

## RESEARCH ARTICLE

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## Key Points:

- We propose a generalized  $H$ - $\kappa$  method with harmonic corrections on  $P$ s and its crustal multiples in receiver functions ( $H$ - $\kappa$ -c method)
- Correcting for the azimuthal variation of arrival times can significantly enhance the  $H$ - $\kappa$  stacking and obtain more robust results
- Application of the method to real data shows clear improvement with large differences in  $H$  and  $\kappa$  mostly in mountainous regions

## Supporting Information:

- Supporting Information S1

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# A Generalized $H$ - $\kappa$ Method With Harmonic Corrections on $P$ s and Its Crustal Multiples in Receiver Functions

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**Abstract** The  $H$ - $\kappa$  method (Zhu & Kanamori, 2000, <https://doi.org/10.1029/1999JB900322>) has been widely used to estimate the crustal thickness ( $H$ ) and the ratio of  $P$  to  $S$  velocities ( $V_P/V_S$  ratio,  $\kappa$ ) with receiver functions. However, in regions where the crustal structure is complicated, the method may produce biased results, arising particularly from dipping Moho and/or crustal anisotropy.  $H$ - $\kappa$  stacking in case of azimuthal or radial anisotropy with flat Moho has been proposed but not for cases with plunging anisotropy and dipping Moho. Here we propose a generalized  $H$ - $\kappa$  method called  $H$ - $\kappa$ -c, which corrects for these effects first before stacking. We consider rather general cases, including plunging anisotropy and dipping interfaces of multiple layers, and use harmonic functions to correct for arrival time variations of  $P$ s and its crustal multiples with back azimuth ( $\theta$ ). Systematic synthetic tests show that the arrival time variations can be well fitted by  $\cos\theta$  and  $\cos 2\theta$  functions even for very complex crustal structures. Correcting for the back azimuthal variations significantly enhances  $H$ - $\kappa$  stacking. We verify the feasibility of the  $H$ - $\kappa$ -c method by applying it to 40 permanent stations in various geological setting across the Mainland China. The results show clear improvement after the harmonic corrections, with clearer multiples and stronger stacking energy, as well as more reliable  $H$ - $\kappa$  values. Large differences in  $H$  (up to 5.0 km) and  $\kappa$  (up to 0.09) between the new and traditional methods occur mostly in mountainous regions, where the crustal structure tends to be more complex. We caution in particular about systematic bias when the traditional method is used in the presence of dipping interfaces. The modified method is simple and applicable anywhere in the world.

**Plain Language Summary** Crustal thickness and crustal  $V_P/V_S$  ratio are important parameters for regional geology and tectonics. We propose a method that corrects for the effect of crustal anisotropy and dipping interface on receiver functions, which results in more reliable estimation of crustal thickness and  $V_P/V_S$  ratio. Synthetic tests and application to real data suggest that this method is powerful and widely applicable.

## 1. Introduction

A receiver function (RF) is the response of the Earth's structure below a seismometer to an incident teleseismic wave and consists of series of  $P$ -to- $S$  or  $S$ -to- $P$  converted waves generated at structural interfaces (e.g., Langston, 1979). It is commonly used to image major interfaces of the Earth (e.g., Zhu & Kanamori, 2000). The Moho-converted  $P$ -to- $S$  ( $P$ s) phase in RF from an incident  $P$  wave has long been used to determine the crustal thickness ( $H$ ) beneath a seismic station, which is an important parameter for understanding regional geology and tectonic evolution, but has a strong trade-off with the average crustal  $V_P/V_S$  ratio ( $\kappa$ ). By including the crustal reverberations (multiples) of  $P$ s in the analysis, the trade-off can be reduced (Zandt & Ammon, 1995; Zhu, 1993; Zhu & Kanamori, 2000). The  $H$ - $\kappa$  method developed by Zhu and Kanamori (2000) has been widely used to estimate the thickness and average  $V_P/V_S$  of the crust through a grid search of  $H$  and  $\kappa$  values. It stacks amplitudes of RFs at the predicted arrival times of  $P$ s and its crustal multiples ( $PpPs$  and  $PpSs + PsPs$ ) for given values of  $H$  and  $\kappa$ . However, the method assumes an isotropic crust with a flat Moho. In the presence of complicated crustal structure and limited data sample, the  $H$ - $\kappa$  results may be biased. Synthetic tests with azimuthal anisotropy or dipping Moho show that the influence on the arrival times of crustal multiples is even stronger than on those of  $P$ s, which would affect  $H$ - $\kappa$  estimates (e.g., Li et al., 2017). Li et al. (2017) showed that in case of dipping Moho, the variations of the arrival times of the crustal multiples can be 5–6 times of those of  $P$ s.

There have been many studies on the variations of  $P_s$  with back azimuth (BAZ)  $\theta$  in cases of dipping interfaces and/or anisotropic structures. These variations may follow a two-lobed ( $\cos\theta$ ) or four-lobed ( $\cos 2\theta$ ) pattern (Bianchi et al., 2010; Cassidy, 1992; Frederiksen et al., 2003; Frederiksen & Bostock, 2000; Levin & Park, 1997a, 1997b; Liu & Niu, 2012; Liu & Park, 2017; McNamara & Owens, 1993; Ozacar & Zandt, 2004; Park & Levin, 2016; Rumpker et al., 2014; Savage, 1998; Schulte-Pelkum & Mahan, 2014; Zhu et al., 1995). Some modifications of the  $H$ - $\kappa$  method were proposed to account for crustal anisotropy, which were shown to reduce the bias on  $H$ - $\kappa$  results, especially for  $\kappa$  (Hammond, 2014; Kaviani & Rumpker, 2015). However, these studies assumed a flat Moho and only considered either azimuthal or radial anisotropy but not anisotropy with a plunge (a tilt of symmetry axis from the horizontal plane).

Here we propose a generalized  $H$ - $\kappa$  method with harmonic corrections ( $H$ - $\kappa$ -c), which considers rather general cases, including plunging anisotropy and dipping interfaces of multiple layers. The basic idea is to use  $\cos\theta$  and  $\cos 2\theta$  functions to correct arrival times of both  $P_s$  and crustal multiples ( $PpPs$  and  $PpSs + PsPs$ ) for the complex effects of the crustal anisotropy and dipping interfaces. Our synthetic tests with different crustal models suggest that  $P_s$  and multiples can be fitted by  $\cos\theta$  and  $\cos 2\theta$  functions even for very complicated crustal structures with significant anisotropy amplitudes and interface dip angles. Correcting for back azimuthal variations significantly enhances the  $H$ - $\kappa$  stacking. We apply the  $H$ - $\kappa$ -c method to 40 Chinese National Digital Seismic Network (CNSN) stations in a variety of geological settings across the Mainland China. The results show apparent improvement, with clearer multiples and stronger stacking energy as well as more reliable  $H$ - $\kappa$  values. The improved estimation of crustal  $V_P/V_S$  ratio, which is directly related to the Poisson's ratio, can provide critical constraint on the composition and thermal condition of the crust. The modified procedure is also simple, making it applicable anywhere in the world.

## 2. Methodology

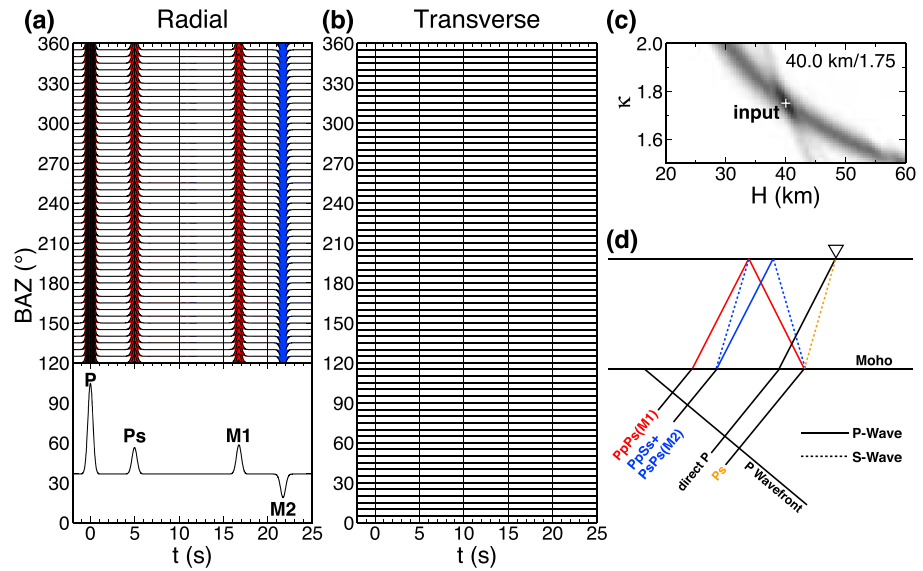
The main goal of the proposed method is to improve the estimation of crustal thickness and  $V_P/V_S$  ratio by correcting for the dip and anisotropy effects before stacking the RFs and also to retain the simplicity of the traditional  $H$ - $\kappa$  method (Zhu & Kanamori, 2000). The method includes four main steps. (1) Apply the traditional  $H$ - $\kappa$  stacking to get the reference arrival times of  $P_s$  and crustal multiples. (2) Perform the incidence moveout corrections on all the RFs. (3) Obtain harmonic fits of the back azimuthal variations of  $P_s$  and multiples. (4) Perform the  $H$ - $\kappa$ -c: use the parameters from (3) to correct the RFs of  $P_s$  and multiples and redo the  $H$ - $\kappa$  stacking with the corrected RFs, or alternatively, use the arrival times from the harmonic fits to calculate values of  $H$  and  $\kappa$  directly using analytical relationships. The analytical values are given in the output as a reference, but the  $H$ - $\kappa$ -c stacking results are recommended (see below). These steps of the method are described in detail in the following sections.

### 2.1. Traditional $H$ - $\kappa$ Stacking

The  $H$ - $\kappa$  method (Zhu & Kanamori, 2000) has become one of the standard seismology techniques. The remarkably simple technique utilizes the  $P_s$  phase and its crustal multiples ( $PpPs$  and  $PpSs + PsPs$ , here referred to as  $M1$  and  $M2$  for convenience; Figure 1) to resolve the trade-off between  $H$  and  $\kappa$ . The crustal thickness ( $H$ ) and velocities and the time separation between  $P_s/M1/M2$  and the direct  $P$  phase in radial RF (R-RF) are related as follows (Zhu & Kanamori, 2000):

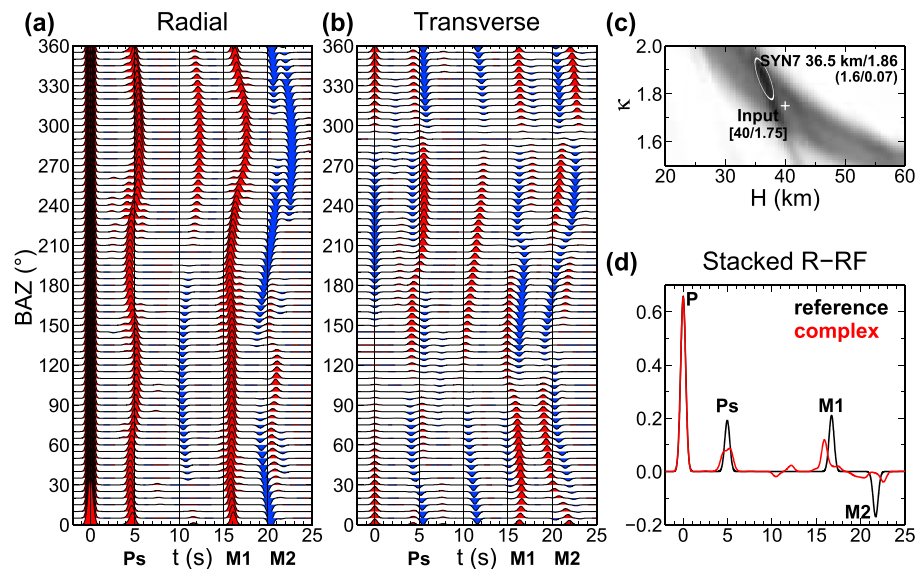
$$H = \frac{t_{Ps}}{\sqrt{1/V_s^2 - p^2} - \sqrt{1/V_p^2 - p^2}} = \frac{t_{M1}}{\sqrt{1/V_s^2 - p^2} + \sqrt{1/V_p^2 - p^2}} = \frac{t_{M2}}{2\sqrt{1/V_s^2 - p^2}} \quad (1)$$

where  $p$  is the ray parameter of the incident wave. The  $H$ - $\kappa$  algorithm stacks the amplitudes of RFs at predicted arrival times for  $P_s$  and crustal multiples for different values of  $H$  and  $\kappa$  in a grid search. It generates an energy map for  $H$  and  $\kappa$ , in which the maximum energy indicates the optimal estimate of  $H$  and  $\kappa$  (Figures 1c and 2c, labels on top right), and the decay shape of the energy distribution around the maximum indicates their error ellipse (one standard deviation or 68% confidence limit; Zhu & Kanamori, 2000; Figure 2c).



