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Dip-angle image gathers computation using Poynting vector
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noise suppression

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Running head: *Dip-angle ADCIG*

ABSTRACT

Angle-domain common-imaging gathers (ADCIGs) are important in analyzing the subsurface discontinuities where reflection waves take place. In elastic reverse-time migration (ERTM), the dip-angle ADCIGs can be computed post-migration via subsurface offset extension. We here obtain dip-angle ADCIG pre-migration in ERTM by using Poynting vector, which is easy to compute during wavefield propagation. The reflection normal of PP imaging is the bisector of the scattering angle whereas that of PS imaging is not. We derive formulas for PP and PS dip-angle estimations, respectively, with some straightforward vector operations. Similar to the subsurface-offset one, our method also outputs dip-angle ADCIGs with the appearance of blocky horizontal coherence. According to local semblance analysis, the signal with a better horizontal coherence promises a higher semblance score, and vice versa. We can thus design a specular filter to suppress incoherent noises according to their corresponding local semblance scores. We validate our methods with numerical examples. Both the Graben and Marmousi data sets show that our methods work effectively in dip-angle ADCIG computation and the following noise suppression in ERTM. We also examine our methods with one field data set.

INTRODUCTION

Angle-domain common-imaging gathers (ADCIGs) are important for migration velocity analysis (MVA) (Biondi and Symes, 2004) and amplitude versus angle (AVA) analysis (Brandsberg-Dahl et al., 2003; Yan and Xie, 2012). Generally, the computation of ADCIGs falls into two categories: before or after applying the imaging condition. The methods within the former category compute the ADCIGs pre-migration (i.e. before applying the imaging condition) by using ray parameters (De Bruin et al., 1990; Prucha et al., 1998; Mosher and Foster, 2000; Koren and Ravve, 2011; Ravve and Koren, 2011), or directional vectors (Wu and Chen, 2006; Yoon and Marfurt, 2006). These methods, which are straightforward and efficient, compute the directions of wavefield propagation per time/depth step. However, accuracy issues may arise when the wavefield becomes complicated in the presence of complex subsurface structures. The methods in the latter category produce ADCIGs post-migration (i.e. after applying the imaging condition) by transforming space- or time-lag image extensions into angle-domain gathers. These methods need image extensions with space lags (Sava and Fomel, 2003; Biondi and Symes, 2004; Biondi and Tisserant, 2004) or time lags (Sava and Fomel, 2006; Vyas et al., 2010) or a combination of both (Sava and Vasconcelos, 2011). The image extensions are then mapped into angle-domain gathers via radial trace transform or plane-wave decomposition (Sava and Fomel, 2003). The post-migration methods are relatively convenient and robust, except for the additional storage and computation costs arising from the image extensions.

The scattering-angle ADCIGs have got wide applications (Jin et al., 2014), and the dip-angle ADCIGs also gain a few attention. Wu et al. (2003), and Wu and Chen (2006) estimate the dip-angle ADCIGs by beamlet decomposition. Browaeys (2008) determines local dip angles with the relations between the horizontal and vertical subsurface offsets. Dafni and Symes (2016a,b) employ the Radon transform operators to map the image extensions into dip-angle ADCIGs. Among them, the methods of Dafni and Symes (2016a,b) are implemented post-migration, and the methods by Wu et al. (2003), Wu and Chen (2006) and Browaeys (2008) are implemented pre-migration. These existing dip-angle ADCIG computation methods are carried out in the acoustic case, while the earth is an elastic solid.

The fact that the solid materials allow for the propagation of both compression and shear waves among others necessitates the consideration of the elastic wave-equation based multi-component imaging (Kuo and Dai, 1984; Chang and McMechan, 1986; Hokstad, 2000; Yan and Sava, 2008), which involves the development of elastic dip-angle ADCIG computations.

We propose a pre-migration method to estimate dip-angle ADCIGs in ERTM by using Poynting vector (Yoon and Marfurt, 2006), without the subsurface-offset extension. This method is efficient because the Poynting vector is easy to calculate during wavefield propagation. To facilitate the computation of the dip-angle direction vectors, we normalize in advance the receiver- and source-side Poynting vectors in a least-squares sense. The estimation of the PP dip-angle ADCIGs is straightforward because the reflection normal is the very bisector of the opening angle. Although the PS case (Rosales et al., 2007) differs from the PP one, we can still provide a simple solution for its dip angles. We finally join the dip-angle ADCIGs with the local semblance analysis method (Neidell and Taner, 1971; Chen et al., 2015), which works well in indicating local directional coherence. This incorporation allows for an efficient suppression of migration artifacts (Dafni and Symes, 2016a,b).

The paper is organized as follows. Firstly, we briefly review the basic theories regarding Poynting vectors within elastic-wave simulation. Then, we introduce the estimation about the PP and PS dip-angle ADCIGs, respectively, simply with some vector operations. Afterward, we apply the local semblance analysis as a specular filter to suppress noises in the dip-angle ADCIGs. Finally, we exemplify our methods with numerical examples and one field data set.

