Dear reviewer：

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).

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.

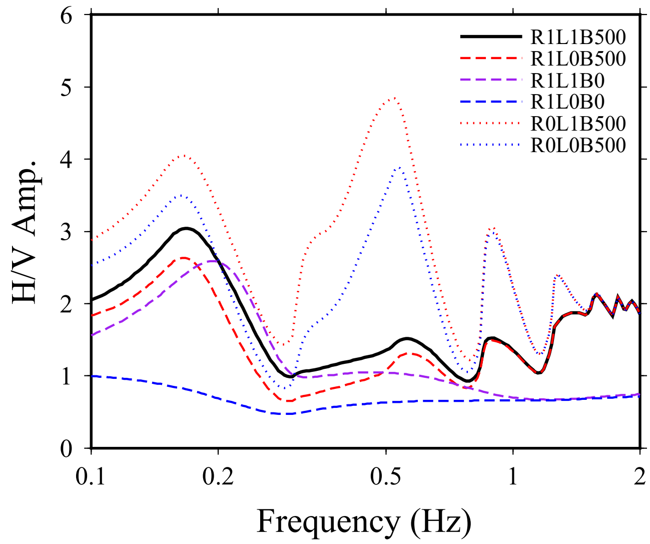

Figure 1. Contribution of different seismic waves. R, L, and B represent Rayleigh wave, Love wave, and Body wave, respectively. The number 1 stands for the mode of the particular wave and 0 indicates that the particular wave was not included in the calculation, while 500 is the number of integral points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

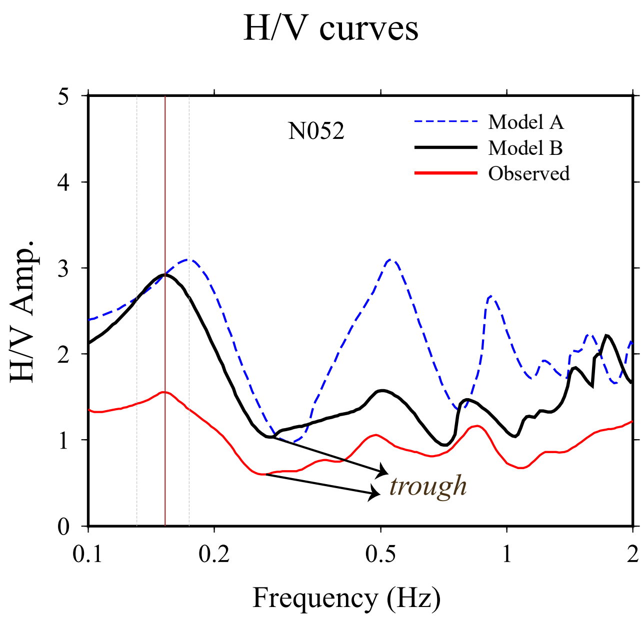

Figure 2. Example of a trough feature in the synthetic and observed H/V curves. A trough can be observed in the synthetic H/V curve using the optimum inversion Vs profile of model B, which is in accordance with that of the observed H/V curve. However, no trough appears in the synthetic H/V curve using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

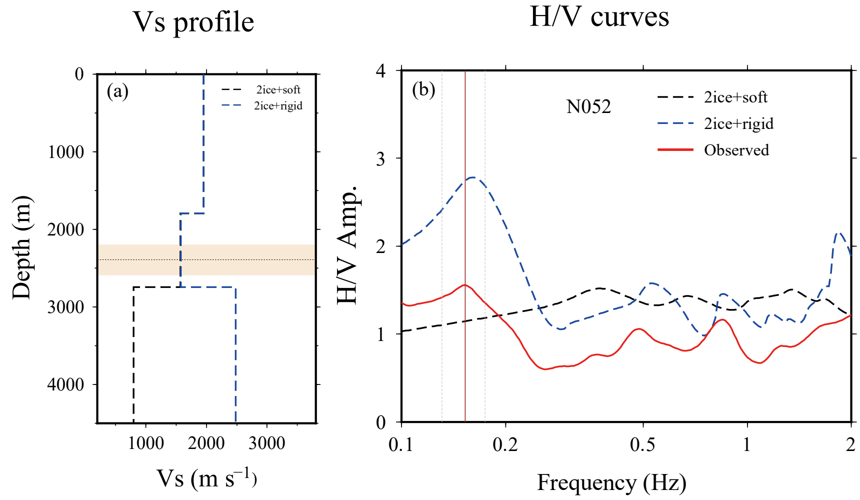

Figure 3. Effect of basal conditions on the H/V spectrum. As shown in panel b, no fundamental resonance frequency correlated to the ice sheet thickness is observed in the spectrum under soft basal condition assumption (black dashed line in panel a). Under rigid basal condition assumption (blue dashed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