**Figure 1.** Illustration of radial and transverse receiver functions (RFs) and  $H$ - $\kappa$  stacking (Zhu & Kanamori, 2000) with the reference model (Table 1, SYN0, model REF;  $H = 40$  km,  $\kappa = 1.75$ ), without dipping interface or anisotropy. (a) Radial receiver functions (R-RFs). Inset shows the stacked R-RF. (b) Transverse receiver functions (T-RFs). (c)  $H$ - $\kappa$  stacking with weighting of 0.7, 0.2, and 0.1. (d) Raypaths of the  $Ps$ ,  $M1$  ( $PpPs$ ), and  $M2$  ( $PpSs + PsPs$ ). BAZ = back azimuth.

In this paper, the RFs are constructed using the time domain iterative deconvolution algorithm (Ligorria & Ammon, 1999) because of its better stability compared with the water-level frequency domain deconvolution. For synthetic tests, the ray-based algorithm “Raysum” (Frederiksen & Bostock, 2000) is implemented to calculate the arrival time and amplitude of each phase in synthetic seismograms ( $Z/R/T$  components). We choose an option (Level 2) in Raysum that calculates multiple reverberations from all discontinuity



**Figure 2.** Radial and transverse RFs and  $H$ - $\kappa$  stacking for a complex model of two layers with different dipping interfaces and plunging anisotropy (Table 1, SYN7, model CPLX). (a) R-RFs. The Moho converted phase ( $Ps$ ) and crustal multiples ( $M1$  and  $M2$ ) are labeled. Note that the  $M2$  phase is more complex with possibility of polarity reversals (as in 60–150° BAZs). (b) T-RFs. (c)  $H$ - $\kappa$  result (weighting 0.7, 0.2, and 0.1). Listed at top right are the values and errors (standard deviations) of  $H$  and  $\kappa$ , where the errors (in parentheses) correspond to the error ellipse in the plot. The input values (cross) are also indicated. (d) Stacked R-RF of the complex model (red) compared with that of the reference model (black, same as Figure 1a inset). BAZ = back azimuth; RF = receiver function.

interfaces in the model. The  $R$  and  $T$  components are then deconvolved with the  $Z$  component, and a Gaussian low-pass filter was applied to reduce the high-frequency noise above  $\sim 1.2$  Hz. The relative weighting of  $P_s$ ,  $M1$ , and  $M2$  is 0.7, 0.2, and 0.1, with  $V_P$  of 6.3 km/s (as in Zhu & Kanamori, 2000). The traditional  $H$ - $\kappa$  stacking would provide the reference arrival times for  $P_s$  and multiples, which can help to narrow down the searching range of the harmonic parameters.

## 2.2. Incident Moveout Correction and Back Azimuthal Binning

Before the harmonic fitting to the R-RFs, we perform the incident moveout corrections (Yuan et al., 1997) and back azimuthal binning. An increase in ray parameter  $p$  (increase in the incident angle from a decrease in epicentral distance) will result in an increase in  $t_{P_s}$  and decrease in  $t_{M1}$  and  $t_{M2}$  in R-RFs, which implies positive moveout for  $P_s$  and negative moveouts for  $M1$  and  $M2$  (Yuan et al., 1997; Liu & Niu, 2012; Chen & Niu, 2013; equation (1)). If they were not corrected properly, the variations of arrival times due to different ray parameters would be mistakenly mapped into the back azimuthal variations from the dipping interfaces and crustal anisotropy.

We use the global 1-D velocity model IASP91 (Kennett & Engdahl, 1991) to compute the moveouts for  $P_s$ ,  $M1$ , and  $M2$  separately and correct them to a reference ray parameter of 0.06 s/km (Yuan et al., 1997). The reference ray parameter is the median of the values (0.04 to 0.08 s/km) for the teleseismic events we used in the construction of the RRs. Tests with different reference velocity models or different  $V_P/V_S$  ratios show negligible difference in the final  $H$ - $\kappa$  results (see section 5.1). Subsequently, in order to obtain relatively uniform back azimuthal coverage and avoid overweighting around the BAZs where there are clusters of RF traces, we stack the corrected R-RFs into back azimuthal bins of  $5^\circ$  (e.g., Kaviani & Rumpker, 2015). The stations with large back azimuthal gaps in RRs (larger than  $90^\circ$  as suggested by Rumpker et al., 2014) will be excluded to ensure the recovery of  $\cos 2\theta$  feature. The stations with inconsistent RRs will also be excluded. In total, we excluded eight out of 48 CNDN stations we examined.

## 2.3. Harmonic Fitting

Theoretical formulations (e.g., Levin & Park, 1997a, 1997b; Liu & Niu, 2012; Savage, 1998) and synthetic tests (Figures S1–S3 in the supporting information, SYN1–3) suggest that when the dip angle of an interface or the strength of anisotropy is not very large, the back azimuthal variation of the arrival times of  $P_s$  and crustal multiples in R-RFs from dipping Moho, azimuthal anisotropy, and plunging anisotropy can be fitted by a  $\cos\theta$  function (two lobed), a  $\cos 2\theta$  function (four lobed), and a combination of  $\cos\theta$  and  $\cos 2\theta$  functions, respectively. This assumes hexagonally symmetric anisotropy and planar interfaces, which are also assumed in this study. Furthermore, we only consider  $S$  anisotropy.  $P$  anisotropy is also important (e.g., Park & Levin, 2016) and will be discussed later (section 5.2). Note that a dipping interface or crustal anisotropy also produces strong and periodic energy on the transverse RF (T-RF), which has been used together with R-RF to study crustal anisotropy (e.g., Liu & Niu, 2012; Liu & Park, 2017; Rumpker et al., 2014). However, here we are mainly interested in crustal average values of  $H$  and  $\kappa$ , and thus only R-RFs are used.

We thus use  $\cos\theta$  and  $\cos 2\theta$  functions to fit the arrival times of  $P_s$  and crustal multiples with BAZ ( $\theta$ ):

$$F(\theta) = A_0 + A_1 \cos(\theta - \theta_1) - A_2 \cos 2(\theta - \theta_2) \quad (2)$$

where  $A_0$  is the central arrival time and  $A_1$ ,  $A_2$  and  $\theta_1$ ,  $\theta_2$  are the amplitudes and phases of the two-lobed and four-lobed variations. Table 1 lists a series of synthetic models we tested in this study with description of model parameters. In the simplest cases of end-member models, a model with dipping Moho has only the  $\cos\theta$  term, where  $A_1$  is related to the dip angle and  $\theta_1$  is related to the dip direction (strike of the plane plus  $90^\circ$ ; Figure S1); a model with azimuthal anisotropy has only the  $\cos 2\theta$  term, where  $A_2$  is related to the amplitude of anisotropy and  $\theta_2$  is related to the strike of the fast axis (Figure S2); and a model with plunging anisotropy has both the  $\cos\theta$  and  $\cos 2\theta$  terms, where  $\theta_2$  still indicates the strike of the fast axis and  $\theta_1$  is either the same as  $\theta_2$  or  $\theta_2 + 180^\circ$  for negative and positive plunge angles (see Table 1 for definition of plunge), respectively (Figure S3; e.g., Levin & Park, 1997a, 1997b; Frederiksen & Bostock, 2000; Frederiksen et al., 2003; Schulte-Pelkum & Mahan, 2014; Park & Levin, 2016). Thus, a plunging anisotropy can mimic a combination of dipping Moho and azimuthal anisotropy, and vice versa. Here we assume a fast axis anisotropy in all cases. In case of a slow-axis anisotropy, the pattern of arrival times would be shifted by  $90^\circ$  in BAZ relative to the fast-axis case (e.g., Schulte-Pelkum & Mahan, 2014) with little difference in amplitudes from our

**Table 1**  
*Description of the Synthetic Models*

| SYN # | Model name | Model description <sup>a</sup>                                                                                                                                                                                                                                                                                               |
|-------|------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 0     | REF        | One-layered crust: thickness $H = 40$ km, $V_P/V_S$ ratio $\kappa = 1.75$ , $V_P$ crust 6.3 km/s, mantle 8.1 km/s; $V_S$ crust 3.6 km/s, mantle 4.5 km/s                                                                                                                                                                     |
| 1     | DIP8       | Dipping Moho: Moho dip $8^\circ$ , direction $90^\circ$                                                                                                                                                                                                                                                                      |
| 2     | ANI8       | Azimuthal anisotropy: anisotropy 8%, fast-axis strike $0^\circ$                                                                                                                                                                                                                                                              |
| 3     | PLG60      | Plugging anisotropy: azimuthal anisotropy 8%, fast-axis strike $30^\circ$ , plunge $60^\circ$                                                                                                                                                                                                                                |
| 4     | S_DIP_ANI  | Smaller dip ( $5^\circ$ , direction $90^\circ$ ) and azimuthal anisotropy (5%, fast-axis strike $45^\circ$ )                                                                                                                                                                                                                 |
| 5     | L_DIP_ANI  | Larger dip ( $10^\circ$ , direction $90^\circ$ ) and azimuthal anisotropy (8%, fast-axis strike $30^\circ$ )                                                                                                                                                                                                                 |
| 6     | DIP_PLG    | Same dip and anisotropy as SYN5 but with plunge of $45^\circ$                                                                                                                                                                                                                                                                |
| 7     | CPLX       | Two-layered crust with different interface dipping planes and anisotropies. Top 20 km: anisotropy 8%, plunge $10^\circ$ , fast-axis strike $15^\circ$ , dip $15^\circ$ , direction $240^\circ$ . Bottom 20 km: anisotropy 10%, plunge $20^\circ$ , fast-axis strike $30^\circ$ , Moho dip $10^\circ$ , direction $290^\circ$ |
| 8     | RDSTR      | Same as SYN7 but uses real RF distribution from station SZN                                                                                                                                                                                                                                                                  |

<sup>a</sup>Anisotropy amplitude indicates the difference between fast and slow speeds relative to the average speed in percent; strike of the fast axis is measured from the north on the horizontal plane ( $0^\circ$  to  $180^\circ$ ); plunge of the fast axis is measured from the horizontal plane ( $-90^\circ$  to  $90^\circ$ , positive and negative when the fast axis rotates clockwise and counterclockwise, respectively); dip of an interface is the angle of the plane with the horizontal plane ( $0^\circ$  to  $90^\circ$  under “the right hand rule”); dip direction is horizontal projection of the downdip direction, measured from the north, which is also equal to the strike of the plane plus  $90^\circ$  ( $0^\circ$  to  $360^\circ$ ). RF = receiver function.

synthetic tests with Raysum (Frederiksen & Bostock, 2000), and thus, such a case would not affect our analyses in this study. In real Earth, the crustal structure could consist of complicated combinations of these end-member models, multiple layers, nonplanar interfaces, complex form of anisotropy (other than the assumed hexagonal symmetry), and heterogeneity; thus, the  $A_1$ ,  $A_2$  and  $\theta_1$ ,  $\theta_2$  would represent the integrated effect of the crust (see below). The parameters  $A_1$  and  $A_2$  are zero or always positive from our assumptions.

