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

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12
13 **Abstract.** We report on a successful application of the horizontal-to-vertical spectral ratio (H/V) method,
14 generally used to investigate the subsurface velocity structures of the shallow crust, to estimate the Antarctic ice
15 sheet thickness for the first time. Using three-component, five-day long, seismic ambient noise records gathered
16 from more than 60 temporary seismic stations located on the Antarctic ice sheet, the ice thickness measured at
17 each station has comparable accuracy to the Bedmap2 database. Preliminary analysis revealed that 60 out of 65
18 seismic stations on the ice sheet obtained clear peak frequencies (f_0) related to the ice sheet thickness in the H/V
19 spectrum. Thus, assuming that the isotropic ice layer lies atop a high velocity half-space bedrock, the ice sheet
20 thickness can be calculated by a simple approximation formula. About half of the calculated ice sheet thickness
21 were consistent with the Bedmap2 ice thickness values. To further improve the reliability of ice thickness
22 measurements, two-type models were built to fit the observed H/V spectrum through non-linear inversion. The
23 two-type models represent the isotropic structures of single- and two-layer ice sheet, and the latter depicts the
24 non-uniform, layered characteristics of the ice sheet widely distributed in Antarctica. The inversion results
25 suggest that the ice thicknesses derived from the two-layer ice models were in good consistence with the
26 Bedmap2 ice thickness database, and their ice thickness differences were within 300 m at almost all stations. Our
27 results support previous finding that the Antarctic ice sheet is stratified. Extensive data processing indicates that
28 the time length of seismic ambient noise records can be shortened to two hours for reliable ice sheet thickness
29 estimation using the H/V method. This study extends the application fields of the H/V method and provides an
30 effective and independent way to measure ice sheet thickness in Antarctica.

31 1 Introduction

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

40 Given the importance of Antarctic ice sheet structures, many geophysical methods, such as drilling, gravity
41 modelling, radio echo sounding (RES), and active seismic approaches including reflection and refraction, have
42 been used in local or regional scale ice sheet thickness investigations since the 1950s (Bentley and Ostenson, 1961;
43 Bentley, 1964; Evans and Robin, 1966; Evans and Smith, 1969; Robin, 1972; Drewry et al., 1982; Cui et al.,
44 2016). By studying gravitational anomalies in the ice sheet, gravimetric measurements provide an indirect way
45 to infer the average ice thickness over a region. Active seismic and RES methods can determine the ice thickness
46 at a much smaller area by converting the echo time of seismic and electromagnetic waves into an estimation of
47 ice thickness. Among these methods, the active seismic and RES methods are the most widely used techniques
48 for ice thickness measurements due to their relatively high accuracy and better spatial resolution, while gravity
49 modelling is used as a complementary way in areas where lack direct ice thickness measurements. Using these
50 methods (with the dominance of the RES method), abundant ice thickness data were collected over the past few
51 decades. Compiled and gridded, these increasing data volumes were used to construct the Bedmap1 and
52 Bedmap2 databases at a resolution of 5 km and 1km, respectively (Lythe et al., 2001; Fretwell et al., 2013).
53 However, traditional methods for estimating ice thickness still have limitations. For example, the accuracy of the
54 gravity method is relatively low because of its intrinsically low sensitivity of a gravimeter to the gravitational
55 anomalies related to the ice sheet-bedrock interface. In the case of the active seismic and RES methods, they
56 require considerable economic and logistical support to collect the data. With the rapid growth of
57 cryo-seismology in the last one to two decades, many passive seismic methods have been applied to cryospheric
58 research (Podolskiy and Walter, 2016; Aster and Winberry, 2017). Given that passive seismic methods can
59 mitigate logistical problem and are relatively cost-efficient (Zhan et al., 2014; Picotti et al., 2017), it is therefore
60 of interest to explore the feasibility of passive seismic methods to contribute additional and/or better constraints
61 to the ice sheet structure.

62 Teleseismic P-wave receiver functions (PRF), as a generally used passive seismic method to determine crustal
63 and mantle discontinuities, is also sensitive to the ice-bedrock interface and the seismic properties of ice sheets.
64 Hansen (2010) successfully modelled ice sheet thickness beneath several stations in East Antarctica using PRF.
65 Wittlinger and Farra (2012, 2015) investigated the anisotropy of the polar ice sheet by modelling the P-to-S

66 wave conversion with the negative PRF amplitude. Yan (2017) confirmed that the ice thickness results derived
67 from PRF are consistent with the Bedmap2 ice thickness database. However, large numbers of teleseismic
68 events are needed to perform PRF; it usually takes at least a one-year period of data collection, thus greatly
69 limiting the application of the PRF method in harsh environments such as those found in Antarctica.

70 In order to improve the efficiency of ice thickness investigation, we selected the horizontal-to-vertical spectral
71 ratio (H/V) method to determine ice thickness. As a passive and non-invasive seismic method, the H/V
72 technique has been extensively used in seismic exploration as a tool to detect sediment thickness (Konno and
73 Ohmachi, 1998; Ibs-von Seht and Wohlenberg, 1999; Bonnefoy-Claudet et al., 2006). Considering that the
74 sediments and ice sheet layer are both low shear-wave velocity (V_s) layers atop the high velocity bedrock, the
75 H/V method should be suitable for determining ice sheet thickness.

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

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

99 **2.1 Data**

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

116 **2.2 Methods**

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

124 During the relatively long history of the H/V method, extensive field experiments and numerical simulations
125 have been carried out to confirm the correspondence between the shear-wave resonance frequency and the H/V
126 peak frequency. Initially Nakamura (1989) proposed that the peak frequency corresponds to the transfer function
127 for vertically incident SH waves (a polarized shear-wave that is generated when an incident shear-wave enters in
128 a heterogeneous medium). Using numerical simulations of ambient noise in a soil layer overlying a hard bedrock,
129 Lachetl and Bard (1994) first showed that the peak frequency is very close to the shear-wave resonance
130 frequency. This correspondence between the H/V peak frequency and the shear-wave resonance frequency was

131 later confirmed by Bard (1998), Ibs-von Seht and Wohlenberg (1999), and reasserted by Nakamura (2008). The
132 peak in the H/V spectrum may also be followed by a trough. Konno and Ohmachi (1998) found such feature in
133 the H/V spectrum in the case of a soft sediment layer atop a hard bedrock. As pointed out by Tuan (2011), the
134 appearance of a trough probably suggests the overlying layer has higher Poisson's ratio (or impedance contrast)
135 than that of the underlying layer. Despite the H/V peak frequency is commonly accepted as a proxy of the
136 resonance frequency of a particular layer, no strong evidences support that the peak amplitude indicates the
137 amplification factor of the site and there are some controversies about the nature of the ambient noise
138 wavefield and its sources (Sánchez-Sesma et al., 2011). During the past few decades, two research branches
139 were formed to interpret the ambient noise wavefield: Rayleigh wave ellipticity (Fäh et al., 2001; Wathelet et
140 al., 2004) and the full wavefield assumptions including distributed surface sources (DSS, Lunedei and
141 Albarello, 2009, 2010) and diffuse field assumption (DFA, Shapiro and Campillo, 2004; Sánchez-Sesma and
142 Campillo, 2006; Sánchez-Sesma et al., 2011; García-Jerez et al., 2013, 2016).

