Dear reviewers：

We really appreciate your time and efforts put in the review of this manuscript. The constructive comments and good suggestions are really helpful to improve our manuscript greatly. Below are the comments (in black) and the corresponding responses (in blue).

Responses to reviews from Andreas Köhler

General comments:

The use of horizontal-to-vertical spectral ratios (H/V) is a well-established method for geophysical shallow sub-surface investigations which is mainly used within the context of seismic site-effect studies and to infer sediment depths. It has been recently applied on glaciers to infer ice thickness for the first time which showed the potential of this passive seismic method to provide complementary observations for cryospheric research. To my knowledge the H/V method has not been applied to measure ice sheets thickness before. Therefore, this study is highly appreciated. The paper is well-written and presents conclusive and encouraging results. I have no major concerns about this manuscript, however, there are a few issues and details I would like the author to comment on and to add in the paper.

(1) I suggest to briefly discuss the origin of the H/V spectra. A full discussion is beyond the scope of this study, but it would be helpful for future applications to know more about the basic assumptions and their reliability. Different contributions to the H/V amplitudes have been discussed since the emergence of this method such as SH wave resonance, Rayleigh wave ellipticity, and Love wave Airy phases. Recently, forward modeling schemes based for example on the diffuse field theory have been proposed that take into account all seismic wave types (Jose Pina-Flores et al, 2017; GarciaJerez, 2016, Lunedei and Malischewsky, 2015). In the present paper this new method is used to invert the spectral ratios for the sub-surface structure. As far as I understood the code of Garcia-Jerez (2016) allows for separate computation of the contribution from

different wave types. In the considered frequency band, ocean microseisms usually contribute most to the background seismic noise, so I would expect the contribution from Rayleigh wave ellipticity to the H/V spectra shape to be dominant. Is this the case here?

Response: Thanks a lot for your helpful and constructive comments. Relative discussions were added in the revised manuscript in terms of the H/V curves interpretation and its reliability.

It is true that along the relative long history of H/V method, different seismic phases (body waves only, surface waves only, or a mix of them) were taken into account to the H/V curves interpretation and synthetic modeling. In this study, we adopted Garcia-Jerez (2016)'s method based on the DFA assumption involving both surface waves and body waves to forward calculate and invert the H/V spectral ratio. We agree that the ocean microseisms contribute most to the background seismic noise in the considered frequency band. In analysis of the contribution of different seismic waves to the H/V spectrum, it turns out that the surface wave plays a dominant role in the lower frequency part (0.1—0.3 Hz), while the body wave controls the shape of the H/V spectrum in the frequency band of 0.3—2 Hz. In particular, it seems that Love wave plays a major role around the fundamental peak frequency. However, no specific effect of the Love wave has been tested as we cannot exclude the Rayleigh wave and the body wave at the same time in the processing. Actually, despite the extensively successful applications, there are still controversies regarding the unknown ambient vibration wavefield composition and the specific contribution of a particular wave component (Langston et al, 2009; Lunedei and Malischewsky, 2015; García-Jerez et al., 2016). Specific theoretical simulation and carefully designed experiments are therefore required to decipher insightful knowledge about the debate.

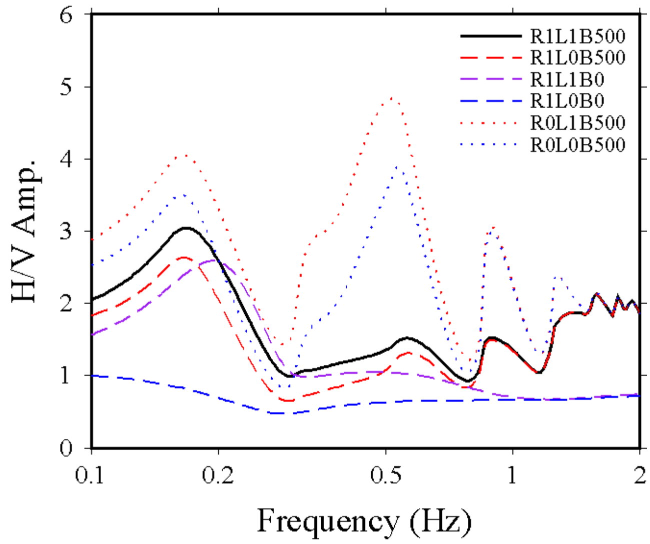

Figure 1. Contribution of different seismic waves. R, L, and B represent Rayleigh wave, Love wave, and Body wave, respectively. The number 1 stands for the mode of the particular wave and 0 indicates that the particular wave was not included in the calculation, while 500 is the number of integral points of Body wave.

(2) What are the limitations of the H/V inversion method (e.g., non-uniqueness) and, most important, what are the error bars of the inverted velocity structures (please add in Figure 5)? How much is the velocity allowed to vary in the parameter space?

Response: Non-uniqueness is an inherent limitation of geophysical inversion. As in the H/V spectral inversion, there is a trade-off between the shear-wave velocity (Vs) and the ice thickness, so the synthetic H/V spectrum of different Vs models (model A and model B) can both fit with the observed H/V spectrum. In this case, some other constraints such as the Bedmap2 ice thickness and reasonable Vs profiles (Wittlinger and Farra, 2012) are necessary to evaluate the inversion results.

Considering the trade-off between the Vs and the ice thickness, we cannot obtain accurate Vs and ice thickness at the same time in the H/V spectrum inversion. We therefore assumed that previous findings regarding the velocities are reasonable (the velocity structure adopted in this study is widely used in previous studies) and didn't set very large ranges for the velocities so as to provide constraint for the H/V spectrum inversion. The range of Vp is 3800—4000 m s^{-1} and of Vs is 1800—2000 m s^{-1} for model A. As for model B, the range of Vp is 3750—4000 m $s^{-1}$and 3500—3750 m s^{-1}

in the upper and lower ice layer, and the range of Vs is 1800—2000 m s^{-1} and 1400—1600 m s^{-1} in the upper and the lower ice layer. In this sense, we therefore don't think it is necessary to add the error bars of the velocity structures in Figure 5.

(3) I am also curious to what extent the other H/V peaks directly tell us something about the sub-surface structure. Can they be interpreted as multiples / overtones of the main peak, or do they correspond to other interfaces within the ice? Is there a peak or a through in the spectrum which corresponds directly to the interface within the ice that you invert for (Model B)?

Response：According to the studies by SESAME (2004), the secondary or third peaks in high frequencies may suggest the existence of shallower impedance contrast interfaces. However, it is not easy to confirm whether it is the case or not due to the lack of information in terms of the ice sheet structure. Based on your comments and the studies by Carcione (2016), another explanation is also possible. In the case of rigid bedrock underneath the ice sheet, the following resonance frequencies has the below relationship with the fundamental resonance frequency (f0):

$$f_n = (2n+1) f_0, \quad n = 0,1,2,..., \quad f_0 = \frac{Vs}{4h}$$

After checking the observed H/V spectra, we found that such relationship is suitable to most stations as the following secondary or third peaks are approximately three times or five times of f0.

According to your suggestion, we find that there is a trough (f1) closely followed the peak (f0) in each spectrum of model B and the ratios of f1/f0 are in the range of 1.6—2.0. However, no trough exists in each spectrum of model A. The same feature can be found in the observed H/V spectra. The trough here probably corresponds to the interface between the lower ice sheet layer and the bedrock as Tuan (2011) indicated a trough appears when the above layer has high passion ratio or the impedance contrast is high enough between the bedrock and the particular overlying layer. Thus, the existence of a tough in the observed spectrum provides additional evidence that the lower ice sheet has low Vs structure.

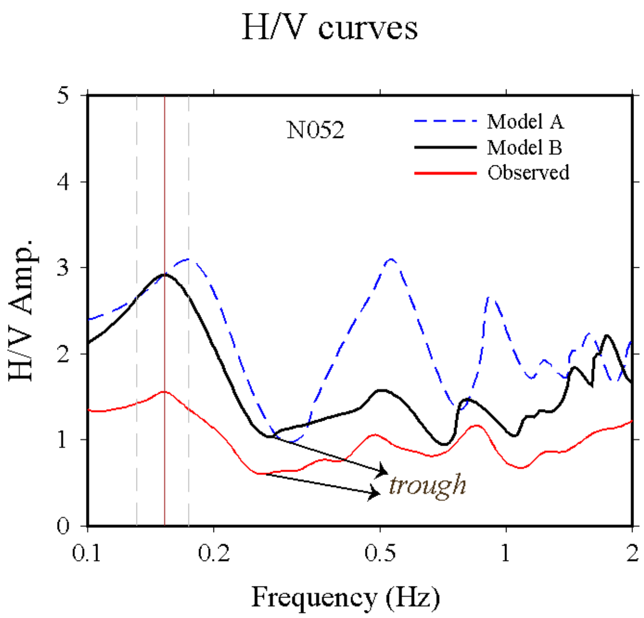

Figure 2. Example of a trough feature in the synthetic and observed H/V curves. A trough can be observed in the synthetic H/V curve using the optimum inversion Vs profile of model B, which is in accordance with that of the observed H/V curve. However, no trough appears in the synthetic H/V curve using the single ice layer model (model A).

In their paper, Picotti et al (2017) discuss the implication of soft-bed vs. hard-bed sub-glacial conditions on the H/V spectra, and interpret the presence of a H/V peak or a through to be related to these conditions. Do you have any indications that the presence of sediments (soft-bed) or sub-glacial lakes lead to similar observations, i.e., a trough in the H/V spectrum that is related to the interface depth, e.g. at station N060? Is the inversion scheme you use able to take this into account? Or in other words, is the half space velocity allowed to become lower than the ice-sheet velocity?

Response： Before conducting the H/V spectrum inversion, we modelled the synthetic H/V spectra under both assumptions of the soft over stiff medium and the stiff over soft medium as pointed out by Carcione (2016) and Picotti (2017), to fit the observed H/V spectrum. It turns out that the soft over stiff medium is more suitable to model the ice sheet-bedrock (as shown in Fig. 3). In other words, unlike the highly deformable sediments and water as found by Picotti (2017) beneath the Whillans Ice Stream, the basal conditions beneath our study sites are probably hard bedrock. Therefore, we didn't set soft half-space in H/V spectrum inversion.

As for the station N060, we tested the influence of a 300—500 m sedimentary layer squeezed between the ice sheet layer and the hard bedrock. It turns out that the sediment slightly shifts the whole H/V spectrum to lower frequency and make the spectrum fluctuate in the frequency band of 1—2 Hz (Fig. 4). Based on your suggestion, we have further changed the half space from a hard bedrock to a soft bedrock. We find that the sediment has similar effect. However, the fundamental resonance frequency disappears and the following secondary and third peaks shift to lower frequency (Fig. 4).

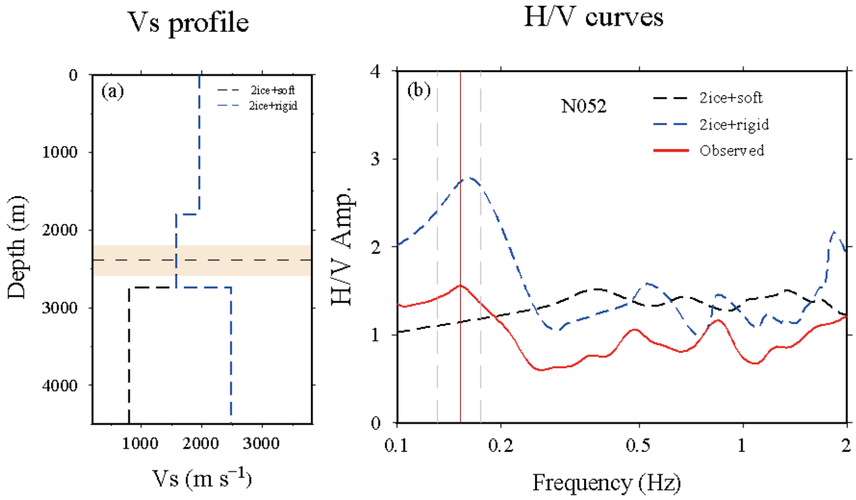

Figure 3. Effect of basal conditions on the H/V spectrum. As shown in panel b, no fundamental resonance frequency correlated to the ice sheet thickness is observed in the spectrum under soft basal condition assumption (black dashed line in panel a). Under rigid basal condition assumption (blue dashed line), the fundamental frequency and the shape of the H/V spectrum are consistence with the observed H/V spectrum.

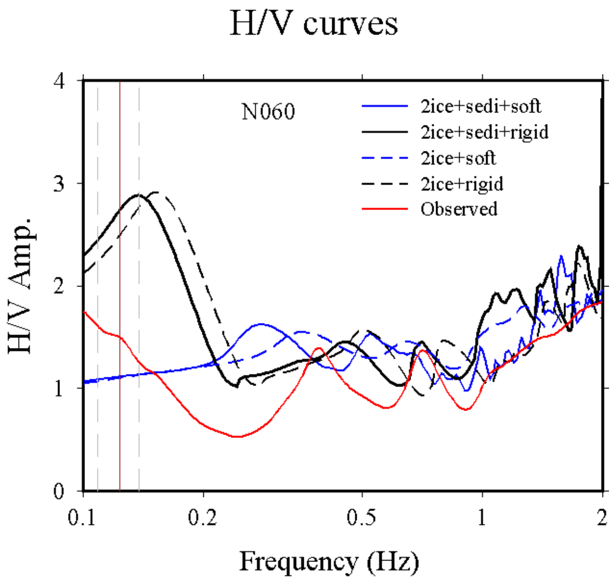

Figure 4. Effects of sediment and basal conditions on the H/V spectrum of station N060. We still cannot figure out the factors that affect the unclear fundamental frequency in the observed H/V spectrum.

(4) What is the physical model behind the two layer ice sheet model (model B)? What is the explanation for the low-velocity ice layer and are the inverted velocity values realistic? Does it make sense or have you tried to use a more complicated structure in the inversion (allow more layers and low velocity layers everywhere)? Maybe this could improve the fit even more.

Response: This study provides results to support the previous finding that the Antarctic ice sheet is stratified. However, we didn't further explore the physical nature of the low-velocity ice layer as it beyond our research scope. According to the studies of Wittlinger (2012, 2015), besides the pressure and the preferred ice crystal orientation, the presence of unfrozen liquids along the ice grain boundaries plays a major role in the remarkable Vs drop in the lower ice sheet.

We agree that the interface separating the ice sheet should be gradual but not be sharp. Following your suggestion, we build a seven-layer model (model C) as the velocity gradually decreases in this model. It turns out that the model C can also fit the observed H/V spectrum well, and the inversion ice thickness is within the error bounds of the Bedmap2 thickness. However, without accurate constraint information, we cannot determine finer-scale ice sheet structure due to the non-uniqueness of H/V spectrum inversion.