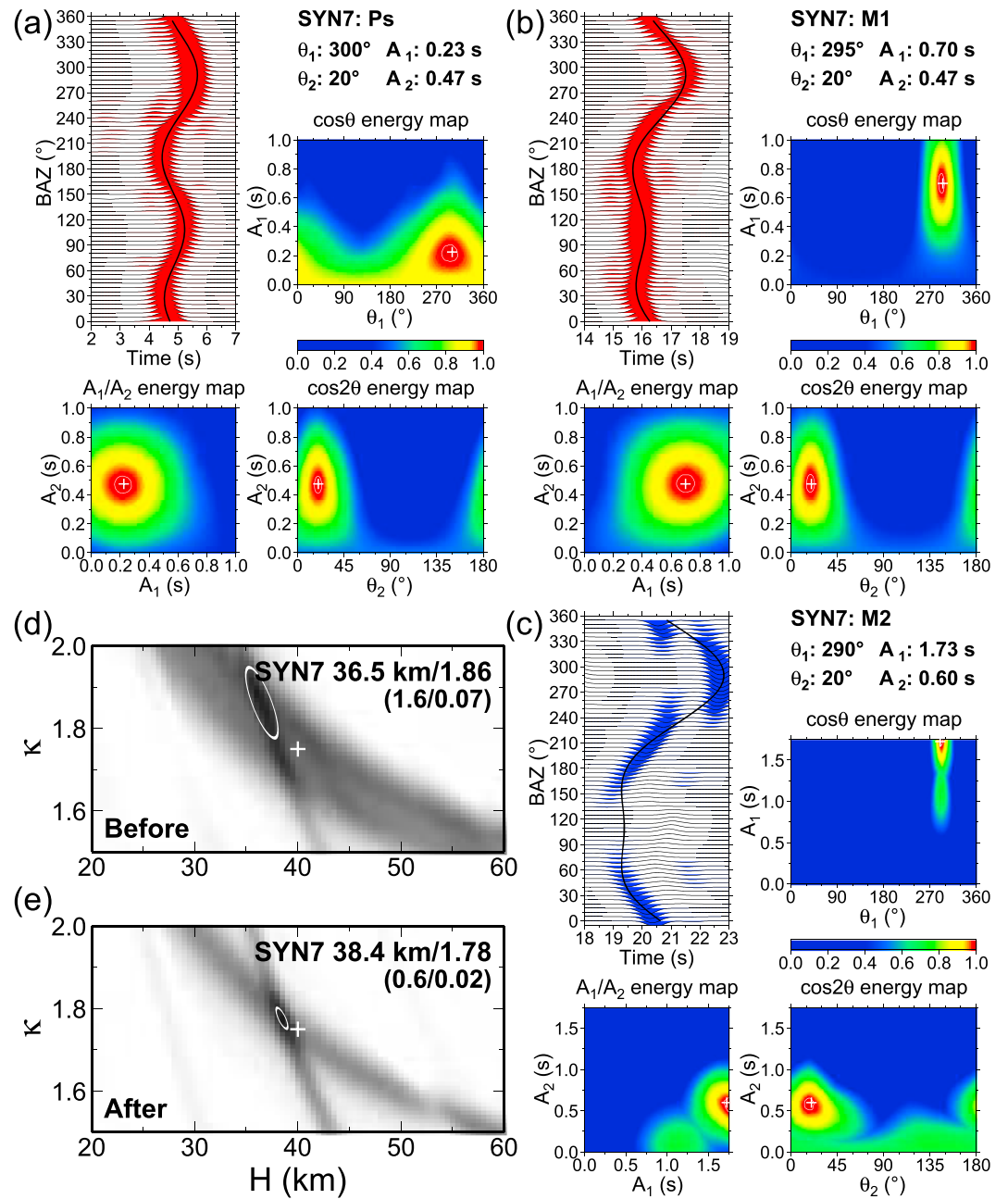
We develop a simple grid search method to perform the harmonic fitting (equation (2)) for  $P_s$ ,  $M1$ , and  $M2$  separately, aiming to find the best solution for five parameters ( $dt = A_0 - t_{\text{ref}}$ ,  $A_1$ ,  $A_2$ ,  $\theta_1$ ,  $\theta_2$ , where  $t_{\text{ref}}$  is the reference arrival time from traditional  $H\text{-}\kappa$ ). The search ranges are as follows:  $dt$ ,  $-1.0$  to  $1.0$  s and  $A_1$  and  $A_2$ ,  $0$  to  $0.5$  s (can be larger for stations with large dip and/or strong anisotropy);  $\theta_1$ ,  $0$  to  $355^\circ$  and  $\theta_2$ ,  $0$  to  $175^\circ$ . For each node of the five-parameter grid, we compute the harmonic curve according to equation (2) and sum the amplitudes at every point on the harmonic curve using the fourth root stacking, which can better reduce the uncorrelated noise compared to the linear or second root stacking (equation (3); Kanasewich et al., 1973; Muirhead, 1968; Pan & Niu, 2011). The result is an “energy map” for all the ranges of parameters (e.g., Figures 3a–3c). The energy maps ( $A_1$  vs.  $\theta_1$ ,  $A_2$  vs.  $\theta_2$ , and  $A_1$  vs.  $A_2$ ) in Figures 3a–3c are 2-D view of the 5-D parameter space. The node (in the 5-D parameter space) with the maximum energy in the energy map is the optimal solution.

$$\text{SUM}_i(dt, A_1, A_2, \theta_1, \theta_2) = \left[ \frac{1}{N} \sum_{\theta}^N \left[ R'_G(t_i) \cdot |R'_G(t_i)|^{-\frac{3}{4}} \right]^4 \right]^{\frac{1}{4}} \cdot \frac{1}{N} \sum_{\theta}^N \left[ R'_G(t_i) \cdot |R'_G(t_i)|^{-\frac{3}{4}} \right]^4 \quad (3)$$

where  $i$  represents the phase ( $P_s$ ,  $M1$ , or  $M2$ ),  $N$  is the number of stacked back azimuthal bins, and  $R'_G$  is the binned radial RFs after the moveout corrections.

#### 2.4. $H\text{-}\kappa\text{-c}$ Stacking

After we obtain the harmonic parameters from the grid search, we use the harmonic function (equation (2)) to correct the R-RFs by shifting each phase to its central arrival time  $A_0$ . The sections of the time series containing  $P_s$ ,  $M1$ , and  $M2$  are corrected separately to form a new series of corrected back azimuthal R-RFs, which are then used to reperform  $H\text{-}\kappa$  stacking (here referred to as  $H\text{-}\kappa\text{-c}$ ; e.g., Figure 3e). For  $H\text{-}\kappa\text{-c}$ , we use relative weighting of 0.5, 0.4, and 0.1 for  $P_s$ ,  $M1$ , and  $M2$ , respectively, after testing for different weighting schemes. We increase the weighting of  $M1$  because the harmonic corrections increase the coherency of the phase and enhance the stacking energy, while keeping the weighting of  $M2$  the same because it is weaker and more complicated, especially in real data. Alternatively, the  $H$  and  $\kappa$  values can also be directly calculated using the central arrival times ( $A_0$  values) of  $P_s$  and  $M1$  of the harmonic fits and the analytical



**Figure 3.** Harmonic fitting to the arrival times of Ps (a), M1 (b), and M2 (c) in radial-receiver functions and  $H$ - $\kappa$  stacking before (d) and after (e) the harmonic corrections. This is a synthetic test example for the complex synthetic model (Table 1, SYN7, model CPLX; Figure 2). Panels (a)–(c) show the fitting curves with  $\cos\theta$  and  $\cos2\theta$  functions, energy stacking maps of the grid search for harmonic parameters, and the search results. The 99% contour is plotted in each energy map to show the empirical uncertainty. The weightings of Ps, M1, and M2 for the  $H$ - $\kappa$  stacking are 0.7, 0.2, and 0.1 in the traditional  $H$ - $\kappa$  in (d; same as Figure 2c) and 0.5, 0.4, and 0.1 in the  $H$ - $\kappa$ -c after the harmonic corrections in (e), respectively. The obtained  $H$  and  $\kappa$  values, their errors, the error ellipse, and the input (cross) are shown in the stack diagrams. BAZ = back azimuth.

relationships in equations (4) and (5) below. The two methods produce identical  $H$  and  $\kappa$  results because the M2 weighting is small. However, we prefer the  $H$ - $\kappa$ -c stacking method because it can provide error estimation and allow visual inspection as in the traditional  $H$ - $\kappa$  method (Zhu & Kanamori, 2000). From equation (1), we have

$$H = \frac{t_{M1} - t_{Ps}}{2 \sqrt{1/V_P^2 - p^2}} \quad (4)$$

$$\kappa = \sqrt{\frac{(t_{M1} + t_{Ps})^2 (1 - p^2 V_P^2)}{(t_{M1} + t_{Ps})^2} + p^2 V_P^2} \quad (5)$$

### 2.5. $H$ - $\kappa$ -c Package

We develop a semiautomatic  $H$ - $\kappa$ -c package to perform the above steps 1 to 4. The input is the R-RFs from standard RF processing (e.g., Huang et al., 2014, 2015; Zhu & Kanamori, 2000; see section 4.1). A reference velocity model (e.g., IASP91) is required for the incident moveout corrections. The output includes harmonic fitting results (the five parameters for  $P_s$ ,  $M_1$ , and  $M_2$ , respectively) and  $H$ - $\kappa$ -c results ( $H$  and  $\kappa$  values and their standard deviations) after the harmonic corrections.

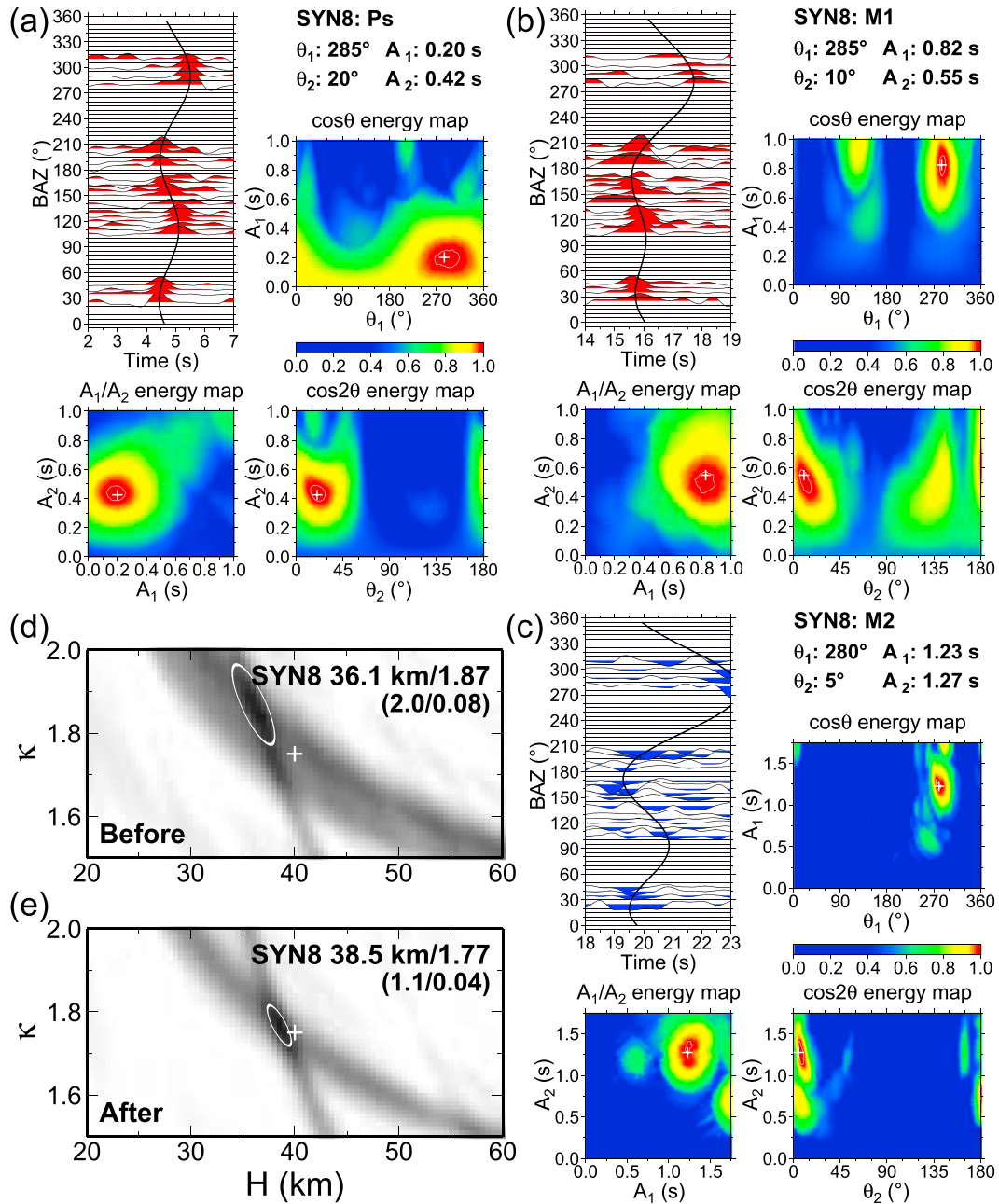
## 3. Synthetic Tests

Based on the Raysum algorithm (Frederiksen & Bostock, 2000), we tested systematically a series of crustal models (eight in total) with different combinations of interface dip and anisotropy (Table 1). The reference model is displayed in Figure 1. We considered simple to complex synthetic models, including three end-member models (dipping Moho, azimuthal anisotropy, and plunging anisotropy, respectively), combinations of dipping Moho and azimuthal anisotropy of different magnitudes, a combination of dipping Moho and plunging anisotropy, and a complex two-layer model (Table 1). For all the models the velocity structure is the same as the reference model. All the synthetics were calculated at the reference ray parameter of 0.06 s/km. We considered transverse isotropy (TI) only, which has a symmetry axis. A TI medium in the Earth is known as horizontal transverse isotropy (or azimuthal anisotropy), vertical transverse isotropy (VTI; or radial anisotropy), or tilted transverse isotropy (or plunging anisotropy) if the symmetry is horizontal, vertical, or tilted, respectively. As discussed above, in this study we assume the symmetry axis to be the fast axis.

