Diffraction imaging and time-migration velocity analysis using oriented velocity continuation

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ABSTRACT
We perform seismic diffraction imaging and time-migration velocity analysis by separating diffractions from specular reflections and decomposing them into slope components. We image the slope components using migration velocity extrapolation in time-space-slope coordinates. The extrapolation is described by a convection-type partial differential equation and implemented in a highly parallel manner in the Fourier domain. Synthetic and field data experiments show that the proposed algorithms are able to detect accurate time-migration velocities by measuring the flatness of diffraction events in slope gathers for single- and multiple-offset data.

INTRODUCTION
Seismic diffraction occurs when a seismic wave encounters a heterogeneity without a clearly defined tangent plane, such as an edge or tip, and the reflection part of the ray theory breaks down (Klem-Musatov, 1994). These divergent diffraction rays have similar behavior to a subsurface secondary source located at the heterogeneity (Keller, 1962). Analyzing diffraction moveout behavior in different domains can provide subsurface velocity information analogous to analyzing reflection moveout behavior from a surface source.

The fact that diffractions migrated with correct velocity collapse to points motivated Harlan et al. (1984) to propose the idea of separating diffractions from specular reflections and using diffraction focusing as a tool for velocity analysis. Separation of diffraction events from seismic data is a necessary step for velocity analysis because diffraction signals are typically significantly weaker than those of reflections (Klem-Musatov, 1994). Fomel et al. (2007) develop a constructive procedure for diffraction separation based on plane-wave destruction and diffraction focusing analysis based on velocity continuation and local kurtosis. The procedure is extended to 3D azimuthally anisotropic velocity analysis by Burnett and Fomel (2011). However, local kurtosis may not be an optimal measure for diffraction focusing because it requires smoothing or windowing in space, which reduces spatial velocity resolution through the smoothing window parameters.

A particularly convenient domain for separating diffractions and reflections and for analyzing migration velocities is dip-angle gathers (Brandsberg-Dahl et al., 2003b; Biondi and Symes, 2004; Landa et al., 2008; Reshef and Landa, 2009; Klokov and Fomel, 2012). In the dip-angle domain, specular reflections appear as hyperbolic events centered at the reflector dip and bending upward, even when over- or under-migrated, and diffractions appear flat when imaged at the location of the diffractor with the correct velocity (Reshef, 2007). Measuring the flatness of diffraction events in dip-angle gathers, as opposed to the flatness of reflection and diffraction events in reflection-angle gathers, provides an alternative constraint on the seismic velocity (Reshef and Landa, 2009). Traditionally, dip-angle gathers are constructed with Kirchhoff migration (Fomel and Prucha, 1999; Xu et al., 2001; Brandsberg-Dahl et al., 2003a; Cheng et al., 2011; Koren and Ravve, 2011; Bashkardin et al., 2012; Klokov and Fomel, 2013).

In this paper, we adopt an analogous method to the dip-angle approach used by Reshef and Landa (2009) to devise a constructive and highly parallel procedure for estimating velocities in time-domain processing using data decomposition in slope (Ghosh and Fomel, 2012) and velocity continuation in the midpoint-time-slope domain. By analogy with the “oriented wave equation” (Fomel, 2003a), we call this approach oriented velocity continuation (OVC) and develop a fast spectral method for its implementation on common-offset data. This differs from the methods devised by
Reshef and Landa (2009), who use a separate Kirchhoff-based angle prestack time or depth migration and calculation of traveltimes tables for each tested migration velocity. OVC uses a continuation approach, in which a single migration is used to determine an initial image in the midpoint-time-slope domain to which a velocity-dependent phase shift is applied over the range of plausible migration velocities, enabling OVC to test a greater number of velocities at a lower computational cost.

Using a field-data experiment, we demonstrate the effectiveness of OVC in zero-offset diffraction imaging and velocity analysis, and using a synthetic model, we observe that higher velocity resolution can be achieved when multiple offsets are included in the process.