METHODS

Poynting vector in elastic wave-equation

The 2-D first-order elastodynamic equations (Virieux, 1986) are

$$\begin{aligned}
 \frac{\partial v_x}{\partial t} &= \frac{1}{\rho} \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} \right), \\
 \frac{\partial v_z}{\partial t} &= \frac{1}{\rho} \left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{zz}}{\partial z} \right), \\
 \frac{\partial \tau_{xx}}{\partial t} &= (\lambda + 2\mu) \frac{\partial v_x}{\partial x} + \lambda \frac{\partial v_z}{\partial z}, \\
 \frac{\partial \tau_{zz}}{\partial t} &= \lambda \frac{\partial v_x}{\partial x} + (\lambda + 2\mu) \frac{\partial v_z}{\partial z}, \\
 \frac{\partial \tau_{xz}}{\partial t} &= \mu \left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x} \right),
 \end{aligned} \tag{1}$$

where ρ is density, and λ, μ are Lamé parameters; $\mathbf{v} = (v_x, v_z)$ is the particle-velocity vector, and $\boldsymbol{\tau} = (\tau_{xx}, \tau_{xz}; \tau_{zx}, \tau_{zz})$ the stress tensor, with $\tau_{xz} = \tau_{zx}$. These equations, each of which has first-order time-derivative on the left-hand side, and first-order spatial-derivatives on the right hand side, are solved within the staggered-grid finite-difference stencil (Virieux, 1986).

The Poynting vector, which represents the directional energy flux of wavefields, can be used in angle-gather estimation (Dickens and Winbow, 2011; Vyas et al., 2011). According to Cervený (2005), and Yoon and Marfurt (2006), the Poynting vectors are calculated via

$$\boldsymbol{\sigma} = -\boldsymbol{\tau} \cdot \mathbf{v}, \tag{2}$$

where $\boldsymbol{\tau}$ is the stress tensor, $\mathbf{v}$ the particle-velocity vector and $\cdot$ the dot-product operator. $\boldsymbol{\tau}$ and $\mathbf{v}$ are available in equation 1. Figures 1c and 1d show, respectively, the calculated x - and z - Poynting vectors by equation 2.

ERTM imaging with separated wave-modes

RTM remains popular in academia and industry due to its potential in imaging complex structures without dip limitation (Whitmore, 1983). Before applying the ERTM imaging condition we perform the P- and S- wavefield separation by Helmholtz decomposition (Aki

and Richards, 2002):

$$\begin{aligned} P &= \nabla \cdot \mathbf{v}, \\ \mathbf{S} &= \nabla \times \mathbf{v}, \end{aligned} \tag{3}$$

where P and $\mathbf{S}$ are the separated compression and shear components. In the 2D case, $\mathbf{S}$ degrades into the scalar SV waves, so in the following we use S instead. Figures 1e and 1f show the separated P and S wavefields. Note that the Helmholtz operators fail in anisotropic wave-mode separation, which requires more sophisticated operators using the polarization vectors from solving the Christoffel equation (Dellinger and Etgen, 1990).

After the wavefield separation, we can obtain the PP and PS images in ERTM by applying the cross-correlation imaging conditions:

$$\begin{aligned} I_{PP}(\mathbf{x}) &= \int P_s(\mathbf{x}, t) P_g(\mathbf{x}, t) dt, \\ I_{PS}(\mathbf{x}) &= \int P_s(\mathbf{x}, t) S_g(\mathbf{x}, t) dt, \end{aligned} \tag{4}$$

where $P_s(\mathbf{x}, t)$ denotes the forward-propagated P-wave source wavefield, $P_g(\mathbf{x}, t)$ and $S_g(\mathbf{x}, t)$ denote the backward-propagated P- and S-wave receiver wavefields, respectively. Because the explosive sources are mainly used in practice, we here only consider the PP and PS images. The cross-correlation imaging condition suffers from the redundant source effects in terms of half-integral filter and band-limited spectrum. We take the strategies in Liu et al. (2016) to remove these redundant effects.

The issue of wavefield-overlapping inherently exists in Poynting vectors. To alleviate this issue, we smooth the P- and S-wave slowness models (Baysal et al., 1984; Loewenthal et al., 1987). The raw RTM images may suffer from the high-amplitude, low-frequency noises. Yoon and Marfurt (2006) propose to suppress such noises within the scattering-angle domain by using Poynting vectors. As for polarity correction in PS imaging (Du et al., 2012; Duan and Sava, 2015), we use the solution in Du et al. (2012): correct the PS polarity according to the sign of the cross-product between P- and S-wave Poynting vectors. Based on the Poynting vectors, we can also expand image extensions for PP and PS scattering-angle ADCIGs (Yan and Sava, 2008; Yan and Dickens, 2016). Here, we focus on the extraction of PP and PS dip-angle ADCIGs in ERTM.

113 A stable vector normalization

114 Figure 2 illustrates the geometric relationship between the source and receiver rays. An
 115 intuitive impression Figure 2 leaves us is that we need the source and receiver ray angles
 116 θ_s and θ_g to obtain the scattering angle α . However, the involved inverse tangent functions
 117 are more expensive than the ordinary addition/subtraction operations. To make it cheaper,
 118 we try to use more vector operations instead.

119 We first carry out a vector normalization on σ as $\sigma/|\sigma|$. This approach is similar to
 120 that in Zhang and McMechan (2011) to facilitate the following operations. However, the
 121 direct normalization approach may suffer from the risk of division-by-zero. Here the zeros
 122 are those connecting the peaks and troughs of the wavefields, rather than those in the null
 123 space. To derive a stabilized vector normalization, we seek a solution from the least-squares
 124 sense:

$$\varepsilon(\hat{\sigma}) = \|\sigma|\hat{\sigma} - \sigma\|_2^2, \quad (5)$$

125 in which σ is the Poynting vector, $|\sigma|$ its Euclidean norm, and $\hat{\sigma}$ the variable. We expect
 126 that equation 5 is locally stabilized within the area Ω around the imaging point. The area
 127 Ω has a constant size of nine points: one imaging point plus its eight surrounding points.
 128 Then, we can obtain the solution to equation 5 as

$$\hat{\sigma} = \frac{\sum_{\Omega} |\sigma| \sigma}{\sum_{\Omega} |\sigma|^2}, \quad (6)$$

129 which performs a stabilized vector normalization. Note that this solution is just for the
 130 division-by-zero issue in the effective wavefield. For the null-space zeros, we simply skip
 131 them once $\sum_{\Omega} |\sigma|^2$ is less than some security threshold.