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

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

$$152 \quad h = \frac{V_s}{4f_0} \quad (1)$$

153 where V_s is the average shear-wave velocity of the sedimentary layer, and f_0 is the observed peak frequency.
154 Provided that a correct estimate of the average shear-wave velocity of the sedimentary layer is available, its
155 thickness can be approximately estimated.

156 Complicated sedimentary internal structures, including anisotropy and low velocity layers beneath stations,
157 will affect the H/V spectrum and consequently violate the assumptions of Eq. (1). Therefore, when inferring
158 complex subsurface structures, an inversion of the full H/V spectrum can be used to explain more accurately the
159 observed H/V spectrum. Based on different assumptions (including Rayleigh wave ellipticity, DSS, and DFA)
160 for the interpretation of ambient noise wavefield composition, several inversion schemes have been proposed
161 and successfully applied to study sedimentary structures (Fäh et al., 2003; Arai and Tokimatsu, 2004; Herak,
162 2008; Lunedei and Albarello, 2009; Sánchez-Sesma et al., 2011). These assumptions differentiate themselves in
163 the scheme of forward calculation of the H/V spectrum. In this study, a more recently developed H/V spectrum
164 forward calculation and inversion method based on the DFA was employed (García-Jerez et al., 2016). The DFA

165 was proposed on the base of the recently stated connection between the diffuse fields and the Green's function
 166 which arises from the ambient noise interferometry theory. Under this assumption, the average spectral power
 167 ($P(\omega)$) of a diffuse field along each Cartesian axis are proportional to the imaginary part of Green's tensor
 168 components at an arbitrary point x and circular frequency ω (i.e. $P_i(\omega) \propto \text{Im}[G_{ii}(x; x; \omega)]$, $i = 1, 2, 3$, where
 169 1 and 2 stand for the horizontal directions and 3 denotes the vertical direction; terms with 1 and 2 in fact are
 170 equal). Thus, the H/V spectral ratio is given as:

$$171 \quad HV(x; \omega) = \sqrt{\frac{P_1(x; \omega) + P_2(x; \omega)}{P_3(x; \omega)}} = \sqrt{\frac{2 \text{Im}[G_{11}(x; x; \omega)]}{\text{Im}[G_{33}(x; x; \omega)]}} \quad (2)$$

172 In a horizontally layered structure, the contribution of both the surface wave and the body wave to the
 173 $\text{Im}[G_{ii}(x; x; \omega)]$ (on the right-hand side of Eq. (2)) can be computed with provided medium properties including
 174 primary- and shear-wave velocities. The detailed formulations are not stated here as they are very complicated
 175 and on account of space limitation, but readers with interest can refer to Sánchez-Sesma (2011), García-Jerez
 176 (2016), and Lunedei and Malischewsky (2015). Thus, the Eq. (2) allows for the H/V spectrum inversion as it
 177 links the real measurements and the theoretical calculation of an H/V spectrum. In the H/V spectrum inversion
 178 procedure, model spaces are set for parameters including primary- and shear-wave velocities, mass density, and
 179 thickness of each layer. The sedimentary structures can be determined when the lowest misfit between the
 180 observed and forward calculated H/V spectrum is obtained using inversion algorithms such as Monte Carlo
 181 sampling and simulated annealing.

$$182 \quad E(m) = \frac{\sum_j (HV^{obs} - HV_j^{theo}(m))^2}{\sigma^2} \quad (3)$$

183 Where $E(m)$ is the lowest value of the misfit in the j iterations, and m represents a model that is comprised
 184 of primary- and shear-wave velocities, mass density, and thickness of each layer in each iteration.
 185 HV^{obs} , $HV_j^{theo}(m)$ are the observed and the j -th forward calculated H/V spectrum, and σ is the standard
 186 deviation associated with the HV^{obs} .

187 The H/V method has been successfully applied in studies of sedimentary structures (Ibs-von Seht and
 188 Wohlenberg, 1999; Langston and Horton, 2014; Civico et al., 2017). However, applications in ice environments
 189 are rare. Lévêque (2010) studied the snow layer thickness and the ice properties beneath four stations in Dome C
 190 region of Antarctica using the H/V method. Picotti (2017) measured ice thickness ranging from tens of meters to
 191 800 m of six glaciers in Italy, Switzerland and West Antarctica. However, the impedance contrast between the
 192 ice sheet layer and the overlying bedrock is not as high as that of sedimentary-bedrock and snow-ice layers.
 193 Moreover, the complex subglacial environment and internal ice structure create other technical obstacles. Thus,
 194 there have been no investigations of ice sheet thickness incorporating the H/V method for measurements or
 195 estimations.

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

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

209 Having acquired the resonance frequency of the ice sheet, we adopted Eq. (1) with a uniform average
210 shear-wave velocity—1900 m s⁻¹ of the ice layer to calculate the ice thickness. This velocity used here is
211 reasonable given that it is in the general range of ice Vs determined by seismic experiments (Kim et al., 2010).
212 Moreover, this velocity has also been widely used in previous studies (Hansen et al., 2010; Wittlinger and Farra,
213 2012; Ramirez et al., 2016). Keeping the velocities set, the ice thickness at each station was calculated using Eq.
214 (1).

215 In the H/V spectrum inversion procedures, Bedmap2 ice thicknesses were used as references to build the
216 initial models, as along with the related seismic elastic parameters (Fig. 2, Wittlinger and Farra, 2012; Ramirez
217 et al., 2016). We adopted two different models assuming the ice sheet is homogenous and inner ice stratified;
218 respectively, as shown in Fig. 2 to perform H/V spectrum inversion. Model A is a simple homogeneous and
219 isotropic ice structure with an ice layer overlying the half-space. In this model, the ice thickness varies from 0.7
220 to 1.3 times the Bedmap2 ice thickness for each station. Model B is constructed following Wittlinger and Farra
221 (2012, 2015) as a two-layer ice structure in which a low shear-wave velocity lies in the lower ice layer. In this
222 model, the thickness of the upper ice layer and the lower ice layer were set to occupy 60—75 and 25—40 percent
223 of the Bedmap2 thickness, respectively. Using the non-linear Monte Carlo method (García-Jerez et al., 2016),
224 we retrieved the optimum solutions for model A and B. These two solutions were best fitted to the observed H/V
225 spectrum.

226 It usually takes a few minutes to about half an hour to collect seismic ambient noise waveforms in the
227 investigations of sedimentary layers with thickness ranging from several tens to hundreds of meters. However,
228 there is no experiences for the time length of recording seismic ambient noise in the Antarctic ice sheet with
229 several kilometers thick. It is necessary to apply the H/V method with a much shorter recording time for seismic
230 ambient noise, considering the harsh environment and logistical support difficulties in Antarctica. Therefore, we

231 investigated the feasibility and reliability of H/V method by testing a range of noise record lengths; eight hour,
232 four hour, two hour, and one hour intervals were tested. The processing strategies remained the same as in H/V
233 spectrum acquisition except the window length was changed to 200 s when calculating the H/V spectrum using
234 different length noise records.

