

P266 WAVE-EQUATION MIGRATION IMAGING AND COST COMPARISON: SURVEY SINKING VS. SHOT PROFILE

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Summary

We examine imaging results from two common categories of wave-equation migration: survey sinking migration (SSM, also commonly referred to as double square root migration or DSR) and shot profile migration (SPM). We sketch an outline of the proof of the two methods equivalence, examine the relative computation cost of the two methods, and compare imaging results. Considerations of image accuracy, velocity model building capability, and the ability to generate prestack gathers lead us to conclude that SSM methods are better suited for marine towed cable acquisition geometries than SPM, while SPM is better suited for OBC and land data. We arrive at this conclusion because SSM methods are orders of magnitude faster in runtime than SPM for marine geometry, allowing inclusion of aperture for steep dips and multiple runs of the migration for effective and realizable convergence to an accurate velocity model.

Introduction

The challenges of exploration in increasingly complex geological areas has led to increased industry interest in wave-equation depth migration methods (Bevc and Biondi, 2002; Ritchie, 2003). Commonly available wave-equation migration solutions available in the industry are those based on Survey Sinking (SSM) or Double Square Root downward continuation (DSR) and Shot Profile Migration (SPM). It has been shown mathematically that properly implemented SSM/DSR and SPM have equivalent accuracy and produce equivalent results (Wapenaar and Berkhout, 1987; Biondi, 2002). The advantage of SSM/DSR methods is that they have significant potential for speedup, and some methods such as Common Azimuth (Biondi and Palacharla, 1996) and Narrow Azimuth (Biondi, 2001) migration, are orders of magnitude faster than competing Shot Profile implementations.

Wave-equation migration methods

The resurgence in popularity of wave-equation methods in 3-D has been spurred by two factors: (1) clever algorithms, and (2) fast and cheap computers. Wave equation methods can be generally grouped by the classification of their computational domain (shot-profile, source-receiver, survey sinking, plane wave) and by the numerical method used to extrapolate or downward continue the wavefield (finite difference, frequency domain, generalized screen propagator (GSP), Fourier finite difference (FFD), etc.). In addition, wave equation methods can be solutions of the two-way wave equation (reverse time) or the one-way wave equation. Two-way wave equation methods are computationally more expensive, although they do promise potential advantages for imaging overturned rays. In this discussion, we limit ourselves to more commonly available solutions based on one-way wave equation downward continuation, and we look at the differences in wave equation methods based on the characterization of their computational domain. In terms of classification by numerical extrapolation method, we simply assert that any choice of migration method must incorporate an extrapolator that uses a high-order efficient extrapolator capable of handling strong lateral velocity variations and steep dips – most commercial applications should incorporate these essential elements, and the technical literature is full of detailed analysis of the various methods.

Equivalence of Survey Sinking Migration and Shot Profile Migration

One of the most common computational domain divisions between wave equation methods in the industry today is that between shot-profile migration (SPM) and source-receiver migration. Source-receiver is also commonly referred to as survey sinking or double-square root (DSR) method, and despite the name, is commonly applied in the midpoint-offset domain.

To understand the two methods, we briefly outline how they work. In shot profile migration, each shot record is migrated individually into an image volume by:

1. downward continuing the receiver wavefield,
2. downward continuing the source (i.e. modeling the shot), and
3. imaging by cross correlation of the two wavefields and extracting the zero lag.

Source receiver downward continuation is performed by applying the DSR equation at each depth step to simultaneously:

1. downward continue the receiver wavefield, and
2. downward continue the source wavefield,
3. at each depth step, the imaging condition is applied by extracting the wavefield at zero time and zero offset.

The observant reader will note that steps one and two are similar. In fact, the downward continuation of receiver and source wavefield commutes, and the order can be rearranged. With some manipulation of equations, it can be shown that the two methods are mathematically equivalent (Wapenaar and Berkhout, 1987; Biondi, 2002). Therefore, shot-profile and source-receiver downward continuation are theoretically equivalent. This means, that properly implemented, the two methods should yield equivalent accuracy and comparable imaging results. The difference then becomes purely an engineering issue, and as we describe below, source-receiver methods offer significant opportunities for algorithmic efficiency based purely on the computational domain.

