SNR is fine when the strongest signals arrive on the expected time lags (from □tds to tds) and you have no signal outside. Have you considered using more robust estimators of the noise level such as median absolute deviation (MAD). What happens when signals are too weak to be observed in a cross-correlation function but arise after stacking?

Authors: This estimation is out of scope of our paper. Signal-to-noise ratio could be estimate by several methods. Of course, the results depend on choice of method for this calculation. The main thing that we were going to demonstrate in our paper is our technique that is using stacking method together with global optimization of signal-to-noise ratio. Analysis of different methods of SNR calculation is task for our further studies, and we agree that there is a potential for further improvement of the method.

Referee: • Pg. 4, lines 14-21: This paragraph is not clear. If I understood what you mean, you need to know seismic velocity in order to measure the azimuth of the strongest source; however, seismic velocity structure is often what we seek in most applications. In addition, you mention that a 2-D array is necessary. Can you further explain how you use it to estimate the azimuth distribution of sources.

Authors: Estimation of time lags intervals with expected signals is calculated according to the plane wave condition as in beamforming. Limits of velocities are selected according to *a priory* information about studied medium. After this such parameters as the SNR, apparent velocity and azimuths are optimized. Therefore, we can estimate probable values of azimuth and velocity. Explanation has been added to the text.

Referee: • Pg. 5, around Fig. 1 & 2: I would personally emphasize in these figures which stations use MEMS and which Trillium Compact.

Authors: Figure caption has been corrected.

Referee: • Pg. 8, line 1: An extra sentence is needed here to explain how you locate highfrequency noise sources at distances from about 0.7 to 3 km from the center of the arrays.

Authors: As we apply standard array methods for location of noise sources, we assumed these values from apertures of these arrays. Additional sentence has been added to the text.

Referee: • Pg. 8, line 17-22: Which is the portion of correlations that conventionally build up the final stack?

Authors: It is difficult to estimate, because it is strongly dependent on features of the noise wavefield. In two cases considered in our study, the number of cross-corelation functions used in the final stack varies from about 8 to 35% of total number of calculated functions.

References

Boué, P., Poli, P., Campillo, M. and P. Roux (2014). Reverberations, coda waves and ambient noise: Correlations at the global scale and retrieval of the deep phases, Earth Planet. Sci. Lett., 391, 137–145, doi:10.1016/j.epsl.2014.01.047

Baig, A., Campillo, M. and F. Brenguier, F. (2009). Denoising seismic noise cross correlations, J. Geophys. Res., 114(B8), 2156–2202, doi:10.1029/2008JB006085

Ventosa, S., Schimmel, M. and E. Stutzmann (2017). Extracting surface waves, hum and normal modes: time-scale phase-weighted stack and beyond, Geophys. J. Int., 211(1), 30–44, doi:10.1093/gji/ggx284

Improving quality of empirical Greens functions, obtained by cross-correlation of high-frequency ambient seismic noise

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Abstract. Studying the uppermost structure of the subsurface is a necessary part for solving many practical problems (exploration of minerals, groundwater studies, geoengineering, etc.). Practical application of active seismic methods is not always possible because of different reasons, such as logistical difficulties, high cost of work, high level of seismic and acoustic noise, etc. That is why developing and improving ~~of~~ passive seismic methods for these purposes is one of the important problems in applied geophysics. In our study, we describe the way of improving quality of Empirical Green's Functions (EGFs), evaluated from high-frequency ambient seismic noise, by using ~~of~~ advanced technique of cross-correlation functions stacking in the time domain (in this paper we use term "high-frequency" for the frequencies higher than 1 Hz). In comparison~~e~~ to existing techniques, based, for example, on weight-stacking, our proposed technique makes it possible to ~~more significantly~~ increase significantly the signal-to-noise ratio and, therefore, the quality of the EGF. The technique is based on ~~both iterative and~~ global optimization algorithms, where the optimized objective function~~parameter~~ is a signal-to-noise ratio of an EGF, retrieved at~~for~~ each iteration. The technique has been tested with the field data acquired in an area with high level of industrial noise (Pyhäsalmi Mine, Finland) and in an area with low level of anthropogenic noise (Kuusamo Greenstone Belt, Finland). The results show that the ~~our~~ proposed technique can be used for extraction of EGFs from high-frequency seismic noise in practical problems of mapping of the shallow subsurface, both in areas with high and low level of high-frequency seismic noise.

1 Introduction

Seismic methods as tools for studying of shallow subsurface structures in exploration geophysics have been developed during many years. Traditionally, seismic surveys (reflection and refraction) have been carried out using active sources. The reflection and refraction controlled-source seismic sounding methods are widely applied in exploration for oil and gas, but less commonly in mineral exploration in crystalline bedrock areas. The reasons for this have been the traditionally high cost of seismic surveys and logistical difficulties (Malehmir et al., 2012). Seismic methods as a mineral exploration tool are very good for delineation of the boundaries of certain types of mineral deposits as well as for estimating their ore potential (Kukkonen et al., 2009; Malehmir et al., 2012). There are, however, challenges in exploration of new deep targets in the vicinity of active mines, that is, in brownfield exploration. In our paper, brownfield means exploration near active mines or at the previously studied area with the purpose of getting new mineral reserves, while greenfield means exploration of new mineral deposits. Due to the large amount of heavy machinery, existing mines themselves produce strong seismic and acoustic noise. This continuous noise is overlapping in frequencies with the signals of the controlled seismic sources, creating a problem for the high-resolution active-source seismic experiments in a brownfield exploration (Place et al., 2015).

In our paper, we describe results of investigating the possibility to use high-frequency passive ambient seismic noise interferometry with ~~h ambient~~ noise with frequencies higher than 1 Hz (hereafter~~in the paper~~ we use the term “high-frequency” for this seismic noise) for extracting information about shallow subsurface ~~deeply seated structures~~ in greenfield and brownfield exploration projects. In our study, shallow subsurface means depths from ground surface to several hundreds meters. For this, we develop a new method of improving~~ncreasing~~ ~~the~~ quality of empirical Green’s function (EGFs) evaluated from high-frequency industrial, anthropogenic or natural seismic noise. We partly use algorithms described in Campillo (2006), Bensen et al. (2007), Groos et al., (2012), Poli et al. (2012a, 2012b, 2013), Afonin et al. (2017) for ambient noise pre-processing and implement a new algorithm of stacking of cross-correlation functions in the time domain.