132 Efficient dip-angle ADCIG estimations

133 In this part, we focus on the PP and PS dip-angle ADCIG estimations in ERTM. From
 134 Figure 2 we notice that θ_d , the angle of the reflection normal, is the dip angle of the reflector
 135 as well. The PP imaging has a symmetrical reflection with $\alpha_1 = \alpha_2$, so the unit vector $\mathbf{n}_d$

of θ_d is given by

$$\mathbf{n}_{d(PP)} = \frac{\hat{\boldsymbol{\sigma}}_{s(P)} + \hat{\boldsymbol{\sigma}}_{g(P)}}{|\hat{\boldsymbol{\sigma}}_{s(P)} + \hat{\boldsymbol{\sigma}}_{g(P)}|}, \quad (7)$$

where $\hat{\boldsymbol{\sigma}}_{s(P)}$ and $\hat{\boldsymbol{\sigma}}_{g(P)}$ are the normalized source- and receiver-side P-wave Poynting vectors by equation 6. The PS case, an asymmetrical reflection, differs from the PP case, so we need special operations for its dip angle. As proved in Appendix A, we have

$$\mathbf{n}_{d(PS)} = \frac{\hat{\boldsymbol{\sigma}}_{s(P)} + \frac{v_P}{v_S} \hat{\boldsymbol{\sigma}}_{g(S)}}{|\hat{\boldsymbol{\sigma}}_{s(P)} + \frac{v_P}{v_S} \hat{\boldsymbol{\sigma}}_{g(S)}|}, \quad (8)$$

with v_P/v_S being the P- and S-wave velocity ratio. Note that although $\mathbf{n}_{d(PP)}$ and $\mathbf{n}_{d(PS)}$ are discussed separately, we do not need to distinguish P- and S-wave Poynting vectors during the implementation of equations 7 and 8. The reason is that after the wave-mode separation by equation 3, the P- and S-wave Poynting vectors account for the P- and S-wave imagings, respectively. Besides the dip angles for PP and PS imagings in equations 7 and 8, Appendix A also lists the SP and SS cases for future study, because we do not discuss the shear-wave sources here.

One reflector point may have various scattering-angle ray pairs, but its dip-angle unit vector stays unique. This uniqueness is one good property of the dip angle such that it can be used for noise suppression. We can thus design some algorithms to pick out the effective signals from dip-angle ADCIGs to enhance the imaging quality of ERTM. The PP and PS dip-angle ADCIGs are, respectively, obtained from the dip-direction vectors $\mathbf{n}_{d(PP)}$ and $\mathbf{n}_{d(PS)}$ with the inverse trigonometric function. Given $\mathbf{n}_d = (n_x, n_z)$, we can estimate dip angle θ_d by

$$\theta_d = \arctan\left(\frac{n_z}{n_x}\right), \quad (9)$$

with its solution ranging between $[-90^\circ, 90^\circ]$. Note that the range of dip angle is different from that of scattering angle. The scattering angle expands between $[0^\circ, 90^\circ]$, thanks to the reciprocity theory of Green's function, with sign information $+/-$ ignored. The dip angle, however, expands between $[-90^\circ, 90^\circ]$, because different signs of dip vectors represent different subsurface orientations. The estimation of $\mathbf{n}_{d(PP)}$ and $\mathbf{n}_{d(PS)}$ can also be extended

to the 3D case, because equations 7 and 8 work within the 2D coplanar space spanned by $\hat{\sigma}_s$ and $\hat{\sigma}_g$.

Specular filter in dip-angle ADCIG

While the scattering-angle ADCIGs has been widely studied and used (Bleistein, 1987; Xu et al., 2001; ten Kroode, 2012), dip-angles ADCIGs also get some attention in recent years. The former provides information about the local reflection scattering angles, and the latter delivers information about the local reflection normal. One imaging point can have various scattering angles but should have only one unique dip angle except for diffractions, faults and conflicting dips. In the case of reflected waves, the uniqueness of the local dip angle is a useful property for resolution enhancement and noise suppression. Several studies, mainly using Kirchhoff migration approaches, improve the imaging quality by restricting the migration aperture or filtering the dip-angle ADCIGs to exclude migration artifacts and noises (Chen, 2004; Bienati et al., 2009; Dafni and Reshef, 2014; Dafni and Symes, 2016b).