235 3 Results

236 In this study, the H/V spectra of 65 stations were obtained. Figure 3 displays the H/V spectra of nine stations
237 selected from three arrays. These examples are representative of all the results, and the remaining spectra are
238 presented in the supplementary Fig. S2. It is clearly shown that in almost all H/V spectra there were two or three
239 clear peaks in the frequency band. Generally, the largest amplitude appears at the first peak located around 0.2
240 Hz or below, and the second and the third peaks with lower amplitudes are located at ~ 0.5 and ~ 0.8 Hz,
241 respectively. Following the general interpretation principles for H/V spectra (Bard and SESAME team, 2005),
242 the peak frequency denoting the largest amplitude should be the resonance frequency of the ice sheet layer, while
243 the peaks appearing with lower amplitudes at higher frequencies may indicate the shallower impedance contrast
244 layers. The reasonableness of considering the first peak frequency with the largest amplitude as the resonance
245 frequency of the ice sheet layer was verified through approximate estimation based on Eq. (1), i.e., for station
246 E012, the Bedmap2 ice thickness at that location is 1050 m, so the resonance frequency according to Eq. (1)
247 should be 0.452 Hz (the given V_s is 1900 m s^{-1}), and as expected was observed (0.418 ± 0.052 Hz) in the H/V
248 spectrum. However, there are exceptions such as station N108 displayed in Fig.3 whose first peak (0.177 ± 0.014
249 Hz) amplitude is slightly lower than that of the following peak observed at higher frequency (1.666 Hz). At this
250 station however, the location of the first peak correlates with the resonance frequencies (0.194 Hz) through
251 approximate estimation. In addition, there are some stations that have no peak frequencies correlating with the
252 ice sheet thickness, despite the existence of peak frequency with strong amplitude in the frequency band. Station
253 ST07 seen in Fig. 3 is such a case, whose fundamental resonance frequency as calculated by Eq. (1) should be
254 0.191 Hz (its Bedmap2 ice thickness is 2490 m). Nevertheless, no clear peak around this expected frequency is
255 observed in the H/V spectrum. We therefore can group the results into three categories:

- 256 1) 42 stations with first peaks denoting the largest amplitude in the observed spectrum related to the ice sheet
257 resonance frequency, like the E012, E018, GM02, N148, P071, ST01, ST02 stations in Fig. 3.
- 258 2) 18 stations with first peaks with slightly lower amplitude but also related to the ice sheet resonance
259 frequency such as station N108.
- 260 3) Five stations without peaks correlating to the resonance frequency, such as station ST07.

261 Figure 4 shows the H/V spectra of stations along four profiles, together with the ice sheet and bedrock
262 elevation extracted from Bedmap2 database for each station. As shown in Fig. 4, although the neighboring
263 stations are 80 km apart for profile AA', 100 km for profile BB' and DD', and 20 km for profile CC', the shape
264 of the spectra are similar along each profile. Also, along each profile, the peaks associated with the ice thickness

265 are clear and the locations of the peaks shift towards lower or higher frequencies cohering with the variation of
266 the corresponding ice thickness. There are four stations (N060, ST04, ST06, ST07) along the four profiles
267 without peak frequencies related to their corresponding ice thicknesses. This may be caused by the bad coupling
268 of the seismometer with the ice surface or possibly a complicated subglacial environment, for example clear
269 evidence indicates the existence of sedimentary layer beneath station N060.

270 Having identified resonance frequencies of the ice sheet, we calculated the ice thickness using Eq. (1) with the
271 average shear-wave velocity— 1900 m s^{-1} . The Equation (1) estimates together with their relative errors to the
272 corresponding Bedmap2 ice thickness are listed in Table 1 (hereafter the ice thickness estimations derived from
273 the approximation Eq. (1) and H/V spectrum inversions using model A and model B are defined as Equation (1),
274 DFA + Model A, and DFA + Model B estimates, respectively). We projected the Equation (1) estimates and the
275 reference Bedmap2 ice thickness for stations along the four profiles in the upper elevation panels in Fig. 4. It is
276 clear that the Equation (1) estimates for some stations along the four profiles are close to the reference ice
277 thickness like the E012, P071, and ST01 stations, while there are large deviations at some stations such as E018,
278 N148, and ST02. It should be noted that the ice thickness obtained from the H/V method reflects the average ice
279 sheet thickness beneath each station in the scale of seismic wavelength (i.e. for a peak at frequency 0.2—1 Hz
280 and seismic wavelength of $\sim 2.0 \text{ km}$, the spatial resolution (or footprint) is about 2—10 km).

281 The optimum shear-wave velocity models derived from H/V spectrum inversion are presented in Fig. 5 and
282 supplementary Fig. S3. The observed H/V spectrum together with the synthetic H/V spectra using the two
283 optimum shear-wave velocity models are plotted in Fig. 6 and shown in supplementary Fig. S4. As Fig. 6 and the
284 supplementary Fig. S4 show, the synthetic H/V spectra of the optimum inversion results for model A and model
285 B at almost all stations, both fit the observed H/V spectra in peak frequency and spectrum shape. However, the
286 DFA + Model A estimates deviate substantially from the Bedmap2 thickness at most stations (such as N108,
287 N148, GM02 and ST02 in Fig. 5), and the difference extends 1 km for some stations (Fig. 7). By contrast, the
288 DFA + Model B estimates are consistent with the Bedmap2 thickness as the differences between them are
289 mostly within 200 m. The overall DFA + Model B estimates are listed in Table 1, as well as the relative errors to
290 the corresponding Bedmap2 ice thickness. We also projected the DFA + Model B estimates for stations along the
291 four profiles in the elevation panels seen in Fig. 4. This figure depicts a good consistency between the DFA +
292 Model B estimates and the reference ice thickness as the ice thickness at 27 stations and 46 stations out of the 48
293 stations along the profiles are within 10 % and 15 % threshold of the Bedmap2 ice thickness.

294 The results of four different length seismic ambient noise records (1 h, 2 h, 4 h, 8 h) used to obtain H/V
295 spectrum are displayed in Fig. 8 (and in supplementary Fig. S5). These plots show that the shape of the spectra of
296 the four tested record lengths are similar to the shape determined using a record five days long. The peak
297 frequencies of the four different length records are all within the margin of error for the peak frequency as
298 determined with the record five days long. Besides, we found that the longer the ambient noise record, the more
299 stable the peak frequency is as there are slight shifts in the peak frequency when determined with 1 h records.

300 This feature is obvious for stations with thin ice (less than 2 km) such as those from stations E018 (Fig. 8), E014,
301 E020, E024, and E028 (shown in supplementary Fig. S5). The quality of the H/V spectrum obtained from one
302 hour long record for stations with thick ice (over 2 km) however, is generally consistent with that determined
303 with the record five days long. This consistency can also be found for all stations when the length of noise record
304 exceeds two hours.