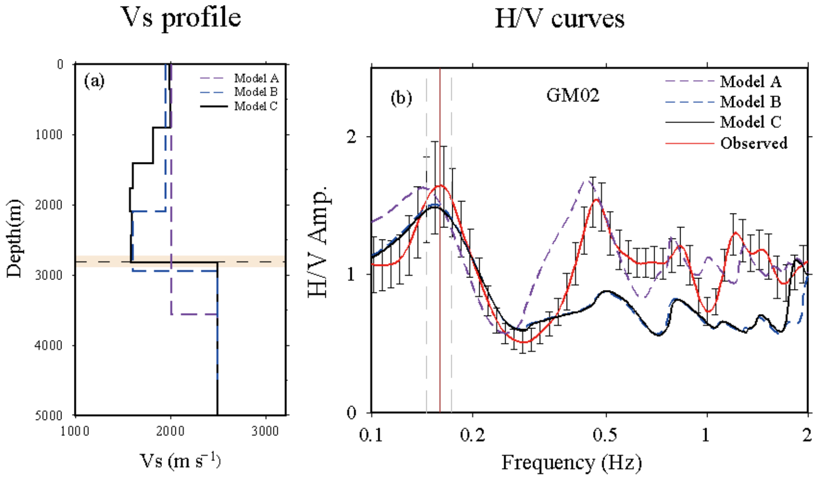

Figure 5. H/V spectrum inversion results of different models. Model A, B, and C are single, two-layer, and seven-layer ice sheet model, respectively. The synthetic H/V spectra using the optimum inversion velocity model B and C (panel a) can both fit the observed H/V spectrum (panel b).

(5) How is the peak frequency and its error estimated? For example in Fig 4 the picked frequency does not seem to correspond to a maximum in the H/V spectra for stations N198 and ST07.

Response: In a target frequency band, i.e. 0.1—2 Hz (in our case), the peak frequency (as the maximum amplitude denotes) and its error (standard deviation) can be calculated using the GEOPSY software with a number of noise waveform windows. We can read the value of peak frequency and its error directly from the H/V spectrum figure, as well as in the output file. As there are 18 stations (such as seismic station N108) whose maximum amplitudes are not related to the ice sheet resonance frequency in the frequency band of 0.1—2 Hz, we therefore narrowed the target frequency band to a smaller one as we can successfully read the peak frequency and its error. Station ST07 is representative of the five stations that are in absence of peak frequency related to the ice sheet resonance frequency, so no peak frequency and error can be obtained in the observed H/V spectrum in any frequency band. However, we marked the expected resonance frequency and the roughly estimated 10% error in the spectrum (as shown in

Fig. 6) using Eq. (1) with its Bedmap2 ice thickness. We also conducted H/V spectrum inversion using their H/V curves, while no inversion results were included and showed in this study for the five stations.

(6) Write some words about the spatial resolution (or footprint) of the H/V method. To what extent and where could existing ice sheet maps in Antarctica (or elsewhere) be improved using the H/V method in future seismic field experiments?

Response: The H/V peak predicts the resonance frequency of a layered medium for surface motion at the interface between the upper low-velocity layer and lower high-velocity layer (Langston, 2009), so the H/V method should reflect the average ice sheet thickness in the scale of seismic wavelength (e.g., for a peak at frequency 0.2—1 Hz and seismic wavelength of ~2.0 km, the spatial resolution is about 2—10 km). Therefore, in areas where the horizontal ice-rock interface rapidly changes within 1—2 kilometers, the ice thickness obtained from the H/V method may have relatively large difference compared with that investigated using the radio echo sounding (RES) method. In areas with relatively flat ice-rock interface, the results obtained from the H/V method can reflect the real structure. Considering that the interstation distance is about a hundred kilometers, the spatial resolution for the results obtained from the H/V method are largely limited by the distribution of the seismic stations. We have added some texts in the manuscript to explain it.

For the H/V method, it can improve the ice sheet map in Antarctica where the ice-rock interface cannot be detected by the RES method (e.g., where soft sediments beneath the ice sheet and no reflection signals in the RES profile). The uncertainty of the ice sheet thickness obtained from the H/V method can be a few hundred meters. The H/V method can also be applied in large scale glaciers in other continents.

(7) Fig 6: It is unclear to me why the synthetic spectra are divided by 2. Isnts.ce-r supposed to be the best fit of the data? Then, why do the amplitudes do not match?

Response: Some parameters affect the amplitude of the H/V spectrum such as variation of the Rayleigh wave ellipticity (Arai and Tokimatsu, 2004), impedance contrast

(SESAME, 2004), and the intrinsic attenuation (Carcione et al., 2016). These effects on the amplitude, however, are not clear and quantitatively determined, making the amplitude not as robust as the peak frequency. We tested different basal conditions by varying the impedance contrast between the lower ice sheet layer and the half space. As it shows in Fig. 6, the higher impedance contrast, the larger the amplitude is. The location of the peak frequency and the shape of the H/V spectrum that we mainly focused on, however, also largely deviate from the observed H/V spectrum. Therefore, we have to make a compromise to adopt the currently used half space parameters that can both fit the peak frequency and the shape of the observed H/V spectrum.

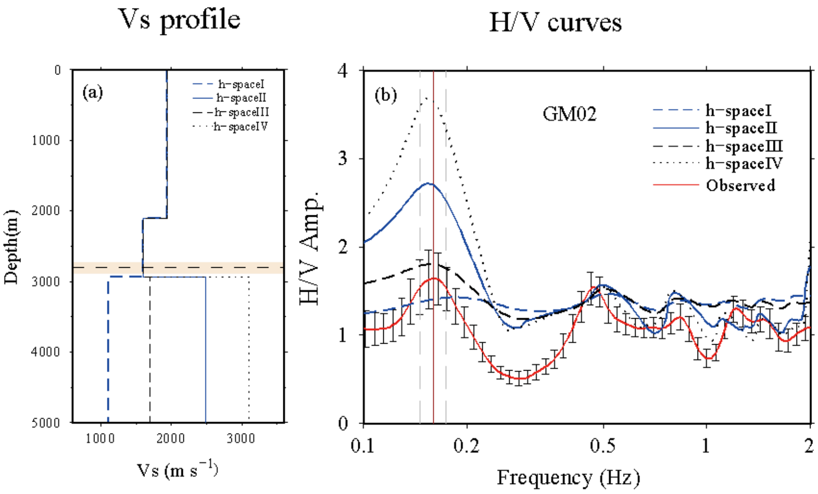

Figure 6. Effect of impedance contrast (basal condition) on the peak amplitude. As shown in panel b, the more rigid the half space (the higher the impedance contrast), the larger the amplitude is. It can be seen from panel b that the peak frequency and the shape of the H/V spectrum deviate from those of the observed H/V spectrum as impedance contrast (basal condition) changes.

Technical corrections:

In references: Change “Jean-Jacues L.” to “J.-J. Leveque”

We have corrected it in the revised manuscript.

References:

Carcione, J. M., Picotti, S., Francese, R., Giorgi, M., and Pettenati, F.: Effect of soil and bedrock anelasticity on the S-wave amplification function. Geophysical Journal International, 1: 424–431, 2016.

Langston, C. A., Chiu, S. C. C., Lawrence, Z., Bodin, P., and Horton, S.: Array observations of microseismic noise and the nature of H/V in the Mississippi embayment. Bulletin of the Seismological Society of America, 99(5), 2893–2911, 2009.

Tuan, T. T., Scherbaum, F. and Malischewsky, P. G.: On the relationship of peaks and troughs of the ellipticity (H/V) of Rayleigh waves and the transmission response of single layer over half-space models. Geophysical Journal International, 184: 793–800, 2011.

SESAME, European Research Project, WP12–deliverable D23.12. Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation, 2004.

Wittlinger, G., and Farra, V.: Observation of low shear wave velocity at the base of the polar ice sheets: evidence for enhanced anisotropy. Geophysical Journal International, 190(1): 391–405, 2012.

Wittlinger, G., and Farra, V.: Evidence of unfrozen liquids and seismic anisotropy at the base of the polar ice sheets. Polar Science, 9.1: 66–79, 2015.

Responses to reviews from Adam Booth

I thought this was a good paper that applies a relatively novel method in an Antarctic environment. The paper is generally well-written, though could benefit from more quantitative discussion and consideration of its limitations. The scope of the paper matches that of The Cryosphere and, with revision, I think it will be a good addition to the literature. I make some specific comments on three main shortcomings below, then mention some smaller issues that would be required in a corrected manuscript.

SPECIFIC COMMENTS:

The authors show the application of the H/V seismic technique for quantifying the thickness of an Antarctic ice sheet. Two approaches are tested, based on the estimation of resonance frequencies and a more-developed inversion approach. Ice thicknesses are then compared to observed depths in Bedmap2, with the authors concluding that inversion approach is preferred but still acknowledging that some mismatch between the inversion and the Bedmap2 reference. In the paragraphs below I suggest some areas where the paper could be improved. I would emphasize that I do think the paper will make a good contribution to The Cryosphere with some attention to these issues.

1) For a paper that considers inversion and quantitative data interpretation, there's a lack of detail in the text. While I appreciate that a thorough description of the inversion approach is perhaps not required, it sits uncomfortably that there is only one simple equation in the paper – and no presentation of the raw data or the inversion approach.

Response：Thanks a lot for this constructive and helpful comment. We have added some texts regarding the H/V method and the inversion approach in the revised manuscript, as well as some relevant references for providing more details for the inversion approach. Besides, an example of raw ambient noise data (a 5-day long noise record) was shown in the supplement.

The authors also consider the uncertainty in Bedmap2, but give much less attention to the uncertainty in their approach (which seems counter-intuitive since I'd suggest that the uncertainty in Bedmap2 is always going to be much less than in the H/V method). Table 1 does list uncertainties in resonance frequencies, but how these are defined should be clarified. For example, peaks E012 and N148 in Figure 3 seem to be more poorly defined than others, yet their uncertainty in Table 1 seems to be consistent with the wider dataset. The lack of uncertainty analysis sits a little uncomfortably with the frequent description of the method being "reliable" (first instance in L16) and robust. These are subjective terms that would be best qualified with numerical evidence. This is not to say that the method is unreliable, but the authors could do more to demonstrate this rather than relying on qualitative descriptions. Just present the observations and let the readership decide!

Response: We agree with your comment that quantitative discussion instead of subjective terms should be used. We first would like to state the reason why we show the uncertainty of Bedmap2 ice thickness in this study. Due to the fact that the Bedmap2 ice thickness are associated with errors that are variable, only sites with small errors (57 stations) can be used as ice thickness validations. We therefore show the uncertainty of the Bedmap2 ice thickness at each study sites. Following your very helpful suggestion, we have calculated and listed relative errors of the calculated and inversion ice thickness to the Bedmap2 ice thickness for each station in Table 1. Relevant expressions were also modified or added in the manuscript.

The GEOPSY software used in this study calculate the peak frequency and its standard deviation using all selected signal windows (i.e. in case of no windows were discarded in the noise record, a 5-day long noise record generates 720 windows with 600 s length, the GEOPSY software calculates the peak frequency for each window and then calculate its standard deviation using all 720 windows, an example is shown in Fig. 1). We read the peak frequency and its standard deviation from the output file. Although the absolute uncertainty for peak E012 and N148 seems to be consistent with other stations, the relative uncertainty to its peak frequency (E012, 12.4%; N148, 12.4%) is larger than the other stations (GM02, 8.8%; P071, 9.3%).

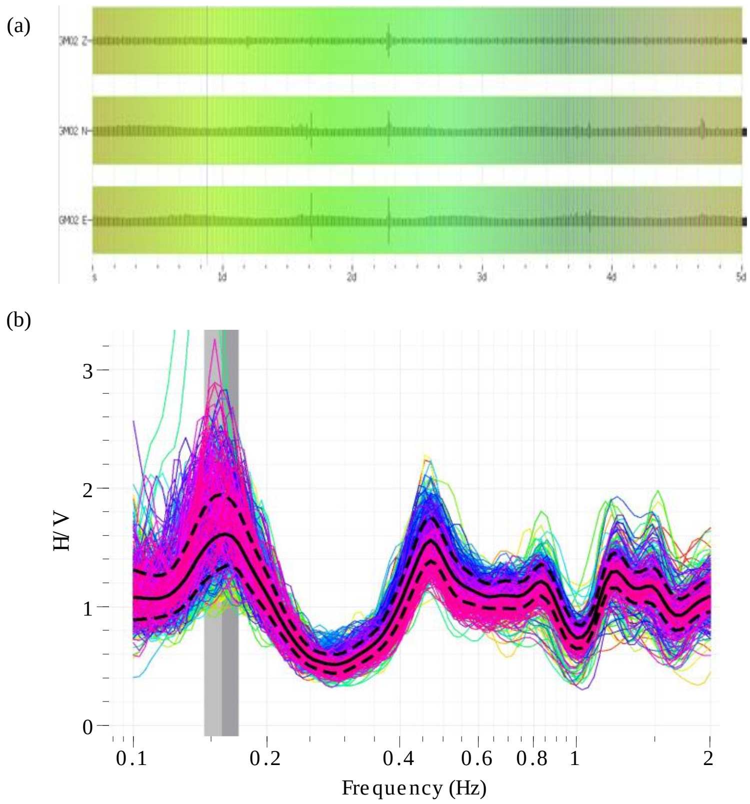

Figure 1. The windows (each window has a length of 600 s) used for H/V processing are colored in panel a, and each H/V curve is calculated using the corresponding selected window (panel b). The solid black curve (in panel b) represents H/V geometrically averaged over all used individual H/V curves.

2) The authors also seem very keen to justify the need for H/V analysis, in part by pointing out the drawbacks in other techniques (e.g., L40-96). Some of these points are valid – gravity modelling is clearly a rather low-resolution technique (although the reference to gravity data processing in L54 is very out-dated) – but I don't see that the 'economic and logistical' requirements of H/V acquisition would be significantly less than RES or seismic. The authors could lessen the criticism of these methods, and present the case for H/V analysis more simply as another interesting option for a field survey.

Additionally, the authors often point out that this is the first application of the technique on an Antarctic ice sheet: I'm also unsure that this in its own right is significant. While the logistics of an Alpine study are likely simpler than an Antarctic deployment, I would suggest that the ‘seismically quiet’ Antarctic – featuring simpler subglacial geometries-likely offers better-quality data than in the Alps (as mentioned in L314-5) so it should be no surprise here that promising results are obtained.

To summarise this paragraph, the justification for the authors’ approach should be slightly moderated: just let the results speak in the own right, and suggest how they would complement (rather than replace) existing geophysical practice.

Response: Thanks for this constructive comments. We have revised relevant expressions according to your suggestions. First of all, we have removed some descriptions regarding the drawbacks of other methods. Secondly, we present the H/V method as a passive seismic method that provides independent constraints to ice sheet thickness and can be used to complement existing methods in the case of the inaccessibility of the active seismic and RES methods in terms of their large logistical support requirements.