Theoretically, one single-dip-valued point should have one unique dip angle. An ideal response in dip-angle ADCIG should be a spike. In practice, however, this response may be blocky due to the imperfectness in seismic observation (Gray, 2013) and the point-spread function in seismic imaging (Fichtner and Trampert, 2011). With the uniqueness in dip angles we aim to filter out the unwelcomed artifacts in dip-angle ADCIGs by keeping the specular energies around the effective dip-angles but suppressing the non-specular noises. The specularity here is referred to a reflection trajectory with its normal being vertical to the local reflector. Dafni and Symes (2016a,b) observe the prominent and unique responses of horizontal coherence in wave-equation based dip-angle ADCIGs, which differs from the "smile" appearance of those in Kirchhoff approaches (Klokov and Fomel, 2012). We also observe this kind of responses with a horizontal orientation in our numerical experiments in Figure 5. Similarly, we evaluate the coherency (Neidell and Taner, 1971; Chen et al., 2015)

for each dip-angle ADCIG via the semblance scores $S(z, \theta_d)$ regarding the dip angle θ_d

$$S(z, \theta_d) = \frac{1}{2N_\theta + 1} \frac{\sum_{iz=z-N_z}^{iz=z+N_z} \left(\sum_{i\theta=\theta_d-N_\theta}^{i\theta=\theta_d+N_\theta} ADCIG(iz, i\theta) \right)^2}{\sum_{iz=z-N_z}^{iz=z+N_z} \sum_{i\theta=\theta_d-N_\theta}^{i\theta=\theta_d+N_\theta} ADCIG^2(iz, i\theta)}, \quad (10)$$

where N_θ is the half-length of the window along dip angle, N_z the half-length of the window along depth. The choice of N_θ and N_z , which involves the frequency bandwidths of the data and the Fresnel zones (Yilmaz, 2001) of the image, varies with datasets. Equation 10 is a local semblance estimator, which indicates the ratio between the stacked energy and the mean energy of local components. This ratio ranges between $[0,1]$, where a perfect agreement yields a value of unity. We can implement equation 10 quickly with boxcar smoothers. The resulting $S(z, \theta_d)$ is a good indicator to measure the specularity of signals. The specular signal with better horizontal coherence corresponds to a higher semblance score in $S(z, \theta_d)$, and vice versa. We can thus design a dip-domain specular filter based on the semblance scores to reweight the signals within dip-angle ADCIG to suppress non-specular signals.

For complex subsurface structure, a weaker specular signal may have a lower semblance score than its nearby stronger specular signal (e.g. in the Marmousi model). To avoid a "hard" suppression over the weaker specular signals, we take the square roots of $S(z, \theta_d)$ as a "soft" specular filter:

$$w(z, \theta_d) = \sqrt{S(z, \theta_d)}. \quad (11)$$

We then use $w(z, \theta_d)$ as point-wise weights to filter dip-angle ADCIGs. Finally, we stack the filtered dip-angle ADCIGs into a denoised imaging profile. It is worth mentioning that although PP and PS images may have different radiation patterns (Aki and Richards, 2002), they both share the identical dip angle at the same imaging point due to the uniqueness of reflector normal. We just need to scan the PP semblance scores once, and then take them as specular filters upon both PP and PS images for noise suppression.

NUMERICAL EXAMPLES

Graben model

The first example is a 4.5km-by-4.5km Graben model, as shown in Figure 3, consisting of Vp and Vs models with three dip orientations: -45° , 0° , and 45° , respectively. We have 40 shots evenly placed at depth 100m. Perfectly matched layers (PMLs) surround the velocity model. Figure 4 shows the stacked PP and PS ERTM images, and Figure 5 shows the PP and PS dip-angle ADCIGs extracted from the locations indicated by the white dashed lines in Figure 4. Similar to those in Dafni and Symes (2016b), our dip-angle ADCIGs have the horizontal and blocky appearance as well. The semblance score maps, ranging between $[0,1]$, are shown in Figure 6. We only scan the PP ones because both PP and PS imagings share the same local reflection normal at one given imaging point, and the PP image is usually cleaner than the PS one. In the dip-angle ADCIGS we can see that the responses of the reflectors are consistent with their corresponding local dips, respectively.

When comparing among the semblance scores in Figure 6, we note that the middle one with a 0° dip angle has the highest coherence values, meaning it has the best data coverage. The physical mechanism behind the different focusing effects of dip-angle ADCIGs may be similar to that of point-spread function (PSF) (Fichtner and Trampert, 2011). When the estimated semblance scores are ready, we use them to weight the signals within dip-angle ADCIGs. The valid signal usually has a better horizontal coherence, which corresponds to a higher semblance score, and vice versa. We can use this property to suppress invalid signals. The square-rooted semblance scores are used as specular filters for "soft" denoising. We impose the specular filters on the raw dip-angle ADCIGs in Figure 5 to obtain the denoised dip-angle ADCIGs in Figure 7. Stacking over the processed ADCIGs yields the denoised PP and PS images in Figure 8.

228 **Marmousi model**

229 The second example is the Marmousi model, 3000-m deep and 9200-m long, consisting of
230 three V_p , V_s , and density models shown in Figure 9. We cover the model with 150 shots
231 spacing at 50m. This model is surrounded by PMLs as well. We generate observed data with
232 the true elastic model, but migrate the data with a smoothed model. We smooth within
233 one wave-length the slowness models rather than the velocity models. During the imaging
234 process, we suppress the low-wavenumber noises in the scattering-angle domain (Yoon and
235 Marfurt, 2006), which can be calculated according to the geometrical relationship between
236 the receiver and source Poynting vectors. Figure 10 displays the raw stacked Marmousi
237 RTM images.

