

# Time-shift imaging condition for converted waves

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## SUMMARY

A typical imaging condition for seismic reflection data involves source and receiver wavefield matching, e.g. by cross-correlation, at every image location. This statement is true no matter how the two wavefields are reconstructed, for example by one-way wavefield extrapolation, or two-way reverse-time extrapolation, or Kirchhoff integral methods. This statement is also true when the source and receiver wavefields are reconstructed using different velocity models, as is the case for imaging of converted waves. Angle-dependent reflectivity information can be extracted from the source and receiver wavefield by retaining multiple lags of the imaging cross-correlation, i.e. by analyzing the match of wavefields shifted relative to one-another. Wavefields can be shifted in space (3D) or in time (1D), and each shift method has an associated angle-decomposition method. This paper explores the various types of imaging condition using space- and time-shifts and derives relations for angle decomposition for converted-wave imaging.

## INTRODUCTION

A key challenge for imaging in complex areas is accurate determination of a velocity model in the area under investigation. Migration velocity analysis is based on the principle that image accuracy indicators are optimized when data are correctly imaged. A common procedure for velocity analysis is to examine the alignment of images created with multi-offset data. An optimal choice of image analysis can be done in the angle domain which is free of complicated artifacts present in surface offset gathers in complex areas (Stolk and Symes, 2004).

Migration velocity analysis after migration by wavefield extrapolation requires image decomposition in scattering angles relative to reflector normals. Several methods have been proposed for such decompositions (de Bruin et al., 1990; Prucha et al., 1999; Mosher and Foster, 2000; Rickett and Sava, 2002; Xie and Wu, 2002; Sava and Fomel, 2003; Soubaras, 2003; Fomel, 2004; Biondi and Symes, 2003). These procedures require decomposition of extrapolated wavefields in variables that are related to the reflection angle.

A key component of such image decompositions is the imaging condition. A careful implementation of the imaging condition preserves all information necessary to decompose images in their angle-dependent components. The challenge is efficient and reliable construction of these angle-dependent images for velocity or amplitude analysis.

In migration with wavefield extrapolation, a prestack imaging condition based on spatial shifts of the source and receiver wavefields allows for angle-decomposition (Rickett and Sava, 2002; Sava and Fomel, 2005a). Such formed angle-gathers describe reflectivity as a function of reflection angles and are powerful tools for migration velocity analysis (MVA) or amplitude versus angle analysis (AVA). However, due to the large expense of space-time cross-correlations, especially in three dimensions, this imaging methodology is not yet used routinely in data processing.

A different form of imaging condition involves time-shifts instead of space-shifts between wavefields computed from sources and receivers (Sava and Fomel, 2005b). Similarly to the space-shift imaging condition, an image is built by space-time cross-correlations of subsurface wavefields, and multiple lags of the time cross-correlation are preserved in the image. Time-shifts have physical meaning that can be related directly to reflection geometry, similarly to the procedure used

for space-shifts. Furthermore, time-shift imaging is cheaper to apply than space-shift imaging, and thus it might alleviate some of the difficulties posed by costly cross-correlations in 3D space-shift imaging condition.

The time-shift imaging concept is applicable to Kirchhoff migration, migration by wavefield extrapolation, or reverse-time migration. This concept is also applicable to migration of single-mode (PP) or converted-mode (PS) waves. In this paper, we develop the theory and show examples of angle decomposition after time-shift imaging of converted waves. All formulas developed for this purpose reduce to the previously-derived formulas for decomposition of single-mode images (Sava and Fomel, 2005a,b).

## IMAGING CONDITION

If we make the assumption that seismic data consists of singly-scattered reflections, we can describe migration as a succession of two steps:

**Wavefield extrapolation**, in which step we construct source and receiver wavefields from synthetic or recorded data. The source and receiver wavefields are four-dimensional objects denoted by the symbols  $\mathbf{u}_s(\mathbf{m}, t)$  and  $\mathbf{u}_r(\mathbf{m}, t)$ , where  $\mathbf{m}$  indicates position in a three-dimensional space, and  $t$  indicates time. In typical migration procedures, the four-dimensional objects  $\mathbf{u}_s$  and  $\mathbf{u}_r$  are not stored explicitly, but they are computed on-the-fly as needed for imaging at a given position  $\mathbf{m}$  in space.

**Imaging condition**, in which step we extract reflectivity information by comparing the source and receiver wavefields. A useful imaging condition produces a map of reflectivity at all locations in space, function of angles of incidence and reflection. This information can be employed in migration velocity analysis (MVA) and amplitude-versus-angle analysis (AVA).

