# Circumventing velocity uncertainty in imaging complex structures

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## Abstract

In areas with irregular topography, complex near surface, and complex subsurface, there is much uncertainty in rms velocity estimation for prestack time migration, whereas interval velocity estimation for prestack depth migration is despairingly challenging. We often attribute the velocity uncertainty to various factors, including strong to severe lateral velocity variations, heterogeneity, anisotropy, mode conversion, and three-dimensional behavior of complex structures. Nevertheless, it is not easy to identify the cause of and account for the uncertainty as it often is a combination of the various factors. And the analyst struggles with much difficulty when estimating a velocity field, whether it is for prestack time or depth migration. Velocity uncertainty invariably gives rise to erroneously high or low migration velocities, which then causes two problems with prestack migration: (1) we fail to preserve reflector amplitudes, and (2) we also fail to position the reflectors correctly and focus diffractions to their apexes. We may choose to solve both problems *simultaneously* as we currently attempt to do with prestack migration workflows, or we may choose to solve them one after the other as we used to do in the 1980s and '90s by workflows that included dip-moveout correction. The quality of image gathers associated with prestack migration may not be adequate for velocity updating and verification and thus may or may not warrant the simultaneous solution. In areas with irregular topography, complex near surface, and complex subsurface, it may not. What then? I propose a workflow, applicable to both 2-D and 3-D seismic data, to solve the two problems with prestack time migration one after the other. The workflow is based on

synthesis of a zero-offset wavefield to capture and preserve all reflections and diffractions, followed by zero-offset time migration.

#### Introduction

Figure 1 shows an image section obtained by prestack time migration (PSTM) using an rms velocity field that was constructed by velocity picking from the image volume obtained by PSTM of shot gathers using a range of constant velocities from a floating datum. The semblance spectrum at location A exhibits a distinctive set of peaks that allows picking a velocity function unambiguously (Figure 2a), whereas the semblance spectrum at location B exhibits a multiplicity of peaks that would give rise to uncertainty in velocity picking (Figure 2b). The structural complexity at the central portion of the line observed in Figure 1 is indicative of the difficulties in velocity picking. Further evidence of the troubling nature of velocity uncertainty is provided by the common-image-point (CIP) gathers associated with PSTM. The CIP gather at location A (Figure 2c) exhibits flat events that confirm the accuracy of the rms velocity field used for PSTM, whereas the CIP gather at location B (Figure 2d) exhibits highly complex and interfering events — again indicative of the velocity uncertainty within the structurally complex portion of the line. This CIP gather not only is a manifestation of the structural complexity resulting in a poor image (Figure 1) but also is practically unusable for velocity update based on flatness of events, nor can it be used for PSTM.

This leads us to the following question: Can we *circumvent* the velocity uncertainty rather than hopelessly struggle to *eliminate* it and yet produce an image in time better than that obtained by conventional PSTM based on a velocity field with much uncertainty? I present a workflow, named *i-cube* for brevity, that provides an answer to this question in the affirmative. The i-cube workflow includes construction of an image volume by PSTM of shot gathers using a range of constant velocities. This image volume can be used to pick rms velocities for PSTM. Yet, the multiplicity of semblance peaks associated with the image volume remains to be perilous. We can sum the image panels within the image volume over the velocity axis to obtain a composite image in time so as to *preserve* all events in the image volume and avoid committing ourselves



Figure 1. An image section obtained by PSTM from a thrust belt. The rms velocity semblance spectra and CIP gathers at locations A and B are shown in Figure 2.

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inadverdently to a velocity field that most likely would have some uncertainty. This summation strategy, however, fails because dipping events and diffractions within the image volume are not stationary in time and space. As a result, they are not preserved in the composite image (Figure 3). To meet the requirement for nonstationarity, we unmigrate each of the image panels within the image volume and then sum over the velocity axis. The resulting composite unmigrated section actually is equivalent to a synthesized zero-offset wavefield, which preserves diffractions and all reflections with conflicting dips. The final step in the workflow is poststack time migration of the synthesized zerooffset wavefield. I shall demonstrate the i-cube workflow using a field data set from a thrust belt.

### Back to the future: Return of the DMO

In the presence of conflicting dips with different stacking velocities, conventional common-midpoint (CMP) stack is not equivalent to a zero-offset wavefield. Within the context of subsurface imaging in time, this is the compelling reason for doing PSTM in lieu of poststack time migration, aside from the fact that the former also is used for rms velocity estimation and updating based on the flatness of events in CIP gathers associated with PSTM. Prior to the age of PSTM, a workflow for time migration developed in the 1980s included dip-moveout (DMO) correction to correct for the dip and



Figure 2. (a) and (b) The rms velocity semblance spectra, and (c) and (d) CIP gathers at locations A and B shown in Figure 1.



