DIP-MOVEOUT BY FOURIER TRANSFORM

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Abstract

The conventional normal-moveout (NMO) and common-midpoint (CMP) stacking process enhances reflections having a particular moveout velocity, while attenuating events (such as multiple reflections) having different moveout velocities. Unfortunately, this process also acts as a dip filter applied to the CMP stack. In other words, NMO and stacking enhances reflections having a particular slope in the CMP stack, while attenuating reflections having different slopes. NMO and stacking, like any dip filter, degrades lateral resolution.

Fortunately, this dip-filtering action can be suppressed by applying, in addition to NMO, a prestack process known variously as *DEVILISH*, *prestack partial migration*, and *dip-moveout*. As the latter term implies, this process is a dip-dependent moveout correction that enables reflections from both horizontal and dipping reflectors to be stacked with the same NMO velocity. Stated another way, NMO velocities estimated from dip-moveout-corrected seismograms are independent of the dips of subsurface reflectors.

Dip-moveout by Fourier transform is a method for performing dip-moveout (DMO) correction in the frequency-wavenumber domain. The implementation of this method, which resembles the implementation of a discrete Fourier transform, is quite different from and compares favorably with previously published finite-difference DMO algorithms. DMO by Fourier transform, unlike DMO by finite differences, is accurate for all offsets and all dips, provided that velocity is constant. Because velocity is never constant, some accuracy is inevitably lost; but the application of DMO by Fourier transform to recorded seismograms demonstrates the ability of this process to enhance (1) the dip bandwidth of CMP stacks and (2) the accuracy of velocity estimates. The application of this process to synthetic seismograms further suggests that velocity variations, which must be considered in NMO correction, may often be ignored in DMO correction. If necessary, however, DMO by Fourier transform may be easily generalized to approximately treat velocity variations with depth.

Prestack migration, although somewhat impractical and seldom used, is generally considered to be the theoretically accurate process for constructing a subsurface image from reflection seismograms. For constant velocity, this single process is exactly equivalent to the following cascade of four processes: NMO, DMO, stack, and poststack migration. Although velocity is never constant, DMO, when combined with the other three more conventional processes, provides a reasonably accurate and very practical alternative to prestack migration.

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The guidance and assistance of many people have enriched this dissertation. Jon Claerbout encouraged me to generalize my initial results and to make dip-moveout the subject of my thesis. Dip-moveout by Fourier transform is built upon fundamentals of computational seismology that Jon taught me. Fabio Rocca provided several intuitive handles that guided me through the development of the theory. His influence was particularly significant in the generalization of dip-moveout to depth-variable velocity and three-dimensional wavefields. I frequently called upon Bert Jacobs, Shuki Ronen, Stew Levin, and Joe Stefani for assistance. Their insight and patience during many lengthy discussions is greatly appreciated. Rick Ottolini quickly tested some of the ideas born in the early stages of research. I was greatly encouraged when, about fifteen minutes after I had derived a key equation, Rick walked into my office and said, "It works."

Throughout my studies at Stanford, I have benefited from the advice of Ken Larner and Walt Lynn of Western Geophysical Company. Largely through Walt's effort, Western provided the seismic data that I used in testing dip-moveout by Fourier transform.

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Background and Introduction

Common-midpoint (CMP) stacking of reflection seismograms is almost routinely used to enhance the exploration seismologist's image of the earth's subsurface. However, as stated recently by Tucker (1982, p. 6),

> *stacking enhances continuity and parallelism of the reflection, but overstacking can destroy the geology. Stacking may attenuate curved or dipping reflections and diffractions, which are very important in fault mapping....*
>
> *Stacking also discriminates against dip. Basically, the greater the dip, the fewer the number of stacks that can be tolerated before the data deteriorate rather than being enhanced. The techniques (such as migration before stack) to get around this are known but they are not routinely practiced.*

In short, the CMP stacking process acts as a dip filter, tending to enhance reflections having a particular slope in the stack, while more or less attenuating reflections having different slopes.