At present, there are ~~the~~ several advanced algorithms, working both in time domain and in frequency domain, ~~advanced algorithms of the data pre-processing (Bensen et al., 2007~~ for~~;~~ ~~Groos et al., 2012) and~~ cross-correlation functions stacking. These methods are trying to improve the quality of the resulting EGFs using evaluation of cross-correlation functions according to some criteria prior to stacking them. After that those functions that do not satisfy these criteria are either excluded from the final stack or cross-correlation functions are “weighted” prior to stacking. The first approach, based on stacking only cross-correlation functions of highly coherent signals was used by several authors in global scale coda wave interferometry studies (Shimmel et al., 2011, Boué et al., 2014). For example, in the method by Shimmel et al. (2011) phases of signal prior to stacking are analysed and used for improvement of the resulting EGFs. The “time-frequency domain phase-weighted stacking” (Li et al., 2017) is using stacking in frequency domain, while the “time-scale phase weighted stacking” (Ventosa et al., 2017) is using stacking in the time domain. These algorithms are not analysing signal-to-noise ratio (SNR) of the final EGF, and it is assumed that signal coherence itself is a guarantee that all non-suitable cross-correlation functions are excluded from the final stack and hence the SNR is automatically improving. This may be true for teleseismic coda wave interferometry, in which azimuthal distribution of noise sources is a-priori known and it is easy to control that only signals within so-called “stationary phase” area are cross-correlated (Wapenaar et al., 2010). However, in ambient noise studies with stochastically, non-evenly distributed in time and space noise sources, the azimuthal distribution of them is not known a-priory. In this case one would need additional control of this distribution, in order to satisfy stationary phase condition. ~~,~~ ~~The methods based on weight stacking are partly solving the problem (Shimmel et al., 2011; Cheng et al., 2015; Li et al., 2017).~~ ~~such as “weight stacking in time domain”, which stack cross-correlation functions according to weight of each of them (Cheng et al., 2015) or stack only correlations with high or low coherence (Boué et al., 2014). In other methods, based on weights, signal coefficients in a transformed domain after a linear stack are used. Among these methods phase cross-correlation with weight stacking (Shimmel et al., 2011), “time-frequency domain phase-weighted stacking” (Li et al., 2017), the time-scale phase weighted stacking (Ventosa et al., 2017).~~ ~~(Cheng et al., 2015)~~The other group of methods, such ~~Moreover, such~~ methods as ~~,~~ “root mean square stacking” or weight stacking ~~also used~~ (Shirzad et al., 2014, Nakata et. al., 2015, Cheng et al., 2015, Li et al. 2017)) are aiming mainly to increase signal-to-noise ratio of the resulting EGF, but they do not take into account coherence of the cross-

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Отформатировано: не выделение цветом correlation functions in the stack~~,~~ ~~phase cross-correlation with weight stacking (Shimmel et al., 2011), “time-frequency domain phase-weighted stacking” (Li et al., 2017)~~. That is why~~-~~ incoherent cross-correlation functions are not totally excluded from stack in these algorithms and this can decrease the quality of evaluated EGFs.

~~These algorithms allow increasing the signal-to-noise ratio of the EGFs extracted from high-frequency seismic noise. Nevertheless, there are some difficulties with application of these algorithms in areas with non-evenly located noise sources. The main problem is using of all cross-correlation functions for building up a final EGF. The methods based on weight stacking are partly solving the problem (Shimmel et al., 2011; Cheng et al., 2015; Li et al., 2017). Nevertheless, the incoherent cross-correlation functions are not totally excluded from building up process and can decrease quality of evaluated EGF. In our paper the term ’coherent’ is used for describing cross-correlation functions with the same time lags of signal maxima and the same dominant frequency.~~ To overcome~~solve~~ ~~th~~limitations of existing techniques,~~is~~ ~~problem,~~ we develop a new algorithm that makes it possible to not only ~~to~~ exclude incoherent cross-correlation functions from EGFs ~~building up~~stacking process, but also to keep control on azimuthal distribution of noise sources and condition of “stationary phase”. In our paper the term ’coherent’ is used for describing cross-correlation functions with the same time lags of signal maxima and the same dominant frequency. We do not use this method in the frequency domain because for stationary phase condition to be satisfied it is important to stack cross-correlation functions with the same time lags and dominant frequencies, in other words, functions that are coherent to each other. As a main criterium for selecting cross-correlation functions to stack, we use increase of SNR of extracted EGFs after stacking. ~~and, therefore, significantly increase the signal-to-noise ratio and quality of extracted EGFs. We do not use this method in the frequency domain because it is important to stack cross-correlation functions with the same time lags and the dominant frequencies, in other words, functions that are coherent to each other.~~

In our paper, we are presenting details of this algorithm and illustrate its performance using passive seismic ambient noise data acquired in two areas of Fennoscandia: Pyhäsalmi mine (as an example of area with high level of industrial noise) and Kuusamo Greenstone Belt area (quiet area prospective for new mining projects (Wiehed et al., 2005; Lehtonen et al., 2009).

2 Advanced technique of cross-correlation functions stacking

For solving the problems described in the introduction, we suggest our method of time-domain stacking of cross-correlation functions calculated for different time windows. We call this method signal-to-noise ratio (SNR) stacking. The general purpose of this method is to select for stacking only those cross-correlation functions that are not only coherent to each other, but correspond to the stationary phase area.~~.~~

Let us assume~~propose~~ that ambient noise in some frequency band is recorded simultaneously at two different points with Cartesian coordinates $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$. ~~, that part of noise sources located in stationary point, which corresponds to Fresnel zone and part of noise sources distributed outside the Fresnel zon~~For each frequency, the stationary phase area for the receiver located in the point r_i , $i=1.2$ corresponds to Fresnel zone of the wave propagating from the source to the receiver with some apparent velocity~~e.~~. In this case, maximum of cross-correlation function~~s with~~ at some time lags would ~~, which~~ correspondent to minimum apparent velocit~~ies~~y and hence, the cross-correlation function would~~ill~~ be close~~r~~ to the “true” EGF. Assume that

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Отформатировано: не выделение цветом noise sources are partly located in a stationary phase area while other noise sources are distributed outside it. For selection of cross-correlation functions~~ s, which~~ corresponding~~ent~~ to stationary phase area~~Fresnel zon,es,~~ it is possible to use both ~~-~~criteria of ~~maximum time lags~~minimum apparent velocity ~~-~~and signal-to-noise ratio increasing after stacking. ~~. These criteria allowing select cross-correlation functions, which coherent to each other in terms of our paper and which correspondent to Fresnel zones.~~ Consider the ~~Global optimization of~~ SNR of EGF after stacking as some generally non-linear function of apparent velocity and ~~,~~backazimuth of noise wavefield and initial time window used to start selection of cross-correlation functions to stack. ~~–~~In this case the global optimisation of this objective function allows retrieving EGFs of higher quality. ~~Coherence between cross-correlation functions and the EGF already retrieved at previous iteration step is estimated by comparison of the signal-to-noise ratio of EGFs before and after stacking with cross-correlation function of a next time window~~. ~~For solution of global optimization task, it is necessary to use parameterization, which based on a-priory information about studied medium.~~