305 4 Discussion

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

319 A comparison of the DFA + Model B estimates and Bedmap2 database reveals that the differences in ice
320 thickness at all the 57 stations are less than 400 m; there are 34 stations whose differences are within 200 m and
321 48 stations within 300 m; the maximum difference was 360 m at stations GM06 and N215. The relative errors of
322 the DFA + Model B estimates to the corresponding Bedmap2 thickness of 23 stations, 36 stations, and 58
323 stations are within 5 %, 10 %, and 15 % threshold, respectively. Given that the Bedmap2 ice thickness are
324 associated with certain uncertainties at each station (i.e. the relative errors of the uncertainty to the Bedmap2 ice
325 thickness are within 10 % at 49 stations) (Fretwell et al., 2013). In this sense, we conclude that the DFA + Model
326 B estimates have comparable accuracy to the Bedmap2 ice thickness at the study sites.

327 Based on the homogenous ice sheet layer assumption, most of the Equation (1) estimates are not compatible
328 with Bedmap2 ice thickness (Fig. 4 and Fig. 7), as the differences at 25 stations can extend 400 m and at 10
329 stations are over 600 m; the maximum difference reaches 910 m at station N036. Moreover, most of the DFA +
330 Model A estimates based on the homogenous ice structure of model A also largely deviate from the reference
331 Bedmap2 thickness (Fig. 7 and supplementary Fig. S3). These large deviations cannot be attributed to the
332 uncertainty in the reference Bedmap2 ice thickness since they made minor contributions to the large differences.

333 The DFA + Model B estimates, however are in good consistence with the Bedmap2 database (Table 1). A
334 close examination of the DFA + Model B estimates shows that it refined the Equation (1) estimates at 47 stations
335 to varying degrees. As at stations E012 and N036, the Equation (1) estimates deviate from Bedmap2 at 90 m and
336 910 m, while the DFA + Model B estimates refine the gaps to 20 m and 320 m.

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

342 The agreement of two-layer ice sheet thickness with the Bedmap2 database, and the consistency of our results
343 to Wittlinger and Farra (2012)'s results, as well as the large deviation of Equation (1) estimates and DFA +
344 Model A estimates jointly support the thesis that the two-layered ice sheet models are more reasonable than an
345 homogeneous ice sheet layer assumption. Moreover, the Equation (1) estimates of 28 stations were close to the
346 reference Bedmap2 database. This consistency, however, does not strongly support the homogenous ice sheet
347 layer assumption as it can be attributed to the fact that the Vs values adopted in approximate estimation was
348 coincidental with the average velocity of the two-layer Vs models.

349 The examples presented in this work clearly show that the H/V method with seismic ambient noise can be
350 effectively used to measure ice sheet thickness. However, there are also some limitations that may affect the
351 results. Shear-wave velocity (V_s), as the key parameter for H/V spectrum inversion and approximate estimation
352 using Eq. (1), will significantly affect the effectiveness and uncertainty of the H/V method. We can see from Fig.
353 6 that the synthetic H/V spectra from the optimum V_s profiles of model A and model B for the N108, GM02 and
354 N148 stations, match the observed H/V spectrum. The DFA + Model A estimates and the DFA + Model B
355 estimates at these stations however, are remarkably different as the DFA + Model B estimates are more closely
356 match the reference Bedmap2 ice thickness than the DFA + Model A estimates (Fig. 5). Also evident in these
357 results is a directly proportional relationship between ice thickness and the V_s as expected from Eq. (1) in
358 approximate estimation. Given a ~5 percent variation in the average shear-wave speed of the ice layer, then ice
359 sheet thickness estimation will result in a similar variation such as 150 m for a station with 3 km thickness.
360 Accurate known V_s profiles are therefore prerequisites when obtaining reliable H/V spectrum inversion results,
361 as well as for approximate estimations using Eq. (1).

362 It is evident that the longer the noise record, the more stable the observed peak frequency is as the sources of
363 the seismic ambient noise are more evenly distributed, spatially and temporally. This is significant for stations
364 with thin ice primarily due to the fact that thin ice sheet layers are excited by high-frequency waves such as
365 winds and other sources (Picotti et al., 2017). Thus, a longer ambient noise record can improve the stability of
366 the H/V spectrum. In our study, we found that the quality of the H/V spectrum is generally better for thick ice
367 sheet layers than for thin ice sheet such as stations E012, E018, E024, E026, and E028 with relatively smaller ice

368 thicknesses than other stations. The H/V spectra for these stations exhibited less stability when the lengths of
369 noise records decreased (Fig. 8 and supplementary Fig. S5). Their peak frequencies obtained from a one hour
370 long record slightly deviate from the peak frequency determined with a five day record. These deviations
371 consequently could lead to uncertainties in ice thickness estimation. While for stations with thick ice, both the
372 shape and the peak frequency determined using a one hour long record are generally consistent with those
373 obtained from a five day long record. Given that the variation of ice thickness at the study sites (from 600 m to
374 about 4 km), generally covers the range of the whole Antarctic ice sheet thickness, we would like to suggest a
375 uniform record length of two hours in H/V method application in Antarctica, in terms of stability and efficiency.
376

377 **5 Conclusions**

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

391
392 Supplementary materials include:

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

394
395 *Competing interests.* The authors declare that they have no conflict of interest.

396
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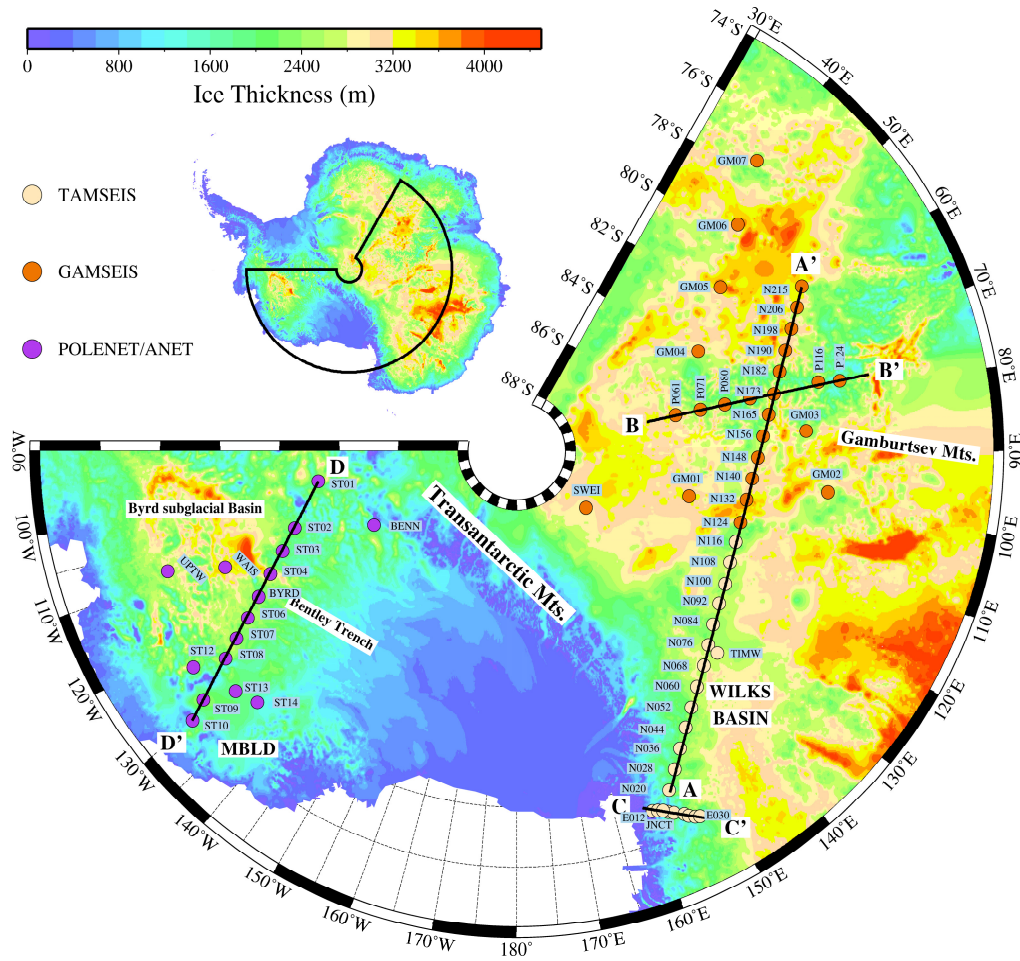
Table 1 Ice thickness results obtained from this study