One of the first economically feasible implementations of wave-equation migration is common azimuth migration (Biondi and Palacharla, 1996). Biondi's implementation exploits the fact that most marine data are acquired in streamer geometry that is very nearly zero azimuth, or can be easily corrected to zero azimuth using an azimuth moveout operator (Biondi et al., 1998). This results in a 4-D downward continuation that is extremely efficient, and is 60 times faster than the equivalent 5-D downward continuation that does not take into account the streamer geometry and the common azimuth approximation. For areas where the common azimuth approximation may be in question, this same approach can be used in a narrow or wide azimuth formulation by including some crossline offset wavenumbers in the downward continuation. The downward continuation propagator applied in common azimuth and plane wave migration is commonly some form of an extended split-step method or generalized screen propagator. Properly applied, these propagators are capable of imaging steep dips in the presence of strong lateral velocity variations.

Computational Cost of SPM vs SSM/DSR

Shot profile migration is commonly applied using a finite difference propagator and a cross-correlation imaging condition. The shot profile approach is a full 5-D downward continuation (shot x,y , receiver x,y , and z), and therefore requires much more cpu than common azimuth or narrow azimuth migration. Its obvious advantage is that it retains all data azimuths, so it is better suited to many land and ocean-bottom cable acquisition geometries. To get around the extreme computational cost of shot profile migration, many practitioners decimate the input data and/or reduce crossline and inline migration aperture in order to make shot profile migration economically feasible for marine streamer data. The disadvantage of decimating the shots in shot profile migration is particularly evident in the quality of prestack volumes for migration velocity analysis or amplitude variation with angle. Even if a decimation factor of 1 to 10 produces little deterioration in the stacked image (particularly on synthetics) it creates a huge problem in the prestack image. The danger of limiting aperture in shot profile migration is that important information is lost. Restricting aperture in shot profile migration (or more precisely stated, the volume into which the shot record is extrapolated) can severely limit steep dip resolution.

ComAz is based on the observation that marine streamer data are collected along relatively narrow streamer arrays, and makes the assumption that multi-streamer data can be represented by an equivalent (after rebinning or azimuth moveout) data set that is purely zero azimuth. The method further assumes that migrated energy does not rotate in azimuth during the downward continuation process of migration imaging. These assumptions are generally good, but an exception occurs for the case of steeply dipping imaging targets that are at 45 degrees azimuth to the data acquisition geometry. Under these conditions the Common Azimuth assumptions break down, and the resulting image is

degraded (this image degradation is typically manifest as a reflector mispositioning or as an apparent velocity error).

Narrow Azimuth Migration (NarAz) addresses this particular issue by allowing the data to retain the narrow azimuth range with which it is acquired. Instead of assuming that the data are all zero-azimuth and are not allowed to rotate during downward continuation, NarAz assumes data are acquired over a narrow crossline azimuth range, and that the data are allowed to rotate over the given azimuth range. When NarAz is implemented to allow an adequate number of crossline azimuths (typically from three to sixteen), it will capture all recorded propagation events and image them accurately for a computational cost that is substantially less than that of SPM.

The cost ratio of SPM to SSM can be calculated by considering the geometry of the input and output computational grids. For implementations that use the same type of propagator, this ratio is given by:

$$\frac{\text{SPM}}{\text{SSM}} = \frac{\text{output_grid_points} * \text{shot_input_grid_points} * 2}{\text{offsets} * \text{cdp_input_grid_points}}$$

Figure1 illustrates the relative geometries of SPM and SSM migration for a typical Gulf of Mexico (GOM) scenario. A derivation of this ratio, and additional scenarios will be presented in the talk.

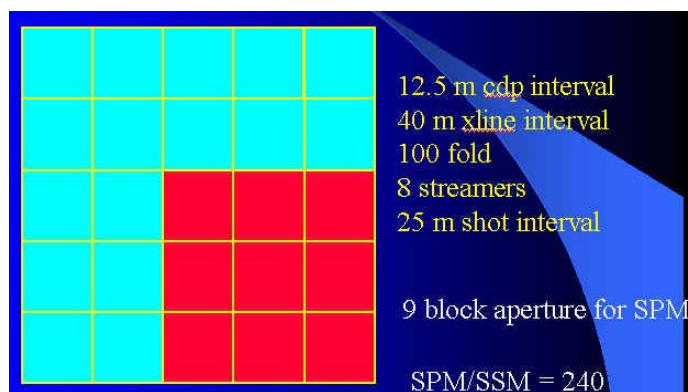


Figure 1. Illustration of geometry for imaging 9 blocks of GOM data. One block imaging halo requires input of 25 blocks. SPM/SSM cost ratio is 240, and SPM has restricted aperture.

Aside from the significant (order of magnitude) speed issue, Common Azimuth and Narrow Azimuth migration have substantial advantages in terms of amplitudes for attribute analysis, and the ability to generate angle gathers at no additional cost for migration velocity analysis and residual moveout.