Assume again that ambient seismic noise is recorded simultaneously at two different points with Cartesian coordinates $\boldsymbol{r_1}$ and $\boldsymbol{r_2}, \boldsymbol{r} = [\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}]$ and continuous recordings are split into $\boldsymbol{n}$ time windows with the same durations. Let $\boldsymbol{a_i}(\boldsymbol{r_1}, \boldsymbol{r_2}, \boldsymbol{t})$ be the cross-correlation function of these seismic records for the time window $\boldsymbol{i}$, $\boldsymbol{i} = \boldsymbol{1} \dots \boldsymbol{n}$, where $\boldsymbol{t}$ is time lag of the seismic records. Let $\boldsymbol{t_m}$ is the maximum time lag in a cross-correlation function (length of cross-correlation); $\boldsymbol{t_{ds}}$ is a maximum time of wave propagation between the two points; $|\boldsymbol{t_m}| \gg |\boldsymbol{t_{ds}}|$ and $-\boldsymbol{t_m} \leq \boldsymbol{t} \leq \boldsymbol{t_m}$. Let $-\boldsymbol{t_{ds}} \leq \cancel{\triangle} \boldsymbol{t_e} \leq \boldsymbol{t_{ds}}$ is the time lag ~~interval~~ on cross-correlation function corresponding to the expected seismic phase (body or surface wave) and ~~.~~ $\triangle \boldsymbol{t_e} = \boldsymbol{t_e} \pm \boldsymbol{T}$, where $\boldsymbol{T}$ is the period of expected signal. Negative values of time lags correspond~~s~~ to acasual part of evaluated EGF. In this case, selection of $\boldsymbol{t_{ds}}$ and $\triangle \boldsymbol{t_e}$ is based upon *a priori* information about seismic velocities in the studied area. The value of $\triangle \boldsymbol{t_e}$ is at least two periods of the expected signal dominant frequency. In the case of evaluation of surface wave parts of EGFs, this frequency usually corresponds to the frequency of noise with the largest amplitude that can be estimated by time-frequency analysis of noise seismic records.

Let $\boldsymbol{a_i^{max}}(\boldsymbol{r_1}, \boldsymbol{r_2}, \triangle \boldsymbol{t_e})$ is the maximum value of cross-correlation function in the time interval $\triangle \boldsymbol{t_e}$. Then, the signal-to-noise ratio of a cross-correlation function calculated for the $\boldsymbol{i\,th}-$ time window ($\boldsymbol{SNR}(\boldsymbol{a_i}(\boldsymbol{r_1}, \boldsymbol{r_2}, \boldsymbol{t}))$) is:

$$SNR(a_i(\boldsymbol{r_1}, \boldsymbol{r_2}, t)) = \frac{a_i^{max}(\boldsymbol{r_1}, \boldsymbol{r_2}, \triangle t_e)}{\frac{1}{2|t_m - t_{ds}|}\left(\int_{t_{ds}}^{t_m} a_i^2(\boldsymbol{r_1}, \boldsymbol{r_2}, t)dt + \int_{-t_m}^{-t_{ds}} a_i^2(\boldsymbol{r_1}, \boldsymbol{r_2}, t)dt\right)} \quad (1)$$

Let $a_i(\boldsymbol{r_1}, \boldsymbol{r_2}, t)$ and $a_j(\boldsymbol{r_1}, \boldsymbol{r_2}, t)$ are cross-correlation functions calculated for different time windows $i \in (1..n)$ and $j \in (1..n)$ and $c(\boldsymbol{r_1}, \boldsymbol{r_2}, t) = a_i(\boldsymbol{r_1}, \boldsymbol{r_2}, t) + a_j(\boldsymbol{r_1}, \boldsymbol{r_2}, t)$ is EGF retrieved from these two cross-correlation functions. If $a_i(\boldsymbol{r_1}, \boldsymbol{r_2}, t)$ and $a_j(\boldsymbol{r_1}, \boldsymbol{r_2}, t)$ are coherent to each other and $i \neq j$, then expressions $SNR(a_i(\boldsymbol{r_1}, \boldsymbol{r_2}, t)) < SNR(c(\boldsymbol{r_1}, \boldsymbol{r_2}, t))$ and $SNR(a_j(\boldsymbol{r_1}, \boldsymbol{r_2}, t)) < SNR(c(\boldsymbol{r_1}, \boldsymbol{r_2}, t))$ have to be true, according to the principle of interference. Condition $i \neq j$ is necessary in order to avoid stacking of functions with itself. Therefore, increasing SNR of the retrieved EGF after stacking with cross-correlation function can be used as a criterion for excluding incoherent functions from the stack and building up the EGF with high signal-to-noise ratio.

Based on the criteria described above, an expression for calculation of EGF for k-th iteration can ~~may~~ be written as

$$G^k(\mathbf{r_1},\mathbf{r_2},t) = \sum_{\substack{i=1\\ i\neq k}}^{n}(G_i^k(\mathbf{r_1},\mathbf{r_2},t) + a_i(\mathbf{r_1},\mathbf{r_2},t) * \delta(G_i^k,a_i)), \tag{2}$$

where $k = 1 \dots n$ is the number of initial function; n is the number of time windows; $i = 1,\dots,n$; $G_i^k(\mathbf{r_1},\mathbf{r_2},t)$ is EGF~~, which~~ correspondings~~s~~ to k-th – initial function and evaluated in previous iterations:

$$G_i^k(\mathbf{r_1},\mathbf{r_2},t) = \begin{cases} a_k(\mathbf{r_1},\mathbf{r_2},t), & i = 1 \\ G_{i-1}^k(\mathbf{r_1},\mathbf{r_2},t), & i \neq 1 \end{cases}. \tag{3}$$

The operator of selection can~~may~~ be written as

$$\delta(G_i^k,a_i) = \begin{cases} 0, SNR\left(G_i^k(\mathbf{r_1},\mathbf{r_2},t) + a_i(\mathbf{r_1},\mathbf{r_2},t)\right) < SNR\left(G_i^k(\mathbf{r_1},\mathbf{r_2},t)\right); \\ 1, SNR\left(G_i^k(\mathbf{r_1},\mathbf{r_2},t) + a_i(\mathbf{r_1},\mathbf{r_2},t)\right) \geq SNR\left(G_i^k(\mathbf{r_1},\mathbf{r_2},t)\right); \end{cases} \tag{4}$$

As a ~~The~~ result of this algorithm we obtain ~~are~~ n candidates for EGF that can be considered as solutions to the optimization problem in some parameter space. Let us denote the signal-to-noise ratio as *f(k)*~~function of~~, where *k* is index of initial functions: ~~index~~ $SNR(G^k(\mathbf{r_1},\mathbf{r_2},t)) = f(k), k = 1,\dots,n$. Then~~,~~ the condition for the final EGF selection can be written as $m = argmax(f(k))$, where m denotes the index of selected EGF. Following~~According to~~ this condition, the EGF with maximum signal-to-noise ratio will be selected as the final one. As the function $f(k)$ may have several local maxima in the parameter space k, *k=1,...,n,* the condition for the final EGF selection ensures selection of the global maximum of this function in the parameter space ~~k~~ considered.~~.~~

In the proposed algorithm, maximizing the signal-to-noise ratio of the retrieved EGF is ensured by stacking of only cross-correlation functions coherent to each other and selection of EGF with the maximum signal-to-noise ratio from all calculated candidate EGFs. In other words, the proposed algorithm is analogous to the direct search methods of global optimization. It is necessary to remember, however, that EGF with maximum signal-to-noise ratio does not correspond to a true EGF~~,~~ if the dominant noise sources are located outside the stationary phase area. Therefore, it is important to use the system of observations that allows estimating azimuthal distribution of noise sources. Moreover, the method is based on assumption that sources of ambient seismic noise produce a signal with relatively broad bandwidth and cannot produce an ideal harmonic signal of single frequency.