The results of the  $H$ - $\kappa$ -c method for the eight synthetic models (Table 1) are presented in Figures 3–5 and S1 to S5. The values of the harmonic fits and the  $H$ - $\kappa$  stacks before and after corrections of all the synthetic tests are summarized in Tables 2 and 3. Readers who are less familiar with RF analyses may start examining the simple end-member models (SYN 1–3; Figures S1–S3) first.

The real data generally show complicated patterns of azimuthal variation (see below). Thus, we use the most complex model to demonstrate our method and its feasibility for the real Earth (Figure 2). It includes two layers with different anisotropy (strength and axis plunge and orientation) and interface dip angles and directions (Table 1, SYN7, model CPLX). The R-RFs are quite complicated, especially for the multiples (Figures 2a and 2d). The  $M_2$  phase even shows polarity reversals in the R-RFs (Figure 2a). There are also complicated energetic arrivals in the T-RFs (Figure 2b), which are not studied here but are useful in future investigation of crustal anisotropy. The traditional  $H$ - $\kappa$  results deviate significantly (by 3.5 km in  $H$  and 0.11 in  $\kappa$ ) from the real input values with large uncertainties (standard errors of 1.6 km in  $H$  and 0.07 in  $\kappa$ ). The stacking energy map is blurry (Figure 2c). Figure 3 shows the harmonic fits of the arrival times of  $P_s$ ,  $M_1$ , and  $M_2$  in R-RFs with  $\cos\theta$  and  $\cos 2\theta$  functions (Figures 3a–3c) and  $H$ - $\kappa$  stacks before (Figure 3d) and after (Figure 3e;  $H$ - $\kappa$ -c) the harmonic corrections. Significant improvement is observed after the corrections, with more accurate and precise  $H$  and  $\kappa$  (deviations from the input values reduced to 1.6 km and 0.03, and standard errors reduced to 0.6 km and 0.02, respectively). The energy map is also much more focused.

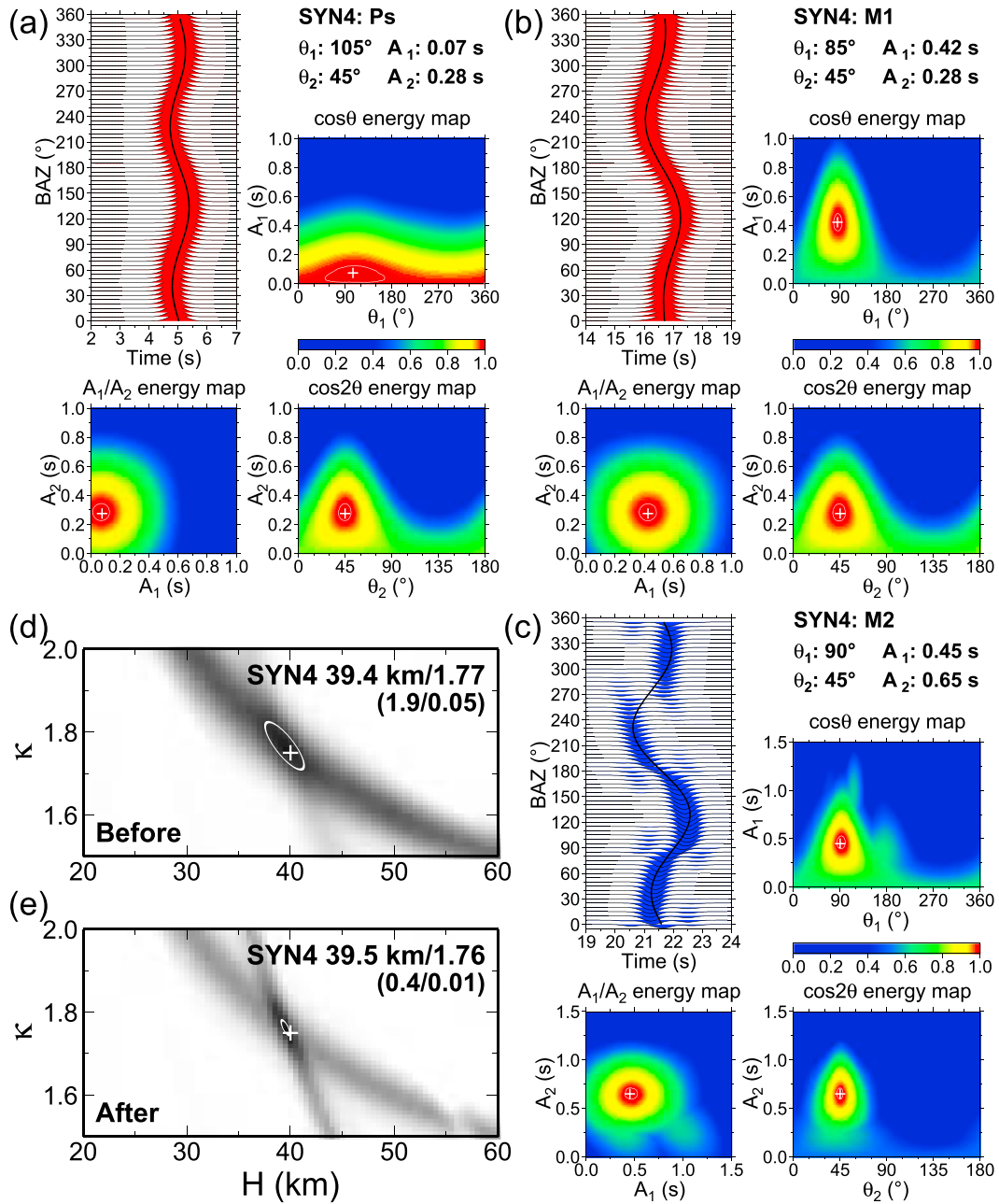
To test the stability of the harmonic fitting in an even more practical case of nonuniform back azimuthal coverage and noisy data, we synthesized RFs and added random noise (Figure 4, SYN8, model RDSTR) using the real distributions of BAZs and distances from station SZN, which has the poorest back azimuthal coverage of the 40 CNDN stations (one trace at 247° was removed to make the back azimuthal gap even larger). Random Gaussian noise was added to each RF trace, the maximum amplitude of which was the same as the average  $P_s$  amplitude (e.g., Kaviani & Rumpker, 2015). The crustal model used was the same as SYN7 (model CPLX). The results from both the  $H$ - $\kappa$  and  $H$ - $\kappa$ -c methods are similar to the case with uniform back azimuthal distribution above. The deviations from the real values are reduced from (3.9 km, 0.12) to (1.5 km,



**Figure 4.** Similar to Figure 3 but for synthetic model SYN8 (RDSTR, Table 1). The model is the same as the complex model (SYN7; Figure 3). The distribution of BAZs and distances is the same as the real data from station SZN, which has the poorest back azimuthal coverage among the 40 CNDSTN stations (with one trace at 247° was further removed in the synthetic test). Random Gaussian noise (same level as average  $P_s$  amplitude) was also added to the receiver function traces. BAZ = back azimuth.

0.04), and the standard errors are reduced from (2.0 km, 0.08) to (1.1 km, 0.04) in ( $H$ ,  $\kappa$ ), respectively. The remarkable improvement of  $H$ - $\kappa$ - $c$  (Figure 4e) after harmonic corrections (Figures 4a–4c) suggests that the harmonic fitting and correction scheme as well as the preprocessing (moveout correction and binning) are stable even with the poorest back azimuthal coverage of our real stations and noisy data.

In a complex model such as the above, the harmonic parameters correspond to the integrated effect of dipping interfaces and layered anisotropy. However, in simple models, the harmonic parameters can be directly related to the model parameters. As an example, Figure 5 shows a test with a relatively small Moho dip (5°) and a relatively weak azimuthal anisotropy (5%; Table 1, SYN4, model S\_DIP\_ANI). In this case,  $\theta_1$



**Figure 5.** Similar to Figure 3 but for synthetic model SYN4 (S\_DIP\_ANI, Table 1). The model has a relatively small dip angle of the Moho and a relatively weak azimuthal anisotropy in the crust. In this simple case,  $\theta_1$  and  $\theta_2$  have physical meaning:  $\theta_1$  is the dip direction of the Moho (input value of  $90^\circ$ ), and  $\theta_2$  is the strike of the fast axis (input value of  $45^\circ$ ).

corresponds directly to the dip direction ( $90^\circ$ ), and  $\theta_2$  corresponds to the fast-axis direction ( $45^\circ$ ), which are well recovered (Figures 5a–5c). This can also be seen from even simpler end models of dipping Moho only (SYN1, model DIP8;  $\theta_1$  corresponding to the dip direction; Figure S1) and azimuthal anisotropy only (SYN2, model ANI8;  $\theta_2$  corresponding to the fast-axis direction; Figure S2). In the case of another end-member model of plunging anisotropy (a rotation of the fast axis along the vertical plane),  $\theta_2$  indicates the fast-axis direction and  $\theta_1$  indicates the plunging direction (same as the fast-axis direction or  $180^\circ$  from it; Figure S3). In the end models of dipping Moho (Figure S1) and azimuthal anisotropy (Figure S2) or in model S\_DIP\_ANI (Figure 5), the harmonic amplitude parameters  $A_1$  and  $A_2$  are directly related to the dipping angle and anisotropy strength, respectively; the relationship would depend on the Moho depth

**Table 2**  
Results of Harmonic Fitting for  $P_s$ ,  $M1$ , and  $M2$ 

| SYN # | Model name | $P_s$      |       |            |       | $M1$       |       |            |       | $M2$       |       |            |       |
|-------|------------|------------|-------|------------|-------|------------|-------|------------|-------|------------|-------|------------|-------|
|       |            | $\theta_1$ | $A_1$ | $\theta_2$ | $A_2$ | $\theta_1$ | $A_1$ | $\theta_2$ | $A_2$ | $\theta_1$ | $A_1$ | $\theta_2$ | $A_2$ |
| 1     | DIP8       | 90         | 0.12  | 0          | 0     | 90         | 0.68  | 0          | 0.03  | 90         | 0.75  | 0          | 0.03  |
| 2     | ANI8       | 0          | 0     | 0          | 0.50  | 0          | 0     | 0          | 0.47  | 270        | 0.05  | 0          | 1.10  |
| 3     | PLG60      | 210        | 0.05  | 30         | 0.10  | 210        | 0.03  | 30         | 0.07  | 0          | 0     | 30         | 0.17  |
| 4     | S_DIP_ANI  | 105        | 0.07  | 45         | 0.28  | 85         | 0.42  | 45         | 0.28  | 90         | 0.45  | 45         | 0.65  |
| 5     | L_DIP_ANI  | 110        | 0.17  | 30         | 0.47  | 80         | 0.78  | 30         | 0.47  | 105        | 1.73  | 35         | 0.55  |
| 6     | DIP_PLG    | 105        | 0.15  | 35         | 0.23  | 85         | 0.82  | 35         | 0.25  | 90         | 1.18  | 45         | 0.53  |
| 7     | CPLX       | 300        | 0.23  | 20         | 0.47  | 295        | 0.70  | 20         | 0.47  | 290        | 1.73  | 20         | 0.60  |
| 8     | RDSTR      | 285        | 0.20  | 20         | 0.42  | 285        | 0.82  | 10         | 0.55  | 280        | 1.23  | 5          | 1.27  |

Note.  $\theta$  angles in degrees;  $A$  values in seconds.

and crustal velocity structure, which affect the total travel times of the rays through the crust. For all the other models, the relationships between the amplitudes and the model parameters are much more complicated.