238 We target three locations at 3200m, 5000m, 6700m, respectively, for detailed investiga-
239 tion of their PP and PS dip-angle ADCIGs. We have run boxcar smoothers horizontally in
240 the three ADCIGs for a preliminary data denoising and interpolation. The 3200-m located
241 one is just in a common case. The 5000-m located one goes across a diffractor. The 6700-m
242 located one goes through complex structures with rapid dip changes. From Figure 11, we
243 observe that the locations of the blocky signals, which have good horizontal coherences,
244 comply well with their corresponding local dip angles. We can find more details by looking
245 into each ADCIG in Figure 11. The left-column ADCIGs have near-zero dips and smooth
246 dip variations. The middle-column ADCIGs have typical diffraction responses at depth
247 1000m, which extends longer than the reflection responses. The right-column ADCIGs
248 have rapid dip changes. Note that the energy blocks correspond to the same dip angles in
249 the PP and PS ADCIGs. The valid signals have horizontal coherences, while the noise is
250 distributed around the valid signals. We can denoise the imaging profiles by suppressing
251 the noises from the dip-angle ADCIGs in Figure 11.

252 Similar to the preceding subsection, we also first obtain the PP semblance scores, as
253 shown in Figure 12, and then take their square roots as the specular filter for denoising.
254 We impose the specular filters onto Figures 11a and 11b, respectively, to get the denoised
255 dip-angle ADCIGs in Figures 13a and 13b. Note that we simply plot out several ADCIGs

for the show, and every imaging point has its ADCIG. Stacking over all the dip-angles in ADCIGs yields the denoised PP and PS images in Figure 14. We furthermore extract some zoom-in views. Figure 15 shows that the artifacts get suppressed well without damage to the effective signals. In practice, we may also get the dip-angle constraints from prior geologic information, scanned dip model, or manually dip-picking to mark out prominent useful signals for imaging or other geophysical applications.

2D Marine data

In this part, we examine our method with a 2D marine dataset, because we do not have an available elastic field dataset. This dataset, consisting of 240 common-shot gathers, is an acoustic one acquired near the water surface, with multiples removed. The recording duration is 8 s, with the sampling rate 2 ms. The dominant frequency is around 10 Hz. Figure 16 shows the migration velocity. During the imaging process, we suppress the low-wavenumber artifacts which have scattering angles greater than 120° (Yoon and Marfurt, 2006). By using the direction-vector information from Poynting vector, we can capture the scattering angle dynamically, without the output of scattering-angle ADCIGs. Figure 17 shows the stacked RTM image, the dip-angle ADCIGs of which are shown in Figure 18.

However, note that the stacked image in Figure 17 is not so clean, with some noises enveloping the reflectors. By examining Figure 18a, we determined that the effective signal coexist with the noise in the dip-angle ADCIGs. These noises impair the imaging quality. Luckily, these effective signals have better blocky, horizontal coherences than do the noises. According to the theory of local semblance analysis, the signal with a better horizontal coherence has a higher semblance score, as shown in Figure 18b. We can thus design specular filters with equation 11 to suppress the incoherent noises by imposing the filters upon the noisy ADCIGs in Figure 18a. Figure 18c shows the filtered dip-angle ADCIGs, in which the noise is basically suppressed, without damage to the valid signal. Afterward, we stack the filtered ADCIGs to form a denoised image, as shown in Figure 19. We also show a zoom-in comparison in Figure 20. The testing on the real data proves that the semblance analysis based specular filter works effectively in improving the reliability and

quality of the stacked RTM image in the dip-angle ADCIGs. Note that we here use the semblance analysis for denoising due to its convenience. In practice, we may design some more advanced filtering methods (e.g. by machine learning) that only keep useful signals. In the dip-angle ADCIGs we can carry out the manual picking of the valid signals as well.

DISCUSSION

Poynting vector is a good direction indicator during wavefield propagation. For reflected waves, they may have various scattering angles but one unique dip angle. Based on this property, we propose a pre-migration approach to calculate and output dip-angle ADCIGs by using Poynting vectors. Our approach is mainly based on some vector operations, and its computational cost and runtime are negligible compared to that of wavefield extrapolation. However, because Poynting vector cannot handle overlapped wavefield well, our approach may perform weakly in diffraction imaging in the case of complicated subsurface structures.

Reflected waves produce specular signals of horizontal coherences in dip-angle ADCIGs. A better horizontal coherence has a higher semblance score and vice versa. The semblance scores can be used to suppress non-specular signals. However, a "hard" filter by directly multiplying the semblance scores to the dip-angle ADCIGs may damage the weak signals, which has a lower semblance score due to the coexistence with noises. To make a "softer" filter, we take the square-roots of the "hard" filter. This way, while suppressing incoherent noises we preserve the specular signals well.

CONCLUSIONS

We present a Poynting-vector based method to estimate and output dip-angle ADCIGs in ERTM. This method runs without the extension of the subsurface offsets. We propose some simple formulas to estimate the PP and PS dip-direction vectors only via some vector operations. In the dip-angle ADCIGs, the valid signals have good horizontal coherences around the specularity dip while the noises do not. The valid signal has a higher semblance score and vice versa. We can use the specular filter to weight the signals in the raw dip-angle

ADCIGS to suppress the unwanted noises. Stacking over the filtered dip-domain ADCIGs yields the ERTM images with better quality and reliability. Because the PP and PS images share the identical reflection normal at the same imaging point, we only need to scan the PP dip-angle ADCIGs for semblance scores. Numerical examples suggest that our dip-angle ADCIGs have similar appearance with those by the subsurface-offset method. We examine our method with two numerical models and one field dataset. In the dip-angle domain, we filter out the kinematic artifacts caused by migration aliasing to make clean the noisy RTM image. The results show that our method performs well in image denoising. Furthermore, we plan to extend our method to anisotropic elastic reverse-time migration.