ORIENTED VELOCITY CONTINUATION

Velocity continuation (Fomel, 2003c) is the imaginary process of a continuous transformation of seismic time-migrated images as they are propagated through different migration velocities. In the most general terms, the kinematics of velocity continuation can be described by an equation of the Hamilton-Jacobi type

\[
\frac{\partial \tau}{\partial v} = F(v, \tau, x, \nabla \tau),
\]

(1)

where \(\tau(x, t)\) is the location of a time-migrated reflector with time-domain coordinates \(x = (x_1, x_2, t)\) imaged with spatially constant time-migration velocity \(v\). The particular form of function \(F\) in equation 1 depends on the acquisition geometry of the input data. For the case of common-offset 2D velocity continuation for data with half-offset \(h\)

\[
F(v, t, x, p) = vtp^2 + \frac{h^2}{v^2},
\]

(2)

and equation 1 corresponds to the characteristic equation of the image propagation process, which describes a propagation of the time-migrated image \(I(t, x, v)\) in velocity \(v\) (Fomel, 2003c). Time-domain imaging can be performed effectively by extrapolating images in velocity and estimating velocity \(v_m(t, x)\) of the best image (Larner and Beasley, 1987; Fomel, 2003b; Fomel and Landa, 2014).

As shown by Fomel (2003a), it is possible to extend the formulation of a wave propagation process from the usual time-and-space coordinates to the phase space consisting of time, space, and slope. Applying a similar approach to equation 1, we first use the Hamilton-Jacobi theory (Courant and Hilbert, 1989; Evans, 2010) to write the corresponding system of ordinary differential equations for the characteristics (velocity rays), as follows:

\[
\frac{dx}{dv} = -\nabla_p F,
\]

(3)

\[
\frac{dp}{dv} = \nabla_x F + \frac{\partial F}{\partial \tau} p,
\]

(4)

\[
\frac{dt}{dv} = F - \nabla_p F \cdot p,
\]

(5)

where \(p\) stands for \(\nabla \tau\), the gradient or slope of time-migrated wavefield energy.

If the image \(I(t, x, v)\) is decomposed in slope components \(\hat{I}(t, x, p, v)\), so that

\[
I(t, x, v) = \int \hat{I}(t, x, p, v) dp.
\]

(6)

we can then look for an equation that would adequately describe a continuous transformation of \(\hat{I}\). To preserve the geometry of the transformation, it is sufficient to require that \(\hat{I}\) transports along the characteristics described by equations 3–5. Applying partial derivatives and the chain rule, we arrive at the equation analogous to the Liouville equation (Engquist and Runborg, 2003):

\[
\frac{\partial \hat{I}}{\partial v} = (F - \nabla_p F \cdot p) \frac{\partial \hat{I}}{\partial v} - \nabla_p F \cdot \nabla_\tau \hat{I} + \left(\nabla_x F + \frac{\partial F}{\partial \tau} p\right) \cdot \nabla_p \hat{I}.
\]

(7)

Equation 7 describes, in the most general form, the process of OVC, image propagation in velocity in the coordinates of time-space-slope. It is a linear first-order partial differential equation of convection type, which operates in the phase space.

Common-offset oriented velocity continuation

To adopt the general theory described above to the case of common-offset 2D OVC, we can substitute equation 2 into 7, arriving at the equation

\[
\frac{\partial \hat{I}}{\partial v} = \left(\frac{h^2}{v^2} - vtp^2\right) \frac{\partial \hat{I}}{\partial v} - 2vtp \frac{\partial \hat{I}}{\partial x} + vp^3 \frac{\partial \hat{I}}{\partial p},
\]

(8)

which describes image propagation in the time-space-slope coordinates rather than the usual time-space coordinates. After this kind of extrapolation, regular images can be reconstructed by stacking over offset and slope.

Slope gathers, analogous to dip-angle gathers, can be extracted before stacking over slope by analyzing \(\{t, p\}\) panels for different image locations \(x\) and velocities \(v\). Measuring flatness of diffraction events in these gathers provides a means for estimating migration velocity (Landa et al., 2008; Reshef and Landa, 2009).

For practical implementation, the formulation of OVC can be simplified by using a change of variable from the regular time coordinate to squared time \(\sigma = t^2\) (Fomel, 2003b). According to this transformation, the Hamilton-Jacobi equation 1 becomes

\[
\frac{\partial \sigma}{\partial v} = \frac{v}{2} \left(\frac{\partial \sigma}{\partial \tau}\right)^2 + \frac{h^2}{v^3},
\]

(9)

which leads to the simpler form of the oriented equation

\[
\frac{\partial \hat{I}}{\partial v} = \left(\frac{2h^2}{v^2} - v^2 q^2\right) \frac{\partial \hat{I}}{\partial \sigma} - vq \frac{\partial \hat{I}}{\partial x},
\]

(10)

where \(q\) corresponds to \(\partial \sigma/\partial x\), and the image is constructed in \(\{\sigma, x, q, h\}\) coordinates instead of \(\{t, x, p, h\}\) coordinates. Applying the Fourier transform, we can further transform equation 10 to

\[
\frac{\partial \hat{I}}{\partial v} = i\omega \left(\frac{v}{2} q^2 - \frac{h^2}{v^3}\right) \hat{I} - ivqk \hat{I}.
\]

(11)
where \( \tilde{I}(\omega, k, q, v, h) \) is the double Fourier transform of \( \tilde{I}(\sigma, x, q, v, h) \) in \( \sigma \) and \( x \).