The method also makes it possible to keep control over a-priory unknown azimuthal distribution of noise sources.~~The method also can be used for calculation of azimuthal distribution of strongest noise sources.~~ For this, a 2-D array of seismic recording stations is necessary. In this case, the time lags, corresponding to expected signal Δt_e in Eq. 1 have to be a function of expected

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seismic velocity and azimuth of expected wave approach $\triangle t_e = f(v,\varphi)$. Then signal-to-noise ratio for each pair of stations of the array is the function of initial function index, velocity and backazimuth: ~~azimuth of approach~~ $SNR(G^k(\boldsymbol{r_1},\boldsymbol{r_2},t)) = f(k,v,\varphi), k = 1,\dots,n,\ v_{min} \le v \le v_{max},\ 0 \le\ \varphi\ \le 360$. Limits of velocity have to be calculated according to *a priory* information about seismic velocities in the studied area. Global maximum of the function corresponds to the strongest or the most coherent wavefiled. Therefore, the method allows estimating azimuths to the strongest source of noise wavefield.

We suggest that this method can be used for extraction of EGFs from high-frequency industrial, anthropogenic, or natural seismic noise. Moreover, this method does not require that a diffuse field is used for calculating EGFs. Therefore, application of this method to the data of optimally selected seismic recording array might decrease significantly the time necessary for registration of ambient seismic noise, which is very important for practical applications of passive seismic interferometry. For studying the possibilities of using this method for extraction of EGFs from high-frequency seismic noise, we use the data from two passive seismic experiments carried out in areas with different seismic noise characteristics. The first area is characterized by high level of industrial noise (Pyhäsalmi underground mine site) that is usually observed in brownfield exploration areas, while the second area is seismically very quiet and characterized by a limited amount of local anthropogenic (roads) and natural (rivers) high-frequency seismic noise sources. Such noise characteristics are typical for greenfield exploration areas.

3 Experimental data

3.1 Pyhäsalmi mine area

As an example of using high level industrial seismic noise for estimation of EGFs, we used the seismic noise at the site of Pyhäsalmi mine, Finland. For this purpose we installed 24 3-component DSU-SA MEMS (microelectromechanical system) seismic sensors with the autonomous RAUD eX data acquisition units manufactured by Sercel Ltd. along a 10-km-long line crossing the mine area with interstation distances of about 100 m (for PLB03-PLB13 and PLB14-PLB22) and 2 km (PLB01, PLB02, PLB23, PLB24) (Figure 1). The seismic stations recorded continuous seismic data from 1.11.2013 to 5.11.2013 with a sampling frequency of 500 samples per second (sps)~~Hz~~.

The profile configuration was selected based on results of test~~previous~~ ~~passive seismic~~ measurements of ambient noise in Pyhäsalmi area made by authors. These studies showed that the mine is the main source of seismic high-frequency noise.

The profile crossing the mine area consists of two parts, and each of these consists of 12 sensors: the western part has direction from the mine to the west (PLB01-PLB13), and the eastern part has direction from the mine to the east (PLB14-PLB24). Each part of the profile includes one sensor installed closest to the mine (PLB13 and PLB14). The horizontal components were oriented to the true N~~n~~orth and E~~e~~ast (NS and EW-components, respectively). Thus, rotation of the horizontal components before seismic noise analysis was not necessary.

3.2 Kuusamo Greenstone Belt area

As an example of an area with low level of anthropogenic seismic noise, we select an area located in the Kuusamo Greenstone Belt (KuGB), Finland, because of numerous previous geological and geophysical studies there (Silvennoinen, 1991; Bruneton et al., 2004; Yliniemi et al., 2004; Silvennoinen et al., 2007; Poli et al., 2012; Pedersen et al., 2013; Silvennoinen et al., 2014; Tiira et al., 2014; Vinnik et al., 2014; etc.). Moreover, according to studies by Weighed et al. (2005) and Lehtonen et al. (2009), this area is prospective for gold- and diamond deposits.

For testing of our method of cross-correlation function stacking, we use the data collected during a passive seismic experiment in KuGB area in ~~the ~~August, ~~ of ~~2014. One of the targets of this experiment was to investigate the possibility of high-frequency EGFs extraction from anthropogenic or natural seismic noise in regions with low ambient noise level.

The temporary seismic array (Figure 2) consisted of five three-component velocimeters Trillium Compact produced by Nanometrics (Canada) and 24 three-component accelerometers DSU-SA MEMS with autonomous RAUD eX data acquisition units manufactured by Sercel Ltd. (France).

As we can see in Figure 2, the seismic array represents a triangle. The lengths of the sides of this triangle are about 4-6 km. The broadband (BB) sensors were installed in the vertices of this triangle and collocated with MEMS accelerometers. In ~~addition~~addition,~~Moreover~~, each of this~~e~~ large triangle vertices ~~was~~were surrounded by a circular array with small aperture (about 1400-1500 m), consisting of six accelerometers. The array recorded continuous seismic data from 28.08.2014 to 10.09.2014 with a sampling rate of 500 sps~~amples per second~~. Such an array configuration makes it possible to estimate the azimuthal distribution of the high-frequency noise sources and also to extract high-frequency EGFs from records of small aperture arrays.

4 Analysis of the seismic noise

4.1 Time-frequency analysis

One of the most important steps of the data preparation before extraction of EGFs is time-frequency analysis. It is necessary for selection of a frequency band with high amplitudes of the ambient noise. For this, we analyse characteristics of the seismic noise recorded at different distances from the potential noise sources. In the Pyhäsalmi experiment, the most probable noise sources are located inside the underground mine and in the open pit. For the time-frequency analysis of the seismic noise, we used records of sensors installed at different distances from the mine and open pit (PLB24 and PLB14 (Figure 1)). Figure 3 (a, b) shows the result of this analysis.

From Figure 3 (a, b), one can see two main frequency bands with high amplitudes of the seismic noise recorded closest to the mine: about 3-4 Hz and about 10-100 Hz, respectively. Moreover, the amplitudes of the noise in these frequency bands decrease with increasing distance from the mine. Therefore, we can assume that the sources of the noise for these frequency bands are located inside the underground mine and in the open pit. Based on this analysis, we selected the frequency band of 1-100 Hz for pre-filtering of the noise prior to~~before~~ calculation of ~~the ~~cross-correlation functions.

In the KuGB experiment, a temporary seismic network was installed in a quiet area without any significant industrial activity; therefore, we can assume that the high-frequency seismic noise might be produced by multiple natural (for example, rivers) and/or anthropogenic (for example, roads) sources. In this case, analysis of ~~analysis of the~~ time-frequency characteristics of the seismic noise is a necessary step. For this, we calculated time-frequency diagrams in the frequency band of 0.1-100 Hz and examples of these diagrams for two stations are presented in Figure 3 (c, d)).