3) The discussion section ends with some conflicting and speculative advice for H/V compliant seismic acquisition. In terms of the conflicting recommendation, the authors propose a desirable record length for acquiring useful H/V acquisition. In L320, the authors caution against using a record length that is only 1 hour long vs. one that is 5-days long. However, in L322-323, they suggest that a ‘proper’ record length of 1-2 hours would be sufficient. Firstly, the word ‘proper’ is misused here and it is unclear what the authors mean by this–presumably they mean “a record length suitable for reliable analysis”? But more importantly, there is an inconsistency between the recommended record lengths. I don’t see how a 1-hour record would be inappropriate, but a 1-2 hour record would be fine. Additionally, in terms of the cost and logistic requirements of a deployment, if you’re going to record seismic noise for 1-2 hours, why not record for 3-4 hours?! The logistic cost is presumably the same, but you’d maybe get better data quality! In terms of the subjectivity of this recommendation, presumably the authors have longer record lengths from their seismic stations? It should be possible to show how the estimate of ice thickness converges (?) on the Bedmap2

thickness as a function of record length, and therefore remove the subjectivity from this argument.

Response： We are sorry that we made an unclear expression here. Due to the "aseismicity" and very limited human activities in Antarctica, the quality of noise waveforms data is generally better than that found in other areas near the urban cities. We found that the shape of the spectra of the four tested record lengths (1h, 2h, 4h, 8h) are very similar to the shape determined using a record five days long. The peak frequencies of the four different length records are all within the margin of error for the peak frequency as determined with the record five days long. Thus, the ice thickness derived from Eq. (1) and H/V spectrum inversion using 1-hour long record would not result in substantial deviations from that of long records. However, we also found that the H/V spectrum exhibited less stability for thin ice sheet when the lengths of noise records decreased, which may be attributed to the interference of the high-frequency waves such as winds and other sources within short recording time intervals (Picotti et al., 2017). Such cases were found for stations BENN, E012, E018, E024, E026, and E028 (their ice thicknesses range from 500 m to 1.8 km) in this study. For these stations, two hours should be good intervals to conduct H/V processing. Therefore, we infer that two-hour long observation is better for areas with thin ice sheet (i.e. the ice thickness is less than 2 km in most places in West Antarctica). Although one-hour record can be sufficient to conduct H/V processing, we however, would like to follow your comment to advice a uniform two-hour recording interval for data acquisition in Antarctica.

SMALLER CORRECTIONS:

L11: "implemented at single stations using seismic ambient noise waveforms" seems rather specific for the first line of the abstract, which is just generally about H/V methods.

Response: We agree with your comment and have revised this sentence.

L16: "reliably measured" is subjective – objectify it with some performance metrics.

Response: Following your very helpful suggestions below, we have calculated the relative errors of the H/V results to the Bedmap2 ice thickness. It shows that the ice thickness derived from the H/V method has comparable accuracy to the Bedmap2 ice thickness. We therefore revised “reliably measured” to “has comparable accuracy to the Bedmap2 database”. The detailed performance metrics were stated in the main text.

L31-33: “global climate change” is misplaced here. While ice sheet thickness is important to know for sea-level rise studies, linking it here to “global climate change” is a step too far.

Response: Thanks for this comments. We have replaced “global climate change” with “sea level change”, which would be intimately connected with ice thickness.

L34: Logical jump. The sentence starting “Moreover” likely needs a new paragraph, or a bit more development from the previous sentence.

Response: “Morevoer” was modified to “Additionally”.

L35: The need for accurate thickness measurements is true, but it’s more likely achieved with RES than it is ever going to be with H/V analysis. Yes, there are places where RES is problematic, but the places that H/V offers better accuracy and/or precision will be few and far between. This links partly to Comment (2) that I made previously.

Response: We agree with your comments. RES method, as a very effective method for ice thickness measurements, played and will keep playing the dominant role in ice thickness investigation in Antarctica. The H/V method, as a passive seismic methods, provides independent and new constraints for ice thickness from other perspective with relatively lower cost and logistical support. Besides, we think the H/V method could be further used to infer basal properties as Picotti (2017) conducted in glacial studies.

L41-42: What is “deep seismic sounding” as opposed to the seismic reflection and refraction methods that are already mentioned?

Response: We made a mistake here and have modified “deep seismic sounding” to “drilling”.

L45: Remove “While”.

Response: Revised accordingly.

L49-51: Reference to Bedmap data seems misplaced at this point in a background

Response: Sorry we didn’t write it clear. We refer to Bedmap data here as to state the contribution of the existing methods for obtaining abundant data.

L54: How big a problem would terrain corrections specifically be in Antarctica? Also, the gravity processing reference (Drewry, 1975) seems very out of date.

Response: We agree that in the year of 1975, the absence of high-resolution topography data may be a big problem for terrain corrections in Antarctica. We believe the recent SRTM high-resolution topography data my greatly improve the accuracy of the terrain corrections. We have deleted this expression in the manuscript.

L59: What complement, specifically, does H/V offer to established methods?

Response: The H/V method provide new constraints on ice sheet thickness with seismic ambient noise data, which we think could also provide complementary information for the strong velocity contrast at the ice-bedrock interface. We acknowledge it may confuse, so we delete this expression in the revision.

L72: Over-selling the technique: "which suggests its powerful effectiveness … etc". As with all techniques, there will be places where H/V is problematic.

Response: We agree and have removed it.

L85: Another logical jump. Before talking specifically about the analysis parameters, you need to explain what the analysis requires.

Response: Thanks for this comments. We have added some texts regarding the reason why shear-wave velocity analysis is needed in the manuscript.

L96: Repetition of the complementary application of H/V spectra (again without clearly explaining the complement).

Response: We have removed this expression in the manuscript.

L103: "relatively sparse" – spares compared to what?

Response: The distribution of the stations was relatively sparse compared to many dense arrays on the other continents where it is relatively easy to deploy seismic stations. We have added some texts in the revised manuscript to make this point clear.

L106: how does burying a station "guarantee" data quality? Presumably, you mean "to improve data signal to noise ratio"?

Response: Yes, we mean to improve the data signal to noise ratio by burying a station below surface snow since it can ensure good coupling and reduce environmental noise (such as wind). We have revised it accordingly in the manuscript.

L124: "is not that robust" – very subjective. Defend and quantify what you mean by this. What kinds of errors result?

Response: We are sorry we didn't express it clear. The peak amplitude is assumed to correspond to the site amplification factor (which of engineering interest), while no agreement has been achieved to support the statement and many studies came to conflict and even wrong results (Lunedei and Malischewsky, 2015). As we are only interested in the peak frequency in this study, we therefore don't give a detailed description about the amplitude here.

L157: Repetition of this point about sedimentary structure investigations.

Response: This sentence was removed.

L162: Capitalise "Geopsy" for consistency with earlier instance.

Response: Revised accordingly.

L208-209: Give the frequencies in the main text. I appreciate that they are listed in the table and in the figures, but key observations could be usefully included here.

Response: Revised accordingly.

L246: Define what you consider to be "consistent" – consistent to within what threshold?

Response: Thanks for this comment. Following your very helpful suggestion, we have calculated the relative error of the inversion ice thickness to the Bedmap2 ice thickness. We found that the ice thickness at 26 stations and 46 stations out of the 48 stations along the profiles are within 10 % and 15 % threshold of the Bedmap2 ice thickness. We have revised this expression accordingly.

L273-274: Again, define what you mean by "adequately constrained" – to what threshold? You could just say (e.g.) that estimates are consistent within a 5% threshold and let the readership decide if this is adequate.

Response: Thanks again for this good suggestion. We calculated the relative errors of the inversion ice thickness to the corresponding Bedmap2 thickness at each station and found that the inversion ice thickness of 22 stations, 35 stations, and 58 stations are within 5 %, 10 %, and 15 % threshold of Bedmap2 ice thickness, respectively. Considering that the Bedmap2 ice thickness is associated with certain error at each site, we then modified this "adequately constraint" expression to "comparable accuracy to the Bedmap2 ice thickness" in the manuscript.

L282: "inverted" rather than "inversion".

Response: Corrected.

L284-287: what is it about these two stations that cause them to perform so differently?

Response: Previous finding shows there are sediment with 300—500 m thick squeezed between the ice and the bedrock layers beneath station N036 (actually, there are sediment layers beneath station N020 to N060, Anandakrishnan and Winberry, 2004; Wittlinger and Farra, 2012; Frederick et al., 2016). The synthetic H/V spectrum modelling shows that the existence of sediment will shift the resonance frequency of the ice layer in the H/V spectrum, thus leading to large uncertainty of calculated ice thickness (Fig. 2).

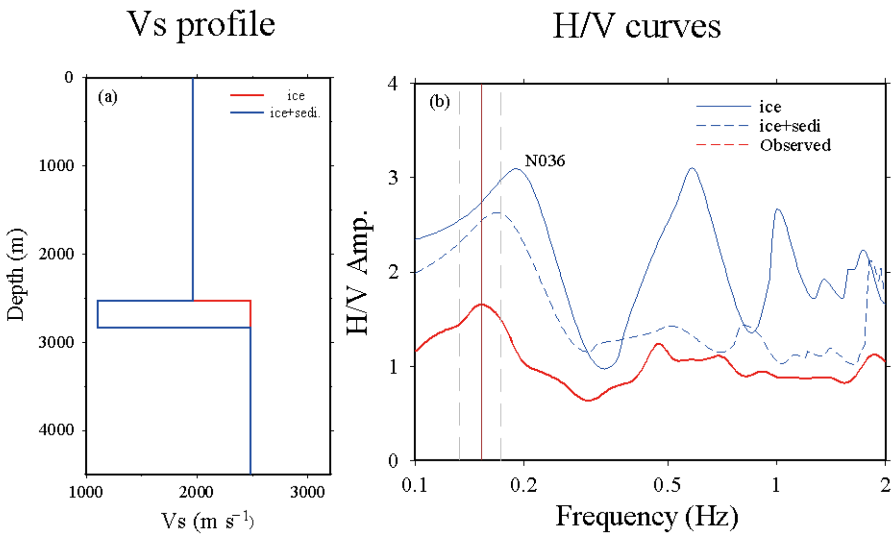

Figure 2. Effect of the sediment on the location of peak frequency. The Vs profiles (panel a) show the Vs structures with and without a 300 m thick sedimentary layer squeezed between the ice sheet and the bedrock layer. The corresponding H/V curve calculated using each Vs model is shown in panel b.

Table 1: Could be useful to have % error, relative to the bedmap thickness?

Response: Thanks for this helpful suggestion, we have revised it accordingly.

Figure 3: Needs a colour key.

Response: The GEOPSY software provides no colour key in the H/V spectrum calculation procedures. In fact, each colour corresponds to a signal windows used for computing the H/V spectrum (i.e. as a 5-day long noise record is divided into windows of 600 s length, the number of windows is 720 and there are 720 colours matching with the 720 H/V spectra, an example is shown in Fig. 1). As some windows were discarded due to transient signals (earthquakes) and some other high frequency signals, the number of windows (colours) used to compute (represent) the H/V spectrum varies for each station.

Figure 4: Plot the elevation panels at the same vertical scale. It's also a little unclear to me what the data in this figure show. If the red dots are the reference Bedmap2 thickness, how is the ice thickness defined in the panels showing the ice/rock interface? It can't be from bedmap, otherwise the red dots would coincide with this interface.

Response: We have tried to plot the elevation panels at the same vertical scale. The figure, however was not as satisfactory as it currently shows since the range of elevations largely varies in different profiles (i.e. the uniform elevation scale to plot the four panels should be 8 km, while the scale for CC' profile is only 4 km).

The elevation data along each profile were extracted using the geographical coordinates of the start and the end stations. We apologize that we made a mistake when extracting the AA profile elevation data by using a wrong longitude value of station N215 and have confused the colors marking the inversion thickness and the Bedmap2 thickness in profile AA and DD panels. This figure was corrected accordingly in the manuscript. Besides, due to the fact that some station sites are not exactly in the straight line defined using the geographical coordinates of the start and the end stations, some red dots still don't exactly coincide with the interface.

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Antarctic ice sheet thickness estimation using the H/V spectral ratio method with single-station seismic ambient noise

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Abstract. ~~The horizontal-to-vertical spectral ratio (H/V) method implemented at single stations using seismic ambient noise waveforms is a fast, noninvasive, efficient method to investigate the subsurface velocity structures of the shallow crust.~~ In this study, we report on a successful application of the horizontal-to-vertical spectral ratio (H/V) ~~H/V~~ method, generally used to investigate the subsurface velocity structures of the shallow crust, ~~-~~to estimate the Antarctic ice sheet thickness for the first time. Using three-component, five-day long, seismic ambient noise records gathered from more than 60 temporary seismic stations located on the Antarctic ice sheet, the ice thickness measured at each station ~~was reliably measured~~has comparable accuracy to the Bedmap2 database. Preliminary analysis revealed that 60 out of 65 seismic stations on the ice sheet obtained clear peak frequencies (f0) related to the ice sheet thickness in the H/V spectrum. Thus, assuming that the isotropic ice layer lies atop a high velocity half-space bedrock, the ice sheet thickness can be calculated by a simple approximation formula. About half of the calculated ice sheet thickness were consistent with the Bedmap2 ice thickness values. To further improve the reliability of ice thickness measurements, two-type models were built to fit the observed H/V spectrum through non-linear inversion. The two-type models represent the isotropic structures of single- and two-layer ice sheet, and the latter depicts the non-uniform, layered characteristics of the ice sheet widely distributed in Antarctica. The inversion results suggest that the ice thicknesses derived from the two-layer ice models were ~~highly~~in good ~~-~~consistence~~t~~ with the Bedmap2 ice thickness database, and their ice thickness differences were within 300 m at almost all stations. Our results support previous finding that the Antarctic ice sheet is stratified. Extensive data processing indicates that the time length of seismic ambient noise records can be shortened to ~~1 – 2~~two hours for reliable ice sheet thickness estimation using the H/V method. This study extends the application fields of the H/V method and provides an ~~complementary~~effective and independent way to measure ice sheet thickness in Antarctica.

1 Introduction

The Antarctic ice sheet is the largest on the Earth, covering over 98 % of Antarctic continent. As a fundamental parameter of the Antarctic ice sheet, ice sheet thickness is significant for dynamic ice sheet modeling of mass balance and sea level changes ~~global climate change~~ (Budd et al., 1991; Gogineni et al., 2001; Bamber et al., 2001; Hanna et al., 2013). ~~Moreover~~Additionally, seismic waves become more complex when traveling through an ice sheet with thickness ranging in hundreds to thousands of meters thick. Thus, accurate ice sheet thickness is a critical metric for recognizing and denoising seismic multiples trapped inside the ice sheet when imaging crustal and mantle structures below the ice sheet (Lawrence et al., 2006; Hansen et al., 2009, 2010). Therefore, better ice sheet thickness and structures can also improve the study of the geological structure underneath the ice sheet in Antarctica.