We can distinguish two parts of an imaging condition: wavefield comparison and angle-decomposition. In the first part, we explore the match of source and receiver wavefields and build objects containing reflectivity information. Cross-correlation at every location in space is an example of wavefield comparison. In the second part, we extract the actual angle-dependent reflectivity information from images produced by space-time wavefield cross-correlation.

We can look at an imaging procedure formulated in this framework as an exercise in matching of two four-dimensional objects. Fundamentally, there is no difference between the four coordinate axes, except for their physical meaning. We can exploit this similitude of coordinate axes in formulating generic wavefield comparison procedures. Deconvolution or cross-correlation are just two particular options. Angle-decomposition, however, requires physical interpretation of the four coordinate axes to extract meaningful information about reflection angles. We exploit those physical relations to derive the formulas presented in this paper.

All types of migration procedures for converted waves, including Kirchhoff migration, migration by wavefield extrapolation, reverse-time migration etc. can be formulated in this framework.

## Conventional imaging condition

A conventional imaging condition for shot-record migration, also known as  $U\bar{D}$  imaging condition (Claerbout, 1985), consists of time cross-correlation at every image location between the source and receiver

wavefields, followed by image extraction at zero time. Mathematically, we can represent this process by the relations

$$\begin{aligned}\mathbf{u}(\mathbf{m}, t) &= \mathbf{u}_s(\mathbf{m}, t) \star \mathbf{u}_r(\mathbf{m}, t), \\ \mathbf{R}(\mathbf{m}) &= \mathbf{u}(\mathbf{m}, t=0).\end{aligned}\quad (1)$$

Here,  $\mathbf{m} = [m_x, m_y, m_z]$  is a vector describing the locations of image points,  $\mathbf{u}_s(\mathbf{m}, t)$  and  $\mathbf{u}_r(\mathbf{m}, t)$  are source and receiver wavefields respectively, and  $\mathbf{R}(\mathbf{m})$  denotes the migrated image, proportional to reflectivity at every location in space. The symbol  $\star$  denotes cross-correlation in time.

A typical implementation of this imaging condition is in the Fourier domain, where the image is produced using the expression

$$\mathbf{R}(\mathbf{m}) = \sum_{\omega} U_s(\mathbf{m}, \omega) \overline{U_r(\mathbf{m}, \omega)}, \quad (3)$$

where summation over frequency  $\omega$  corresponds to imaging at zero time. The over-line represents a complex conjugate applied on the receiver wavefield  $U_r$  in the Fourier domain.

### Space- and time-shift imaging condition

We can formulate a more general imaging condition based on cross-correlation of the source and receiver wavefields after shifting in both time and space. Mathematically, we can represent this process by the relations

$$\begin{aligned}\mathbf{u}(\mathbf{m}, \mathbf{h}, t, \tau) &= \mathbf{u}_s(\mathbf{m} - \mathbf{h}, t - \tau) \star \mathbf{u}_r(\mathbf{m} + \mathbf{h}, t + \tau), \\ \mathbf{R}(\mathbf{m}, \mathbf{h}, \tau) &= \mathbf{u}(\mathbf{m}, \mathbf{h}, \tau, t=0).\end{aligned}\quad (4)$$

Here,  $\mathbf{h} = [h_x, h_y, h_z]$  is a vector describing the local source-receiver separation in the image space, and  $\tau$  is a time-shift between the source and receiver wavefields prior to imaging. In this imaging condition we do not assume that the source and receiver wavefields maximize image strength at the zero-lag of the space-time cross-correlation. Instead, we probe wavefield similitude at other lags using both shifting in space and time.

This imaging condition can be implemented in the Fourier domain using the expression

$$\mathbf{R}(\mathbf{m}, \mathbf{h}, \tau) = \sum_{\omega} U_s(\mathbf{m} - \mathbf{h}, \omega) \overline{U_r(\mathbf{m} + \mathbf{h}, \omega)} e^{2i\omega\tau}. \quad (6)$$

Special cases of this imaging condition correspond to purely space-shift  $\tau = 0$ , when the imaging condition reduces to (Sava and Fomel, 2005a)

$$\mathbf{R}(\mathbf{m}, \mathbf{h}) = \sum_{\omega} U_s(\mathbf{m} - \mathbf{h}, \omega) \overline{U_r(\mathbf{m} + \mathbf{h}, \omega)}, \quad (7)$$

or purely time-shift  $\mathbf{h} = 0$ , when the imaging condition reduces to (Sava and Fomel, 2005b)

$$\mathbf{R}(\mathbf{m}, \tau) = \sum_{\omega} U_s(\mathbf{m}, \omega) \overline{U_r(\mathbf{m}, \omega)} e^{2i\omega\tau}. \quad (8)$$

The imaging procedures described in this section produce images that can be used for angle decomposition of reflectivity at every image location, thus making this imaging procedure useful for MVA or AVA.