Figure 3 (c, d) shows that noise records of both~~from both~~ stations have amplitude maximums in the frequency band of 0.1-1 Hz. Seismic noise recorded by ~~the~~ KU05 station is also characterized by periodically high amplitudes in the frequency band of 40-100 Hz (Figure 3 (c)). This noise may be caused by anthropogenic (transport) or natural (for example, wind) sources~~factors~~. Station KU02 is located close to the river that can be a source of continuous seismic noise with high amplitudes in the frequency band of 40-80 Hz (Figure 3 (d)). Therefore, for estimation of high-frequency EGF, we select to pre-filter the data band-pass filter of 1-100 Hz.

4.2. Analysis of azimuthal distribution of the noise sources

Classical methods of passive seismic interferometry are based on diffuse field approximation (Wapenaar et al., 2008, 2010). One of the most important conditions for using this approximation is isotropic and homogeneous azimuthal distribution of noise sources (Mulargia, 2012). Therefore, the second important procedure of data preparation before estimation of EGFs is analysis of the azimuthal distribution of the noise sources during the experiment's period. In our study, we considered two cases. In the first case, the main sources of high-frequency seismic noise in the Pyhäsalmi area are most probably located inside the mine and in the open pit. Thus, the assumption about isotropic and homogeneous azimuthal distribution is not valid. As shown in Wapenaar et al. (2010), in such cases one cannot assume diffuse field approximation. That is why the measurements of the noise were made along a profile (linear array) consisting of two parts crossing the mine site and oriented EW. However, signals from other noise sources outside the stationary field area can be also present in the wavefield acquired during the data acquisition period. That is why we made additional analysis of azimuthal distribution of noise sources. For calculation of the azimuthal distribution~~ of the noise sources~~, the well-known methods are frequency-wavenumber (f-k) analysis (Neidell et al., 1971; Douze et al., 1979) and beamforming in the time domain (Rost et al., 2002; Schweizer et al., 2012). The linear configuration of the Pyhäsalmi array does not allow application of f-k analysis and beamforming, however. For understanding of the directivity of the seismic noise wavefields for different frequency bands, we applied~~y~~ the horizontal-to-vertical ratio rotate method proposed in Nakamura et al. (1989), investigated in Barazza et al. (2009), and implemented into Geopsy software (http://www.geopsy.org).

In our study, we analyse records of seismic noise with duration of 10 min for each hour of records. We apply this procedure to records from stations which are the most distant from the mine and~~,~~ located in both parts of the profile (PLB01 and PLB24). ~~and for.~~ We have selected two frequency bands (2-5 Hz and 5-10 Hz) for analysis, because they characterize strong and stable seismic noise, from which it is possible to retrieve surface waves. The result is shown in Figure 4 as a percentage of record time during which the recorded wavefields approached from ~~a~~ certain azimuths with respect to the total time of the record. In Figure 4, azimuth of 0 degree corresponds to the true N~~n~~orth and shadowed sectors denote the azimuths to the noise sources. Radial sizes of these sectors are proportional to the relative source-acting time calculated as a percentage of the total measurement time. Ang~~l~~ular sizes of the sectors denote errors of the azimuth calculation.

In Figure 4 (a, b) one can see strong directivity of the noise wavefields from the E~~e~~ast. This proves that the main noise source for the eastern part of the profile for frequency bands of 2-5 Hz and 5-10 Hz is the mine. Considering the western part of the profile, there is no such clear directivity of the noise wavefields as revealed for the eastern part. One can see near-homogenous azimuthal distribution of the noise sources for azimuths between about 250 and 300 degrees. This could be explained by location of the profile close to the open pit that occupies a larger area than the underground mine. Because of this, the point-source approximation of noise sources is not valid. From these results we can conclude that if we simply stack all calculated cross-correlation functions for a pair of stations (in particular, in the eastern part of the profile), the final EGF will be biased. Therefore, for estimation of the EGF with minimum bias, we need to apply the advanced method of stacking described above.

In the second case, we considered the KuGB area with low level of high-frequency noise. In order to investigate spatial and azimuthal distribution of the strongest noise sources, we applied the procedure described above to the data of each of small-aperture arrays. The crosscorrelation functions were calculated between the central sensor and the other sensors of the array. Figure 5 presents results of the calculations of the azimuths of the strongest seismic noise sources.

In Figure 5, one can see that for the different small-aperture arrays there are also different azimuths to the sources in the different frequency bands and directions to the sources depend on the frequency. Taking into account the size of our temporary array (aperture of the large array is 3 km and apertures of each small arrays are 0.7 km), we can assume that the sources of high-frequency seismic noise are located at distances of about 0.7-3 km from the centres of the small-aperture arrays.

5 Empirical Green's functions estimation

For estimation of EGFs, it is necessary to apply a procedure for data preparation. This procedure includes several steps, such as spectral whitening, removing parts of records with earthquakes, blasts and missed data. This procedure is applied to the data of both experiments in our study. In the previous parts of our paper, we have demonstrated that the Pyhäsalmi mine is the source of continuous and strong seismic noise in the frequency band of 1-10 Hz. Therefore, we extract EGFs separately for the eastern ~~-~~and western parts of the profile.

Each part of the profile includes one sensor installed in the closest vicinity to the mine, and we calculated cross-correlation functions between those sensors and each of the other sensors in both~~each corresponding~~ parts of the profile. Industrial seismic noise may consist of surface and body waves, because of different types of noise sources.

There are several methods of stacking the cross-correlation functions in the time domain, for example, the root-mean-square method of Shirzad et al. (2014) and the weighted stack by Cheng et al. (2015). We compare the signal-to-noise ratio of EGFs estimated by our method and the root-mean-square and weighted methods of cross-correlation functions stacking for the

Pyhäsalmi experiment with respect to the surface wave signal seen in EGFs. Results of this comparison are presented in Figure 6.

In Figure 6, one can see that after application of SNR-stacking method we obtained the EGF with the highest signal-to-noise ratio of surface waves compared to the other two methods of stacking. This is because we used only cross-correlation functions coherent to each other in our stacks. As one can see from Figure 7, the algorithm selects only several cross-correlation functions for the final stack.~~to~~ ~~building up the EGF.~~ Nevertheless, it does not mean that there are only few cross-correlation functions coherent to each other. It means that after some iterations the signal-to-noise ratio might not increase any more by adding new functions to stack~~stacking~~.

We analysed the apparent velocities obtained from the maximums of each of the cross-correlation functions and the apparent velocities from the cross-correlation functions selected by our algorithm of stacking (Figure 8). This figure shows that most of the retrieved EGFs have group velocities of about 4500 m/s. After applying simple stacking procedure to these cross-correlation functions, the group velocity of the surface wave part of the resulting EGF is about 4500 m/s. This cannot be true velocity, as it is too high for surface waves propagating in the uppermost layer. As can be seen from Figure 8, our SNR-stacking algorithm has selected only EGFs with group velocity of about 3400 m/s. This velocity is close to the minimal from all group velocities and is in agreement with group velocities of surface waves and S-wave velocities in the uppermost part of the bedrock in Fennoscandia (Kobranova, 1986; Dortman, 1993; Silvennoinen et al., 2007; Janik et al., 2009; Poli et al., 2013, etc.). Therefore, after applying our stacking method, we can analyse retrieved EGFs with true group velocity and minimal error.