Equation 11 has the analytical solution

\[
\tilde{I}(\omega, k, q, v, h) = \tilde{I}(\omega, k, q, v_0, h) e^{i(\omega q^2/4 + k q h/2)(v^2 - v_0^2) + i \omega h^2 (v - v_0)/v_0^2},
\]

(12)

where \( v_0 \) is a constant nonzero initial migration velocity.

Stacking over offset provides a slope-decomposed formulation for OVC:

\[
\tilde{I}(\omega, k, q, v) = \sum_h \tilde{I}(\omega, k, q, v_0, h) e^{i(\omega q^2/4 + k q h/2)(v^2 - v_0^2) + i \omega h^2 (v - v_0)/v_0^2}.
\]

(13)

This derivation suggests the following algorithm for time-domain imaging using common-offset 2D OVC:

1) Start with the initial time migration with a constant velocity \( v_0 \) to generate \( I(t, x, v_0, h) \).
2) Map \( I \) from \( t \) to \( \sigma = t^2 \).
3) Apply the Fourier transform from \( \sigma \) to \( \omega \).
4) Perform slope decomposition (described in the next section) to generate \( \tilde{I}(\omega, x, q, v_0, h) \). Note that this operation is parallel in \( \omega \) and \( h \).
5) Apply the Fourier transform from \( x \) to \( k \) to generate \( \tilde{I}(\omega, k, q, v_0, h) \). Note that this operation is parallel in \( q \) and \( h \).
6) Apply the phase-shift filter from equation 12 to generate \( \tilde{I}(\omega, k, q, v, h) \) for multiple values of \( v \). Note that this operation is data intensive but parallel in \( q \), \( k \), and \( h \).
7) Stack over the offset to generate \( \tilde{I}(\omega, k, q, v) \).
8) Apply an inverse double Fourier transform to generate \( I(\sigma, x, q, v) \).
9) Map \( \tilde{I} \) back from \( \sigma \) to \( t \).
10) Stack over \( q \) and extract the slice at time-migration velocity \( v_m(t, x) \) to generate the final time-migrated image \( I(t, x, v_m(t, x)) \).

To estimate the velocity \( v_m(t, x) \), we apply the workflow described above to diffraction imaging and modify it as follows:

- Before step 1, we separate reflections and diffractions in the common-offset data using local plane-wave destruction (Fomel, 2002; Fomel et al., 2007; Decker et al., 2013).
- After step 9, we analyze slope gathers \( I(t, x, q, v) \) and automatically pick the velocity \( v_m(t, x) \) that corresponds to the maximum flatness (semblance) over \( q \) using the picking algorithm described by Fomel (2009b). This approach follows the principle of flatness of diffraction events in slope gathers (Landa et al., 2008; Reshef and Landa, 2009; Klokov and Fomel, 2012).

The computational cost associated with determining velocity using OVC is linear with the number of time samples, spatial samples, offsets, velocities, and slopes considered. It is parallel in spatial samples, offsets, velocity, and slope. The cost may then be considered as \( O(N_t N_s N_h N_v N_p / N_c) \), where \( N_c \) is the number of cores available.
SLOPE DECOMPOSITION

To perform the initial slope decomposition (step 4 in the algorithm above), we adopt the method of Ghosh and Fomel (2012). The idea of slope decomposition was discussed previously by Ottolini (1983) and implemented using the local-slant stack transform (Ventosa et al., 2012). The slope-decomposition algorithm suggested by Ghosh and Fomel (2012) is based on the time-frequency decomposition of Liu and Fomel (2013). Namely, at each frequency $\omega$, we apply regularized nonstationary regression (Fomel, 2009a) to transform from space $x$ to space-slope $x-q$ domain. The nonstationary regression amounts to finding complex coefficients $A_n(\omega, x)$ in the decomposition

$$D(\omega, x) = \sum_{n=1}^{N_p} D_n(\omega, x),$$  \hspace{1cm} (14)

where $D(\omega, x)$ is the image slice and $D_n(\omega, x)$ is its slope component corresponding to slope $q_n$:

$$D_n(\omega, x) = \sum_{n=1}^{N_p} A_n(\omega, x)e^{i\omega x q_n}.$$  \hspace{1cm} (15)

Equation 14 is the discrete analog of equation 6. Similarly to the time-frequency decomposition proposed by Liu and Fomel (2013), shaping regularization is used to control the variability of the $A_n$ coefficients and to accelerate the algorithm.