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APPENDIX A

DIP-VECTOR ESTIMATIONS IN PP AND PS IMAGINGS

In Figure 2, the unit vectors of the incident ray, reflection ray and reflection normal are, respectively, denoted by $\hat{\mathbf{n}}_s$, $\hat{\mathbf{n}}_g$ and $\hat{\mathbf{n}}_d$; the incident, reflection and dip angles are, respectively, denoted by α_1 , α_2 and θ_d . Note that the angle of reflection normal equals that of reflector dip.

When P-wave is the incident and P-wave the reflection, this is a symmetrical mirror reflection case with $\alpha_1 = \alpha_2$. It is easy to figure out that

$$\hat{\mathbf{n}}_d = \frac{\hat{\mathbf{n}}_s + \hat{\mathbf{n}}_g}{|\hat{\mathbf{n}}_s + \hat{\mathbf{n}}_g|}, \quad (\text{A-1})$$

which works for the case of PP imaging.

When P-wave is the incident and S-wave the reflection, this is an asymmetrical reflection case with $\alpha_1 \neq \alpha_2$. According to the Snell's law, we have

$$\frac{\sin \alpha_1}{v_P} = \frac{\sin \alpha_2}{v_S}, \quad (\text{A-2})$$

with v_P and v_S being the P- and S- velocities. Within the 2-D space spanned by the coplanar vectors $\hat{\mathbf{n}}_s$, $\hat{\mathbf{n}}_g$ and $\hat{\mathbf{n}}_d$, we do not need to consider the signs of their cross-products, so we have $\hat{\mathbf{n}}_s \times \hat{\mathbf{n}}_d = |\hat{\mathbf{n}}_s| |\hat{\mathbf{n}}_d| \sin \alpha_1$, $\hat{\mathbf{n}}_d \times \hat{\mathbf{n}}_g = |\hat{\mathbf{n}}_d| |\hat{\mathbf{n}}_g| \sin \alpha_2$. Because of $|\hat{\mathbf{n}}_s| = |\hat{\mathbf{n}}_g| = |\hat{\mathbf{n}}_d| = 1$ equation A-2 changes into

$$\frac{\hat{\mathbf{n}}_s \times \hat{\mathbf{n}}_d}{v_P} = \frac{\hat{\mathbf{n}}_d \times \hat{\mathbf{n}}_g}{v_S}. \quad (\text{A-3})$$

We can rewrite equation A-3 as

$$\hat{\mathbf{n}}_d = \frac{\hat{\mathbf{n}}_s + \frac{v_P}{v_S} \hat{\mathbf{n}}_g}{\left| \hat{\mathbf{n}}_s + \frac{v_P}{v_S} \hat{\mathbf{n}}_g \right|}, \quad (\text{A-4})$$

which works for the case of PS imaging. Appendix B will detail the proof from equations A-3 to A-4.

Similarly, when S-wave is the incident and P-wave the reflection, we have

$$\hat{\mathbf{n}}_d = \frac{\hat{\mathbf{n}}_s + \frac{v_S}{v_P} \hat{\mathbf{n}}_g}{\left| \hat{\mathbf{n}}_s + \frac{v_S}{v_P} \hat{\mathbf{n}}_g \right|}, \quad (\text{A-5})$$

which works for the case of SP imaging.

When S-wave is the incident and S-wave the reflection, we have

$$\hat{\mathbf{n}}_d = \frac{\hat{\mathbf{n}}_s + \hat{\mathbf{n}}_g}{|\hat{\mathbf{n}}_s + \hat{\mathbf{n}}_g|}, \quad (\text{A-6})$$

which works for the case of SS imaging.

APPENDIX B

PROOF FROM EQUATIONS A-3 TO A-4

In the 2D case, assuming $\hat{\mathbf{n}}_s = (x_s, z_s)$, $\hat{\mathbf{n}}_g = (x_g, z_g)$, and $\hat{\mathbf{n}}_d = (x_d, z_d)$, we have equation A-3 as

$$\frac{x_s z_d - z_s x_d}{v_P} = \frac{-x_g z_d + z_g x_d}{v_S}, \quad (\text{B-1})$$

which can be furthermore expressed as

$$\left(x_s + \frac{v_P}{v_S} x_g\right) z_d = \left(z_s + \frac{v_P}{v_S} z_g\right) x_d. \quad (\text{B-2})$$

That is,

$$z_d/x_d = \left(z_s + \frac{v_P}{v_S} z_g\right) / \left(x_s + \frac{v_P}{v_S} x_g\right). \quad (\text{B-3})$$

Equation B-3 indicates that the direction of $\hat{\mathbf{n}}_d$ is along $\hat{\mathbf{n}}_s + \frac{v_P}{v_S} \hat{\mathbf{n}}_g$. After the normalization by $\left|\hat{\mathbf{n}}_s + \frac{v_P}{v_S} \hat{\mathbf{n}}_g\right|$, we can get the formulation of equation A-4 as

$$\hat{\mathbf{n}}_d = \frac{\hat{\mathbf{n}}_s + \frac{v_P}{v_S} \hat{\mathbf{n}}_g}{\left|\hat{\mathbf{n}}_s + \frac{v_P}{v_S} \hat{\mathbf{n}}_g\right|}. \quad (\text{B-4})$$

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FIGURE LISTS

Figure 1: Elastic wave-mode separation in isotropic media by using Poynting vector. (a) and (b): X- and Z- wavefield components. (c) and (d): X- and Z- Poynting vector components. (e) and (f): Separated P- and S- wavefields.