Note that a Moho dip causes a much (more than five times) smaller time shift (smaller  $A_1$  value) on the  $P_s$  phase than on  $M1$  or  $M2$  phase (Figure S1), while an azimuthal anisotropy causes a similar time shift on the  $P_s$  phase and the  $M1$  phase (Figure S2). This is the exact reason for the small  $A_1$  value in the  $P_s$  fit for model S\_DIP\_ANI above, which in turn explains the  $15^\circ$  deviation of  $\theta_1$  from the input value (dip direction  $90^\circ$ ; Figure 5a). Obviously, if the amplitude ( $A_1$  or  $A_2$ ) vanishes, the phase information ( $\theta_1$  or  $\theta_2$ ) is not meaningful. The  $A_1$  values for the  $M1$  phase (Figure 5b) and the  $M2$  phase (Figure 5c) are much larger, and the  $\theta_1$  values are much closer to the input. Similarly, the azimuthal anisotropy in model S\_DIP\_ANI causes significant amplitudes in  $A_2$  in all the three phases and thus the fast-axis direction ( $45^\circ$ ) is exactly recovered from each of the phases (Figures 5a–5c).

We have discussed six models above. Figures S4 and S5 show the results for the other two models (L\_DIP\_ANI and DIP\_PLG, respectively). Comparing the final results from all the models (Table 3), the largest deviations from the true values are 1.6 km in  $dH$  and 0.05 in  $d\kappa$  with the  $H$ - $\kappa$ -c method, reduced from 3.9 km and 0.12 with the traditional method. The  $H$ - $\kappa$ -c method yields averaged reductions of 53% in  $dH$  and 78% in  $d\kappa$ , compared with the traditional method, in the four more complex models SYN5–8.

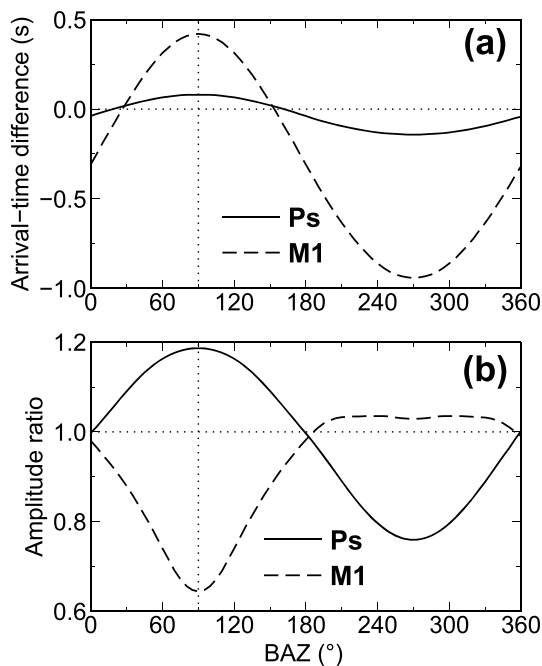
Among the eight models, the  $H$  and  $\kappa$  values for the model of azimuthal anisotropy only (ANI8) are best (almost perfectly) recovered from  $H$ - $\kappa$ -c method (Table 3). This is due to the fact that both amplitude and time variations are perfectly symmetric with respect to BAZ for all the three phases (Figures S2a–S2c). For all the models with dipping interface(s), the  $dH$  values are all negative, either before or after the harmonic corrections. The reason is that neither amplitude variation nor arrival time variation of any of the three

phases is perfectly symmetric with respect to BAZ (i.e., not a perfect  $\cos\theta$  function; Cassidy, 1992; Figure). A dipping Moho changes the amplitudes and times of the rays differently at updip and downdip directions. In particular, its effect is greatly amplified at the important  $M1$  phase, relative to  $P_s$ , making it highly nonsymmetric (Figure 6). For model DIP8 (dip direction  $90^\circ$ ), at the updip directions (BAZ  $0$ – $180^\circ$ ), the  $M1$  phase is mostly delayed with smaller amplitudes (relative to the reference model) with the smallest amplitude arriving at the latest at BAZ of  $90^\circ$ ; at the downdip directions (BAZ  $180$ – $360^\circ$ ), the  $M1$  phase is greatly sped up with slightly larger and nearly constant amplitudes (relative to the reference model). Thus, the  $M1$  phase of the stacked RF will arrive earlier than that of the reference model. On the other hand, the dipping Moho has a very small impact on the stacked  $P_s$  phase because of the small time shifts with respect to BAZ (Figure 6a). From equation (4), a decreased  $t_{M1}$  will result in smaller  $H$  in the traditional  $H$ - $\kappa$  stacking (e.g.,  $dH = -2.1$ ,  $-3.5$  km for models DIP8 and CPLX, respectively; Table 3). The

**Table 3**  
Errors of Traditional  $H$ - $\kappa$  and  $H$ - $\kappa$ -c From Synthetic Tests

| SYN # | Model name | Traditional $H$ - $\kappa$ |             | $H$ - $\kappa$ -c |           |
|-------|------------|----------------------------|-------------|-------------------|-----------|
|       |            | $dH$ (km)                  | $d\kappa$   | $dH$ (km)         | $d\kappa$ |
| 1     | DIP8       | <b>−2.1</b>                | 0.04        | −0.9              | 0.01      |
| 2     | ANI8       | 0                          | 0.06        | −0.1              | 0.01      |
| 3     | PLG60      | 0                          | −0.05       | 0                 | −0.05     |
| 4     | S_DIP_ANI  | −0.6                       | 0.02        | −0.5              | 0.01      |
| 5     | L_DIP_ANI  | <b>−3.1</b>                | <b>0.11</b> | −1.5              | 0.03      |
| 6     | DIP_PLG    | <b>−2.5</b>                | 0.02        | −1.5              | 0         |
| 7     | CPLX       | <b>−3.5</b>                | <b>0.11</b> | −1.6              | 0.03      |
| 8     | RDSTR      | <b>−3.9</b>                | <b>0.12</b> | −1.5              | 0.02      |

Note. The  $H$ - $\kappa$  stacking results are shown by the differences ( $dH$  and  $d\kappa$ ) from the input values of 40 km and 1.75. The values larger than 5% (2 km or 0.0875) are in bold.



**Figure 6.** Variation of arrival times (a) and amplitudes (b) with BAZ for  $P_s$  (solid) and  $M1$  (dashed) for synthetic model with dipping Moho (SYN1, model DIP8), relative to the reference model. The arrival time variation is calculated by subtracting the  $P_s$  or  $M1$  arrival time of the reference model, and the amplitude ratio is calculated by dividing by the  $P_s$  or  $M1$  amplitude of the reference model. The horizontal dotted line at 0 or 1 is shown as a reference, and the vertical dotted line marks the dip direction ( $90^\circ$ ). BAZ = back azimuth.

problem is alleviated after the harmonic corrections. However, because the time variation (for any of the three phases) is not perfectly symmetric and cannot be fitted perfectly by the second-order harmonics and the amplitude variation is highly nonsymmetric, a residual effect remains, resulting in a decreased but nonzero  $dH$  value (e.g.,  $-0.9$  and  $-1.6$  km for models DIP8 and CPLX, respectively). In the  $H$ - $\kappa$  stacking, the  $P_s$  energy generally dominates, resulting in the trade-off between the  $H$  and  $\kappa$  values (e.g., Figures 3 and S1). This explains the all positive  $dk$  values (0.2 to 1.2) for models with dipping interface(s) (except with plunging anisotropy) using the  $H$ - $\kappa$  method and much reduced but still positive values (0.01 to 0.03) using the  $H$ - $\kappa$ -c method (Table 3). It is worth noting that the systematic bias in the  $H$  and  $\kappa$  involving dipping interface(s) or complex models may be even more severe when the back azimuthal coverage is not uniform and the traditional method is used. The cases with plunging anisotropy are discussed later (section 5.4).

## 4. Application to Real Data

### 4.1. Data and Processing

The data used in this study are from 40 CNDN broadband stations, which are widely distributed in a variety of geological settings (Figure 7). There are a total of 48 stations initially, but eight of them are discarded due to insufficient back azimuthal coverage or inconsistent waveforms.

The construction of RFs followed a routine procedure (e.g., Huang et al., 2014, 2015; Zhu & Kanamori, 2000). Earthquakes of  $M > 5$  at epicentral distances from  $30^\circ$  to  $95^\circ$  were selected. All the vertical component waveforms were visually inspected for consistency by discarding noisy events. After that, we removed the mean and linear trend in the waveform data and downsampled them to 10 Hz. A band-pass filter from 0.05 to 2 Hz

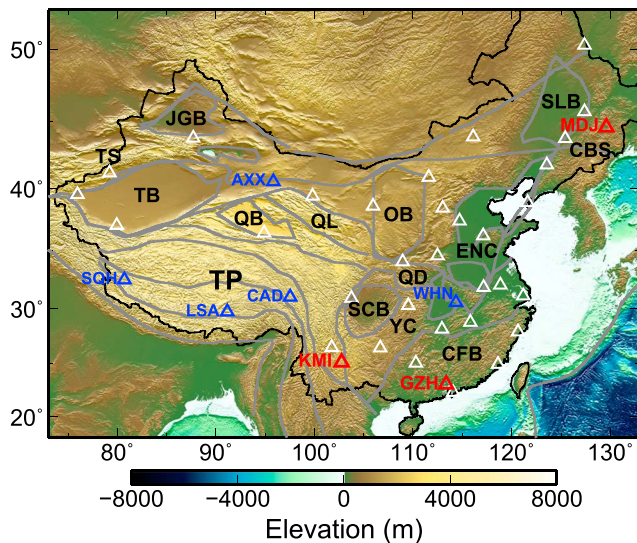
was applied. We used three-component  $P$  wave waveforms (30 s before direct  $P$  and 90 s after) to calculate the RFs at each station using time domain iterative deconvolution method (Ligorria & Ammon, 1999). A Gaussian low-pass filter (Gaussian parameter of 2.5) was applied to reduce the noise above  $\sim 1.2$  Hz. For each station, all RFs were sorted by BAZ and inspected to identify and remove poor RFs (with inconsistent waveforms or obviously wrong negative direct  $P$  pulses). RFs with similar BAZs and ray parameters were stacked to remove clustered events (e.g., Huang et al., 2014, 2015).

### 4.2. $H$ - $\kappa$ -c Results

Figures 8–10 show three representative examples of harmonic fitting and  $H$ - $\kappa$  stacking results, which are at different locations and geological settings (Figure 7) and represent different RF behaviors.

As a typical example, station GZH (Figure 8) in South China has very clear  $P_s$ ,  $M1$ , and  $M2$  phases and energy maps (Figures 8a–8c) and shows little difference in  $H$  and  $\kappa$  before and after the corrections. All the phases show clear back azimuthal variations, but the variations of  $M1$  and  $M2$  are much larger than that of  $P_s$ . The error ellipse is smaller, and the phase traces are clearer after the corrections (Figure 8e) than those before the corrections (Figure 8d).

Station MDJ in NE China (Figure 9) also has clear phases and stacking energy but shows some difference in  $H$  and  $\kappa$  values before and after the corrections. Station KMI in SW China (SE Tibet; Figure 10) has complicated traces of  $P_s$ ,  $M1$ , and  $M2$ . The harmonic correction results in differences in  $H$  and  $\kappa$  much larger than the standard deviations in  $H$ - $\kappa$ -c (Figure 10e). Independent verifications are difficult to find. However, the station KMI is right near a profile that has been recently studied using joint inversion of RFs, surface wave dispersions, and  $P$  velocity constraints (Li et al., 2017). Their values at the KMI location of about 40 km and 1.79 for  $H$  and  $\kappa$ , respectively, are much closer to the  $H$ - $\kappa$ -c results (40.5 km, 1.74) than the traditional  $H$ - $\kappa$  results (45.5 km, 1.68).



**Figure 7.** Map of topography, major blocks (block boundaries indicated by gray lines), and distribution of the 40 Chinese National Digital Seismic Network stations (triangles) in this study. The marked stations are examples highlighted in the main figures (red) or elsewhere in the main text or the supplementary material (blue). The abbreviations are as follows: Tien Shan (TS), Junggar Basin (JGB), Tarim Basin (TB), Qaidam Basin (QB), Tibetan Plateau (TP), Qilian Orogenic Belt (QL), Ordos Block (OB), Qinling-Dabie Orogen (QD), Sichuan Basin (SCB), Yangtze Craton (YC), Cathaysia Fold Belt (CFB), Eastern North China Craton (ENC), Songliao Basin (SLB), and Changbaishan (CBS).

the error ellipses in these stations of the mountainous areas (including examples shown: KMI, MDJ, LSA, AXX, and WHN). Overall, the standard deviations of  $H$  and  $\kappa$  of the 38 stations are reduced from an average of  $\sim 3.50$  km,  $\sim 0.074$  to an average of  $\sim 1.88$  km,  $\sim 0.049$ , corresponding to  $\sim 71\%$  and  $\sim 56\%$  variance reduction in  $H$  and  $\kappa$ , respectively (Figure 12).