EXAMPLES

Toy model example

We first illustrate the concept of OVC using a simple toy model (Landa et al., 2008; Klokov and Fomel, 2013), with constant 1.0 km/s velocity containing one dipping and one flat reflector and a single diffractor centered at 0.5 km (Figure 1a). Figure 1b shows data mapped to squared time.

Mapped data are decomposed into their constituent slope components and initially under-migrated using $v_0 = 0.5$ km/s. The initial slope decomposed image is shown in Figure 2, which illustrates a slope gather centered above the diffractor on the right panel, and a partial image containing energy with the slope of the top dipping reflector on the front panel. The partial image contains energy of the top dipping reflector, which has the selected slope, diffraction energy with that slope, and a small portion of the energy from the flat bottom reflector. Stacking over all constituent slopes provides an image.

The slope decomposed initial migration from Figure 2 is propagated through a suite of plausible migration velocities. We illustrate the initial migration and example velocities of 0.75, 1.0 (the correct

Figure 3. Slope gathers centered at (left) 0.25 km, (center) 0.5 km, and (right) 0.75 km for migration velocities of (a) initial under-migration with 0.5 km/s, (b) under-migration with 0.75 km/s, (c) the correct migration velocity of 1.0 km/s, and (d) over-migration with 1.25 km/s.
velocity), and 1.25 km/s. Slope gathers showing this process are shown in Figure 3. Stacking these propagated images over slope produces the image in Figure 4.

Examining the slope gather of the initial migration in Figure 3a, the three panels contain points of energy corresponding, from the top to bottom, to the top reflector, the diffractor, and the bottom reflector. The energy of each reflector is contained at the same lateral position in the three panels due to the constant slope of the reflector, although the vertical position of the top dipping reflector changes through the panels because the reflector dips downward to the right.

The diffraction has a hyperbolic moveout rather than a constant slope, so energy appears at different slopes in different slope gathers, with zero slope in the gather centered over the diffractor at 0.5 km. As we propagate data through velocity, this pattern holds: The reflection energy is stationary at its slope location for all gathers, and the diffraction energy has zero slope when viewed in the gather above the diffractor and nonzero slope for other gathers.

The initially migrated image is propagated to the higher time-migration velocity of 0.75 km/s using OVC, and slope gathers are

Figure 4. Toy model data propagated through OVC for different migration velocities.

Figure 5. Toy model image using 1.0 km/s migration velocity.
illustrated in Figure 3b. Reflection energy now bends upward about the stationary point of each reflection in “smiles” that become more accentuated with larger migration velocities. The diffraction event bends upward as well, but this only holds for the current case of under-migration.

Figure 3c shows the image propagated to the correct migration velocity. Diffraction energy is planar in all three gathers and flat in the middle gather centered above the diffractor. Stacking the energy in each gather over slope collapses the flat diffraction energy in the central gather to a point at the location of the diffractor. The sloping diffraction energy in the right and left panels cancels out when summed over the slope. This flatness is essential to using OVC as a tool for determining the correct migration velocity.

When data are further propagated to over-migration with velocity of 1.25 km/s in Figure 3d, the diffraction event bows downward in a “frown” juxtaposed against the upward bending reflection smiles.

Stacking over the slope provides images for these four velocities (Figure 4). In these images, the diffraction event incrementally evolves from having a hyperbolic downward character in the top under-migrated row, to collapsing to a point in the bottom left panel with the correct migration velocity, to bowing hyperbolically upward in the bottom right over-migrated image. The changing geometry of diffraction energy in the gathers can be harnessed to determine the proper migration velocity (Landa et al., 2008; Reshef and Landa, 2009). The correct migration velocity will be the one that maximizes the “flatness” of the slope decomposed diffraction events, as measured by coherence or another appropriate metric. Selecting 1.0 km/s, the velocity that produces flat diffraction energy, provides us with a properly migrated image (Figure 5).