Figure 2: Schematic diagram of the acquisition system in geophysical survey. The directional angles of source and receiver rays are, respectively, indicated by θ_s and θ_g . The dip angle is θ_d . The incident angle is α_1 and the scattered angle is α_2 . In the case of symmetrical mirror reflection, for example, PP imaging, we have $\alpha_1 = \alpha_2$. In the case of asymmetrical mirror reflection, for example, PS imaging, we have $\alpha_1 \neq \alpha_2$.

Figure 3: Elastic Graben V_P (left) and V_S (right) models with three different dip orientations of -45° , 0° , -45° .

Figure 4: Stacked ERTM PP (left) and PS (right) images of the elastic Graben model. We extract dip-angle ADCIGs from the three white lines at 1000m, 2250m, 3500m, respectively, for detailed demonstrations.

Figure 5: (a) Top row from left to right: three PP dip-angle ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 4a. (b) Bottom row from left to right: three PS dip-angle ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 4b. From all of them (top and bottom), we notice that for no matter PP or PS imaging, the dip-angles are consistent with their corresponding local dip angles.

Figure 6: The semblance scores estimated from Figure 5a. We only estimate the PP-imaging ones for the following two reasons: the PP image is usually less noisy than the PS image; the local reflection normal is unique for both PP and PS images. We notice that the scanned semblance in the middle is more focused and stronger, due to its better data coverage than the others.

Figure 7: The filtered (a) PP and (b) PS dip-angle ADCIGs from Figure 5. We use the square roots of the semblance scores in Figure 6 as weights to scale the raw dip-angle

ADCIGs. We can see the invalid signals get suppressed, while the valid signals with good horizontal coherence get preserved. Stacking over such ADCIGs yields denoised ERTM images.

Figure 8: Stacked PP and PS images from the denoised dip-domain ADCIGs in Figure 7. When compared with the raw images in Figure 4, we can find the valid reflectors get preserved well, and the migration artifacts get diminished.

Figure 9: Elastic Marmousi (a) Vp and (b) Vs and (c) density models.

Figure 10: Raw stacked (a) PP and (b) PS RTM images of the elastic Marmousi model. We extract dip-angle ADCIGs from the three white lines at 3200m, 5000m, 6700m, respectively, for detailed demonstration.

Figure 11: (a) Three dip-angle PP ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 10a. (b) Three dip-angle PS ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 10b. The left-column ADCIGs exhibit the ordinary subsurface structures with near-zero dipping and smooth dip changes. The middle-column ADCIGs have the typical diffraction responses at depth 1000m, which extends much longer than the reflection responses. The right-column ADCIG have rapid dip changes.

Figure 12: Semblance scores estimated from the PP dip-angle ADCIGs in Figure 11a. We only estimate the PP one because the PP image is usually cleaner than the PS image. The square roots of the scanned semblance will be used as weighting filter in noise suppression.

Figure 13: (a) The filtered dip-angle ADCIGs from Figure 11a. (b) The filtered dip-angle ADCIGs from Figure 11b. We here take the local semblance scores in Figure 12 as weights to scale the amplitude of the dip-angle ADCIGs. Because the uniqueness of the reflection normal is independent of the PP or PS imaging, we can directly impose the specular filter estimated from PP image onto both the raw PP and PS images in Figure 11.

Figure 14: The denoised stacked (a) PP and (b) PS images after the filtering in the dip-angle domain.

Figure 15: (a) and (b): zoom-in views from raw PP image in Figure 9a and denoised PP image in Figure 13a, respectively. (c) and (d): zoom-in views from PS image in Figure 9b and denoised PS image in Figure 13b, respectively. We can see that after the denoising in the dip-angle domain by the specular filters, the signal-noise-ratio (SNR) of the images gets improved, without the introduction of damages to the valid reflectors.

Figure 16: 2D Vp migration velocity for the real data.

Figure 17: Raw RTM image of the real data.

Figure 18: Dip-angle ADCIGs extracted from CDP [550, 850] in Figure 17, and (b) its corresponding semblance scores. (c) The filtered dip-angle ADCIGs after the imposing of specular filters onto (a). We here take the square roots of the semblance scores as specular filters.

Figure 19: New RTM image after the noise suppression in the dip-angle ADCIGs. We notice that this RTM image becomes clearer than before.

Figure 20: Zoom-in views between CDP number [100, 1500] and depth [1.25 km, 2.5 km]. (a) is from Figure 17, and (b) is from Figure 19. We can see that (b) becomes cleaner than (a) while its main reflectors get preserved well.

Figure 1a

28x28mm (300 x 300 DPI)

Figure 1b
28x28mm (300 x 300 DPI)

Figure 1c

28x28mm (300 x 300 DPI)

Figure 1d
28x28mm (300 x 300 DPI)

Figure 1e

28x28mm (300 x 300 DPI)

Figure 1f: Elastic wave-mode separation in isotropic media by using Poynting vector. (a) and (b): X- and Z-wavefield components. (c) and (d): X- and Z- Poynting vector components. (e) and (f): Separated P- and S-wavefields

28x28mm (300 x 300 DPI)

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Figure 3: Elastic Graben V_P (left) and V_S (right) models with three different dip orientations of $\{-45^\circ, 0^\circ, -45^\circ\}$.

71x35mm (300 x 300 DPI)

Figure 4: Stacked ERTM PP (left) and PS (right) images of the elastic Graben model. We extract dip-angle ADCIGs from the three white lines at 1000m, 2250m, 3500m, respectively, for detailed demonstrations.