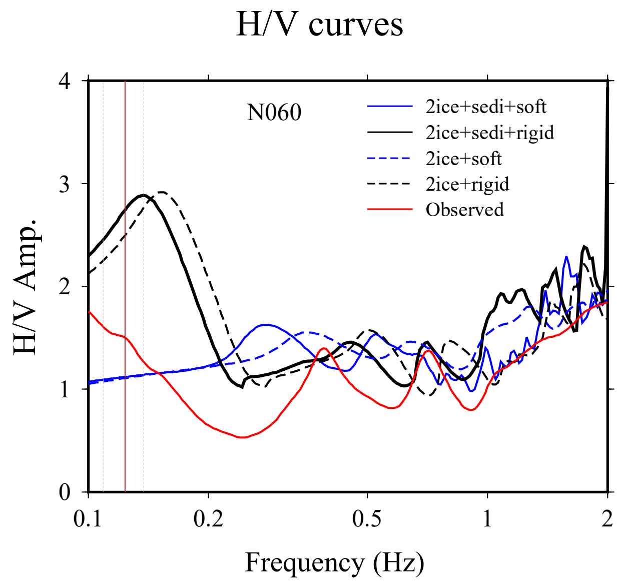

Figure 4. Effects of sediment and basal conditions on the H/V spectrum of station N060. We still cannot figure out the factors that affect the unclear fundamental frequency in the observed H/V spectrum.

(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.

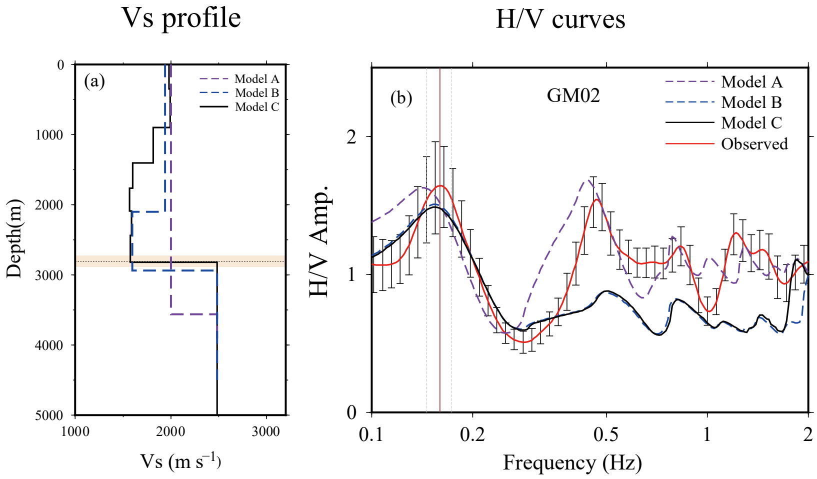

Figure 5. H/V spectrum inversion results of different models. Model A, B, and C are single, two-layer, and seven-layer ice sheet model, respectively. The synthetic H/V spectra using the optimum inversion velocity model B and C (panel a) can both fit the observed H/V spectrum (panel b).

(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.

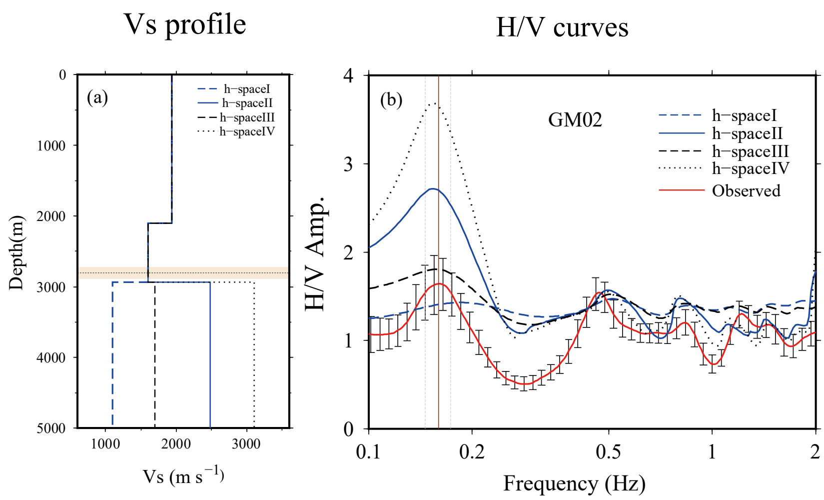

Figure 6. Effect of impedance contrast (basal condition) on the peak amplitude. As shown in panel b, the more rigid the half space (the higher the impedance contrast), the larger the amplitude is. It can be seen from panel b that the peak frequency and the shape of the H/V spectrum deviate from those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