To properly estimate the migration velocity using diffraction flatness, reflection events must first be filtered out from the diffraction data, or else the contribution of reflection smiles may dominate and bias the flatness measure.

**Synthetic example**

To test OVC and its velocity resolution, we generate a synthetic data set using a model with a constant velocity gradient beginning with a 2.0 km/s surface velocity. Diffractors are created as reflectivity spikes within the model with random spatial and magnitude distributions. Kirchhoff forward modeling is used to generate 24 offsets with a 50 m interval.

Zero-offset data are shown in Figure 6a, and 1.0 km common-offset data appear in Figure 6b. A time shift between the data is noticeable.

The zero and common-offset data are mapped to squared time, slope decomposed, and migrated with a 2.0 km/s initial velocity. The initially migrated slope decomposed images are propagated through a range of plausible migration velocities using OVC. Common-offset partial images are then stacked over the offset for each continuation velocity.

Figure 7 illustrates the slope gathers for zero and 1.15 km offsets generated for the image location \( x = 2.32 \) km, with migration...
velocities 2.1, 3.0, and 3.9 km/s. Here, 3.0 km/s is the correct velocity for the diffractor at 1.4 s located directly underneath the midpoint of this gather. When a different velocity is used, the shape of the event deviates from planar. We perform velocity analysis by testing the semblance, or flatness, of diffraction events in slope gathers over the range of velocities. Because velocity does not vary laterally in our synthetic model, we average the semblance across midpoints to generate semblance panels for the zero-offset and common-offset cases (Figure 8a and 8b, respectively).

As seen from the slope gathers (Figure 7), for the zero-offset case, there is a stationary point corresponding to diffraction energy with zero slope, which does not shift vertically under velocity perturbations. For the 1.15 km common-offset case, perturbing velocity changes the slope decomposed diffraction shape and shifts it vertically. Slope gathers with incorrect velocities (Figure 7b) are time shifted with respect to those generated for the zero-offset case (Figure 7a). When the correct migration velocity is used, horizontal common-offset diffraction energy appears at the same time as for the zero-offset case. The vertical shift of incorrectly migrated common-offset data leads to a sharper change in estimated flatness values while converging on the correct migration velocity, and it therefore improves velocity resolution. Therefore, common-offset semblance panel appears to have higher spatial and vertical resolution than the zero-offset case. This higher spatial resolution can be attributed to the improved illumination of scattering objects with the full range of offsets.

Final images for zero-offset and stacked common-offset cases using migration velocities estimated from the semblance panels are shown in Figure 9. Differences between the two images are too small to easily detect in this example. However, due to the higher velocity resolution visible in the semblance panel resulting from the consideration of multiple offsets, Figure 8b, we expect the stacked
common-offset image to be better resolved and less prone to noise than zero-offset case when applied to field data sets.

Field data example

We demonstrate an application of zero-offset (poststack) OVC on a deep water 2D line acquired to image the Nankai Trough subduction zone. Data acquisition parameters as well as processing results can be found in Moore et al. (1990), where the line is referred to as NT62-8. Structural interpretation can be found in Moore and Shipley (1993). Here, we consider a fragment of the line (CMPs 900-1301) used previously by Forel et al. (2005).

Conventional velocity analysis resolution suffers in this data set from the limitations imposed by the depth of a seabed in the area (average of approximately 4.5 km) and a relatively short 2 km streamer length. For deepwater data sets, diffractions may exhibit better illumination than reflections because the diffraction aperture is not restricted to the recording array length, enabling them to provide a potentially more detailed velocity distribution. This behavior makes OVC migration velocity analysis appealing.

The dip moveout (DMO) stacked section considered in this study is shown in Figure 10. Diffractions are extracted via plane-wave destruction (Figure 11), mapped to squared time, and decomposed into the slope. Figure 12 shows slope decomposed data mapped back to

![Figure 11. Nankai separated diffractions.](image1)

![Figure 12. Slope decomposition of Nankai diffraction data.](image2)

![Figure 13. Slope gathers centered above x = 4100 m migrated with (a) 1.4 km/s, (b) 2.5 km/s, and (c) picked migration velocity.](image3)
regular time for ease of comparison with slope decomposed images appearing later. Next, we take the decomposed data through OVC over a range of 60 constant migration velocities beginning with \( v_0 = 1.4 \text{ km/s} \) using a 20 m/s step. Diffraction events bend upward in the slope gather centered above \( x = 4100 \text{ m} \) with the minimum tested migration velocity (Figure 13a), indicating under-migration. Diffraction events in the slope gather centered above the same location with the maximum tested migration velocity (Figure 13b) bend downward, indicating over-migration.