71x35mm (300 x 300 DPI)

Figure 5a

71x35mm (300 x 300 DPI)

Figure 5b: (a) Top row from left to right: three PP dip-angle ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 4a. (b) Bottom row from left to right: three PS dip-angle ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 4b. From all of them (top and bottom), we notice that for no matter PP or PS imaging, the dip-angles are consistent with their corresponding local dip angles.

71x35mm (300 x 300 DPI)

Figure 6: The semblance scores estimated from Figure 5a. We only estimate the PP-imaging ones for the following two reasons: the PP image is usually less noisy than the PS image; the local reflection normal is unique for both PP and PS images. We notice that the scanned semblance in the middle is more focused and stronger, due to its better data coverage than the others.

75x35mm (300 x 300 DPI)

Figure 7a

71x35mm (300 x 300 DPI)

Figure 7b: The filtered (a) PP and (b) PS dip-angle ADCIGs from Figure 5. We use the square roots of the semblance scores in Figure 6 as weights to scale the raw dip-angle ADCIGs. We can see the invalid signals get suppressed, while the valid signals with good horizontal coherence get preserved. Stacking over such ADCIGs yields denoised ERTM images.

71x35mm (300 x 300 DPI)

Figure 8: Stacked PP and PS images from the denoised dip-domain ADCIGs in Figure 7. When compared with the raw images in Figure 4, we can find the valid reflectors get preserved well, and the migration artifacts get diminished.

71x35mm (300 x 300 DPI)

Figure 9a

104x35mm (300 x 300 DPI)

Figure 9b

104x32mm (300 x 300 DPI)

Figure 9c: Elastic Marmousi (a) V_p and (b) V_s and (c) density models.
104x32mm (300 x 300 DPI)

Figure 10a

95x35mm (300 x 300 DPI)

Figure 10b: Raw stacked (a) PP and (b) PS RTM images of the elastic Marmousi model. We extract dip-angle ADCIGs from the three white lines at 3200m, 5000m, 6700m, respectively, which will be shown in Figure 11 below.

95x32mm (300 x 300 DPI)

Figure 11a

71x35mm (300 x 300 DPI)

Figure 11b: (a) Three dip-angle PP ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 10a. (b) Three dip-angle PS ADCIGs extracted from the three locations indicated by the white dashed lines in Figure 10b. The left-column ADCIGs exhibit the ordinary subsurface structures with near-zero dipping and smooth dip changes. The middle-column ADCIGs have the typical diffraction responses at depth 1000m, which extends much longer than the reflection responses. The right-column ADCIG have rapid dip changes.

71x35mm (300 x 300 DPI)

Figure 12: Semblance scores estimated from the PP dip-angle ADCIGs in Figure 11a. We only estimate the PP one because the PP image is usually cleaner than the PS image. The square roots of the scanned semblance will be used as weighting filter in noise suppression.

75x35mm (300 x 300 DPI)

Figure 13a
71x35mm (300 x 300 DPI)

Figure 13b: (a) The filtered dip-angle ADCIGs from Figure 11a. (b) The filtered dip-angle ADCIGs from Figure 11b. We here take the local semblance scores in Figure 12 as weights to scale the amplitude of the dip-angle ADCIGs. Because the uniqueness of the reflection normal is independent of the PP or PS imaging, we can directly impose the specular filter estimated from PP image onto both the raw PP and PS images in Figure 11.

71x35mm (300 x 300 DPI)

Figure 14a

95x35mm (300 x 300 DPI)

Figure 14b: The denoised stacked (a) PP and (b) PS images after the filtering in the dip-angle domain.

95x32mm (300 x 300 DPI)

Figure 15a

66x35mm (300 x 300 DPI)

Figure 15b

66x32mm (300 x 300 DPI)

Figure 15c

66x35mm (300 x 300 DPI)

Figure 15d: (a) and (b): zoom-in views from raw PP image in Figure 9a and denoised PP image in Figure 13a, respectively. (c) and (d): zoom-in views from PS image in Figure 9b and denoised PS image in Figure 13b, respectively. We can see that after the denoising in the dip-angle domain by the specular filters, the signal-noise-ratios (SNRs) of the images are improved, without introduction of damages to the valid reflectors.

66x32mm (300 x 300 DPI)

Figure 16: 2D Vp migration velocity for the real data.
68x41mm (300 x 300 DPI)

Figure 17: Raw RTM image of the real data.

59x41mm (300 x 300 DPI)

Figure 18a
71x41mm (300 x 300 DPI)

Figure 18b

75x41mm (300 x 300 DPI)

Figure 18c: (a) Dip-angle ADCIGs extracted from CDP $\{[550, 850]\}$ in Figure 17, and (b) its corresponding semblance scores. (c) The filtered dip-angle ADCIGs after the imposing of specular filters onto (a). We here take the square roots of the semblance scores as specular filters.

71x41mm (300 x 300 DPI)

Figure 19: New RTM image after the noise suppression in the dip-angle ADCIGs. We notice that this RTM image becomes clearer than before.

59x41mm (300 x 300 DPI)

Figure 20a
58x19mm (300 x 300 DPI)

Figure 20b: Zoom-in views between CDP number [100, 1500] and depth [1.25 km, 2.5 km]. (a) is from Figure 17, and (b) is from Figure 19. We can see that (b) becomes cleaner than (a) while its main reflectors get preserved well.

58x17mm (300 x 300 DPI)

DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author.