Given the importance of Antarctic ice sheet structures, many geophysical methods, such as drilling, gravity modelling, radio echo sounding (RES),~~ and~~ and active seismic approaches including reflection and~~,~~ refraction, ~~and deep seismic sounding,~~ have been used in local or regional scale ice sheet thickness investigations since the 1950s (Bentley and Ostenso, 1961; Bentley, 1964; Evans and Robin, 1966; Evans and Smith, 1969; Robin, 1972; Drewry et al., 1982; Cui et al., 2016). By studying gravitational anomalies in the ice sheet, gravimetric measurements provide an indirect way to infer the average ice thickness over a region. ~~While~~ A~~a~~ctive seismic and RES methods can determine the ice thickness at a much smaller area by converting the echo time of seismic and electromagnetic waves into an estimation of ice thickness. Among these methods, the active seismic and RES methods are the most widely used techniques for ice thickness measurements due to their relatively high accuracy and better spatial resolution, while gravity modelling is used as a complementary way in areas where lack direct ice thickness measurements.~~.~~ Using these methods (with the dominance of the RES method), abundant ice thickness data were collected over the past few decades. Compiled and gridded, ~~After compiling and gridding the data derived from these methods,~~ these increasing data volumes were used to construct the Bedmap1 and Bedmap2 databases at a resolution of 5 km and 1km, respectively ~~Bedmap2 at a resolution of 1 km ice sheet thickness databases covering south of 60° S were constructed~~ (Lythe et al., 2001; Fretwell et al., 2013). However, traditional methods for estimating ice thickness still have limitations. For example, the accuracy of the gravity method is relatively low because of its intrinsically low sensitivity of a gravimeter to the gravitational anomalies related to the ice sheet-bedrock interface~~ and the approximated terrain correction assumptions necessary for data processing (Drewry, 1975)~~. In the case of the active seismic and RES methods, ~~despite their high accuracy~~ they require considerable economic and logistical support~~,~~ to collect the data. With the rapid growth of cryo-seismology in the last one to two decades, many passive seismic methods have been applied to cryospheric research (Podolskiy and Walter, 2016; Aster and Winberry, 2017). Given that passive seismic methods can mitigate logistical problem and is relatively cost-efficient (Zhan et al., 2013; Picotti et al., 2017), it is therefore of interest to explore the feasibility of passive seismic methods to contribute additional and/or better constraints to the ice sheet structure.

~~The RES method has a further limitation as the echo free zone (EFZ) in areas of high temperature ice, possibly related to signal scattering or signal disappearance, making data collection impossible in these areas (Drews et al., 2009). To enrich the ice thickness database in Antarctica and make a complementary for the existing methods, more geophysical methods have to be explored for determining ice sheet thickness reliably, accurately, and efficiently at low cost.~~

~~Passive seismic methods, such as the t~~Teleseismic P-wave receiver functions (PRF), as a generally used passive seismic method to determine crustal and mantle discontinuities, is also sensitive to the ice-bedrock interface and the seismic properties of ice sheets. Hansen (2010) successfully modelled ice sheet thickness beneath several stations in East Antarctica using PRF. Wittlinger (2012, 2015) investigated the anisotropy of the polar ice sheet by modelling the P-to-S wave conversion with the negative PRF amplitude. Yan (2017) confirmed that the ice thickness results derived from PRF are consistent with the Bedmap2 ice thickness database. However, large numbers of teleseismic events are needed to perform PRF; it usually takes at least a one-year period of data collection, thus greatly limiting the application of the PRF method in harsh environments such as those found in Antarctica.

In order to improve the ~~reliability, accuracy, and~~ efficiency of ice thickness investigation, we selected the horizontal-to-vertical spectral ratio (H/V) method to determine ice thickness. As a ~~noninvasive and~~ passive and non-invasive seismic method, the H/V technique has been extensively used in seismic exploration as a tool to detect sediment thickness ~~, which suggests its powerful effectiveness in subsurface structure investigations~~ (Konno and Ohmachi, 1998; Ibs-von Seht and Wohlenberg, 1999; Bonnefoy-Claudet et al., 2006; Bao et al., 2017). Considering that the sediments and ice sheet layer are both low shear-wave velocity (Vs) layers atop the high velocity bedrock, the H/V method should be suitable for determining ice sheet thickness.

Lévêque~~Jean-Jacques~~ (2010) applied the H/V method to four stations in the Dome C region of Antarctica for inferring the uppermost snow layer thickness and its corresponding ice properties a few meters depth. Picotti (2017) recently adopted the H/V method to detect glacial ice thickness ranging from a few tens of meters to ~800 m in Italy, Switzerland, and West Antarctica. The H/V method has been validated for its reliability to measure glacial thickness comparing with the radio-echo sounding, geoelectric, and active seismic methods implemented at or near the same study sites. The great advantage of the H/V method over other approaches is that there is no need to record earthquakes or active sources, since it utilizes seismic ambient noise. Moreover, the H/V method requires only a few tens of minutes of seismic ambient noise recordings at single portable three-component seismometers. This greatly enhances efficiency and reduces cost and logistical support requirements.

Shear-wave velocity is an important parameter that controls the shear-wave impedance contrast (product of density and shear-wave velocity) at the interface between the upper and the lower layers. Since ~~Since~~ the shear-wave velocity of an ice sheet is ~1900 m s^{-1}, and generally much higher than a snow layer (~700 m s^{-1}), therefore the impedance~~velocity~~ contrast of the ice sheet-bedrock half-space is not as high as that of the snow-ice sheet layer. Moreover, the H/V spectrum may be more complicated than that of a glacier or snow layer given the complex subglacial environment since there might be subglacial lakes and sedimentary layers. In addition, the internal ice structure might affect the H/V spectrum given the variations in seismic velocities induced by changes in density, and temperature, as well as the ice crystal size and orientation of an ice sheet. Whether the H/V method can be used to estimate the ice sheet thickness or not remains an open question. Although the H/V method has been successfully applied to study snow and shallow glacial thickness (Lévêque~~Jean-Jacques~~ et al., 2010; Picotti et al., 2017), to our knowledge, the H/V method has not been performed to estimate Antarctic ice sheet thickness yet. In this study, we present estimated ice thickness results from 65 stations with a typical coverage deployed on the Antarctic ice sheet to verify the feasibility of using the H/V method as an effective ~~complementary~~ way to ~~existing methods for~~ measur~~in~~e~~g~~ ice thickness.

2 Data and methods

2. 1 Data

Over the past two decades, several temporary seismic arrays have been deployed in Antarctica, including the Transantarctic Mountains Seismic Experiment (TAMSEIS, 2000—2003) (Lawrence et al., ~~et al.,~~ 2006), the Gamburtsev Antarctic Mountains Seismic Experiment (GAMSEIS, 2007—2012) (Hansen et al., ~~.,~~ 2010), and the Polar Earth Observing Network/Antarctic Network (POLENET/ANET，2007—2016) (Chaput et al.，2014). Despite their relatively sparse distribution compared to many dense seismic arrays on other continents, these three arrays together effectively cover East, and West Antarctica as well as the Transantarctic Mountain region (Fig. 1). In these three arrays, all stations are equipped with the Güralp CMG-3T or Nanometrics T-240 broadband sensors with a sampling rate of 25 Hz or 40 Hz. Most stations are buried 1—2 meters below the surface snow to guarantee data quality (mainly to ensure good coupling and to dampen wind noise) (Anthony et al., 2015). Equipped with solar panels and rechargeable batteries, the GAMSEIS and POLENET/ANET stations work continuously year round except the TAMSEIS, and provide abundant seismic ambient noise waveforms for the H/V processing. To investigate the effectiveness of the H/V method for ice thickness measurements and the proper time length for H/V processing, we selected seismic ambient noise records lasting about five days (an example of such raw ambient noise record is shown in supplementary Fig. S1), which is much longer than that used in usual H/V data processing (only a few minutes' records for sedimentary investigations with tens to hundreds of meters thick). In total, 65 stations deployed on the Antarctic ice sheet were used in this study.

2.2 Methods

The single-station H/V method, extensively used in sediment structure detection, acquires reliable sediment thickness and shear-wave velocities (Nogoshi and Igarashi, 1971；Nakamura, 1989). In this method, seismic ambient noise data are collected by a three component seismometer and the ratio between the horizontal (H) and vertical (V) Fourier spectra are calculated. The principle of the technique can be understood by assuming a low velocity sedimentary layer overlying a high velocity bedrock half-space. Due to the sharp impedance contrast at the interface between the two layers, the shear-wave energy within the sedimentary layer produces a prominent peak that can be observed in the H/V spectrum.

During the relatively long history of the H/V method, e~~E~~xtensive field experiments and numerical simulations have been carried out to confirm the correspondence between the shear-wave resonance frequency and the H/V peak frequency. Initially Nakamura (1989) proposed that the peak frequency corresponds to the transfer function for vertically incident SH waves. Using numerical simulations of ambient noise in a soil layer overlying a hard bedrock, Lachetl and Bard (1994) first showed that the peak frequency is very close to the shear-wave resonance frequency. This statement was later confirmed by Bard (1998), Ibs-von Seht and Wohlenberg (1999), and reasserted by Nakamura (2008) after modification of the previous assumption. Besides the peak in the H/V spectrum, a trough followed the peak may also appear in the spectrum. Konno and Ohmachi (1998) found such feature in the H/V spectrum in the case of a soft sediment layer atop a hard bedrock. As indicated by Tuan (2011), the appearance of a trough probably suggests the above layer has high Poisson's ratio or the impedance contrast is high enough between the bedrock and the particular overlying layer. Despite the H/V peak frequency is commonly accepted as a proxy of the resonance frequency of a particular layer, no strong evidences support that the peak amplitude indicates the amplification factor of the site and there are some controversies about the nature of the ambient noise wavefield and its sources (Sánchez-Sesma et al., 2011). During the past few decades, two research branches were formed to interpret the ambient noise wavefield: Rayleigh wave ellipticity (Fäh et al., 2001; Wathelet et al., 2004) and the full wavefield assumptions including distributed surface sources (DSS, Lunedei and Albarello, 2009, 2010) and diffuse field assumption (DFA, Shapiro and Campillo, 2004; Sánchez-Sesma and Campillo, 2006; Sánchez-Sesma et al., 2011; García-Jerez et al., 2013, 2016). ~~verify the reliability of the H/V spectrum as derived from the H/V method. Although the amplitude value of the H/V spectrum peak frequency is not that robust since the contributing factors are complicated, the H/V spectrum peak frequency is commonly accepted as a proxy of the resonance frequency of a particular layer (Field and Jacob, 1993; Lachetl and Bard., 1994; Javier and Chávez-García, 1994; Delgado et al., 2000; Fäh et al., 2001; Lunedei and Malischewsky, 2015; Picotti et al., 2017).~~

~~-~~To calculate the H/V spectrum, a specialized GEOPSY program was developed by the European SESAME team, and widely used to investigate the sediment structures (Bard and SESAME team, 2005). Then an approximation equation or H/V spectrum inversion approach can be used to derive the sedimentary layer thickness with the H/V spectrum.

Under the assumption of one-dimensional velocity subsurface conditions, in cases of homogenous and isotropic sedimentary layers over a homogenous half-space, the observed peak frequency equals the fundamental resonant frequency of the sedimentary layer. Thus, the resonance frequency of the low velocity layer is closely related to its thickness h through the following relationship (Ibs-von Seht and Wohlenberg, 1999; Parolai et al., 2002; Picotti et al., 2017; Civico et al., 2017):

$$h = \frac{Vs}{4 f_0} \qquad (1)$$

Where Vs is the average shear-wave velocity of the sedimentary layer, and f_0 is the observed peak frequency. Provided that a correct estimate of the average shear-wave velocity of the sedimentary layer is available, its thickness can be roughly estimated.

Complicated sedimentary internal structures, including anisotropy and low velocity layers beneath stations, will affect the H/V spectrum and consequently violate the assumptions of Eq. (1). Therefore, when inferring complex subsurface structures, an inversion of the full H/V spectrum can be used to explain more accurately the observed H/V spectrum. Based on different assumptions (including Rayleigh wave ellipticity, DSS, and DFA) for the interpretation of ambient noise wavefield composition, several inversion ~~approaches~~ schemes have been proposed and successfully applied to study sedimentary structures (Fäh et al., 2003; Arai and Tokimatsu, 2004; Herak, 2008; Lunedei and Albarello, 2009; Sánchez-Sesma et al., 2011). These assumptions differentiate themselves in the scheme of forward calculation of the H/V spectrum. ~~(Fäh et al., 2003; Arai and Tokimatsu, 2004; Herak, 2008; Lunedei and Albarello, 2009; Sánchez-Sesma et al., 2011).~~ In this study, a more recently developed H/V spectrum forward calculation and inversion method based on the DFA was employed (García-Jerez et al., 2016). The DFA was proposed on the base of the recently stated connection between the diffuse fields and the Green's function which arises from the ambient noise interferometry theory. Under this assumption, the average energy densities of a diffuse field along each Cartesian axis are proportional to the imaginary part of Green's tensor components at an arbitrary point x and circular frequency ω (i.e. $P_i(\omega) \propto \mathrm{Im}[G_{ii}(x;x;\omega)]$, $i =$ 1, 2, 3). Thus, the H/V spectral ratio is given as:

$$HV(x;\omega) = \sqrt{\frac{P_1(x;\omega) + P_2(x;\omega)}{P_3(x;\omega)}} = \sqrt{\frac{2\,\mathrm{Im}[G_{11}(x;x;\omega)]}{\mathrm{Im}[G_{33}(x;x;\omega)]}} \qquad (2)$$

Based on a layered isotropic structure with the known primary- and shear-wave velocities, mass density and thickness of each layer, the contribution of surface wave and body wave can be separately computed. The detailed formulations are not stated here as they are very complicated and on account of space limitation, but readers with interest can refer to Sánchez-Sesma (2011), García-Jerez (2016), and Lunedei and Malischewsky (2015). In the H/V spectrum inversion procedure, model spaces are set for parameters including primary- and shear-wave velocities, mass density, and thickness of each layer. The sedimentary structures can be determined when the lowest misfit between the observed and forward calculated H/V spectrum is obtained using inversion algorithms such as Monte Carlo sampling and simulated annealing.

$$E(m) = \frac{\sum_j (HV^{obs} - HV_j^{theo}(m))^2}{\sigma_j^2} \qquad (3)$$

Where $E(m)$ is the lowest value of the misfit in the j iterations, and m represents a model in each iteration. HV^{obs}, $HV_j^{theo}(m)$ are the observed and the j-th forward calculated H/V spectrum, respectively.