Gather semblance is calculated for each continuation velocity, and migration velocity is automatically picked by attempting to maximize semblance for plausible velocity values at each CMP location.

Combining the semblance velocity picks from each CMP provides a time-migration velocity field, shown in Figure 14. Several anomalously low velocity zones exist in the picked field, primarily between \( t = 6.5 \) and 7 s, where the attempted flattening of out of plane diffractions leads to a low picked velocity.

Gathers corresponding to the picked velocity are selected and combined to create the slope decomposed diffraction image (Figure 15). Examining a slope gather from \( x = 4100 \text{ m} \) generated using the picked migration velocity (Figure 13c), diffraction events now appear flat, particularly the one located near \( t = 6.4 \text{ s} \), indicating that they have been correctly migrated.

Stacking the slope decomposed diffraction image over slope provides the diffraction image in Figure 16. We apply OVC to the DMO stacked data from Figure 10, and we stack over gathers selected with the appropriate velocity to generate the image of reflections and diffractions in Figure 17. Both images highlight the fault surfaces. Finer discontinuities, such as those associated with the rough surface of the subducting plate crust, located near \( t = 7.5 \text{ s} \) (Moore and Shipley, 1993), are more prominent on the diffraction image and tend to be well-focused, supporting the accuracy of the picked velocity.

**DISCUSSION**

The synthetic and field data experiments shown in this paper highlight the effectiveness of OVC at determining time-domain migration velocity. The synthetic experiments correctly determine the model velocity for zero and common-offset data and illustrate how including additional offsets can better constrain migration velocity. The field data experiment generates a plausible migration velocity field that successfully focuses diffraction energy and flattens slope-decomposed diffraction gathers. The method has difficulty in determining water velocity because there are no diffractors in the water column of a large enough size to be detectable in the OVC process, and out-of-plane diffractions from the rugose seabed flatten at a lower velocity than the true water column velocity.

The use of OVC for time-migration velocity analysis using seismic diffractions requires successfully separating diffractions from the reflection signal in the zero or common-offset data domain. In the field data experiment presented in this paper, we extract sufficient diffraction signal for the method to function. When implementing this method on other data sets, it is important to seek optimal diffraction and reflection separation; otherwise, the ability of OVC to determine the migration velocity may be significantly compromised.

We have formulated OVC as a type of time migration capable of determining migration velocities with limited offset data. Time mi-

![Figure 14. Velocity picked from the slope gather flattening.](image)

![Figure 15. Slope decomposition of Nankai diffraction image.](image)

![Figure 16. Diffraction image generated with the velocity from Figure 14.](image)
tended to the depth domain (Fomel, 2003a). The utility of OVC
other problems.
searchers will be inspired to apply the oriented wave equation to
wavefield continuation methods. The usefulness of such treatments
to overcome difficulties associated with traveltime uniqueness in
examining each slope component of a wave separately, it is possible
determined by the position and orientation of the wave. Thus, by
a wave travels, and hence its traveltime between points, is uniquely
techniques and the oriented wave equation in general is that the path
Brookshire et al., 2015; Meckel and Mulcahy, 2016).

Figure 14. 

Figure 17. Conventional image generated with the velocity from
Figure 14.

CONCLUSION

We have developed and demonstrated a highly parallel and con-structive procedure for time-domain velocity estimation. The method operates by decomposing data by slope and propagating slope components in velocity in the midpoint-time-slope domain. Semblance in slope gathers is used as a measure for selecting velocities that correspond to correctly migrated flat diffraction events, which applies even for single-offset data. This semblance measure is observed to achieve higher resolution when multiple offsets are considered in the OVC process. If data with multiple offsets are available, OVC could be used to better constrain the velocity model when used in conjunction with traditional reflection moveout analysis. Chosen velocities can be used to generate diffraction and reflection images. The powerful ability of OVC to operate with only zero-offset data enables accurate migration velocity analysis in situations in which only limited-offset data are available.

Flatness of slope-decomposed diffraction events is more responsive to velocity perturbation than diffraction focusing because it does not require smoothing or windowing in space. Therefore, the proposed method has the potential for diffraction velocity estima-

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