Figure 3. Stack of the migration-cube panels. Note the smearing of the dipping events as a result of their nonstationary behavior.

source-receiver azimuth effects on stacking velocities (Levin, 1971; Sherwood et al., 1978; Yilmaz and Claerbout, 1980; Deregowski, 1982; Hale, 1984; Beasley and Klotz, 1992; Yilmaz, 2001). With the increase in computational power, this resource-intensive workflow with multiple stages of velocity analysis soon was abandoned and replaced in the 1990s by the familiar PSTM workflows.

Nevertheless, we can draw a lesson from DMO processing to devise a workflow for PSTM that circumvents velocity uncertainty. By applying DMO correction to normal-moveout (NMO)corrected CMP gathers and stacking, we obtain a close approximation to a zero-offset wavefield, which by definition includes all reflections and diffractions as symbolically described by equation 1 in Figure 4. The image in time obtained by the DMO workflow essentially is equivalent to the image obtained by PSTM, provided lateral velocity variations are within the bounds

Back to the future: Return of the DMO		
NMO + DMO + stack	= zero-offset wavefield	(1)
NMO + DMO + stack + tmig	= PSTM	(2)
NMO + DMO + stack + tmig + demig =	= PSTM + demig	(3)
NMO + DMO + stack	= PSTM + demig	(4)
zero-offset wavefield	= PSTM + demig	(5)
NMO: normal-moveout correction, DMO: dip-moveout correction, PSTM: prestack time migration, <i>tmig</i> : poststack time migration, <i>demig</i> : demigration (inverse of <i>tmig</i> )		

Figure 4. Back to the future: return of the DMO. Inspired by the DMO workflow, I developed the i-cube workflow described in Figure 5.

of time migration. This statement is symbolically expressed by equation 2 in Figure 4, where *tmig* stands for poststack time migration. Add demig to both sides of this equation to get equation 3, where demig stands for demigration — in this case, inverse of *tmig*. This means that the terms *tmig* and *demig* on the left side of equation 3 cancel each other, and we obtain equation 4. Note that the left side of equation 4 yields the zero-offset wavefield as in equation 5. This means that, as an alternative to the DMO workflow, we can obtain the zero-offset wavefield by PSTM followed by demigration of the resulting image. However, equation 5 implies a commitment to an rms velocity field for PSTM, which may have much uncertainty.



Figure 5: The i-cube workflow is based on synthesis of a zero-offset wavefield to capture and preserve all reflections and diffractions, followed by zero-offset time migration.

## The i-cube workflow

I propose the following workflow to synthesize a zero-offset wavefield without the commitment to an rms velocity field so as to circumvent velocity uncertainty:

- Estimate a model for the near surface by nonlinear traveltime inversion applied to first-arrival times picked from shot gathers and calculate the medium- to long-wavelength shotreceiver statics.
- (2) Apply shot-receiver statics and an appropriate single-channel signal processing sequence to shot records. This sequence, aside from geometric spreading correction, may include time-variant spectral whitening to account for the signal nonstationarity and flatten the spectrum within the signal passband so as to reduce the strength of the large-amplitude, low-frequency surface waves, and predictive deconvolution to shape the spectrum to a bell curve that is slightly asymmetric in favor of the low-frequency side of the signal band with its peak coincident with the dominant signal frequency.
- (3) Estimate short-wavelength shot-receiver residual statics based on stack-power optimization, and apply them to moveoutcorrected CMP gathers.
- (4) Now perform multichannel signal enhancement in the CMP domain: Radon transform to attenuate multiples, coherent linear noise, and random noise.
- (5) Return to the shot-receiver domain and, if required, perform additional multichannel signal enhancement to further attenuate coherent linear noise and random noise.
- (6) Perform PSTM of all shot gathers using a range of constant velocities and obtain a set of image panels that form an image volume in (V, X, T) coordinates, where V is the rms velocity, X is the midpoint, and T is the event time after migration. This image volume is referred to as *migration cube* in Figure 5.
- (7) Perform multichannel signal processing to each of the velocity panels (X, T) of the migration cube to increase signal coherency.