The imaging conditions presented in this section make no assumption on the nature of the source and receiver wavefields. We can reconstruct those two wavefields using any type of extrapolation, or using different velocity models for extrapolation of the source and receiver wavefields.

In the following section, we discuss angle-decomposition based on the images obtained by conditions described in the current section. For angle decomposition, we cannot ignore anymore the physical nature of the two wavefields we are comparing, and we need to specify what type of wave (P or S) do the various wavefields correspond to. For the following analysis, we will assume that source wavefields correspond to incident P waves, and receiver wavefields correspond to reflected S waves.

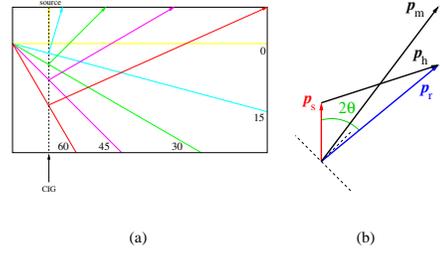


Figure 1: (a) Synthetic PS reflection experiment, and (b) Geometric relations between ray vectors at an image point.

### ANGLE DECOMPOSITION

We can develop procedures for angle-decomposition starting from the multi-lag cross-correlations constructed in the preceding section. At this stage, we need to exploit the physical meaning of the various lags, either along space axes or along the time axis. In general, 3-D angle-decomposition should define reflectivity function of reflection and azimuth angles. In this paper, we concentrate on decomposition function of the reflection angle only.

Using the definitions introduced in the preceding section, we can make the standard notations for source and receiver coordinates, respectively:  $\mathbf{s} = \mathbf{m} - \mathbf{h}$  and  $\mathbf{r} = \mathbf{m} + \mathbf{h}$ . The traveltime from a source to a receiver is a function of all spatial coordinates of the seismic experiment  $t = t(\mathbf{m}, \mathbf{h})$ . Suppose we could identify the function  $t(\mathbf{m}, \mathbf{h})$ , then differentiating  $t$  with respect to all components of the vectors  $\mathbf{m}$  and  $\mathbf{h}$ , and using the standard notations  $\mathbf{p}_\alpha = \nabla_\alpha t$ , where  $\alpha = \{\mathbf{m}, \mathbf{h}, \mathbf{s}, \mathbf{r}\}$ , we can write  $\mathbf{p}_m = \mathbf{p}_r + \mathbf{p}_s$  and  $\mathbf{p}_h = \mathbf{p}_r - \mathbf{p}_s$ . Therefore, we can also write equivalent relations  $2\mathbf{p}_s = \mathbf{p}_m - \mathbf{p}_h$  and  $2\mathbf{p}_r = \mathbf{p}_m + \mathbf{p}_h$ .

By analyzing the geometric relations of various vectors at an image point, Figure 1(b), we can write the trigonometric expressions:

$$4|\mathbf{p}_h|^2 = |\mathbf{p}_s|^2 + |\mathbf{p}_r|^2 - 2|\mathbf{p}_s||\mathbf{p}_r|\cos(2\theta), \quad (9)$$

$$4|\mathbf{p}_m|^2 = |\mathbf{p}_s|^2 + |\mathbf{p}_r|^2 + 2|\mathbf{p}_s||\mathbf{p}_r|\cos(2\theta). \quad (10)$$