We apply our method of stacking to cross-correlation functions calculated for the eastern and western parts of the profile for the frequency bands 2-5 Hz and 5-10 Hz separately. After stacking, we analyse particle-motion diagrams of the waves retrieved from the seismic noise. Figure 9 shows result of stacking and particle motion analysis of EGFs.

In Figure 9, we present~~ed~~ only EGFs that probably contain also body waves, because other EGFs, namely those calculated for the western part in the band of 5-10 Hz and the eastern part in the band of 2-5 Hz include only surface-wave parts. Figure 9 (a) shows that the seismic noise recorded in the western part of the profile retrieves mainly Rayleigh waves with group velocity of about 3400 m/s. Other wave is marked on figure 9 (a) as an S-wave because the particle motion diagram corresponds to this type of wave. Nevertheless, this wave has apparent velocity of 5700 m/s, which is too high. Therefore, we speculate that this can be an artefact that cannot be used for further analysis. In the frequency band of 5-10 Hz, the EGFs calculated for the eastern part of the profile (Figure 10, b) consists of Rayleigh wave. The other arrivals could correspond to one reflected P-wave and three reflected S-waves. Apparent velocities of reflected P-, S1-, S2-, and S3-wave are about 4480 m/s, 3192 m/s, 3261 m/s and 2543 m/s, respectively. Our assumption that these phases may correspond to retrieved body waves is based upon comparison of their travel times with travel times of body waves recorded during previous active source experiment in Pyhäsalmi (Heinonen et al., 2012). Alternatively, the extracted waves may correspond to other phases, for example, to direct waves generated by sources inside the mine. In the same time, these phases can be also artefacts. Unfortunately, these assumptions cannot be proved using our data and it would be necessary to use the higher density array for precise phase identification of body waves. The group velocity of the Rayleigh wave is about 3400 m/s. In our study, the error in velocities estimation is assumed proportional to about 0.25 of the wavelength of an extracted signal. The error of the polarization calculation is about 1-3 degrees.

For the KuGB experiment, we calculate cross-correlation functions for each small-aperture array and apply the SNR-stacking algorithm for EGFs evaluation. Cross-correlation functions are calculated between the central sensor and each other sensor of the corresponding small-aperture array. In Figure 10 (b), we present result of EGFs calculation by this method for one of the small-aperture array (SK1-SK8 in Figure 2).

In Figure 10, one can see that after application of simple stacking, there are many implicit maximums in the retrieved EGFs. Due to this, it is not possible to calculate the azimuth to noise sources and seismic wave velocities. However, application of the SNR-stacking allows retrieval of the EGFs with maximums corresponding to surface wave propagating from a virtual source with apparent velocity of about 320-350 m/s. These waves could be Rayleigh wave, or acoustic wave propagating in the air. This assumption is based on the fact that velocity of 350 m/s is close to both ~~to~~ velocity of sound in the atmosphere and to the velocity of surface wave propagating in the shallow quaternary sediments in the uppermost subsurface. For precise determination of the wave type, it would be necessary to have more dense observation network. Thus, using our SNR-stacking algorithm we extracted surface waves from high-frequency seismic noise. As we noticed in previous section~~s~~, the noise sources were distributed stochastically, both in ~~the~~ space and in ~~the~~ time, and intensity of these noise sources was small. The body waves are not seen in the Figure 10 (b), because a higher density array is necessary for their identification ~~a higher density array is necessary~~.

6 Discussion

The classical passive seismic interferometry is based on diffuse-field approximation, because of the equivalence of correlation properties of the multiple-scattering and resulting wavefields. Therefore, it is possible to evaluate EGFs from averaged cross-correlation functions (Campillo et al., 2003). In practice, one needs averaging over long ~~-~~time intervals (more than 1 year) because of ~~the~~ heterogeneous~~inhomogeneous~~ and anisotropic distribution of ambient seismic noise sources during short time intervals (Wapenaar et al., 2010). This is a serious limitation for ~~is a limitation for~~ practical application of passive seismic interferometry as a method of applied geophysics, because it is not always possible to have long-term data acquisition experiments for solution of applied problems (mining exploration, microseismic zonation etc.). In such applied problems, the alternative may be to use ballistic waves, not scattered from heterogeneities, but produced by some localized sources of seismic noise (Mulargia, 2012). The major challenge in this case is retrieving body waves from seismic noise. Recently, some techniques of body-wave extraction were proposed in Almagro Vidal et al. (2014) and Panea et al. (2014). The main idea of these techniques is separating ambient seismic noise into a body-wave part and a surface-wave part. One could expect that combination of these separation methods with our technique of stacking would significantly increase the quality of retrieved body waves. Nevertheless, for this it would be necessary to have the data of dense high-resolution seismic arrays, so making new experiments would be a next step in development of our technique.

There are several methods based on weighted-stacking of cross-correlation functions, both in time and frequency domains, which allow significantly increase quality of extracted EGFs (Shimmel et al., 2011; Cheng et al., 2015; Liu et. al., 2016; Li et. al. 2017, etc.). We showed in previous sections that our time-domain algorithm based on signal-to-noise ratio increasing criteria makes it possible to ~~Nevertheless, the full~~ exclude~~sion~~ ~~of~~ incoherent cross-correlation functions from stacking and generally ~~the process of building up the EFGs, based on signal-to-noise ratio increasing criteria,~~ allows to obtain EGFs of even better quality~~, as has been shown in previous sections~~. Of course, signal-to-noise ratio increasing criteria is possible to use in the frequency domain, but this would make the algorithm significantly more complicated. It is necessary to remember, however, that this algorithm can be applied because ambient noise sources are generally characterized by relatively wide frequency band. In this case one can expect that increasing ~~of~~ signal-to-noise ratio for dominant frequency would result in increase of signal-to-noise ratio of all other frequencies of the signal, as shown in Bensen et. al. (2007).

The algorithm proposed in this paper has several limitations and drawbacks. One of the most important limitations is relationship between the time of seismic wave propagation between neighbouring sensors and the dominant period of the retrieved EGFs. If the time of surface-wave propagation is about one or two periods of this wave, then it would not be possible to separate body and surface waves, similarly as in seismic experiments with active sources. Moreover, the increase of signal-to-noise ratio of one event, for example, a retrieved surface wave, might lead to ~~the~~ decrease of the signal-to-noise ratio of other ~~f~~phases, in particular, ~~or a retrieved~~ body waves. ~~Another one drawback of the method is that~~ Our proposed technique of stacking allows increasing signal-to-noise ratio, but it has to be applied in combination with array configuration, which allow to keep control over azimuthal distribution to noise sources and to guarantee that the stationary phase condition is satisfied. In certain ~~situations~~situations, increasing ~~of~~ SNR after addition of a new function to stack is not always correspondings~~s~~ to coherence of stacked functions. For example, if coda wave part in a cross-correlation function gets smaller, then the SNR increases, nevertheless stacked functions might not be coherent to each other. The results of testing algorithm with real data ~~obtained~~ demonstrated, however, that the algorithm works fine with the high-frequency seismic noise acquired in two completely different areas. The results obtained for KuGB area demonstrate t~~, however, t~~hat ~~using~~ the SNR stacking method might be useful for building up an EGF by stacking ballistic surface wave signals retrieved from the ambient noise. In our study t~~T~~he high quality of surface waves in EGF was achieved both for brownfield and greenfield exploration areas. Experimental data used in our study is insufficient to make detailed evaluation how this technique is working with body wave signals, and it will be the subject for our ~~future~~ research in the future.