(Error of Equation (1) estimates listed in column 4 is obtained by averaging the thickness using the resonance frequency f_0 and its corresponding standard deviation σ (i.e. $\Delta h = \left(\left(\frac{V_s}{f_0} - \frac{V_s}{f_0 + \sigma} \right) + \left(\frac{V_s}{f_0 - \sigma} - \frac{V_s}{f_0} \right) \right) / 2$). The relative errors listed in column 5 and 7 are calculated using $\frac{|Equation(1) - Bedmap2|}{Bedmap2} \cdot 100\%$ and $\frac{|DFA + ModelB - Bedmap2|}{Bedmap2} \cdot 100\%$, respectively)

| Station | Bedmap2 (km) | Resonance freq. (Hz) | Equation (1) (km) | Relative error | DFA+Model B (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) | Equation (1) (km) | Relative error | DFA+Model B (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 | 1.93 | 0.236±0.019 | 2.01±0.16 | 4.35% | 1.96 | 1.33% |
| 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% |



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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.

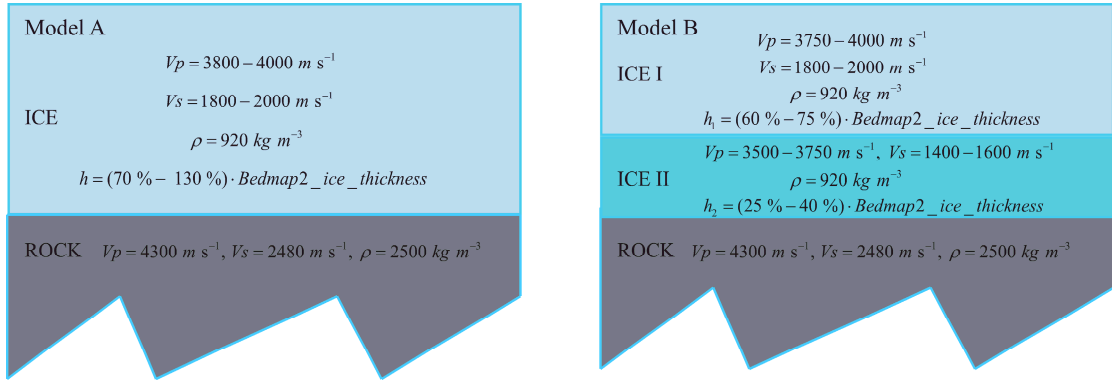
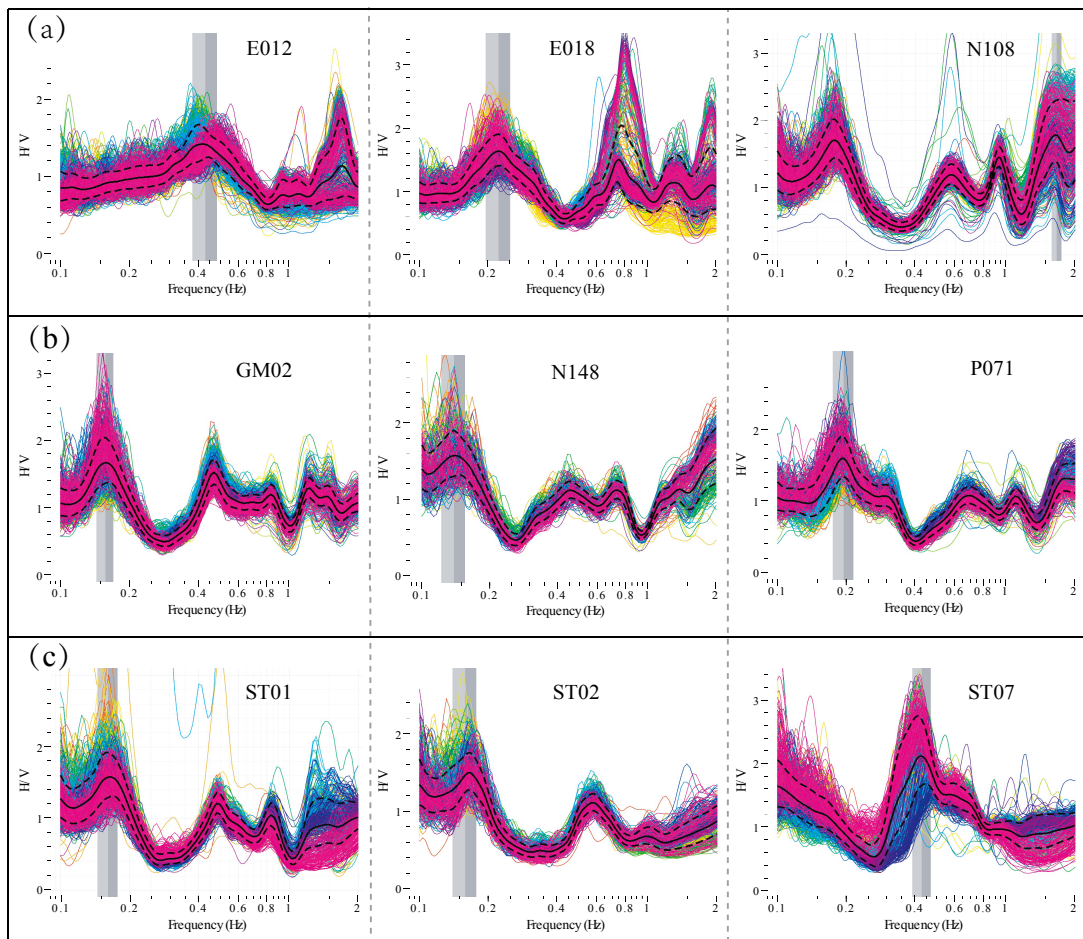
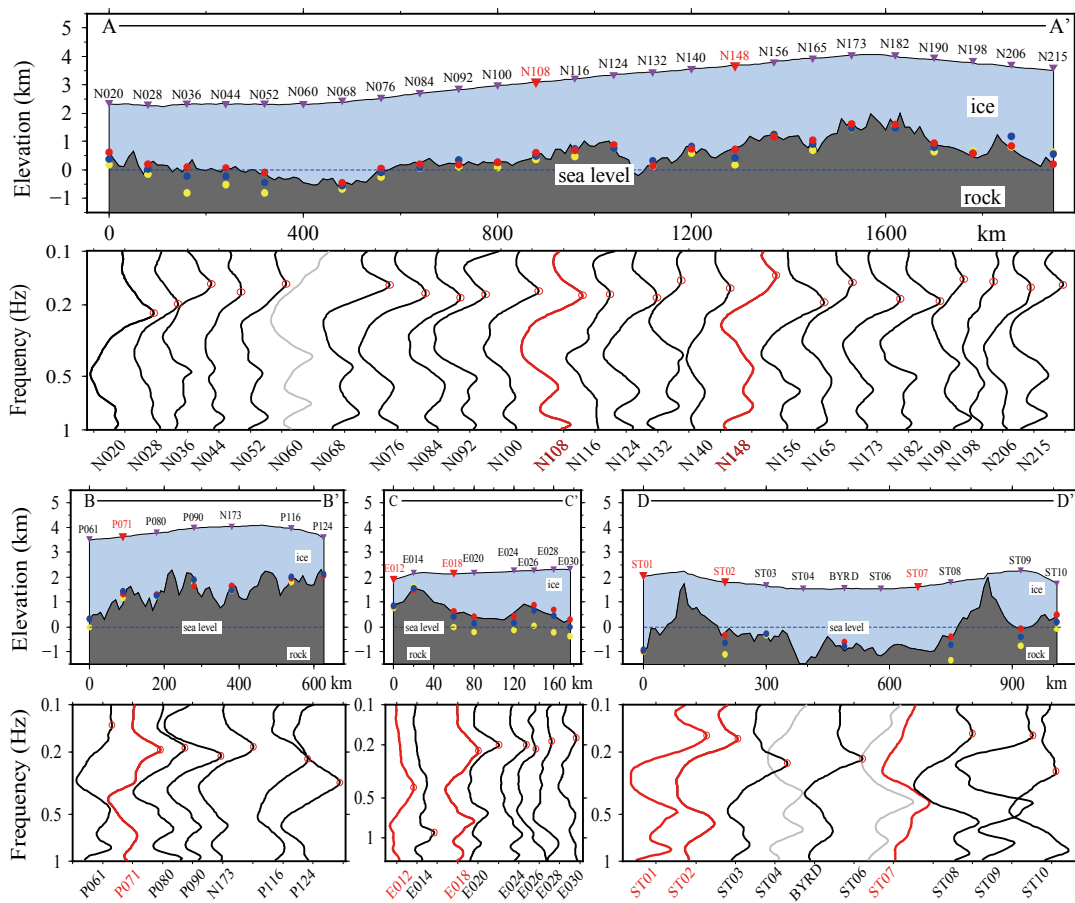


