3D PreSDM Model Building Techniques: A Review

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Foreword

In this review article, we outline the development of model building techniques over the past decade, with specific emphasis on the limitations of the techniques, and some of the pitfalls that open themselves to the unwary model-builder.

To give this article a broad perspective, I have included contributions from several colleagues throughout the industry, so as to represent the diverse approaches in use. The contributing organisations include BP, CGG, Delft, ENSMP, IFP, Paradigm, SEP, Shell, TFE, Veritas & WesternGeco.

Summary

Model building techniques fall into two broad categories: 'model-scan & picking', and, 'picking & tomographic inversion'.

Models themselves also fall into two major categories, reflecting the underlying geological environments: layer-based, and non- layer-based.

Layer based models are typical of say, the Canadian east coast, or North Sea, where the velocity (and velocity compaction gradient) are bounded by sedimentary interfaces. Here, it is sufficient to pick seismic reflection events as the partitions to the velocity regions in the model.

Non layer-based models (as found for example in the Gulf of Mexico) have velocity regimes dominated by compaction gradients which sub-parallel the sea bed. In the case of salt or shale tectonics, the scenario is complicated by the presence of these irregular bodies set within the background compaction gradient driven velocity field. In overthrust tectonic regimes such as found in the Canadian Foothills & Rockies, the problem is further complicated by anisotropy with a tilted axis.

Both geological environments present difficult challenges in model building, and in addition present challenges in the design of model updating software, as the assumptions for each case are quite different.

Data-Fitting & Tomographic Techniques

All inversion techniques involve the definition of some objective criterion of 'error' in the estimate of a model, and proceed to perturb the model so as to minimize this error.

The trade-off between speed (and robustness) and accuracy is the key element in an inversion scheme: we make some assumptions about the physical process involved, and try to represent some aspect of the process with a tractable set of equations which can allow us to relate some measurements to the model..

We minimize the differences between the observed data, and data computed (in light of our assumptions) in association with the present rendition of the model.

Thus inversion has two basic steps:

- forward model & compute differences between calculated and observed 'data'
- perturb model so as to reduce the magnitude of the differences, and iterate until satisfied.

Some techniques involve picking of data: this can be tedious; so various schemes exist for automating this part of the process. In addition, various data reduction schemes can be employed, such as stacking, so that the picking need only be done on one data volume (the zero offset cube, for example) instead of on many finite-offset volumes.

For example, the trade-off of picking on stacked data, constitutes a speed-up in the overall inversion process, but by stacking, we loose information: the complexity we are trying to recover in a complex model will often manifest itself in the non-hyperbolicity of the moveout in the pre-stack data. In stacking, we assume hyperbolicity, thus stacking destroys useful information in this case

3D Tomographic inversion of picked zero-offset stack times and stacking velocities:

In this technique, a 3D model is globally perturbed (in say a Marquart-Levenberg scheme), and for each perturbation, the finite-offset ray traced CMP arrival times are fitted with an hyperbola. This Hyperbola is used to determine a computed 'stack' time and stacking velocity associated with the current model perturbation. The model is iteratively perturbed so as to minimize the differences between observed and calculated stack times and stacking velocities.

This scheme is well suited for first arrivals, where the picks from the stack are reliable. However, when the stack is questionable, as it often is for complex geometries, then the input data to the inversion is suspect.

Because the scheme relies on picking from a stack, we have a much-reduced data volume involved in the picking (compared to pre-stack picking), but here the trade-off relates to accepting the corruption caused by the stacking process itself.

The technique can also be used for multi-arrivals by breaking the data into overlapping patches.

To a large extent, these techniques are limited to providing an initial model, as the imposed hyperbolic assumption (as the input data were picked from a stack) does not permit the resolution of velocity changes giving rise to anhyperbolicity.

We will see this in one example, where during an iterative preSDM update scheme we obtained progressively flatter gathers, but a run of tomography using each model could not distinguish between them on the basis of the tomographic objective function. In other words the differences in the modes which compensated for non-hyperbolic effects lay within the null-space of the inversion.

Tomographic inversion of picked zero-offset time-migrated times and DMO velocities:
As above, but with the benefit of using observables picked from migrated data: thus the input data are more reliable for complex geometries. However, the requirements for the scheme to internally de-migrated the picks, and back-out the effect of DMO from the velocities does also restrict its usefulness.

Tomographic Inversion of pre-stack finite-offset arrival times.
In conjunction with automated picking of horizons in the pre-stack data volumes, this technique can yield a rapid starting model to precede subsequent iterative updates. However, it faces the problem common to all picking of unmigrated data that the picking in complex area is very difficult.

Tomographic Inversion of pre-stack time migrated migrated finite-offset arrival times.
Here we avoid the problems of attempting to pick on unmigrated data in order to obtain the pre-stack finite offset input for the tomographic inversion scheme. Some schemes permit either cross-line migrated or fully 3D migrated data as input, and the migration used would usually be a full Kirchhoff finite-offset pre-stack time migration.

Tomographic Inversion of pre-stack depth migrated finite-offset arrival depths.
As above, we avoid the problems of attempting to pick on unmigrated data. Picks of residual depth error are made for all offsets on an event, and these picks fed to the inversion scheme so as to minimize these residual errors. As part of the inversion process, 3D ray-tracing occurs from the subsurface point where the residual errors were picked.