7 Conclusion

Results of our study suggest that classical approaches for EGFs evaluation from ambient seismic noise (Campillo, 2003) cannot be considered as a universal tool for extracting high-frequency EGFs. In particularly, in quiet areas with low level of

~~antropogenic~~anthropogenic and industrial noise the method would require long registration time because sources of high-frequency wavefield are weak and stochastically distributed both in space and time. One of the ways to treat the problem is to use ballistic waves and develop and improve methods for~~of~~ selection of ~~the~~ coherent parts of the ambient noise wavefield. Study of azimuthal distribution of ambient noise sources using array techniques is necessary to do prior to making passive seismic experiments, both in greenfield and brownfield exploration areas.

The presented algorithm of cross-correlation functions stacking in a time domain allows to increase significantly signal-to-noise ratio of retrieved EGFs. In our study we demonstrated that under certain conditions the body waves could be extracted from high-frequency industrial seismic noise using the proposed ~~algoritm~~algorithm~~ of stacking in the time domain~~. This was illustrated with the data collected during passive seismic experiment near the Pyhäsalmi underground mine. Nevertheless, for more detailed testing of possibility of extracting body waves, it would be necessary to analyse the data collected with a higher-density seismic array near mine. ~~Our proposed technique allows increasing signal-to-noise ratio, but not guaranty estimating of true EGF, because source may be outside of stationary phase area. Nevertheless, using of our technique together with array configuration, which allow to estimate azimuth to noise source make it possible to evaluate EGF of high quality.~~

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The presented algorithm of stacking makes it possible to extract EGFs from ambient seismic noise with frequencies higher than 1 Hz recorded in the quiet area without strong sources of industrial noise using 2-D seismic arrays. This has been demonstrated by application of our new technique to the data collected in the Kuusamo Greenstone belt area that is characterized by low level of anthropogenic seismic noise and has no industrial sites located nearby.

8 Acknowledgements~~es~~

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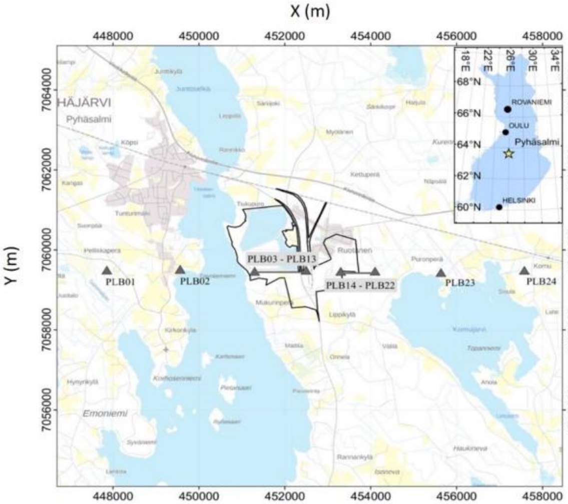

Figure 1: Map of the experiment near the Pyhäsalmi mine in Universal Transverse Mercator coordinate system with the two parts of the profile (PLB01-PLB13 – west part of profile; PLB14-PLB24 – east part of profile). Black lines are the boarders of the mine and open-pit territories. On locations PLB01, PLB02, PLB03, PLB13, PLB14, PLB22, PLB23, PLB24 both MEMS and Trillium Compact sensors was installed.

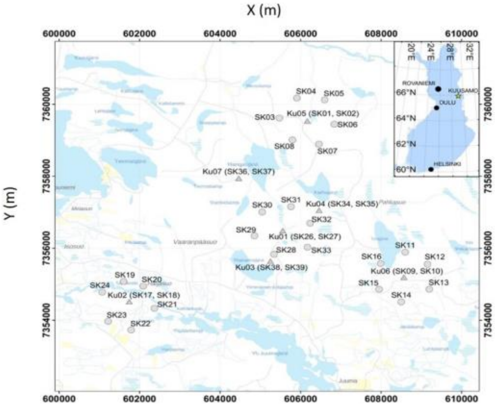

Figure 2: Configuration of the temporary seismic array on Kuusamo area in Universal Transverse Mercator coordinate system: white triangles – positions of ~~geophones~~broadband sensors (Trillium compacts); white dots – positions of accelerometers (MEMS).

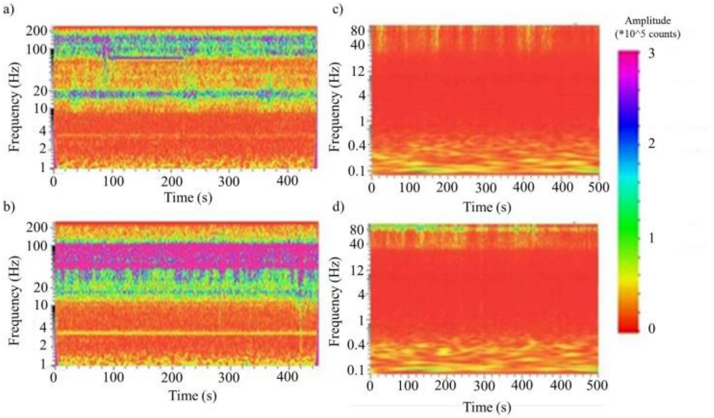

Figure 3: Result of time-frequency analysis of seismic noise recorded by the sensor a) the most distant from the mine in the Pyhäsalmi experiment, b) closest to the mine in the Pyhäsalmi experiment, c) most distant from a noise source (river) (KU05) in the large-aperture array in Kuusamo experiment, d) KU02 which is closest to the river in the large-aperture array in Kuusamo experiment.

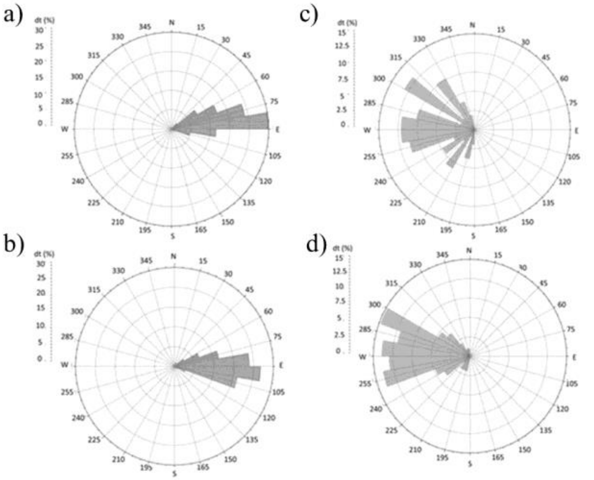

Figure 4: Result of azimuthal distribution calculation for different frequency bands for the Pyhäsalmi experiment: a) west part of profile, band of 2-5 Hz; b) west part of profile, band of 5-10 Hz; c) east part of profile, band of 2-5 Hz; d) east part of profile, band of 5-10 Hz.