A qualitative understanding of this dip-filtering action requires only the knowledge that the normal-moveout (NMO) velocity for a dipping reflector is greater than that for a horizontal reflector. Dix (1955) and Levin (1971) showed, for a constant-velocity subsurface, that a reflection due to a dipping reflector has an NMO velocity v_{NMO} related to the true velocity v by a cosine factor,

$$v_{NMO} = \frac{v}{\cos\theta} ,$$

where θ is the reflector dip in the direction of source-receiver offset. This equation indicates that NMO correction for dipping events is best performed using a velocity v_{NMO} that is higher than the true velocity v. Unfortunately, conventional NMO and stack processing permits only one choice of v_{NMO} for a particular CMP and traveltime. So, choosing a v_{NMO} is equivalent to choosing an optimally stacked dip θ for that CMP and time.

The dip selectivity of NMO and stack was well illustrated by Judson et al (1978) in a paper presented at the 48th Annual International SEG Meeting. In their paper, the authors described a prestack process called *DEVILISH* (which stands for *dipping event velocity inequalities licked*). Their claim was that after applying DEVILISH, dipping events "up to approximately 60 degrees" could be NMO-corrected and stacked at the same velocity as horizontal events. Examples of the application of their process to seismic data supported this claim, demonstrating that the dip-filtering tendency of NMO and stack could be substantially reduced. Unfortunately, Judson et al never published the DEVILISH details beyond noting that the "dip-correction is performed using finite difference migration operators acting on the data in common offset sections."

Yilmaz and Claerbout (1980), attacking the same problem, published an algorithm that they called *prestack partial migration* (PSPM). The authors noted the difference between (1) the conventional processing sequence of NMO, stack, and migration and (2) the less practical, more costly, but theoretically more correct process of migration before stack. PSPM represents an approximation to this difference that, when combined with the conventional processing sequence, yields approximately the result of migration before stack. The approximation is poor for large source-receiver offsets and steep dips, but the algorithm effectively increased the dip bandwidth of conventional processing when applied to recorded seismograms. Yilmaz and Claerbout's PSPM, like DEVILISH, was implemented using finite-difference migration operators.

Following the work of Judson et al and Yilmaz and Claerbout, Deregowski and Rocca (1981) and Bolondi et al (1982) described alternative algorithms for reducing the dip selectivity of NMO and stack. Their *dip-moveout* (DMO) correction, like PSPM and DEVILISH, is an addition to the conventional processing sequence of NMO and stack, and is intended to make conventional processing approximate the result of migration before stack. Their DMO algorithms are based on the concept of offset continuation, and are analogous in implementation to conventional poststack migration algorithms, the latter being based on a similar concept of downward continuation. Again, the approximations made in deriving these DMO algorithms break down at large offsets and steep dips.

DEVILISH, PSPM, and DMO represent different algorithms for performing the same function that, for brevity, will hereafter be referred to as simply DMO. Just as migration algorithms may differ, so may DMO algorithms differ. DMO by Fourier transform, the subject of this dissertation, is an algorithm for performing DMO correction in the frequency-wavenumber domain.

In chapter I, DMO by Fourier transform is derived from traveltime equations for a constant velocity subsurface. This DMO algorithm, unlike those published previously, is accurate for all offsets and all dips. The practical application of the algorithm, particularly with regard to velocity estimation, is also discussed in chapter I. The effectiveness of the algorithm in enhancing the dip bandwidth of CMP stacks and improving velocity estimates is demonstrated in chapter I by application to recorded seismograms.

The assumption that velocity is constant, which is never satisfied in practice, leads one to question the accuracy of DMO by Fourier transform derived in chapter I. I know of no exact algorithm for DMO correction in the presence of velocity variations, but an approximate generalization of DMO by Fourier transform for depth-variable velocity is provided in chapter II. As demonstrated by both synthetic and recorded seismograms, the correction to DMO by Fourier transform for variable velocity may often be negligible.

Chapter III is a rigorous discussion, for both two- and three-dimensional seismic wavefields, of the relationship between DMO correction and migration before stack. The latter process is generally considered to be the theoretically accurate process for constructing a subsurface image from reflection seismograms. For constant velocity, this process is exactly equivalent to the following cascade of four processes: NMO, DMO, stack, and poststack migration. In fact, DMO is defined in chapter III to be the process left over after the more conventional NMO, stack, and poststack migration processes are identified in the prestack migration equations. The DMO process so defined is consistent with that derived in chapter I from traveltime equations.