The H/V method has been successfully applied in studies of sedimentary structures, such as studies of thickness and shear- wave velocities (Ibs-von Seht and Wohlenberg, 1999; Langston and Horton, 2014; Civico et al., 2017; Bao et al., 2017). However, applications in ice environments are rare. Lévêque~~Jean-Jacques~~ (2010) studied the snow layer thickness and the ice properties beneath four stations in Dome C region of Antarctica using the H/V method. Picotti (2017) measured ice thickness ranging from tens of meters to 800 m of six glaciers in Italy, Switzerland and West Antarctica. However, the impedance contrast between the ice sheet layer and the overlying bedrock is not as high as that of sedimentary-bedrock and snow-ice layers. Moreover, the complex subglacial environment and internal ice structure create other technical obstacles. Thus, there have been no investigations of ice sheet thickness incorporating the H/V method for measurements or estimations.

In this study, the H/V spectra of 65 stations deployed on ice were processed by using the GEOPSY software~~,~~. ~~which has been used for sedimentary structure investigations in many regions.~~ Under the general assumption that the seismic properties are stable throughout the whole ice column, we calculated the ice thickness using Eq. (1) as in most seismological applications to approximate the ice sheet as a homogeneous layer. Meanwhile, a non-linear H/V spectrum inversion method developed by García-Jerez (2016) was adopted to constrain the observed H/V spectrum to infer the ice structure, comprised of shear-wave velocity and thickness.

During H/V spectrum acquisition using the ~~Geopsy~~ GEOPSY software, we remove the transient signals (earthquakes) from noise records with the STA/LTA technique and divide the records into 600 s length windows with an overlap of 5 %. Time series were tapered with a 5 % cosine function, and the FFT was calculated for each component. The spectra were smoothed with a Hanning window in a bandwidth of 0.1—2 Hz on a logarithmic frequency scale. The spectra of the two horizontal components (NS and EW) were merged to one horizontal component spectrum by calculating their geometric mean. The spectral ratios and corresponding standard deviation estimates between the horizontal component and the vertical component were calculated.

Having acquired the resonance frequency of the ice sheet, we adopted Eq. (1) with a uniform average shear-wave velocity—1900 m s^{-1} of the ice layer to calculate the ice thickness. This velocity used here is reasonable given that it is in the general range of ice Vs determined by seismic experiments (Kim et al., 2010). Moreover, this velocity has also been widely used in previous studies (Hansen et al., 2010; Wittlinger and Farra, 2012; Ramirez et al., 2016). Keeping the velocities set, the ice thickness at each station was calculated using Eq. (1).

In the H/V spectrum inversion procedures, Bedmap2 ice thicknesses were used as references to build the initial models, as along with the related seismic elastic parameters (Fig. 2, Wittlinger and Farra, 2012; Ramirez et al., 2016). We adopted two different models assuming the ice sheet is homogenous and inner ice stratified; respectively, as shown in Fig. 2 to perform H/V spectrum inversion. Model A is a simple homogeneous and isotropic ice structure with an ice layer overlying the half-space. In this model, the ice thickness varies from 0.7 to 1.3 times the Bedmap2 ice thickness for each station. Model B is constructed following Wittlinger (2012, 2015) as a two-layer ice structure in which a low shear-wave velocity lies in the lower ice layer. In this model, the thickness of the upper ice layer and the lower ice layer were set to occupy 60—75 and 25—40 percent of the Bedmap2 thickness, respectively. Using the non-linear Monte Carlo method (García-Jerez et al., 2016), we retrieved the optimum solutions for model A and B. These two solutions were best fitted to the observed H/V spectrum.

It usually takes a few minutes to about half an hour to collect seismic ambient noise waveforms in the investigations of sedimentary layers with thickness ranging from several tens to hundreds of meters. However, there is no experiences for the time length of recording seismic ambient noise in the Antarctic ice sheet with several kilometers~~s~~ thick. It is necessary to apply the H/V method with a much shorter recording time for seismic ambient noise, considering the harsh environment and logistical support difficulties in Antarctica. Therefore, we investigated the feasibility and reliability of H/V method by testing a range of noise record lengths; eight hour, four hour, two hour, and one hour intervals were tested. The processing strategies remained the same as in H/V spectrum acquisition except the window length was changed to 200 s when calculating the H/V spectrum using different length noise records.

3 Results

In this study, the H/V spectra of 65 stations were obtained. Figure 3 displays the H/V spectra of nine stations selected from three arrays. These examples are representative of all the results, and the remaining spectra are presented in the supplementary Fig. ~~S1~~S2. It is clearly shown that in almost all H/V spectra there were two or three clear peaks in the frequency band. Generally, the largest amplitude appears at the first peak located around 0.2 Hz or below, and the second and the third peaks with lower amplitudes are located at ~0.5 and ~0.8 Hz, respectively. Following the general interpretation principles for H/V spectra (Bard and SESAME team, 2005), the peak frequency denoting the largest amplitude should be the resonance frequency of the ice sheet layer, while the peaks appearing with lower amplitudes at higher frequencies may indicate the shallower impedance contrast layers. The reasonableness of considering the first peak frequency with the largest amplitude as the resonance frequency of the ice sheet layer was verified through rough estimation based on Eq. (1), i.e., for station E012, the Bedmap2 ice thickness at that location is 1050 m, so the resonance frequency according to Eq. (1) should be 0.452 Hz (the given Vs is 1900 m s^{-1}), and as expected was observed (0.418±0.052 Hz) in the H/V spectrum. However, there are exceptions such as station ~~N148~~ N108 displayed in Fig.2 whose first peak (0.177±0.014 Hz) amplitude is slightly lower than that of the following peak observed at higher frequency (1.666 Hz). At this station however, the location of the first peak correlates with the resonance frequencies (0.194 Hz) through rough estimation. In addition, there are some stations that have no peak frequencies correlating with the ice sheet thickness, despite the existence of peak frequency with strong amplitude in the frequency band. Station ST07 seen in Fig. 3 is such a case, whose fundamental resonance frequency as calculated by Eq. (1) should be 0.191 Hz (its Bedmap2 ice thickness is 2490 m). Nevertheless, no clear peak around this expected frequency is observed in the H/V spectrum. We therefore can group the results into three categories:

1) 42 stations with first peaks denoting the largest amplitude in the observed spectrum related to the ice sheet resonance frequency, like the E012, E018, GM02, N148, P071, ST01, ST02 stations in Fig. 3.
2) 18 stations with first peaks with slightly lower amplitude but also related to the ice sheet resonance frequency such as station N108.
3) Five stations without peaks correlating to the resonance frequency, such as station ST07.

Figure 4 shows the H/V spectra of stations along four profiles, together with the ice sheet and bedrock elevation extracted from Bedmap2 database for each station. As shown in Fig. 4, although the neighboring stations are 80 km apart for profile AA', 100 km for profile BB' and DD', and 20 km for profile CC', the shape of the spectra are similar along each profile. Also, along each profile, the peaks associated with the ice thickness are clear and the locations of the peaks shift towards lower or higher frequencies cohering with the variation of the corresponding ice thickness. There are four stations (N060, ST04, ST06, ST07) along the four profiles without peak frequencies related to their corresponding ice thicknesses. This may be caused by the bad coupling of the seismometer with the ice surface or possibly a complicated subglacial environment, for example clear evidence indicates the existence of sedimentary layer beneath station N060.

Having identified resonance frequency of the ice sheet, we calculated the ice thickness using Eq. (1) with the average shear-wave velocity—1900 m s^{-1}. The results together with their relative errors to the corresponding Bedmap2 ice thickness are listed in Table 1. We projected the calculated ice thickness and the reference Bedmap2 ice thickness for stations along the four profiles in the upper elevation panels in Fig. 4. It is clear that the calculated ice thickness for some stations along the four profiles are close to the reference ice thickness like the E012, P071, and ST01 stations, while there are large deviations at some stations such as E018, N148, and ST02. It should be noted that the ice thickness obtained from the H/V method reflects the average ice sheet thickness beneath each station in the scale of seismic wavelength (i.e. for a peak at frequency 0.2—1 Hz and seismic wavelength of ~2.0 km, the spatial resolution (or footprint) is about 2—10 km).

The optimum shear-wave velocity models derived from H/V spectrum inversion are presented in Fig. 5 and supplementary Fig. ~~S2~~S3. The observed H/V spectrum together with the synthetic H/V spectra using the two optimum shear-wave velocity models are plotted in Fig. 6 and shown in supplementary Fig. ~~S3~~S4. As Fig. 6 and the supplementary Fig. ~~S3~~ S4 shows, the synthetic H/V spectra of the optimum inversion results for model A and model B at almost all stations, both fit the observed H/V spectra in peak frequency and spectrum shape. However, the inversion ice thickness from model A deviates substantially from the Bedmap2 thickness at most stations (such as N108, N148, GM02 and ST02 in Fig. 5), and the difference extends 1 km for some stations (Fig. 7). By contrast, the inversion thickness from model B is consistent with the Bedmap2 thickness as the differences between them are mostly within 200 m. The overall inversion ice thicknesses from model B are listed in Table 1, as well as the relative errors to the corresponding Bedmap2 ice thickness. We also projected the inversion thickness for stations along the four profiles in the elevation panels seen in Fig. 4. ~~, which depicts~~This figure depicts a good ~~high level~~ consistency between the inversion and the reference ice thickness ~~at these stations~~as the ice thickness at 26 stations and 46 stations out of the 48 stations along the profiles are within 10 % and 15 % threshold of the Bedmap2 ice thickness.

The results of four different length seismic ambient noise records (1 h, 2 h, 4 h, 8 h) used to obtain H/V spectrum are displayed in Fig. 8 (and in supplementary Fig. ~~S4~~S5). These plots show that the shape of the spectra of the four tested record lengths are similar to the shape determined using a record five days long. The peak frequencies of the four different length records are all within the margin of error for the peak frequency as determined with the record five days long. Besides, w~~W~~e found that the longer the ambient noise record, the more stable the peak frequency is as there are slight shifts in the peak frequency when determined with 1 h ~~and 2 h~~ records~~;~~. This feature is obvious for stations with thin ice (less than 2 km) such as those from stations E018 (Fig. 8), E014, E020, ~~and~~ E024, and E028 (shown in supplementary Fig. ~~S4~~S5). The quality of the H/V spectrum obtained from one hour long record for stations with thick ice (over 2 km) however, is generally in consistence with that determined with the record five days long. This consistency can also be found for all stations when the length of noise record exceeds two hours. ~~Despite variation in ice thickness from 600 m to about 4 km at the study sites, the length for recording seismic ambient noise suited for H/V methods can be as short as 1 – 2 hours, in terms of stability and efficiency.~~

4 Discussion

Bedmap2 ice thickness were used as reference to verify the ice thickness derived from Eq. (1) and H/V spectrum inversion since we lacked actual ice thickness as obtained from the more direct and accurate ice-core drilling, RES and active seismic methods at or near each study site. Because of various factors contributing to the uncertainty in the Bedmap2 database such as data coverage, basal roughness, and ice thickness measurement and gridding error, however, the Bedmap2 ice thickness is not exactly accurate with uncertainty varying from site to site. We obtained the uncertainty of the Bedmap2 ice thickness at each station from the grids of ice thickness uncertainty (Fretwell et al., 2013, also, the uncertainty at our study sites can be roughly seen in supplementary Fig. ~~S5~~S6). A close examination of the uncertainty of the Bedmap2 ice thickness reveals that the uncertainty at 52 stations ranges from 59 m to about 200 m, and the uncertainty at 57 stations is below 300 m. As the accuracy of the H/V method is at the same scale with the uncertainty of the Bedmap2 ice thickness at the 57 stations, the Bedmap2 ice thicknesses are adequate to verify the results derived from the H/V method. The remaining three stations including ST09, ST13, and ST14 are excluded for validation as the uncertainty of the reference ice thickness at these stations reaches 1000 m.

A comparison of the inversion ice thickness from Model B and Bedmap2 database reveals that the differences in ice thickness at all the 57 stations are less than 400 m; there are 33 stations whose differences are within 200 m and 47 stations within 300 m; the maximum difference was 370 m at station ST03. The relative errors of the inversion ice thickness to the corresponding Bedmap2 thickness of 22 stations, 35 stations, and 58 stations are within 5 %, 10 %, and 15 % threshold, respectively. Given that the Bedmap2 ice thickness are associated with certain uncertainties at each station (i.e. the relative errors of the uncertainty to the Bedmap2 ice thickness are within 10 % at 49 stations) ~~uncertainty of the Bedmap2 database can reach 300 m in some study sites~~ (Fretwell et al., 2013). In this sense, we conclude that the inversion ice thickness has comparable accuracy to the Bedmap2 ice thickness at the study sites.~~, it is certain that the inversion ice thicknesses are adequately constrained at over 47 stations.~~

Based on the homogenous ice sheet layer assumption, most of the ice thickness estimations derived from Eq. (1) are not compatible with Bedmap2 ice thickness (Fig. 4 and Fig. 7), as the differences at 26 stations can extend 400 m and at 10 stations are over 600 m; the maximum difference reaches 910 m at station N036. Moreover, most of the inversion ice thickness results based on the homogenous ice structure of model A also largely deviated from the reference Bedmap2 thickness (Fig. 7 and supplementary Fig. ~~S2~~S3). These large deviations cannot be attributed to the uncertainty in the reference Bedmap2 ice thickness since they made minor contributions to the large differences.

The inversion ice thickness from model B, however were highly consistent with the Bedmap2 database. A close examination of the inversion thickness from model B shows that it refined the rough estimation results at 47 stations as calculated with Eq. (1) to varying degrees. As at stations E012 and N036, the calculated ice thicknesses using Eq. (1) deviate from Bedmap2 at 90 m and 910 m, while the inversion ice thickness from model B refines the gaps to 20 m and 320 m.

We compared our results with those found in Wittlinger (2012). Using the PRF method and a grid search stacking technique, he found that the Antarctic ice is stratified, possibly due to the preferred orientation of ice crystals and fine layering of soft and hard ice layers under pressure. In Fig.9, we present the ice thickness results for 12 stations common to both studies. It is clear that the interface separating the upper and the lower ice sheet layers determined using the H/V method and the PRF method, is consistent for almost all stations.

The agreement of two-layer ice sheet thickness with the Bedmap2 database, and the consistency of our results to Wittlinger`s results, as well as the large deviation of ice thickness estimated using Eq. (1) and model A jointly support the thesis that the two-layered ice sheet models are more reasonable than an homogeneous ice sheet layer assumption. Moreover, the ice thickness of 28 stations derived from Eq. (1) were close to the reference Bedmap2 database. This consistency, however, does not strongly support the homogenous ice sheet layer assumption as it can be attributed to the fact that the Vs values adopted in rough estimation was coincidental with the average velocity of the two-layer Vs models.