### Space-shift angle decomposition for converted waves

We can transform the expressions (9)-(10) using the notations  $|\mathbf{p}_s| = s$  and  $|\mathbf{p}_r| = \gamma s$ , where  $\gamma(\mathbf{m})$  is the  $v_p/v_s$  ratio, and  $s(\mathbf{m})$  is the slowness associated with the incoming ray at every image point:

$$|\mathbf{p}_h|^2 = s^2(1 + \gamma^2 - 2\gamma\cos 2\theta), \quad (11)$$

$$|\mathbf{p}_m|^2 = s^2(1 + \gamma^2 + 2\gamma\cos 2\theta). \quad (12)$$

If we eliminate  $\omega$  and make the notations  $|\mathbf{k}_h| = |\mathbf{p}_h|/\omega$  and  $|\mathbf{k}_m| = |\mathbf{p}_m|/\omega$ , we obtain the expression (Sava and Fomel, 2005c)

$$\tan^2 \theta = \frac{(1 + \gamma)^2 |\mathbf{k}_h|^2 - (1 - \gamma)^2 |\mathbf{k}_m|^2}{(1 + \gamma)^2 |\mathbf{k}_m|^2 - (1 - \gamma)^2 |\mathbf{k}_h|^2}, \quad (13)$$

that can be used for angle decomposition for converted waves after space-shift imaging condition. For PP reflections ( $\gamma = 1$ ), this expression reduces to

$$\tan^2 \theta = \frac{|\mathbf{k}_h|^2}{|\mathbf{k}_m|^2}. \quad (14)$$

### Time-shift angle decomposition for converted waves

Using the same definitions for  $|\mathbf{p}_s|$  and  $|\mathbf{p}_r|$  as in the preceding subsection, we can use equation (12) to derive the relation

$$\cos^2 \theta = \frac{1}{\gamma} \frac{|\mathbf{p}_m|^2}{4s^2} - \frac{(1 - \gamma)^2}{4\gamma}. \quad (15)$$

For PP reflections ( $\gamma = 1$ ), this expression reduces to

$$\cos \theta = \frac{|\mathbf{p}_m|}{2s}. \quad (16)$$

## ALGORITHMS

In the most general case described in this paper, a seismic image is a multi-dimensional object function of position  $\mathbf{m}$ , space-shift  $\mathbf{h}$  and time-shift  $\tau$ ,  $\mathbf{R}(\mathbf{m}, \mathbf{h}, \tau)$ . We can use the relations between space and time coordinates developed in the preceding section to define various angle-decomposition algorithms. Since  $\mathbf{R}(\mathbf{m}, \mathbf{h}, \tau)$  is a large object that is unlikely, in practice, to be computed or stored completely, we design algorithms involving subsets of this large image:

### Space-shift angle decomposition

If we construct a seismic image using only space-shift  $\mathbf{R}(\mathbf{m}, \mathbf{h})$ , we use equation (13) for angle decomposition of converted-mode waves. The computation and storage requirements are high, since we need to store images for 3-D cross-correlation lags. However, if only the reflection angle is of interest, we can reduce cost by storing only the absolute value of the space-shift vector (Sava and Fomel, 2005a).

A decomposition algorithm is as follows:

$$\mathbf{R}(\mathbf{m}, \mathbf{h}) \rightarrow \mathbf{R}(\mathbf{k}_m, \mathbf{k}_h) \rightarrow \mathbf{R}(\mathbf{k}_m, |\mathbf{k}_h|/|\mathbf{k}_m|) \rightarrow \mathbf{R}(\mathbf{m}, \theta)$$

where each arrow indicates a transformation from one domain to another, and  $\mathbf{k}_m$  and  $\mathbf{k}_h$  are the Fourier duals of position  $\mathbf{m}$  and space-shift  $\mathbf{h}$ . The transform from  $(\mathbf{m}, \mathbf{h})$  to  $(\mathbf{k}_m, \mathbf{k}_h)$  and back represent Fourier transforms, and the transformation from  $(\mathbf{k}_m, \mathbf{k}_h)$  to  $(\mathbf{k}_m, |\mathbf{k}_h|/|\mathbf{k}_m|)$  represents slant-stacking. The decomposition from the slant-stack parameter  $|\mathbf{k}_h|/|\mathbf{k}_m|$  to the reflection angle  $\theta$  requires a space-domain correction based on the  $v_p/v_s$  ratio  $\gamma$ .

### Time-shift angle decomposition

If we construct a seismic image using only time-shift  $\mathbf{R}(\mathbf{m}, \tau)$ , we use equation (15) for angle decomposition of converted-mode waves. The computation and storage requirements are small, since we need to store images for 1-D cross-correlation lags. However, although the cost is smaller, we lose the option of computing the azimuth of the reflection and we are limited only to the reflection angle.