Figure 2. Sketches of the two ice layer models used for H/V spectrum inversion. Model A comprises a single ice layer, while model B is a two-layer ice structure with low shear-wave velocity in the lower ice layer. The parameters used in the two models are consistent with Wittlinger and Farra (2012).



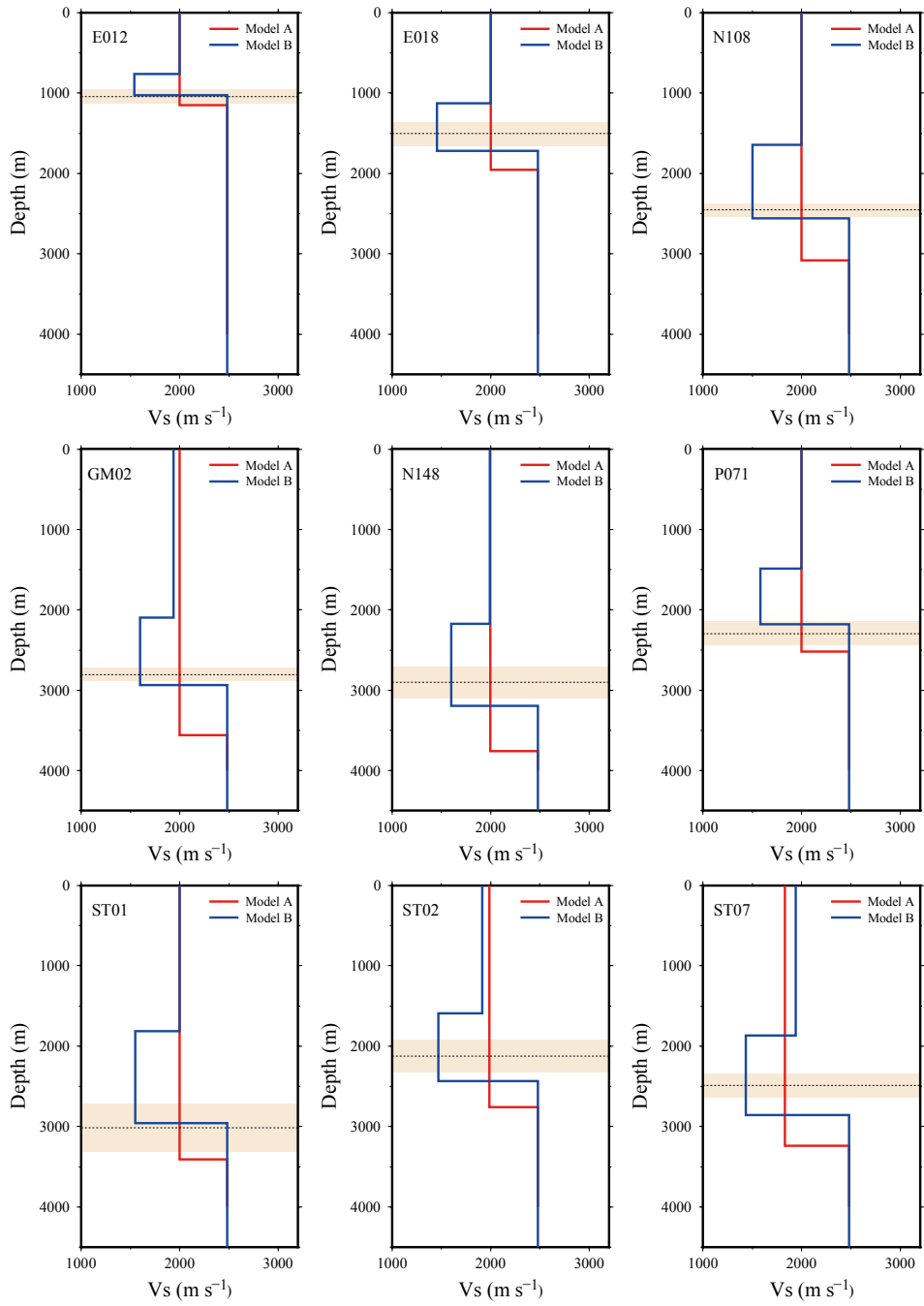
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571 **Figure 3.** H/V spectra of nine stations shown as representative of all results in this study. Panel a, b, and c
 572 is comprised of three stations that belong to TAMSEIS, GAMSEIS, and POLENET/ANET array, respectively (The locations
 573 can be seen in profiles displayed in Fig. 4). The H/V spectra were calculated using five-day long ambient noise record. In
 574 each spectrum, the value at the limit between the two vertical gray areas is the peak frequency, while the two gray areas
 575 denote its standard deviation. The spectra of the E012, E018, GM01, N148, P071, ST01 and ST02 stations represent 42
 576 stations whose clear first peaks with the largest amplitudes are in agreement with the resonance frequency of the ice sheet
 577 layer. Station N108 is representative of 18 stations whose first peaks are related to the ice sheet resonance frequency but
 578 with slightly lower amplitude than peaks in higher frequencies. ST07 is the example that no peak frequency correlating to
 579 the ice thickness appears as expected in the observed H/V spectrum.