The greater speed of processing offered by NarAz over SPM translates into shorter turn-around times. Provided the turn-around times are sufficiently short, the processing, depth imaging and perhaps the interpretation phases of a 3D seismic survey may allow for several, very significant iterations and consequently better results. This latter speed-of-processing advantage and access to much larger blocks of survey data may enable a significant change in imaging, target definition and characterization. This is not feasible with conventional older and slower algorithms (such as SPM).

Examples

The Pluto 1.5 synthetic data set produced by the SMAART JV simulates a deepwater Gulf of Mexico imaging objective with steep dips and significant velocity contrast. SPM and DSR migrations of Pluto 1.5 are presented in Figure 2. Figure 3 is a closeup of the central salt body showing the imaging of steep dips and sediment truncations against the salt flanks. The Pluto synthetic is sampled more densely in receivers than in shots, and is therefore better suited geometrically to SPM than to SSM/DSR which operates in the midpoint-offset domain; nonetheless, both migrations produce similar results, imaging subsalt sediment, diffractor targets, and flat reflector targets. Steep dips are better imaged in the DSR result, and runtime for DSR on 3-D data is typically orders of magnitude faster than SPM. Additional examples from SMAART Sigsbee model, the SEG/EAGE C3 synthetic 3-D data, and real 3-D data will be presented in the talk.

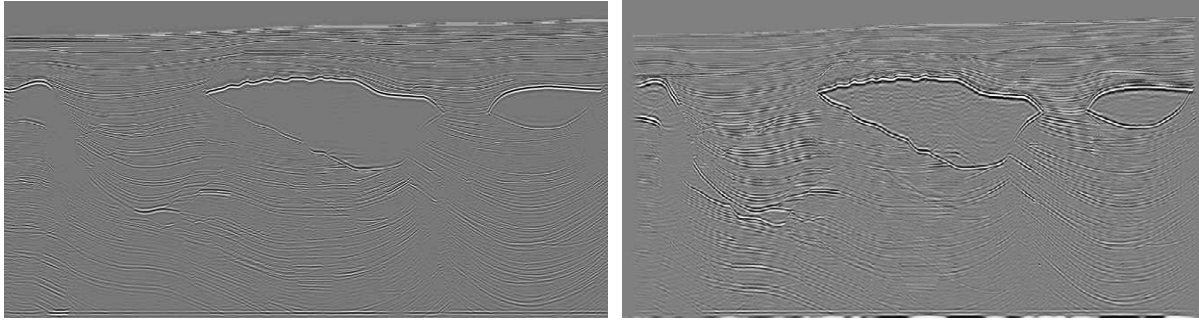


Figure 2. Migration of Pluto 1.5 Synthetic data. Shot Profile on the left, Survey Sinking on the right.

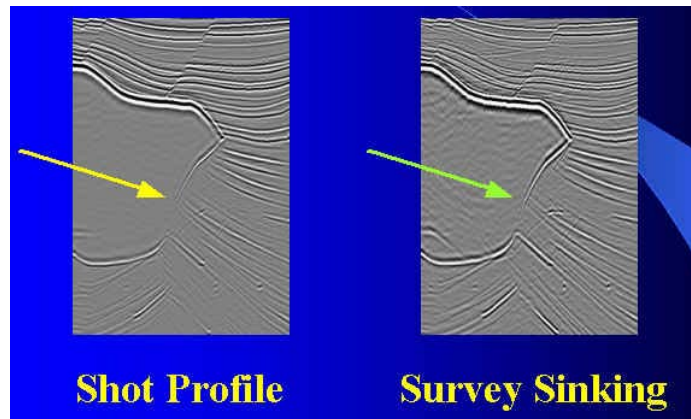


Figure 3. Closeup of Pluto 1.5 synthetic migration results comparing imaging of steep dips and continuation of sediments up to the salt flank.

Conclusions

Based on algorithmic considerations and imaging results, there are different areas of applicability for different imaging formulations. Shot profile wave equation algorithms are well suited for land and ocean bottom data, while DSR-based wave equation migration is best for marine streamer data. The prospective explorationist should be aware of the strengths and weaknesses of the various imaging methods, the approximations and assumptions that are invoked, and what effect these will have on the desired outcome.

The key to depth imaging is the velocity model, and to get the correct velocity model, it is critical to be able to output prestack gathers so that wave equation MVA can be performed with angle or offset domain image gathers. It is also critical to perform the velocity updating in a manner that is consistent with the migration engine that will be ultimately used for the final image, and to be able to perform as many iterations as are necessary.

References

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