A decomposition algorithm is as follows:

$$\mathbf{R}(\mathbf{m}, \tau) \rightarrow \mathbf{R}(\mathbf{k}_m, \omega) \rightarrow \mathbf{R}(\mathbf{k}_m, |\mathbf{k}_m|/\omega) \rightarrow \mathbf{R}(\mathbf{m}, \theta)$$

where  $\mathbf{k}_m$  and  $\omega$  are the Fourier duals of position  $\mathbf{m}$  and time-shift  $\tau$ . The decomposition from the slant-stack parameter  $|\mathbf{k}_m|/\omega$  requires a space-domain correction based on the slowness  $s$  and the  $v_p/v_s$  ratio  $\gamma$ .

## EXAMPLE

We illustrate the imaging and angle-decomposition methods derived in this paper with a synthetic example. The reflectivity model consists of five reflectors of increasing slopes, from  $0^\circ$  to  $60^\circ$ , as illustrated in Figure 1(a). In this experiment, the P-wave velocity is  $v_p = 3200$  m/s and the S-wave velocity is  $v_s = 800$  m/s. We chose those velocities in order to capture reflections off the steeper dipping reflectors in a reasonable acquisition geometry. In this experiment, we analyze one common-image gather located at the same horizontal position as the surface seismic source. In this way, the reflector dip is equal to the angle of incidence on each reflector.

Figure 1(a) shows a schematic of a converted-mode (PS) experiment. Given the constant velocity of the model, the single-mode data from

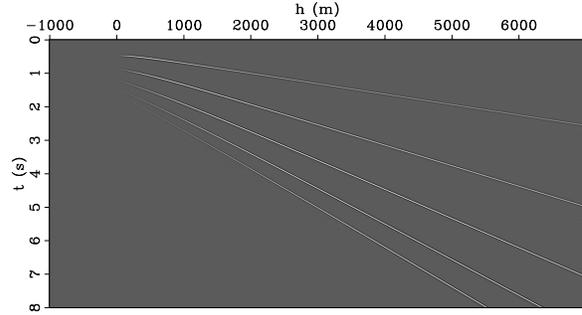


Figure 2: Synthetic PS reflection data

the reflector dipping more than  $45^\circ$  would not be recorded at the surface. In contrast, the converted-mode data from all reflectors are recorded at the surface.

Figure 2 shows the converted-mode seismic data from all five reflectors. We analyze the positive offsets of the seismic data which contain the reflections from the interfaces in the model.

We migrate this shot using one-way wavefield extrapolation using space-shift and time-shift imaging conditions. Figure 3 shows the migrated image at zero shift. As predicted by theory, this image is identical for both space-shift and time-shift imaging conditions when the values of the shift is zero.

Figures 4(a)-4(c) show different views of the common-image gather (CIG) located at the same horizontal location as the source  $x = 1000$  m. Panel (a) depicts the CIG resulting from the space-shift imaging condition. The vertical axis represents depth  $z$  and the horizontal axis represents horizontal space-shift labeled, for simplicity,  $h$ . Panel (b) depicts the same CIG after slant-stack in the  $z-h$  space. The horizontal axis is the slant-stack parameter, which is related to the reflection angle at every reflector, except for a correction based on dip and the  $v_p/v_s$  ratio. Panel (c) depicts the same CIG after transformation to reflection angle  $\theta$  using local values of P and S velocities, as well as a correction for the structural dip measured on the migrated image depicted in Figure 3. As expected, each reflector is represented in this final plot at a specific angle of incidence. The vertical lines indicate the correct reflection angles of converted waves reflecting from the interfaces dipping at angles between  $0^\circ$  and  $60^\circ$ .

Figures 5(a)-5(c) show a similar analysis to the one in Figures 4(a)-4(c) but for imaging using time-shift. Panel (a) depicts one CIG at  $x = 1000$  m, panel (b) depicts the CIG after slant-stack in the  $z-\tau$  space, and panel (c) depicts the CIG after transformation to reflection angle, including the space-domain corrections for structural dip and  $v_p/v_s$  ratio.

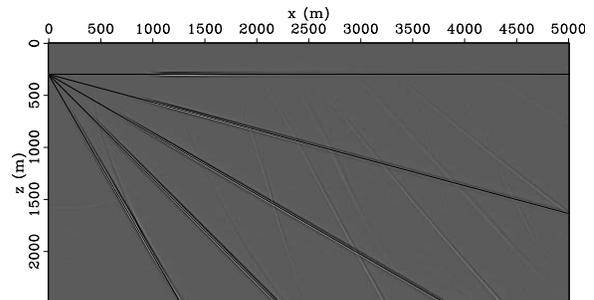


Figure 3: Migrated image for PS data

As for the space-shift images, the energy corresponding to every reflector from the CIG obtained by time-shift imaging concentrates well in the slant-stack panels, Figures 4(b) and 5(b). However, a striking difference occurs in the  $z - \theta$  panels: while the energy for every reflector in Figure 4(c) concentrates well, the energy in Figure 5(c) is much less focused, particularly at small angles.