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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 gray lines. The spectra together with their station names that shown with red color, are correspondence to the stations displayed in Fig. 3. 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 Equation (1) estimates and the DFA + Model B estimates, respectively.



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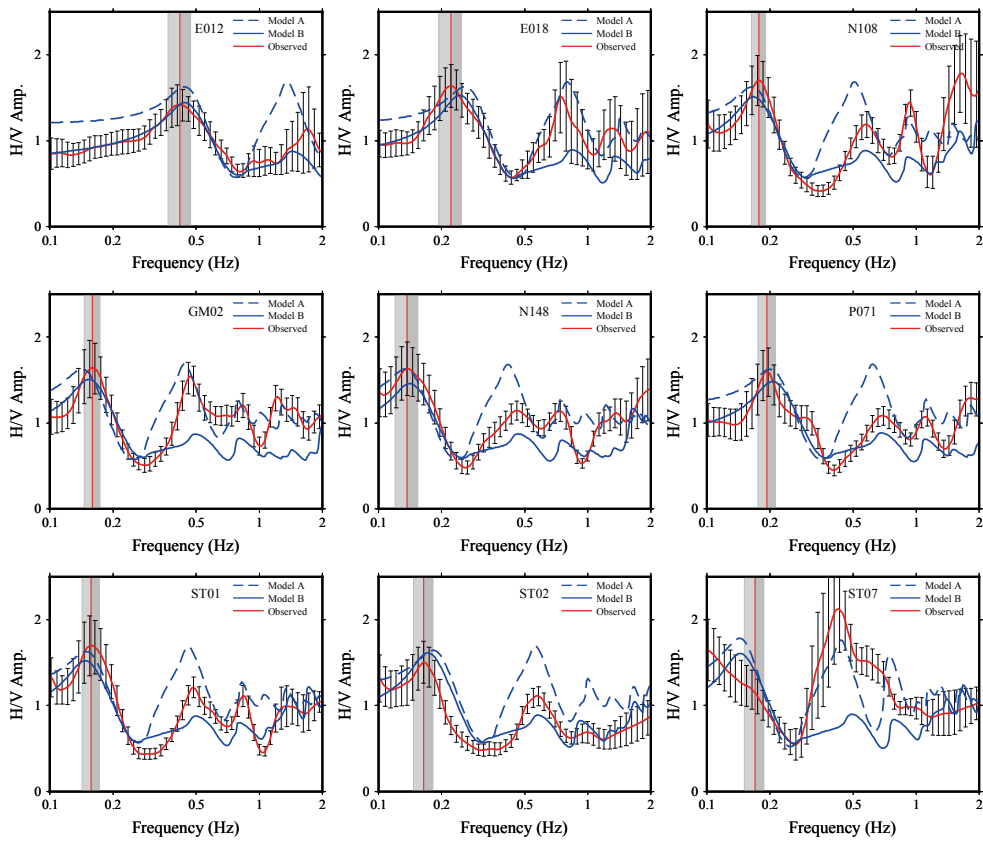
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Figure 5. The optimum inversion shear-wave velocity models for the nine stations. The horizontal dashed line in each plot indicates the reference Bedmap2 ice thickness, and the shaded area shows the uncertainty of the Bedmap2 ice thickness. Apparently, 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).