The examples presented in this work clearly show that the H/V method with seismic ambient noise can be effectively to measure ice sheet thickness. However, there are also some limitations that may affect the results. Shear-wave velocity (Vs), as the key parameter for H/V spectrum inversion and rough estimation using Eq. (1), will significantly affect the effectiveness and uncertainty of the H/V method. We can see from Fig. 6 that the synthetic H/V spectra from the optimum Vs profiles of model A and model B for the N108, GM02 and N148 stations (Fig. 5), match the observed H/V spectrum. The inversion ice thickness from model A and model B at these stations however, are remarkably different as the results from model B are more closely match the reference Bedmap2 ice thickness than those from model A (Fig. 5). Also evident in these results is a directly proportional relationship between ice thickness and the Vs as expected from Eq. (1) in rough estimation. Given a □5 percent variation in the average shear-wave speed of the ice layer, then ice sheet thickness estimation will result in a similar variation such as 150 m for a station with 3 km thickness. Accurate known Vs profiles are therefore prerequisites when obtaining reliable H/V spectrum inversion results, as well as for rough estimations using Eq. (1).

It is evident that the longer the noise record, the more stable the observed peak frequency is as the sources of the seismic ambient noise are more evenly distributed, spatially and temporally. This is significant for stations with thin ice primarily due to the fact that thin ice sheet layers are excited by high-frequency waves such as winds and other sources (Picotti et al., 2017). Thus, a longer ambient noise record can improve the stability of the H/V spectrum. In our study, we found that the quality of the H/V spectrum ~~ar~~is~~e~~ generally better for thick ice sheet layers than for thin ice sheet such as stations ~~BENN,~~ E012, E018, E024, E026, and E028 with relatively smaller ice thicknesses than other stations. The H/V spectra for these stations exhibited less stability when the lengths of noise records decreased (Fig. 8 and supplementary Fig. S54). ~~Also, t~~Their peak frequencies~~y~~ obtained from a one hour long record slightly deviate~~s~~ from the peak frequency determined with a five day record. These deviations consequently could lead to uncertainties in ice thickness estimation. While for stations with thick ice, both the shape and the peak frequency determined using a one hour long record are generally consistent with those obtained from a five day long record. Given that the variation of ice thickness at the study sites (from 600 m to about 4 km), generally covers the range of the whole Antarctic ice sheet thickness, we would like to suggest a uniform record length of two hours in H/V method application in Antarctica, in terms of stability and efficiency.

~~The efficiency and the cost of noise record acquisition in Antarctica however, are equally important. In this sense, the proper record length in H/V method application is 1 – 2 hours.~~

5 Conclusions

Given the vital role that ice sheet thickness plays in ice mass balance and sea level changes~~global climate~~ studies, many methods have been used to estimate ice sheet thickness, obtaining abundant results. However, new methods ~~must~~ should be explored to enrich the database considering the vast area of the Antarctic ice sheet and to provide additional constraints to the ice sheet structure from other perspectives. ~~and the limitations of the existing methods.~~

In this study, the H/V method is proposed as a reliable, efficient method to investigate the Antarctic ice sheet thickness. The H/V method is effective for identifying the fundamental resonant frequency correlating with the ice sheet thickness. In this approach, the ambient noise recording length can be as short as ~~1—~~2 hours, reducing costs and increasing efficiency. Equation (1) can retrieve a fast and rough estimation of the ice thickness but should be used with care since the shear-wave velocity varies at different sites. H/V spectrum inversion, however, unlike estimation with Eq. (1), is robust and can obtain reliable ice thickness results with given seismic properties. Moreover, the H/V spectrum inversion ice sheet thickness results are consistent with the reference Bedmap2 database. Our results also support the argument that the Antarctic ice sheet has a two-layer structure. The H/V method is an excellent ~~complementary~~ approach that provides new and independent ice sheet thickness estimations.~~to the most commonly used RES and active seismic methods for ice sheet thickness measurements in terms of its effectiveness.~~ What makes this new approach most attractive are the ease and economy of seismic ambient noise waveforms collection when deploying a single seismometer for short time intervals. Finally, we hope that specific seismic experiments can obtain more accurate shear-wave velocity profiles in the ice sheet, thus making better constraints for H/V method results.

Supplementary materials include:

Figure S1, S2, S3, S4, S5, S6 in pdf format

Competing interests. The authors declare that they have no conflict of interest.

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Table 1 Ice thickness results obtained from this study

(Thickness I, II are ice thickness values obtained from Eq. (1) and model B, respectively)

Station	Bedmap2 (km)	Resonance freq. (Hz)	Thickness I (km)	Relative error	Thickness II (km)	Relative error
BENN	1.56	0.222±0.034	2.14±0.33	37.18%	1.73	10.90%
BYRD	2.16	0.222±0.022	2.14±0.21	0.93%	2.33	7.87%
E012	1.05	0.418±0.052	1.14±0.14	8.57%	1.03	1.90%
E014	0.66	0.914±0.085	0.52±0.05	21.21%	0.60	9.09%
E018	1.50	0.222±0.028	2.14±0.27	42.67%	1.72	14.67%
E020	1.75	0.200±0.011	2.38±0.13	36.00%	2.01	14.86%
E024	1.83	0.200±0.019	2.38±0.22	30.05%	2.09	14.21%
E026	1.40	0.215±0.028	2.2±0.29	57.14%	1.61	15.00%
E028	1.61	0.188±0.032	2.5±0.44	55.28%	1.85	14.91%
E030	2.02	0.177±0.024	2.68±0.37	32.67%	2.32	14.85%
GM01	3.10	0.155±0.018	3.07±0.36	0.97%	3.12	0.65%
GM02	2.81	0.159±0.014	2.98±0.26	6.05%	2.94	4.63%
GM03	2.52	0.159±0.018	2.98±0.33	18.25%	2.88	14.29%
GM04	2.80	0.157±0.015	3.02±0.29	7.86%	3.08	10.00%
GM05	3.47	0.146±0.020	3.26±0.45	6.05%	3.17	8.65%
GM06	3.47	0.150±0.015	3.16±0.32	8.93%	3.10	10.66%
GM07	3.03	0.148±0.012	3.21±0.26	5.94%	3.08	1.65%
JNCT	1.19	0.349±0.031	1.36±0.12	14.29%	1.26	5.88%
N020	1.71	0.222±0.021	2.14±0.21	25.15%	1.95	14.04%
N028	2.06	0.197±0.020	2.41±0.25	16.99%	2.24	8.74%
N036	2.21	0.152±0.020	3.12±0.41	41.18%	2.53	14.48%
N044	2.21	0.169±0.023	2.81±0.39	27.15%	2.51	13.57%
N052	2.39	0.152±0.022	3.12±0.45	30.54%	2.75	15.06%
N068	2.87	0.155±0.014	3.07±0.28	6.97%	2.98	3.83%
N076	2.46	0.172±0.014	2.76±0.23	12.20%	2.59	5.28%
N084	2.47	0.183±0.016	2.60±0.23	5.26%	2.59	4.86%
N092	2.63	0.175±0.016	2.72±0.25	3.42%	2.48	5.70%
N100	2.68	0.167±0.015	2.85±0.26	6.34%	2.68	0.00%
N108	2.45	0.177±0.014	2.68±0.21	9.39%	2.56	4.49%
N116	2.50	0.175±0.024	2.72±0.39	8.80%	2.46	1.60%

Table 1 (continued)

Station	Bedmap2 (km)	Resonance freq. (Hz)	Thickness I (km)	Relative error	Thickness II (km)	Relative error
N124	2.42	0.185±0.019	2.56±0.26	5.79%	2.57	6.20%
N132	3.24	0.146±0.018	3.26±0.40	0.62%	3.07	5.25%
N140	2.79	0.162±0.022	2.93±0.42	5.02%	2.69	3.58%
N148	2.9	0.137±0.017	3.46±0.44	19.31%	3.20	10.34%
N156	2.55	0.194±0.016	2.45±0.20	3.92%	2.48	2.75%
N165	2.81	0.150±0.021	3.16±0.44	12.46%	2.95	4.98%
N173	2.38	0.185±0.017	2.56±0.24	7.56%	2.54	6.72%
N182	2.42	0.191±0.014	2.49±0.19	2.89%	2.54	4.96%
N190	3.01	0.144±0.017	3.31±0.41	9.97%	3.15	4.65%
N198	3.32	0.148±0.017	3.21±0.38	3.31%	3.30	0.60%
N206	2.96	0.159±0.022	2.98±0.41	0.68%	2.61	11.82%
N215	3.48	0.155±0.017	3.07±0.33	11.78%	3.12	10.34%
P061	3.16	0.135±0.018	3.52±0.46	11.39%	3.17	0.63%
P071	2.3	0.194±0.018	2.45±0.23	6.52%	2.18	5.22%
P080	2.47	0.188±0.018	2.52±0.25	2.02%	2.52	2.02%
P090	2.34	0.212±0.022	2.24±0.23	4.27%	2.09	10.68%
P116	2	0.222±0.023	2.14±0.22	7.00%	1.93	3.50%
P124	1.54	0.314±0.033	1.51±0.16	1.95%	1.47	4.55%
ST01	3.02	0.157±0.015	3.02±0.28	0.00%	2.95	2.32%
ST02	2.12	0.164±0.018	2.89±0.32	36.32%	2.43	14.62%
ST03	2.49	0.236±0.019	2.01±0.16	19.28%	2.86	14.86%
ST08	2.18	0.152±0.016	3.12±0.34	43.12%	2.50	14.68%
ST09	2.32	0.157±0.020	3.02±0.4	30.17%	2.66	14.66%
ST10	1.23	0.266±0.030	1.79±0.21	45.53%	1.51	22.76%
ST12	1.89	0.185±0.020	2.56±0.28	35.45%	2.15	13.76%
ST13	1.94	0.167±0.018	2.85±0.32	46.91%	2.23	14.95%
ST14	1.54	0.339±0.038	1.40±0.16	9.09%	1.44	6.49%
SWEI	2.84	0.162±0.017	2.93±0.31	3.17%	2.93	3.17%
TIMW	2.57	0.175±0.020	2.72±0.32	5.84%	2.65	3.11%
WAIS	3.37	0.127±0.015	3.73±0.43	10.68%	3.71	10.09%

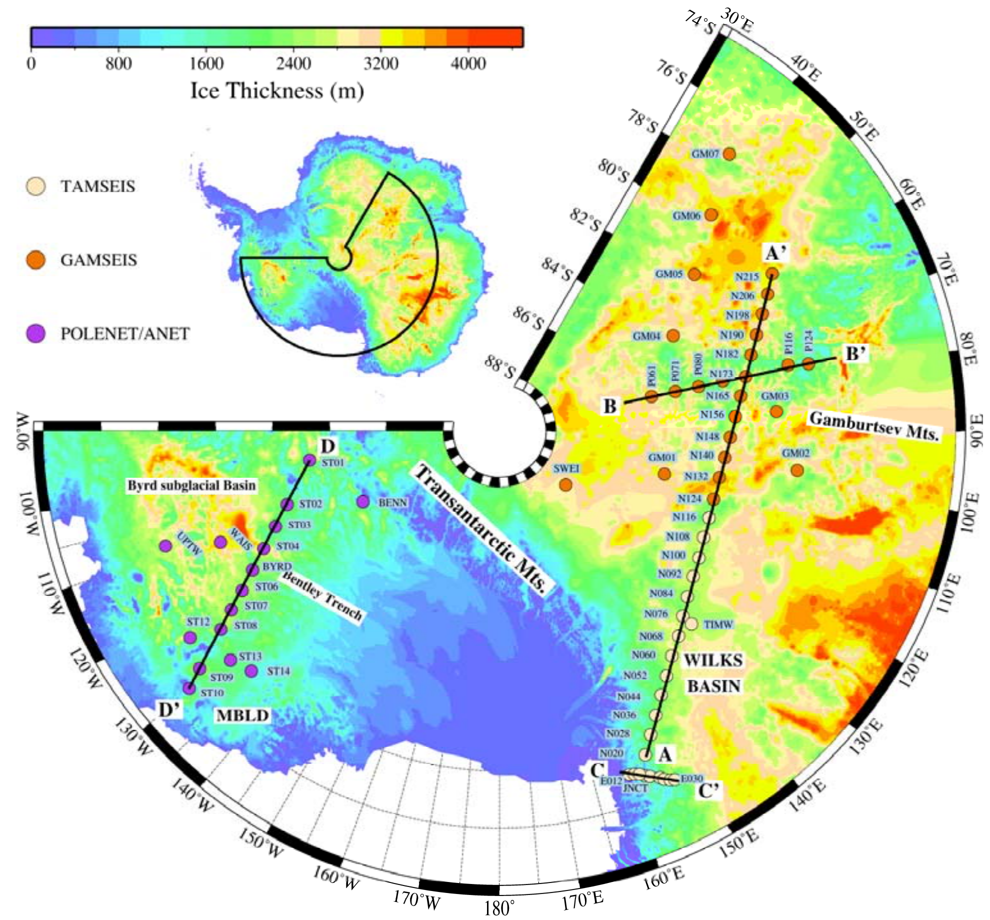


Figure 1. Locations of the three seismic arrays used in this study. Some stations are lined to four profiles marked with AA', BB', CC' and DD'. TAMSEIS：TransAntarctic Mountains Seismic Experiment; GAMSEIS：Gamburtsev Antarctic Mountains Seismic Experiment; POLENET/ANET：The Polar Earth Observing Network/Antarctic Network. Ice sheet thickness data in this plot come from Bedmap2 database.

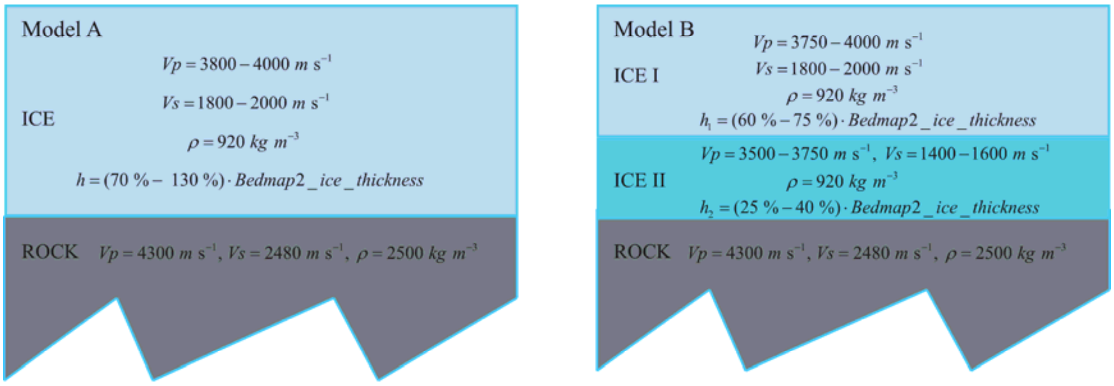


Figure 2. Sketches of the two ice layer models used for H/V spectrum inversion. Model A comprises a single ice layer, while model B is a two-layer ice structure with low shear-wave velocity in the lower ice layer. The parameters used in the two models are referred to Wittlinger (2012).