This phenomenon was observed and discussed in detail by Sava and Fomel (2005a), and it is related to the lower angular resolution for time-shift imaging at small angles. This fact is illustrated in Figures 6(a)-6(b) depicting impulse response transformations for time-shift imaging: panel (a) depicts various events in a slant-stack panel, similar to Figure 5(b), and panel (b) depicts the same events in a reflection angle panel, similar to Figure 5(c). At small reflection angles, the angular resolution is low, but it increases at large reflection angles to levels comparable with those of reflections mapped using space-shift imaging. The simple explanation for this phenomenon is that the space-shift transformation involves the  $\tan\theta$  trigonometric function whose slope at  $\theta \rightarrow 0$  is equal to 1, while the time-shift transformation involves the  $\cos\theta$  function whose slope at  $\theta \rightarrow 0$  is equal to 0. Thus, even given equivalent slant-stack resolutions, the angle resolution around  $\theta = 0$  is poorer for time-shift imaging than for space-shift imaging because of the different trigonometric function.

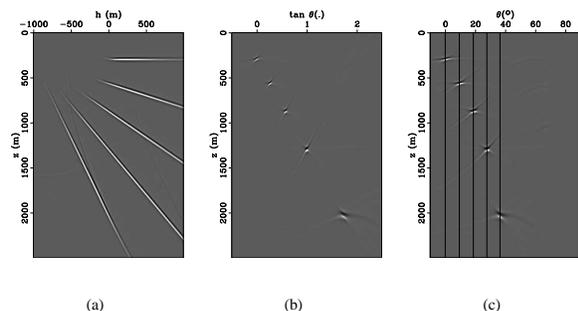


Figure 4: Common-image gather at  $x = 1000$  m for space-shift imaging condition: common-image gather (a), slant-stack gather (b) and common-angle gather (c).

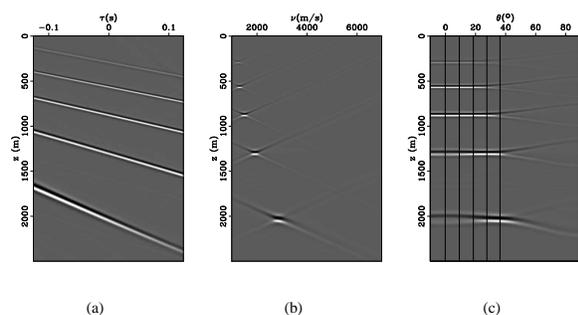


Figure 5: Common-image gather at  $x = 1000$  m for time-shift imaging condition: common-image gather (a), slant-stack gather (b) and common-angle gather (c).

## CONCLUSIONS

We develop imaging conditions for converted waves based on time-shifts between source and receiver wavefields. This method is applica-

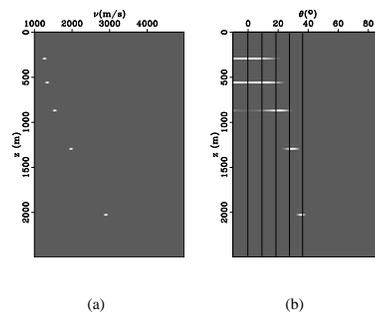


Figure 6: Resolution experiment for time-shift imaging condition: simulated slant-stack (a) and angle-decomposition (b). Although the slant-stack is well focused for all events both function of depth  $z$  and slant-stack parameter  $v$ , the resolution of the angle transformation is lower at small angles and higher at large angles.

ble to Kirchhoff, reverse-time and wave-equation migrations and produces common-image gathers indicative of velocity errors. In wave-equation migration, time-shift imaging is more efficient than space-shift imaging, since it only involves a simple phase shift prior to the application of the usual imaging cross-correlation. Disk storage is also reduced, since the output volume depends on only one parameter (time-shift  $\tau$ ) instead of three parameters (space-shift  $\mathbf{h}$ ). We show how this imaging condition can be used to construct angle-gathers from time-shift gathers. Although time-shift imaging is, in principle, capable of representing the same information as space-shift imaging, in practice the angular resolution of the angle decomposition for time-shift is much lower than the one for space-shift. This inconvenience needs to be addressed by future research.

## ACKNOWLEDGMENT

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