## 5. Discussion

In this section, we discuss important factors that may affect the estimation and interpretation of  $H$ - $\kappa$  stacking results (especially for  $\kappa$ ) and the robustness of the  $H$ - $\kappa$ -c method.

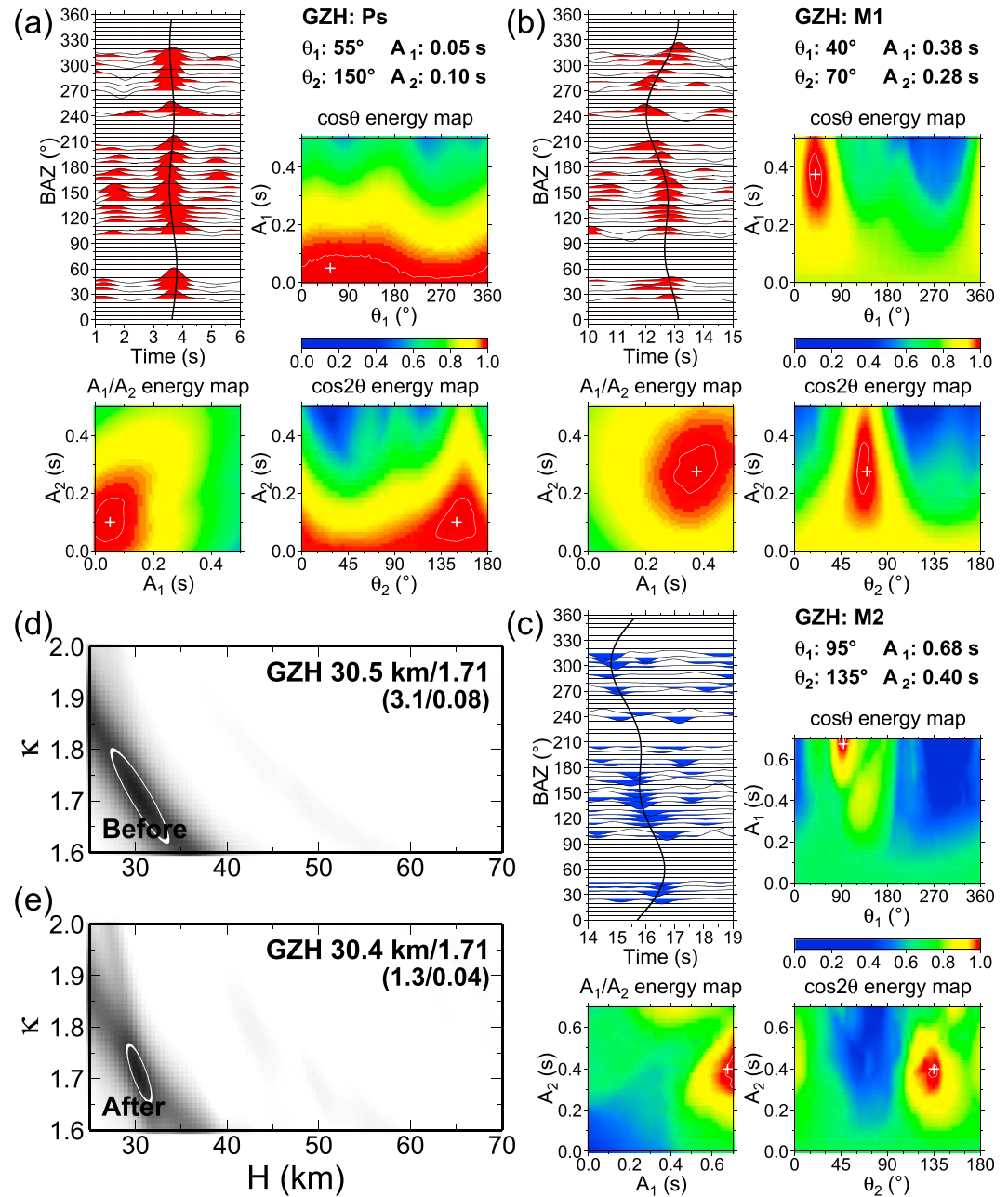
### 5.1. Velocity Models for the Incident Moveout Correction

A reference velocity model is required to compute the incident moveout corrections (above). To examine the influence of the reference model on the moveout correction, we compared several models, including the global model IASP91 (used in this study) and the regional  $V_S$  model by Bao et al. (2015) from surface-wave tomography (Figures 13 and 14). Figure 13 shows the results for station LSA (in the Tibetan Plateau) as an extreme example. The crustal model of the station is very different from the global IASP91 with the thickest crust among our 38 stations, resulting in the largest difference in the moveout corrections. The moveout amount for a RF trace with ray parameter of  $0.042$  s/km (largest departure from the reference  $0.06$  s/km) at LSA can differ by  $\sim 0.1$ ,  $0.3$ , and  $0.2$  s on  $P_s$ ,  $M_1$ , and  $M_2$ , respectively, between the two models (Figures 13a–13c), suggesting the importance of the velocity model on an individual trace. However, the crustal  $V_P/V_S$  ratio has negligible effect on the moveout correction (Figures 13d–13f); thus, the global average of  $1.75$  can always be used.

The  $H$ - $\kappa$  or  $H$ - $\kappa$ -c method relies on the stacking of traces at different azimuths and distances (ray parameters). We performed the  $H$ - $\kappa$ -c stacking on all stations after applying the moveout corrections using the  $V_S$  model by Bao et al. (2015; setting  $V_P/V_S$  to  $1.75$ ) instead of IASP91 in step 2 of the method (section 2). Compared with the results using IASP91 as the reference model, the differences in  $H$  and  $\kappa$  are small (Figure 14). The largest differences are  $1.62$  km in  $H$  and  $0.027$  in  $\kappa$  for station LSA. For all the other

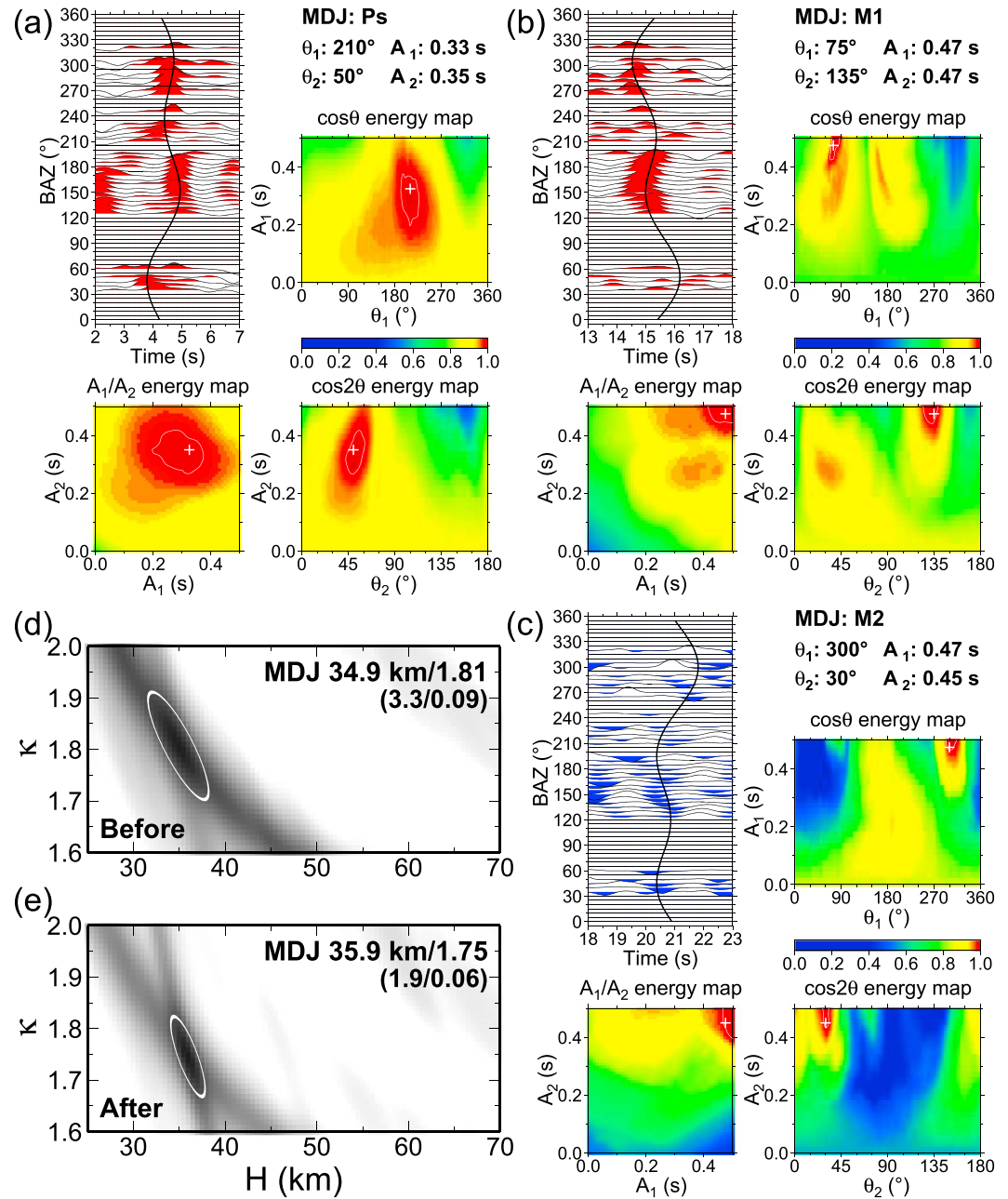
Three other examples in different geological settings with significant differences in  $H$  and/or  $\kappa$  before and after the harmonic corrections are shown in Figure S6. Station AXX in N-NW China and station WHN in Central-Eastern China have relatively clear phases. The error ellipses are much smaller after the corrections. The  $H$  and  $\kappa$  values differ by  $(0.9$  km,  $0.04)$  and  $(2.0$  km,  $0.07)$  for AXX and WHN, respectively. The crustal multiples at station LSA in the Tibetan Plateau are complicated. The  $H$  and  $\kappa$  values change from  $(61.6$  km,  $1.97)$  to  $(66.5$  km,  $1.88)$  after the  $H$ - $\kappa$ -c stacking, which appears more reasonable with a thicker crust and a less extreme crustal  $V_P/V_S$  ratio.

Figures 11 and 12 summarize the  $H$ - $\kappa$  stacking results before and after the harmonic corrections for the 38 CNDSN stations, excluding two stations in Tibetan Plateau (SQH and CAD) because of their poor stacking results (below). The general patterns of  $H$  and  $\kappa$  (Figures 11a and 11b) are consistent with results based on the traditional  $H$ - $\kappa$  method (e.g., He et al., 2014), with thicker crust ( $>60$  km) and higher  $V_P/V_S$  ratios ( $1.80$ – $1.90$ ) in the Tibetan Plateau and thinner crust and lower  $V_P/V_S$  ratios in the South China and North China craton ( $25$ – $35$  km,  $1.65$ – $1.73$ ). Figures 11c and 11d show the difference in  $H$  and  $\kappa$  before and after the harmonic corrections ( $H$ - $\kappa$ -c), with maximums of  $4.98$  km in  $dH$  and  $0.092$  in  $d\kappa$ , respectively. It is noticeable that these large values are mostly located at the mountainous areas, such as the Tibetan Plateau, SE Tibet, Tien Shan, Qilian Orogenic Belt, Qinglin-Dabie Orogen, and Changbaishan, where strong anisotropy and/or dipping Moho may exist. We carefully examined the fitting curves and stacking maps for each station. The harmonic corrections have improved significantly the  $H$ - $\kappa$  stacking maps and reduced