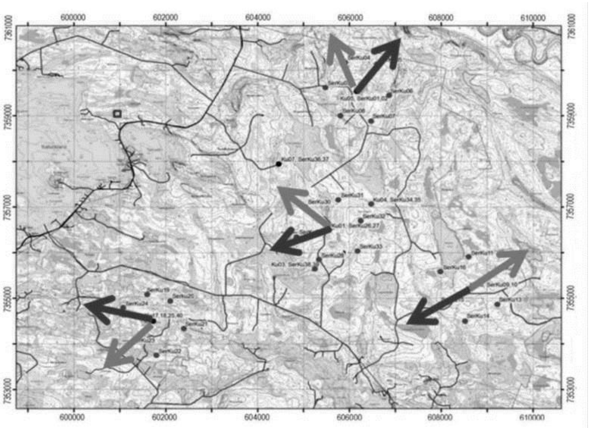

Figure 5: Azimuths to main noise sources: dots – stations of the temporary seismic array; black arrows show azimuths to noise sources in the frequency band 10-50 Hz; grey arrows show azimuths to noise sources in the frequency band 5-10 Hz.

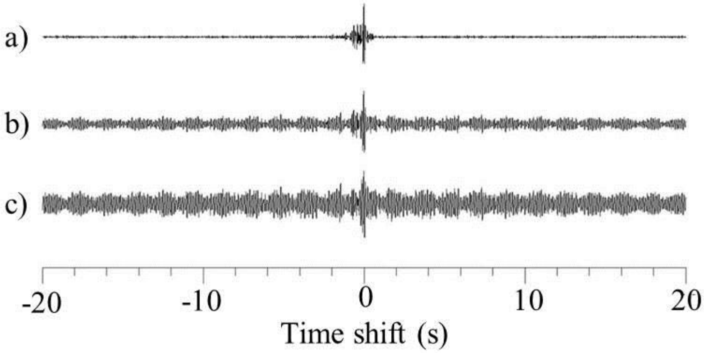

Figure 6: Final EGF's (vertical components) calculatedby different methods of stacking in the time domain for the frequency band 5-10 Hz: a) SNR-stacking (SNR=~~71~~40); b) Weight-stacking (SNR=15~~0~~.64); c) RMS-staking (SNR=10~~5~~.4~~6~~).

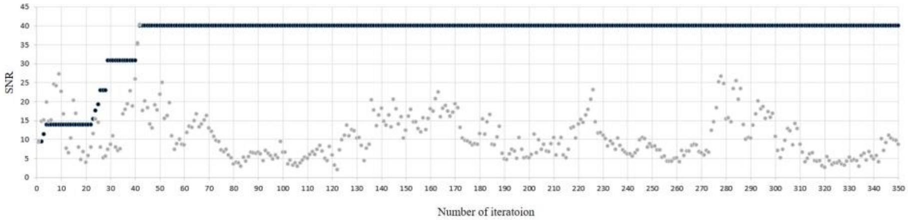

Figure 7: Build up process of EGF from cross-correlation functions by different methods: black dots – by SNR-stacking, grey dots – by simple stacking.

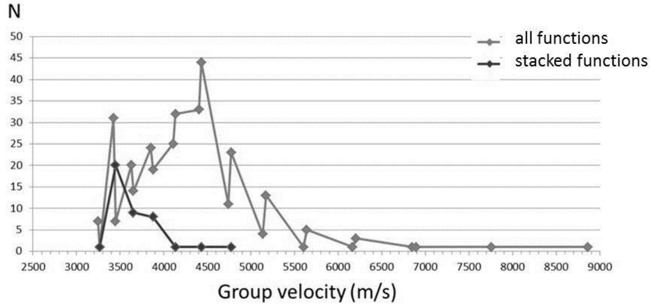

Figure 8: Distribution of EGF by group velocities for frequencies of 5-10 Hz.

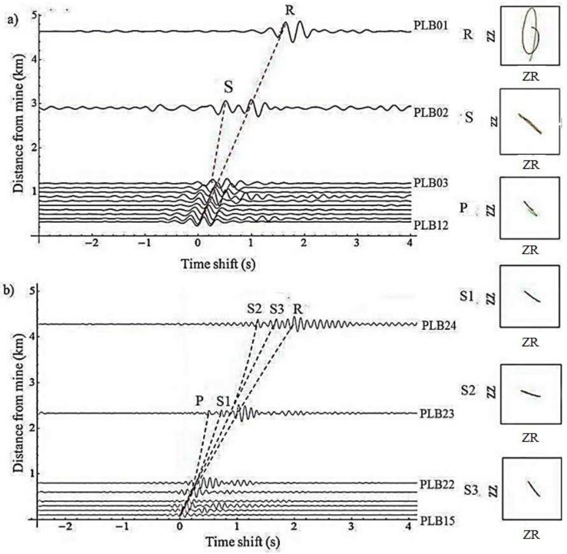

Figure 9: Result of stacking and particle analysis of EGF, evaluated in Pyhäsalmi experiment: a) western part of the profile in the frequency band 2-5Hz; b) eastern part of the profile in the frequency band 5-10Hz.

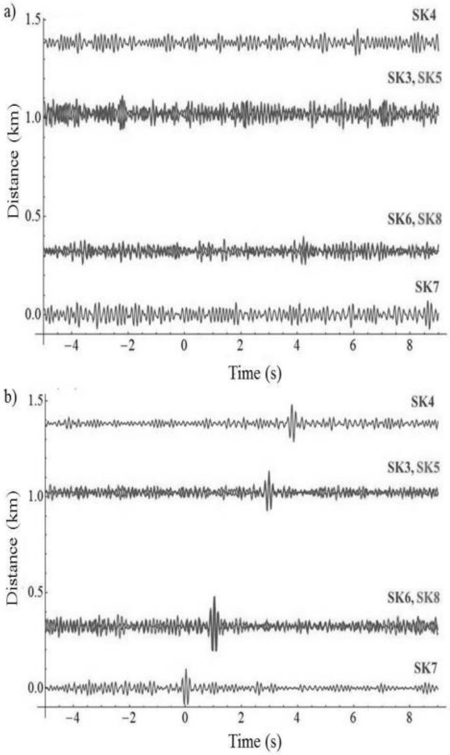

Figure 10: Empirical Green's functions calculated from records of small-aperture array in Kuusamo experiment in the frequency band of 5-10 Hz and stacked (vertical components): a) by simple stacking method; b) by SNR-stacking method. The EGFs in subplots a) and b) are sorted according to distance from sensor SK7.