- (8) Demigrate each of the velocity panels using the same constant velocity that was used for PSTM in step 6, and create a zero-offset volume in (V, X, T) coordinates, where V is the rms velocity, X is the midpoint, and T is the zero-offset event time before migration. We have preserved in this unmigrated volume all reflections and diffractions that are present in the signal-processed shot gathers. This unmigrated volume is referred to as *demigration cube* in Figure 5.
- (9) Apply Radon transform to each of the velocity gathers in (V, T) coordinates of the demigration cube to reduce the horizontal smearing of amplitudes associated with finite cable length and discrete sampling along the offset axis.
- (10) Since events are stationary both in time and space in the demigration cube, we can sum over the velocity axis to synthesize a zero-offset wavefield (Figure 5) so as to *preserve all reflections and diffractions* and avoid committing ourselves inadverdently to a velocity field that most likely would have some uncertainty. The synthesized zero-offset wavefield is shown in Figure 6.
- (11) Now return to the migration cube (step 7) and estimate an rms velocity field that should have lateral velocity variations only within the bounds of time migration (Figure 5).
- (12) Perform poststack time migration of the synthesized zero-offset wavefield from step 10 (Figure 6) using the rms velocity field from step 11 (Figure 5). This is the *principal image* in time that can be used for structural interpretation (Figure 7). Compare this image with the image obtained by conventional PSTM shown in Figure 1, and note the significant improvement of the structural complexity in the central portion of the line.
- (13) Perform Dix conversion of the rms velocity field from step 11 to obtain an interval velocity field.
- (14) Finally, perform poststack depth migration of the synthesized zero-offset wavefield from step 10 (Figure 6) using the interval velocity field from step 13. This is the *auxiliary image* in depth that can be used for structural interpretation (Figure 8).



Figure 6. The synthesized zero-offset wavefield obtained by stacking the panels of the demigration cube (step 10 of the workflow described in the text).



**Figure 7.** Poststack time migration of the synthesized zero-offset wavefield shown in Figure 6. This is the *principal image* in time that can be used for structural interpretation. Compare this image with the image obtained by conventional PSTM in Figure 1, and note the significant improvement of the structural complexity in the central portion of the line.



**Figure 8.** Poststack depth migration of the synthesized zero-offset wavefield shown in Figure 6. This is the *auxiliary image* in depth accompanying the *principal image* in time shown in Figure 7 that can be used for structural interpretation.

Needless to say, spatial sampling of the recorded data must be adequate to circumvent the adverse effect of spatial aliasing on the multichannel signal processing in various domains (steps 4, 5, 7, and 9), PSTM (step 6), demigration (step 8), and migration of the synthesized zero-offset wavefield (step 12). Additionally, structural imaging in thrust belts can be significantly improved by recording large-offset data to capture wide-angle reflections (Nicanoff et al., 2006; Yilmaz et al., 2010).

An alternative to the summation over the velocity axis of the demigration cube in step 10 is summation within a velocity corridor. Based on a weighted summation over the velocity axis, Landa (2013) also proposed a path-integral method to obtain an unmigrated section from a set of constant-velocity stacked sections. Application of this method to obtain the time-migrated image from the image volume described in step 6 is proposed by Landa et al. (2006) and its use for migration velocity analysis is suggested by Schleicher and Costa (2009). It is worth to explore in the future the potential use of the pathintegral method for an improved synthesized zero-offset wavefield.

# Time versus depth migration — A philosophical perspective

I refer to the image in depth as auxiliary, for velocity-depth model estimation in areas with strong to severe lateral velocity variations is perilously time-consuming. More importantly, the estimated velocity-depth model will always have inaccuracies such that the resulting image in depth will not be as useful as the image in time for structural interpretation. I wish to express this underlying philosophy for imaging in time and in depth in areas with severe lateral velocity variations by the following lines of poetry:

## Kronos gave us the Arrow of Time So that we may observe Depths of the Earth. But then Hades deceived us with the Arrow of Depth

So that we may fall into our Death. Exhausting even futile can it be Pursuit for Earth Model in Depth. When truly in need wiser may it be To be content with Earth Image in Time.

#### Conclusions

The proposed i-cube workflow essentially involves a transformation from the observation domain (field records) to the zerooffset domain (demigration cube) to preserve reflections and diffractions. Rather than struggle to *eliminate* the uncertainty in velocity estimation for PSTM completely - an impossible task, specifically, in areas with complex near-surface and irregular topography and structurally complex subsurface — the i-cube workflow circumvents the velocity uncertainty. Because events in the zero-offset volume (demigration cube) are stationary both in time and space, we can sum over the velocity axis to obtain a composite (synthesized) zero-offset wavefield so as to preserve all events contained in the volume and avoid committing ourselves inadverdently to a velocity field which most likely would have some uncertainty. The resulting synthesized zero-offset wavefield can then be migrated by poststack time migration. The resulting image would have all the events, albeit some may be mispositioned because of velocity errors. The poststack time migration, however, can be repeated using a revised rms velocity field to position the events correctly. If, on the other hand, an rms velocity field with much uncertainty is used for PSTM, the resulting image not only would have mispositioned events but also some events with incomplete focusing or missing altogether. To remedy the problems of event mispositioning, incomplete focusing, and missing events, the velocity field would have to be updated and PSTM would have to be repeated - a formidably time-consuming and resourceintensive exercise, especially in case of 3-D imaging. In contrast, the proposed i-cube workflow produces a synthesized zero-offset wavefield and only requires poststack time migration that can be repeated at much less cost.

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