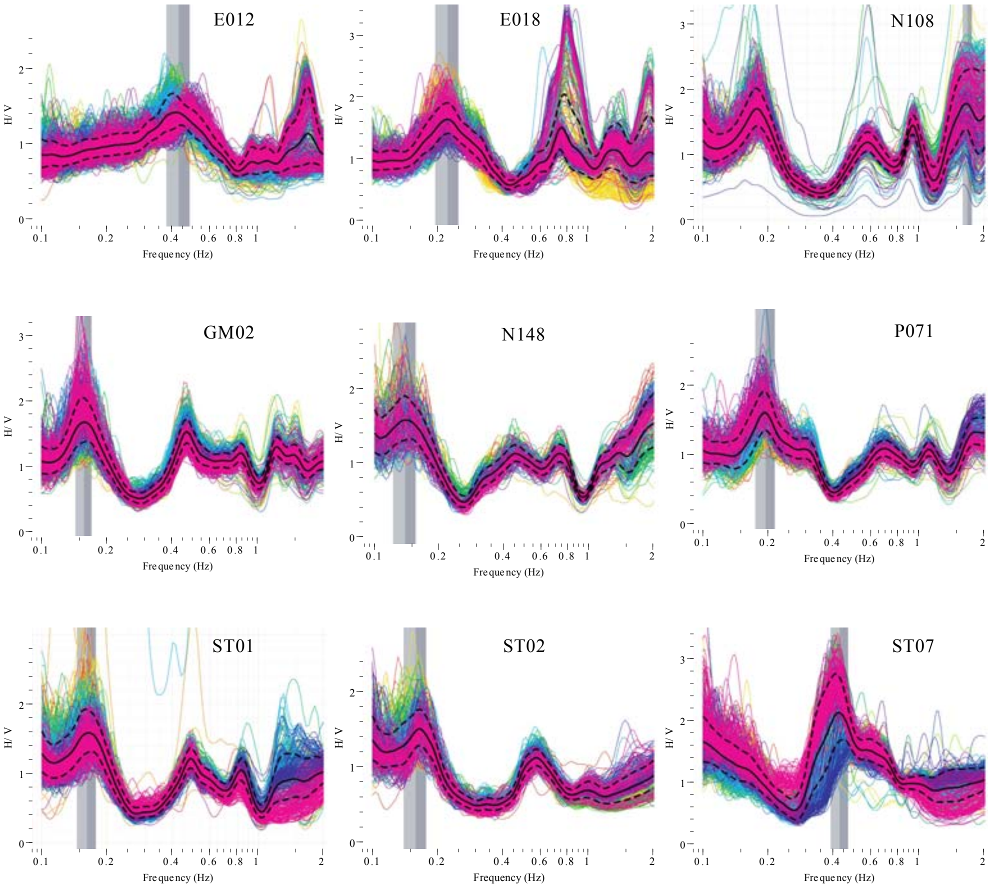
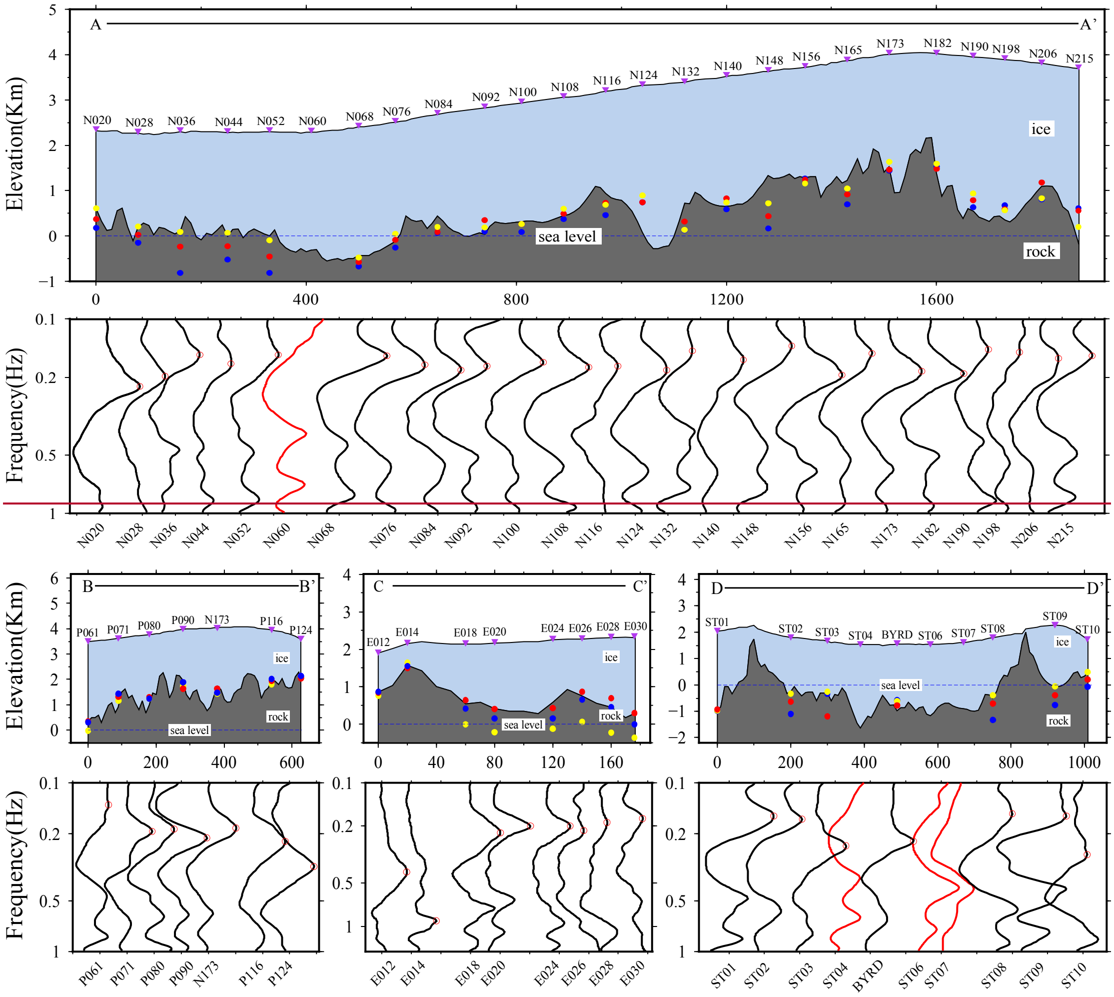


Figure 3. H/V spectra of nine stations shown as representative of all results in this study. The H/V spectra were calculated using five-day long ambient noise record. The spectra of the E012, E018, GM01, N148, P071, ST01 and ST02 stations represent 42 stations whose clear first peaks with the largest amplitudes are in agreement with the resonance frequency of the ice sheet layer. Station N108 is representative of 18 stations whose first peaks are related to the ice sheet resonance frequency but with slightly lower amplitude than peaks in higher frequencies. ST07 is the example that no peak frequency correlating to the ice thickness appears as expected in the observed H/V spectrum.


A
A'
Elevation(Km)
N020 N028 N036 N044 N052 N060 N068 N076 N084 N092 N100 N108 N116 N124 N132 N140 N148 N156 N165 N173 N182 N190 N198 N206 N215
ice
sea level
rock
0 400 800 1200 1600
Frequency(Hz)
0.1 0.2 0.5 1
B
B'
P061 P071 P080 P090 N173 P116 P124
C
C'
E012 E014 E018 E020 E024 E026 E028 E030
D
D'
ST01 ST02 ST03 ST04 BYRD ST06 ST07 ST08 ST09 ST10
sea level
ice
rock

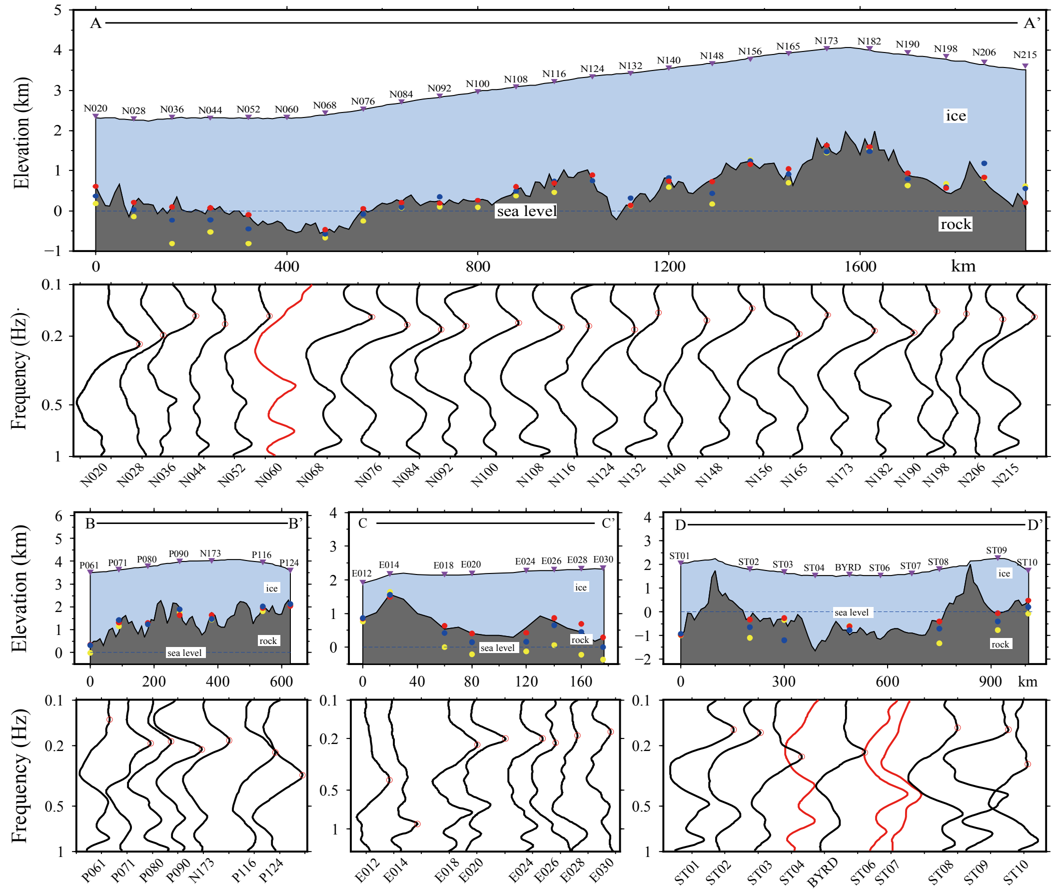


Figure 4. Cross section showing H/V spectra and the ice sheet thickness obtained from the H/V method at stations along the four profiles (Fig. 1). In the below H/V spectra cross section panels, the red circles denote the resonance frequencies correlating to the ice thickness for each station, and the spectra of the four stations without clear peaks are plotted with red lines. The upper panels show the variation of the bedrock and ice surface elevation along each profile obtained from Bedmap2 database. In these plots, the red dots indicate the reference Bedmap2 ice thickness, while the yellow and the blue dots represent the calculated ice thickness using Eq. (1) and the inversion ice thickness from model B, respectively.

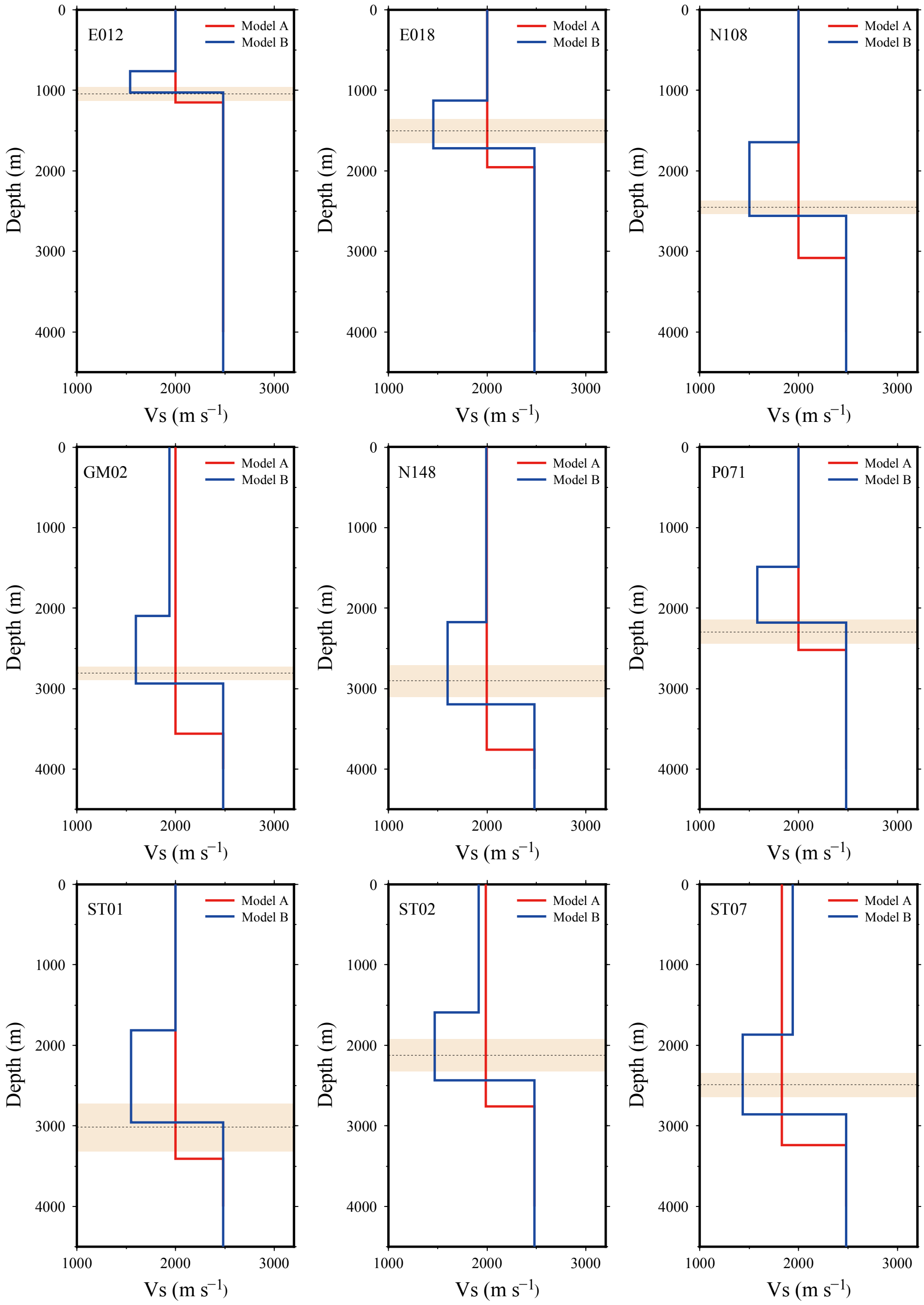


Figure 5. The optimum inversion shear-wave velocity models for the nine stations. The horizontal dashed line in each plot indicates the reference Bedmap2 ice thickness, and the shaded area shows the uncertainty of the Bedmap2 ice thickness. Apparently, the inversion ice thickness results derived from the two-layer structure (model B) are much closer to the Bedmap2 thickness than those determined using the single ice layer (model A).