Such a technique is not constrained to updating only layer based models, as the picks can be considered as a ‘cloud’ of update constraints. Thus, this kind of scheme is very versatile.

It can also be used in conjunction with the CRP scanning technique, such that the input to the inversion can be picked from the flattest gathers resulting from a preSDM with a suite of perturbed velocity models.

Stereo Tomography.
In this pre-stack technique, two ‘dips’ are picked. In 2D, the dips could be the geological dip picked on an offset section, plus the time dip (gradient to the local tangent) seen for the event at the corresponding offset on a shot gather. In 3D, the ‘dips’ could be the gradients seen in shot and receiver gathers for the same event.

Migration Scanning Techniques.
As an issue separate from tomography and inversion, there exist several techniques based on model perturbation, and picking of the ‘best’ result, or of picking residual moveout from pre-stack migrated gathers.

These techniques are in-turn followed by an inversion (even if only vertical Dix) to update the velocity model on the basis of the picked ‘best’ result, or residual moveout correction.

The Deregowski Loop
This is the most basic technique for simple update of a model. The data are migrated, and the resulting gathers subjected to a residual moveout analysis. The results from this analysis (a new RMS velocity value) are used to update the interval velocity model.

It suffers from two inherent problems. Firstly, the fact that residual moveout exists in the migrated gathers indicates that the event being picked is located at the wrong spatial location. Secondly, the RMS error picked is then inverted vertically using the Dix equation.

To correctly update the model, we should pick the velocity error in its correct spatial location, and then update the velocity model by inverting along the normal to the reflector being updated.

The CRP-Scan
In this technique, a unique migration is performed for each of a suite of models, and the resulting scan of CRP gathers inspected to select the flattest (for the current horizon). In this way, we pick the error in its correct spatial location (the error here being the percentage perturbation value used to produce the flattest gather).

The perturbation can be performed either from the surface of the model, or for the last layer only.

Once the error has been determined, it is then updated either vertically for simple geometries, or along the normal to the subsurface event. When the update is computed back along the normal to the subsurface picking point, we can usually update more than one layer at a time.

Forward Modelling
Despite having said that we have two broad categories of model update, there are two techniques that rely primarily on forward modelling to provide information for obtaining an image. These are the Common Focus Point (CFP) technique (introduced by the Delft consortium), and coherency inversion.

CFP analysis
This is not so much a model update technique, as a method for finding the travel times that match that data via one-way ray tracing between the source to the subsurface. One-way travel times from a subsurface point (on a picked reflector) are perturbed so as to minimize the differences between the observed shot data and the modelled arrivals. No velocity model is produced in this process, and the zero offset image is produced as part of the CFP process. If we want to access the velocity model associated with the process, we would have to invert the CFP operators.

Coherency Inversion:
This quasi-1D scanning technique was originally based on ray-tracing through an initial model, so as to compute the move-out corridor for computing the coherency (semblance) in a velocity analysis window centred on the obtained trajectory corridor.

The velocity in the layer under investigation was then perturbed, and the (3D) ray-tracing repeated so as to yield a new semblance corridor for the subsequent velocity analysis element. By scanning over a range of perturbed velocities, the maximum semblance could be chosen by picking, and the velocity updated at this CMP location.

This technique is fast, but not very accurate, as there is no actual 3D migration of data involved, but merely a 1D perturbation of the local velocity field. Hence, we are assuming that we can accept a constant velocity perturbation within the ray bundle, and update the model point by point.

Due to its speed and ease of use (especially when using horizon consistent velocity analysis) this technique is often used for initial model construction. It involves no picking of seismic data, so avoids the pitfalls related to interpretation.

The Non-Layer-Based Case
The techniques mentioned above are easily applied to layer based velocity regimes, as the update information can simply be picked along reflector boundaries. The situation is less evident when the velocity field does not follow visible reflectors. In this case, we need an a-priori assumption of how the shape (geometry) of the velocity regions behaves. We then need to estimate a compaction gradient, which commences from a given depth (usually the sea bed). The compaction gradient and the starting velocity are in general spatially variant.

In order to update such a velocity field, we still need to pick information associated with reflectors, but the understanding is now that the update derived from a pick is not constrained to follow the horizon. Thus a scatter of picks is made, and the resulting ‘cloud’ of values input to the inversion scheme.

Acknowledgements
My sincere thanks to various colleagues throughout the industry for their comments on and contributions to this paper, including: Jan Kommedal (BP), Francois Audebert, Patrice Guillaume, & Jacques Negron (CGG), Eric Verschuur & Guus Berkhout (Delft), Gilles Lambare (ENSMP), Pierre Hardy, JeanPaul Jeannot, & Nick Bernitsas (GXT), Zvi Koren (Paradigm), Biondo Biondi (SEP), Dirk Smit (Shell Expro), Philippe Berthet, Vincent Devaux & Etienne Robein (TFE), Larry Lines (Univ. Calgary), Gareth Williams & Peter Whiting (Veritas), Robert Bloor & Jose Navarro (WesternGeco).

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