**Figure 8.** Similar to Figure 3 but for real data at station GZH in South China.

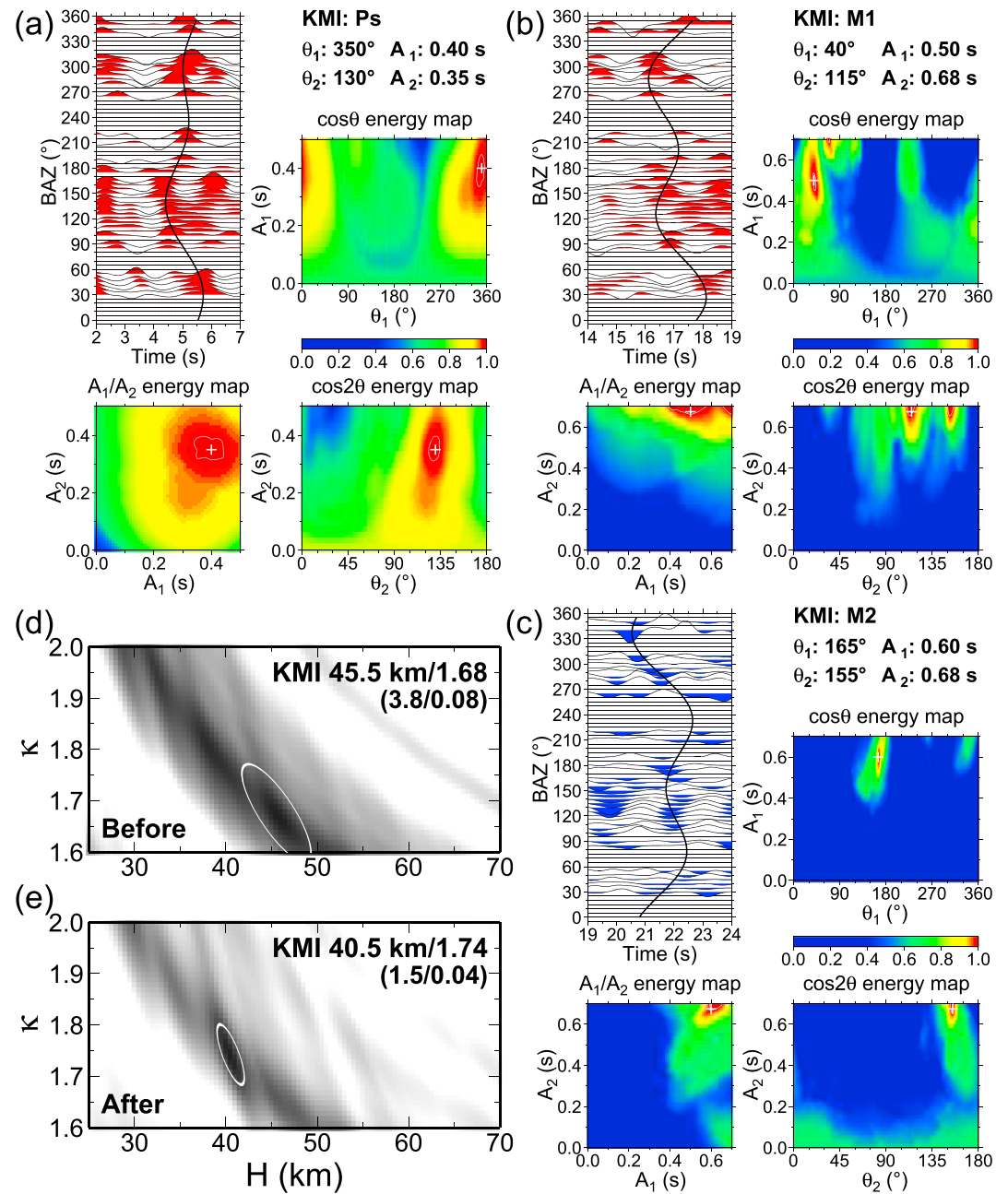
stations, the  $H$  value differs less than 1 km and the value differ less than 0.02. Essentially, although a reference model can affect the incident moveout correction for an individual RF, different moveout amounts in individual RFs fluctuate around zero moveout (at the reference and median ray parameter). Thus, we conclude that the reference model used in the moveout correction in the  $H$ - $\kappa$ - $c$  method is not important as long as the back azimuthal coverage is adequate. A global 1-D reference model would suffice. The IASP91 model was used in the final results of this study as the reference model for the moveout corrections. If the real crustal structure differs substantially from the reference model (e.g., a station in Tibetan Plateau), using a regional model may improve the results, particularly when the back azimuthal coverage is not very good.



**Figure 9.** Similar to Figure 3 but for real data at station MDJ in NE China.

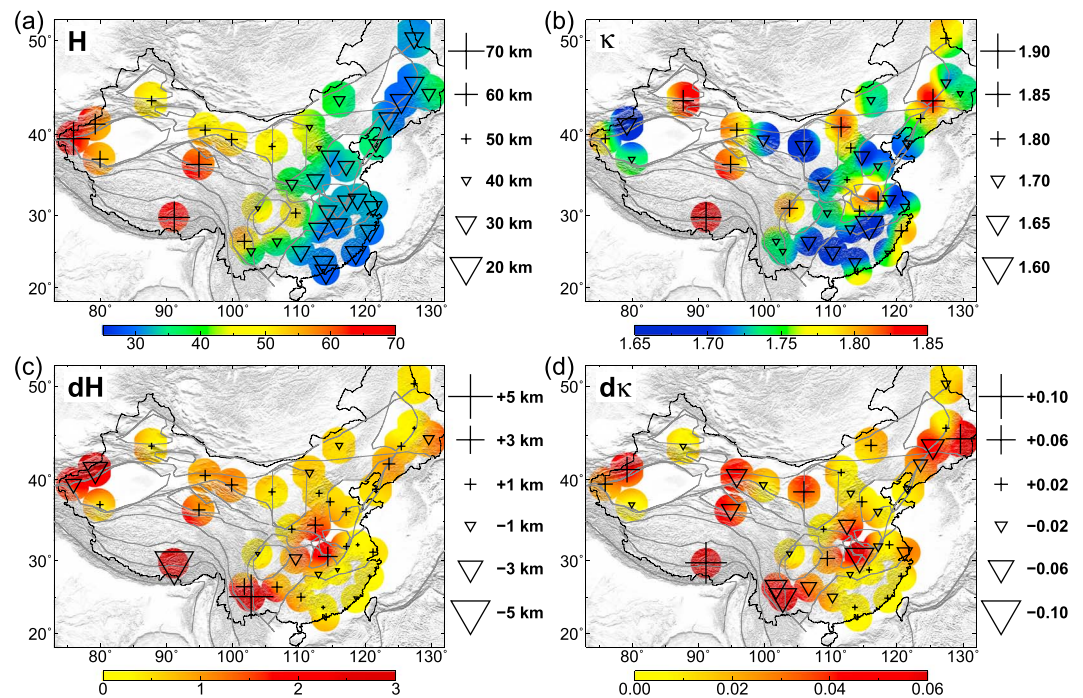
## 5.2. Search Parameters for Harmonic Fitting

Because the five harmonic parameters (equation (2)) are determined by crustal structure, they may not be independent for the three RF phases ( $Ps$ ,  $M1$ , and  $M2$ ), particularly the phase parameters  $\theta_1$  and  $\theta_2$ . For example, for an end-member model (SYN1 to SYN3, dipping Moho, azimuthal anisotropy, and plunging anisotropy, respectively), the phase parameters  $\theta_1$  and  $\theta_2$  represent the Moho dip direction and anisotropy fast-axis direction, respectively. Their values are the same for the three RF phases (except when the corresponding amplitude is small). However, for a more general model, the relationship is not clear (see discussion in section 3). We examined this issue and determined that it is better to treat both the amplitudes and phase parameters as independent for different RF phases ( $Ps$ ,  $M1$ , and  $M2$ ) as in our search algorithm above, based on the following considerations.



**Figure 10.** Similar to Figure 3 but for real data at station KMI in SW China.

First, the dependency of the phase parameters  $\theta_1$  and  $\theta_2$  between different RF phases is uncertain. For a relatively more complex synthetic model that includes dipping interface(s) and crustal anisotropy (or multiple layers of anisotropy; SYN4 to SYN8), the  $\theta_1$  and  $\theta_2$  values are generally not the same for different RF phases, especially when the anisotropy strength and/or dip is large. Essentially, the effects of the dip angle and the anisotropy are not the same or linear. The time shifts from a dipping Moho at different BAZs are about 5–6 times in M1 or about 6–7 times in M2 relative to Ps. When the Moho dip is large, it will even result in polarity reversal at certain BAZ range in M2 (Figure 2). For a crustal anisotropy, the time shifts in Ps and M1 are similar while in M2 are about doubled. Crustal anisotropy results in split waveforms and waveform distortions and amplitude changes. The composite effects on the RF phases are nonlinear particularly when the anisotropy/dip is large or the crustal anisotropy model is complex. In this case, the parameters  $\theta_1$  and  $\theta_2$  vary for different RF phases and the variation depends on the composite effects, which are uncertain. For

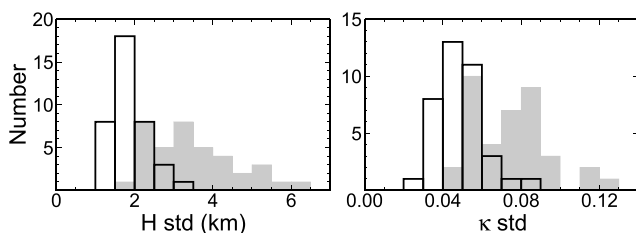


**Figure 11.** Summary of  $H$ - $\kappa$  stacking results before and after harmonic corrections for the 38 Chinese National Digital Seismic Network stations (after excluding two poor stations; see text). The result for each station is color coded within  $2^\circ$  of the station. (a) Crustal thickness ( $H$ ) from  $H$ - $\kappa$ -c (after the corrections). (b) Crustal  $V_p/V_s$  ratio ( $\kappa$ ) from  $H$ - $\kappa$ -c. (c) Difference in  $H$  ( $dH$ ) for  $H$ - $\kappa$  stacking before and after the harmonic corrections. (d) Difference in  $\kappa$  ( $d\kappa$ ) for  $H$ - $\kappa$  stacking before and after the harmonic corrections.

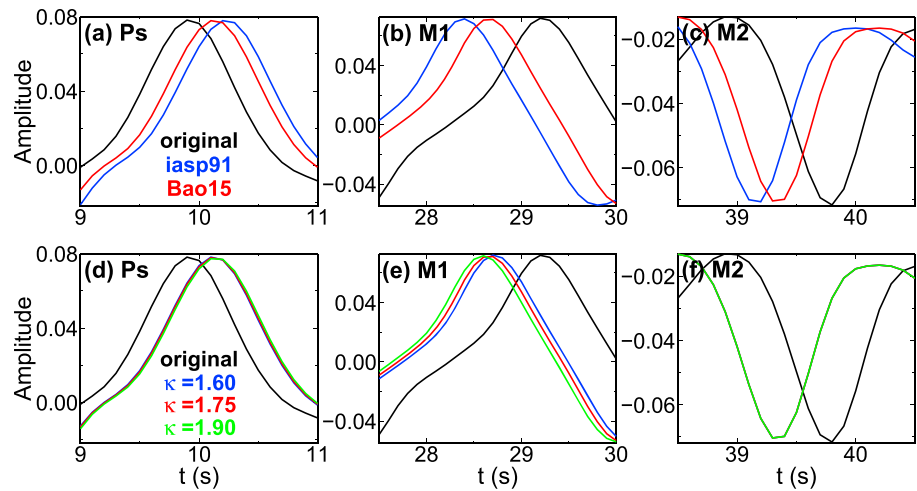
example, in the relatively simple case of SYN5 (a dipping Moho and one-layer horizontal anisotropy but with relatively large values), the curves from even the best solutions do not fit the maximum amplitudes for all the traces (Figure S4), suggesting that they cannot be perfectly represented by equation (2). Furthermore, if we fix the  $\theta_1$  and  $\theta_2$  parameters to the input values and search for  $A_0$ ,  $A_1$ , and  $A_2$  only, the stacked energy would be smaller, suggesting that the fixed values are not the optimal solution. Nevertheless, in the synthetic cases (SYN1 to SYN8), the  $\theta_1$  and  $\theta_2$  parameters for  $P_s$  and  $M1$  are close (within  $30^\circ$ ) when  $A_1$  and  $A_2$  values are meaningful (e.g., greater than 0.05; Table 2). The  $M2$  phase is even more complex, but it is less important in the  $H$ - $\kappa$  stacking (much lower weight); thus, we can largely ignore it in this discussion.

Second, in the real Earth, as the raypaths of the  $P_s$ ,  $M1$ , and  $M2$  phases are different, they are affected by the 3-D anisotropic structures near the station, and thus, the harmonic patterns ( $\theta_1$  and  $\theta_2$ ) may not agree. We have carefully examined real data of several stations with clear  $P_s$  and  $M1$  back azimuthal patterns and found that it is not possible to fit the observations with the same harmonic patterns (same  $\theta_1$  and  $\theta_2$ ; Figure S7). As the  $P_s$  phase is generally better observed than  $M1$  (or  $M2$ ), if we fix the  $\theta_1$  and  $\theta_2$  values obtained from  $P_s$  to fit the  $M1$  phase, the result is quite often a straight line with little correction on  $M1$  (very small  $A_1$  and  $A_2$  values; Figure S7).