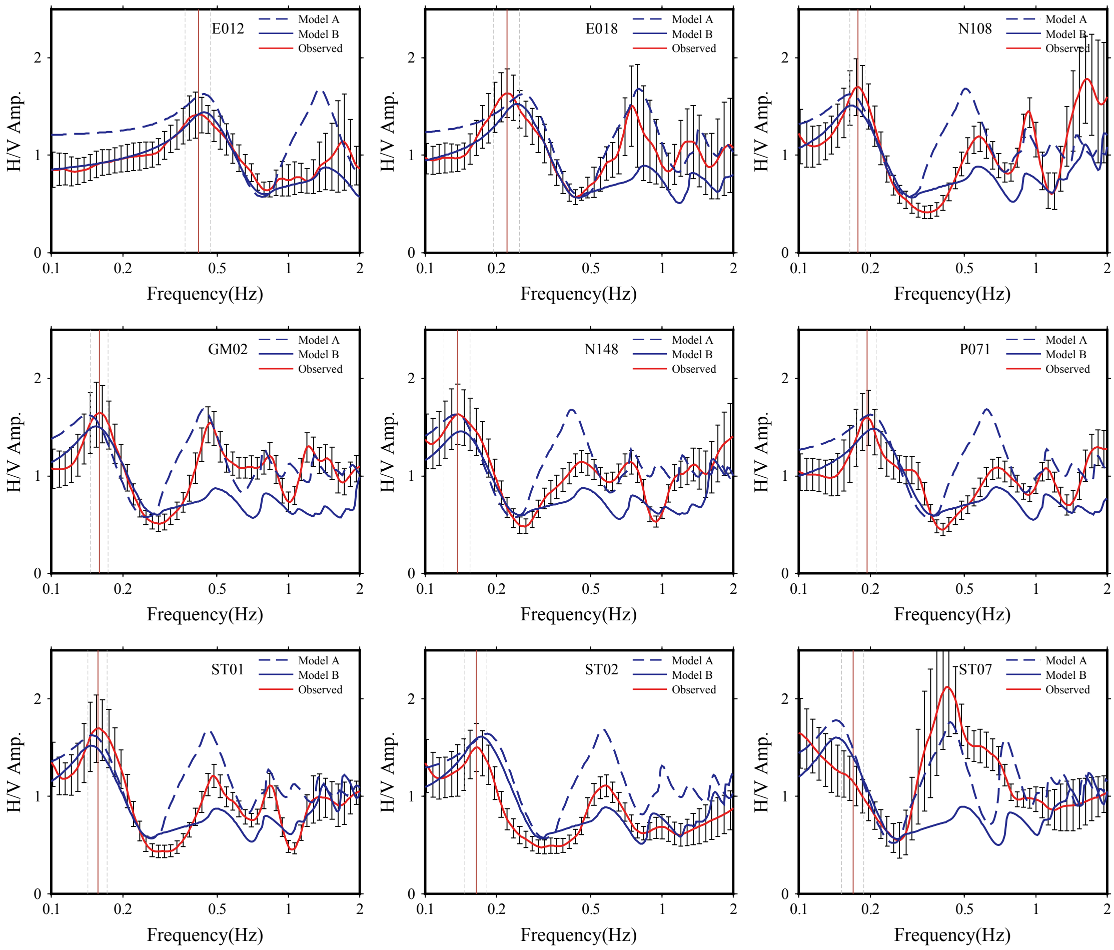


Figure 6. The synthetic H/V spectra and the observed H/V spectrum for the nine stations. The synthetic H/V spectra are modelled using the optimum inversion shear-wave velocity profiles for model A and model B. The two synthetic H/V spectra are both in good agreement with the observed H/V spectrum. Note that the amplitudes of the synthetic H/V spectra are normalized by dividing 2 in the whole frequency band.

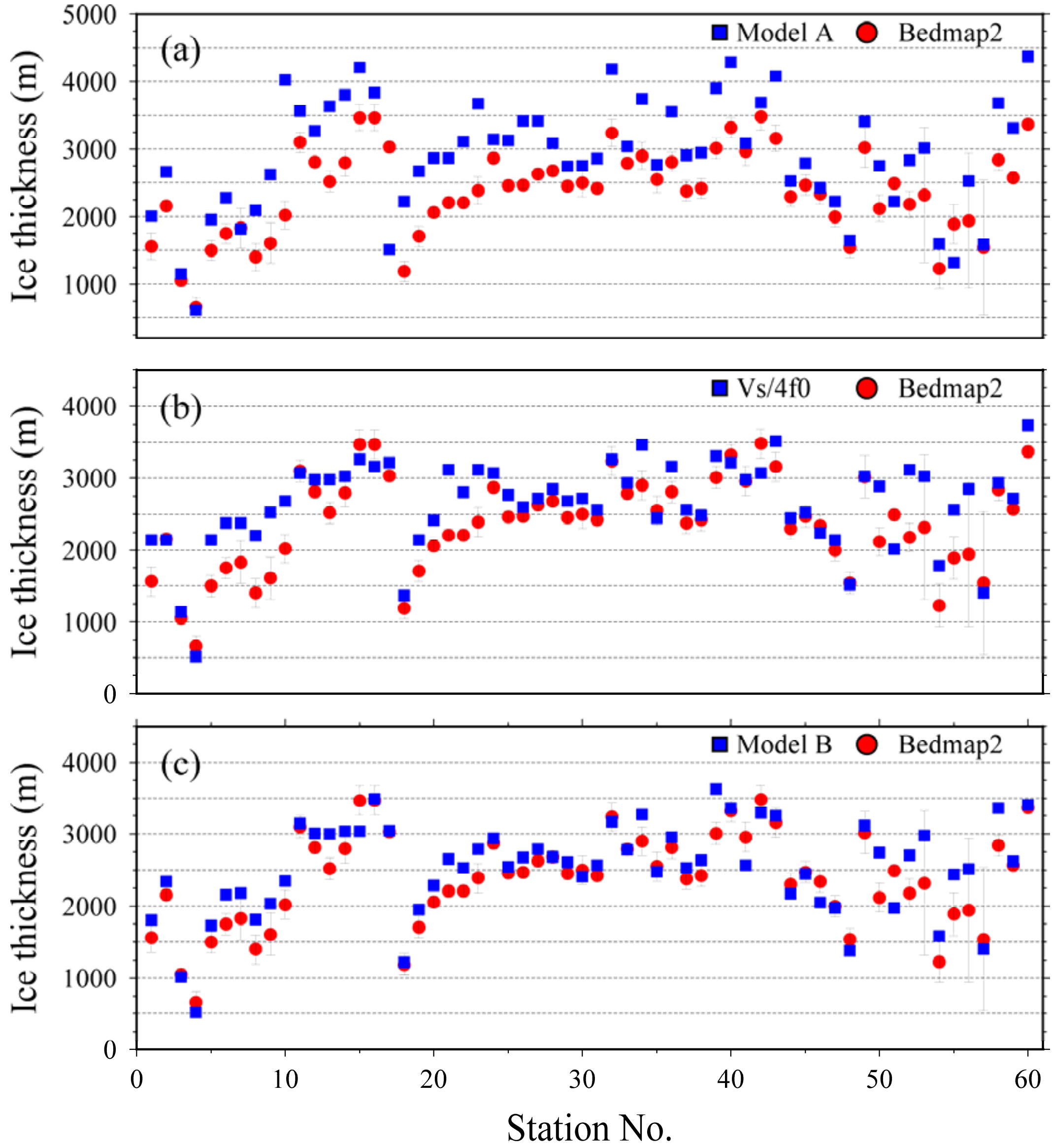


Figure 7. Ice thickness derived from the H/V method versus the reference Bedmap2 ice thickness. The blue squares in panel (a), (b), and (c) represent ice thickness estimations from model A, Eq. (1), and model B, respectively. The red circles in each panel denote the Bedmap2 ice thickness and each Bedmap2 value is marked with its corresponding error bar obtained from the uncertainty grids (Fretwell et al., 2013).

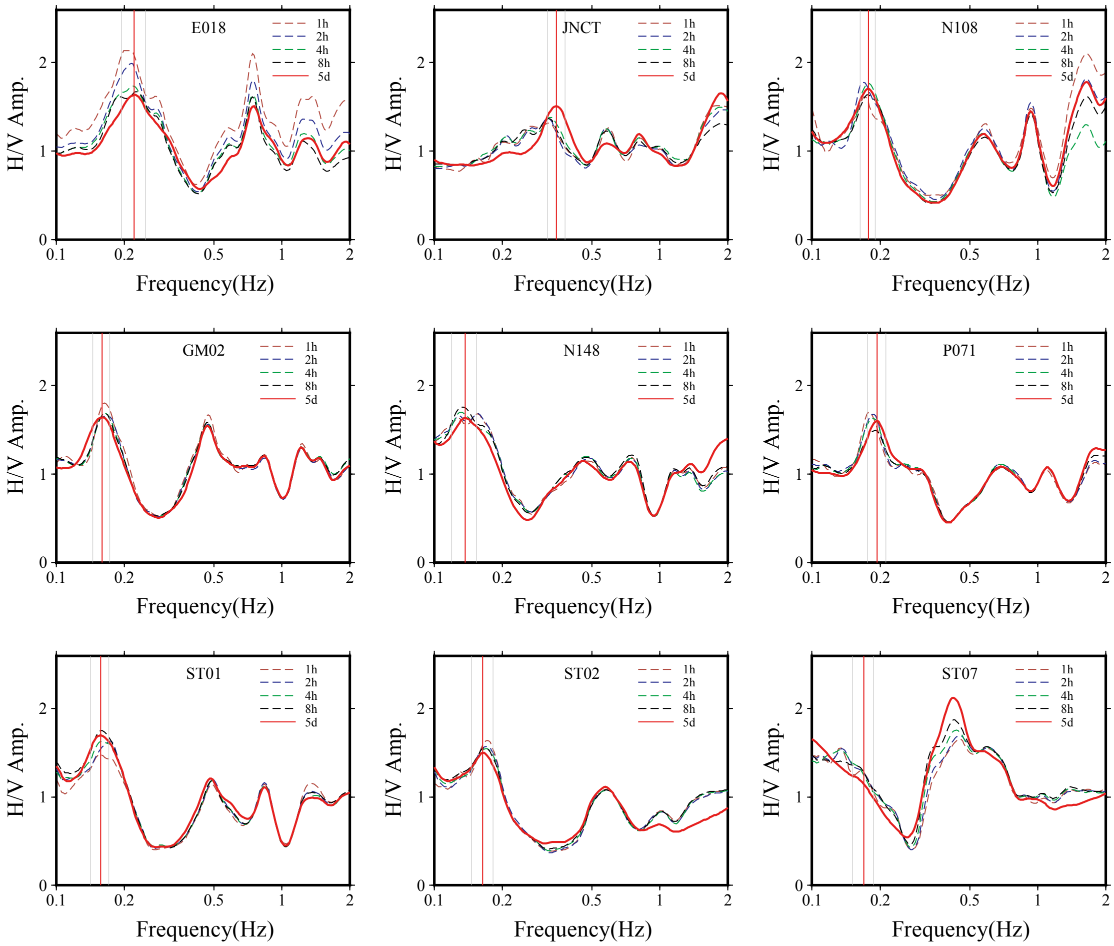


Figure 8. H/V spectra calculated using different lengths of ambient noise records. There is a good consistence between H/V spectra determined with different tesing length of noise records (1 h, 2 h, 4 h and 8 h) and the spectrum with record five-day long, both in locations of peak frequencies and the spectra shape. However, the peak frequency obtained from 1 h record slightly deviates the peak frequency determined using 5 d record for the E012 station.

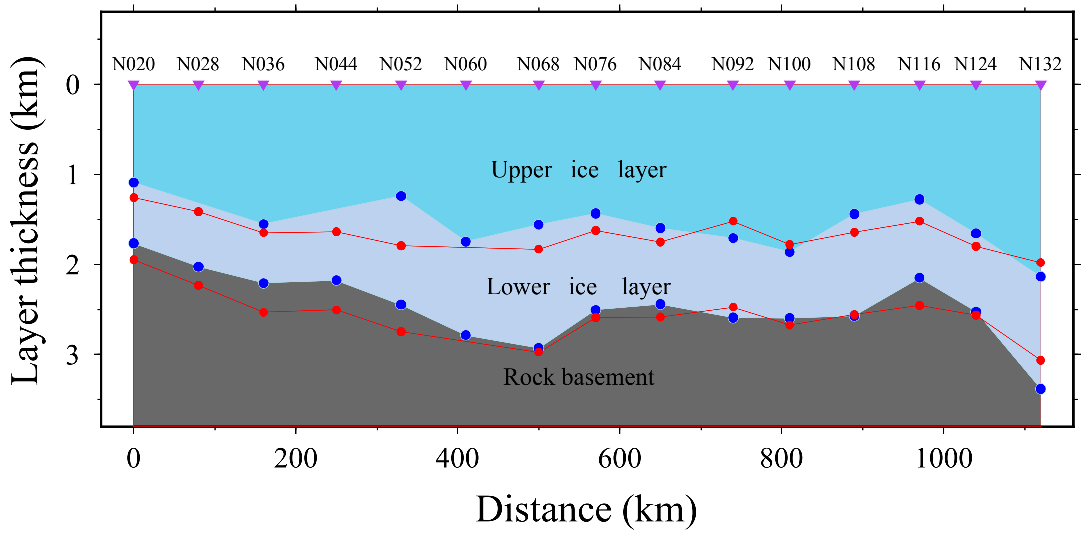


Figure 9. Comparisons of the two-layer ice thickness results obtained from our study and Wittlinger's. The red dots denote the ice thickness derived from H/V spectrum inversion in our study, and the blue dots indicate the ice thickness determined with the PRF method and a grid search stacking technique (Wittlinger and Farra, 2012, Table1).