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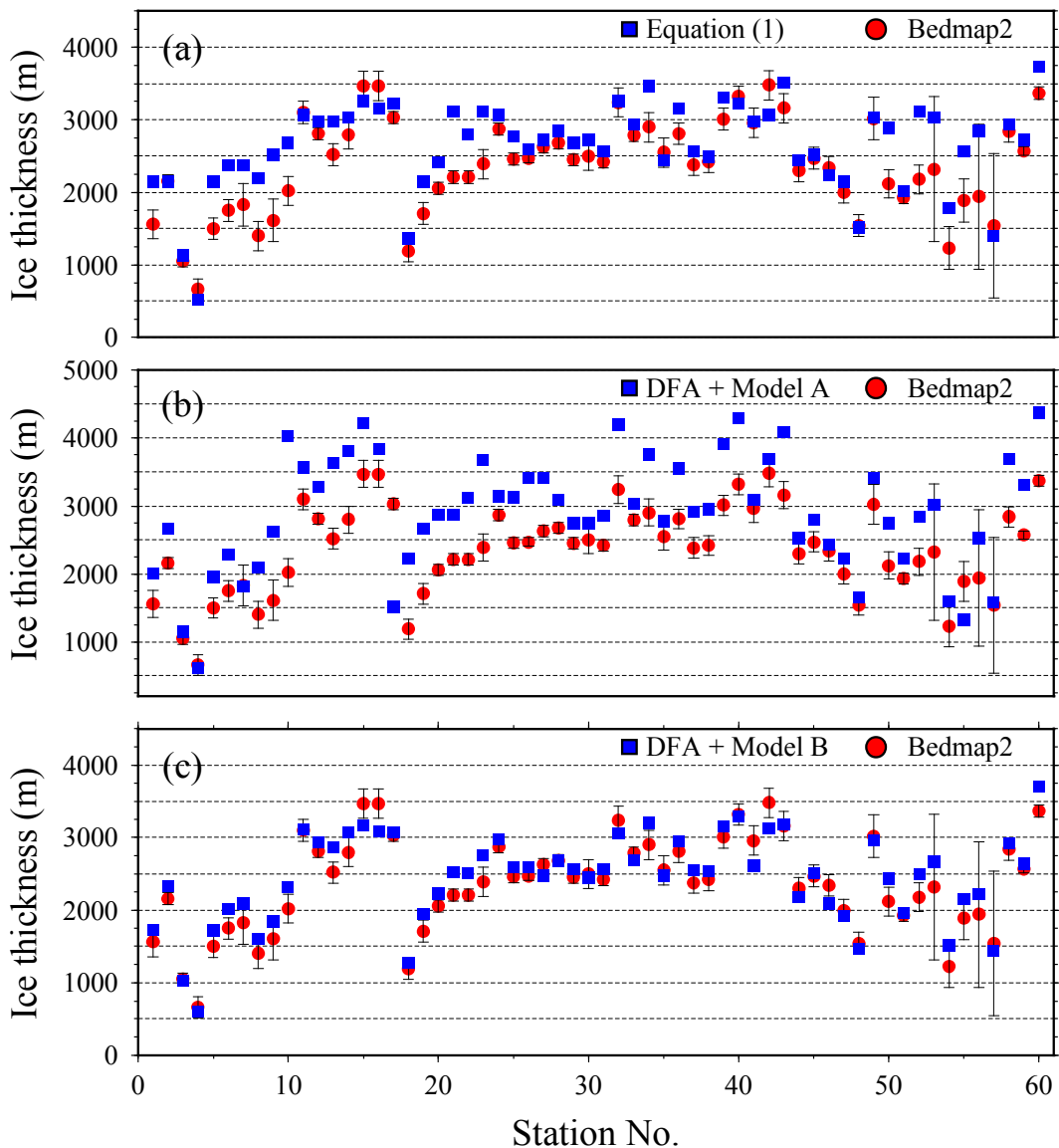
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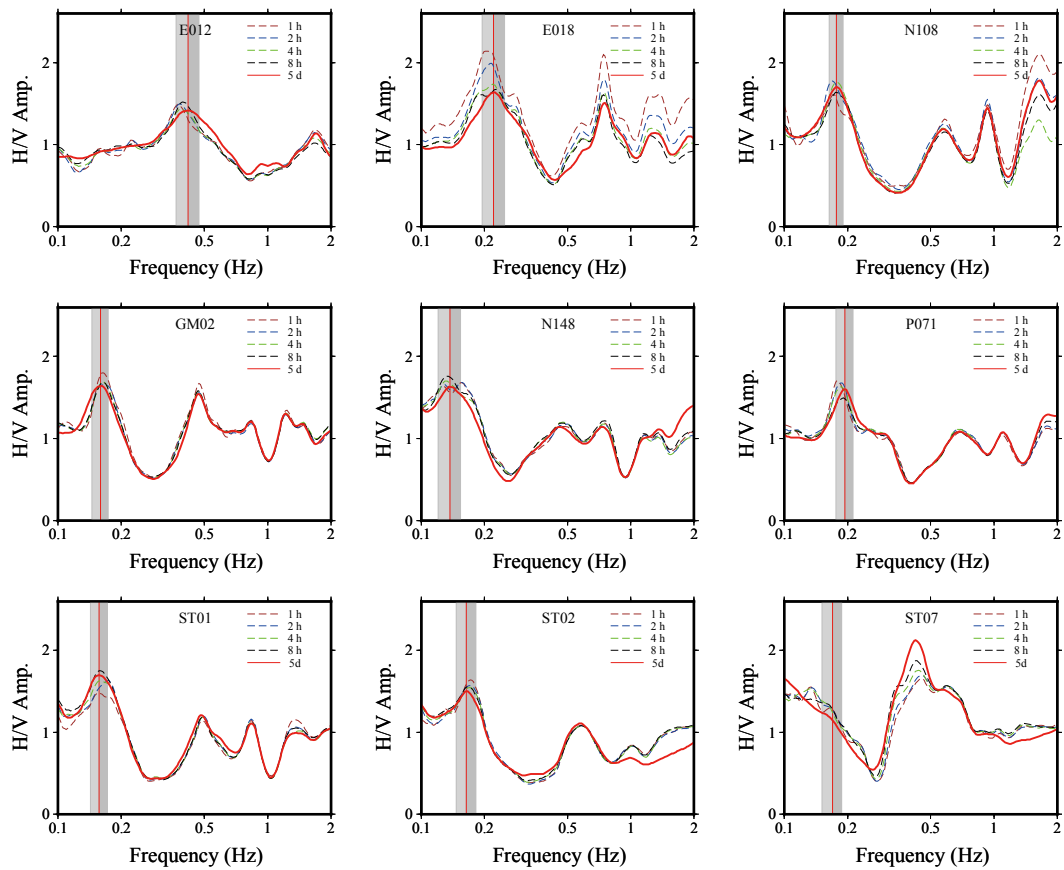
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Figure 6. The synthetic H/V spectra and the observed H/V spectrum for the nine stations. The synthetic H/V spectra are modelled using the optimum inversion shear-wave velocity profiles for model A and model B. In all plots except for the last one, the vertical bars are the same as those in Fig.3 (i.e. the real peak frequency and the associated standard deviation). As for the last one, the peak frequency is approximately calculated using Eq. (1) with its Bedmap2 ice thickness, and the deviation is also approximated with a relative error of 10 % to its peak frequency. 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.



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Figure 7. Ice thickness derived from the H/V method versus the reference Bedmap2 ice thickness. The station number of this figure is in the same order of the stations listed in Table 1. The blue squares in panel (a), (b), and (c) represent Equation (1), DFA + Model A, and DFA + Model B estimates, 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).



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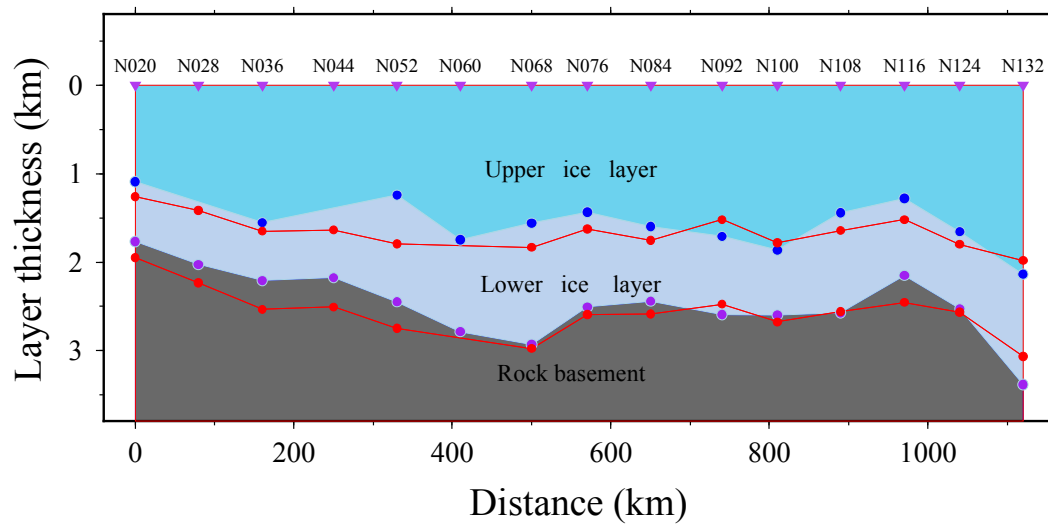
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Figure 8. H/V spectra calculated using different lengths of ambient noise records. The vertical bars in all panels except for the last one represent the peak frequencies and the corresponding standard deviations the same as those in Fig. 3 and Fig. 6. 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.



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625 **Figure 9.** Comparisons of the two-layer ice sheet structure obtained from our study and Wittlinger and Farra (2012)'s.
 626 The red dots shown in shallower depth denote the interface between the upper and the lower ice sheet obtained in this study.
 627 The interface is generally consistent with that (as the blue dots shown) determined with the PRF method and a grid search
 628 stacking technique (Wittlinger and Farra, 2012, Table 1). The red dots shown in deeper depth represent the overall ice
 629 thickness derived from model B, which is also consistent with the radar ice thickness (as the purple dots shown) adopted
 630 by Wittlinger and Farra (2012).
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