Third, for practical application, we would like to keep the data processing procedure as simple as possible. The current harmonic fitting procedure searches for five parameters ( $A_0$ ,  $A_1$ ,  $A_2$ ,  $\theta_1$ , and  $\theta_2$ ), and the search is carried out for each RF phase ( $P_s$ ,  $M1$ , and  $M2$ ) separately. Even if we could assume that the parameters  $\theta_1$ ,  $\theta_2$  are the same for all the RF phases, the joint search for the three RF phases would require 11 parameters, greatly increasing the computational cost. The examples of real data above suggest that assuming the same parameters  $\theta_1$ ,  $\theta_2$  for all the RF phases is problematic. If we do, the results are likely similar to the traditional  $H$ - $\kappa$  with small harmonic corrections.



**Figure 12.** Histograms of the errors (standard deviation, std) of  $H$  and  $\kappa$  before (gray) and after (black) the harmonic corrections for the 38 Chinese National Digital Seismic Network stations.



**Figure 13.** Tests of different velocity models (a–c) or  $V_P/V_S$  ratios (d–f) on the incident moveout correction. The original trace is the receiver function with the smallest ray parameter of 0.042 s/km at station LSA. Note that only the portions of the receiver function phases ( $P_s$ ,  $M1$ , or  $M2$ ) are shown. At depths greater than 160 km, all tests assume the model of IASP91. (a–c) Results using 1-D IASP91 model (Kennett & Engdahl, 1991) and  $V_S$  model (0–160 km) from Bao et al. (2015) with  $V_P/V_S$  of 1.75. (d–f) Results using  $V_P/V_S$  of 1.60, 1.75, and 1.90 and  $V_S$  model (0–160 km) from Bao et al. (2015).

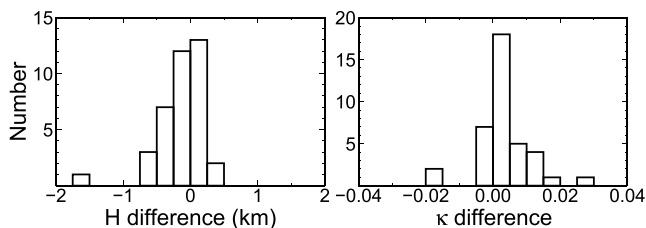
We have demonstrated above, even in synthetics, that the arrival times at the maximum amplitudes cannot be perfectly fitted with first and second harmonics of BAZ (equation (2)) for general cases (with dipping interfaces, anisotropy, and multiple layers; e.g., Figure 3). We could always include higher orders (e.g.,  $\cos 3\theta$ ) in the fitting function as a Fourier series expansion. The higher orders arise due to not only complicated shifts in time but also nonlinear interferences between fast and slow arriving waves. We have tested some examples with higher-order harmonic fits and concluded that the inclusion is not worthy of further effort with added cost of computational time and insignificant improvement in  $H$  and  $\kappa$  results.

The central goal of the paper is to recover better the  $H$  and  $\kappa$  values. Although the  $H$ - $\kappa$ - $c$  method proposed here cannot perfectly recover the input model even in the synthetic cases, it improves over the traditional  $H$ - $\kappa$  method significantly, particularly in the  $\kappa$  value (Table 3). The new procedure also reduces the  $H$  and  $\kappa$  uncertainties as indicated by the error ellipses in the synthetic tests and in the real data. Certainly, the harmonic parameters are linked to the underlying crustal structure. However, linking the harmonic parameters to crustal anisotropy and interface dip parameters is not unique. Such an effort would certainly need to involve T-component RFs (e.g., Liu & Niu, 2012; Liu & Park, 2017; Rumpker et al., 2014).

### 5.3. $P$ Azimuthal Anisotropy

In this study, we consider only  $S$  anisotropy in the crust, but  $P$  anisotropy is also important (e.g., Park & Levin, 2016). It would affect the travel times of the  $P$  traces (e.g., direct  $P$  and  $P$  segments in  $M1$  and  $M2$ ) and thus the arrival times of all phases. We tested several synthetic models: 5%  $S$  azimuthal anisotropy

(no  $P$  anisotropy), 5%  $P$  and  $S$  azimuthal anisotropy (same fast axis), 5%  $P$  azimuthal anisotropy (no  $S$  anisotropy), and 10%  $P$  azimuthal anisotropy (no  $S$  anisotropy; Figure S8). The stacked R-RF from 5%  $S$  azimuthal anisotropy has almost identical  $P_s$  and  $M1$  arrival times as the reference one and splits the  $M2$  phase with smaller amplitudes, which has less influence on  $H$ - $\kappa$  stacking. However, the stacked R-RFs from  $P$  azimuthal anisotropy show smaller  $P_s$  times but larger  $M1$  times (Figures S8a–S8c), which magnifies as  $P$  anisotropy increases. The difference is about  $-0.4$  s in  $P_s$  time and  $+0.3$  s in  $M1$  time for 10%  $P$  azimuthal anisotropy. The difference in  $M2$  time is smaller, by only about  $-0.1$  s. The time shifts can lead to deviations of 1.1 km,  $-0.05$  in  $H$  and  $\kappa$  values for 5%  $P$  azimuthal anisotropy and 2.4 km,  $-0.1$  for 10%  $P$  azimuthal anisotropy in the  $H$ - $\kappa$ - $c$  stacking (Figures S8d and S8e). The effect on  $H$  may not be



**Figure 14.** Histograms of the differences between the  $H$ - $\kappa$ - $c$  results at the 38 Chinese National Digital Seismic Network stations when two different velocity models are used for the incident moveout correction. The velocity models used are IASP91 and Bao et al. (2015) ( $V_P/V_S = 1.75$ ). The largest difference is at station LSA with  $dH$  of 1.62 km and  $d\kappa$  of 0.027.

significant, but  $-0.1$  or  $-0.05$  deviation in  $\kappa$  may be important for geological interpretations. Note that the presence of  $P$  azimuthal anisotropy increases the  $H$  value and reduces the  $\kappa$  value, because the teleseismic wavefield arrives at the seismic station at steep angle thus samples the relatively slow direction of the  $P$  wave. In the R-RF, this speeds up  $P_s$  and slows down  $M1$ , increasing the time difference between the two phases (Figure S8a), which increases  $H$  and decreases  $\kappa$  according to equations (4) and (5).

Therefore, care must be taken when some low  $V_P/V_S$  ratios are observed, since they could come from crustal  $P$  azimuthal anisotropy. However, as there is very little harmonic variation in the R-RFs from  $P$  azimuthal anisotropy (Figure S8c), the harmonic corrections would not improve the  $H$  and  $\kappa$  estimations. A priori information about the  $P$  anisotropy is needed in order to correct for its effect.

#### 5.4. Plunging/Radial Anisotropy

Figure S3 (SYN3, model PLG60) shows a case of 8%  $S$  anisotropy with a plunging anisotropic axis of  $60^\circ$ , which causes a deviation of  $-0.5$  in  $\kappa$  that cannot be improved by the  $H$ - $\kappa$ -c. We further conduct synthetic tests with different plunges for 8%  $S$  or  $P$  anisotropy (Figure S9). For a general case of plunging  $S$  anisotropy (tilted transverse isotropy; Figures S9a, S9c, and S9e), the deviation in  $\kappa$  increases with the plunge and reaches the maximum at plunge of  $90^\circ$ , which actually becomes radial anisotropy or VTI. In this case, the effect of plunging  $S$  anisotropy is similar to that of azimuthal  $P$  anisotropy, both mainly on the  $V_P/V_S$  ratio. For plunging  $P$  anisotropy, however, the pattern of  $H$ - $\kappa$ -c deviation is more complicated, which becomes relatively small at plunge of  $90^\circ$ . Thus, the influence of plunging anisotropy is not negligible. However, as suggested by Kaviani and Rumpker (2015), RF analysis is not able to detect the presence of VTI and resolve its influence on  $\kappa$ . The issue again does not come from the  $H$ - $\kappa$ -c method as the traditional  $H$ - $\kappa$  method has the same problem. Nevertheless, in cases of  $S$  anisotropy, when the plunge is relatively small (e.g.,  $<45^\circ$ ; Figure S9a), the  $H$ - $\kappa$  results (regardless of the traditional method or the modified one) would be less affected by the plunge.

#### 5.5. $H$ - $\kappa$ Weighting and Parameter Range

In this study, we use the weighting of 0.7, 0.2, and 0.1 on  $P_s$ ,  $M1$ , and  $M2$  phases in the traditional  $H$ - $\kappa$  (before harmonic corrections) and 0.5, 0.4, and 0.1 in the  $H$ - $\kappa$ -c (after corrections). The primary reason for the weighting change is the enhanced coherency of the  $M1$  phase after the corrections. To test the influence of the weighting, we performed  $H$ - $\kappa$  stacking before and after the corrections with different weightings (0.7, 0.2, 0.1; 0.5, 0.4, 0.1 or 0.33, 0.33, 0.33). For most stations, the weighting would only affect the error ellipse but little on the  $H$  and  $\kappa$  values, as shown by an example of station KMI (Figure S10). The station KMI already has complicated R-RFs, but the results are very stable, suggesting that the difference in  $H$ - $\kappa$  results is not from different weightings. If we compare the difference by using the more common weightings (0.7, 0.2, 0.1 vs. 0.5, 0.4, 0.1), it is within 0.6 km in  $H$  and 0.02 in  $\kappa$  for all the 38 CNDSN stations.

Among the 40 CNDSN stations that have sufficient back azimuthal coverage for our study, two stations (CAD and SQH in Tibetan Plateau) have particularly poor  $H$ - $\kappa$  stack maps (Figure S11). The  $H$ - $\kappa$ -c method produces smaller error ellipses than the traditional  $H$ - $\kappa$  method. However, the stack energy is poorly focused. If we limit the search range for  $H$  to 80 and 70 km, the results are different with values of ( $\sim 75$  km,  $\sim 1.70$ ) and ( $\sim 66$  km,  $\sim 1.81$ ), respectively. Essentially, the multiples are too weak, even after the enhancement from the harmonic corrections. In this regard, visual inspections of the harmonic corrections and  $H$ - $\kappa$  stacks are helpful in judging the quality of the results. We excluded the two stations in the  $H$  and  $\kappa$  maps (Figure 11).

### 6. Conclusions

We propose a generalized  $H$ - $\kappa$  method with harmonic corrections ( $H$ - $\kappa$ -c method). The method corrects for the effect of dipping interface(s) and crustal anisotropy on arrival times of  $P_s$  and its crustal multiples before  $H$ - $\kappa$  stacking. Systematic synthetic tests suggest that  $P_s$  and crustal multiples can be well fitted by  $\cos\theta$  and  $\cos 2\theta$  functions even for very complex crustal structures with realistic back azimuthal distribution of RFs. Correcting for the back azimuthal variations of arrival times can significantly enhance the  $H$ - $\kappa$  stacking and obtain more accurate and precise values.

We verify the feasibility of the  $H$ - $\kappa$ -c method by application to 40 CNDSN stations with sufficiently good back azimuthal coverage in a variety of geological setting across the Mainland China. With the exception of two stations in the Tibetan Plateau that show poor stacking patterns, the results show clear improvement after

the corrections, with clearer multiples and more focused stacking energy as well as reduced errors of the  $H$ - $\kappa$  values. The resulting maps of the  $H$  and  $\kappa$  variations are consistent with the geological blocks in China. Large differences in  $H$  and  $\kappa$  values before and after the harmonic corrections are mostly at stations located in mountainous areas, where strong anisotropy and/or dipping Moho may exist. We caution, in particular, about systematic bias in the  $H$  and  $\kappa$  values when the traditional  $H$ - $\kappa$  method is used in the presence of dipping interfaces or complex crustal structures. We also caution the interpretation of  $\kappa$  values about the bias by  $P$  wave azimuthal anisotropy or plunging anisotropy, the effect of which cannot be corrected by the harmonic corrections.

Future application of  $H$ - $\kappa$ -c method to more dense seismic arrays can provide better constrained estimations of crustal thickness ( $H$ ) and  $V_p/V_s$  ratio ( $\kappa$ ) with improved precision and accuracy. On a broader note, the usage of this approach in the future will highlight the challenges that a classical methodology in structural seismology will face in case of complex structures. The study also calls for reassessment of many oversimplifications that are often followed in observational seismology.

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