Local Angle Domain (LAD) Common Image Gathers (CIG) for Reflection Tomography and AVA(Z) in Complex Geological Areas

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Introduction

Advanced seismic tomography systems for velocity model updating are designed to enhance the accuracy and resolution of different types of background velocity models that include both velocity heterogeneity and anisotropy. They should be able to efficiently handle high-resolution, large-scale models using different types of input data, and should have the ability to impose different types of geological constraints.

Tomography is based on measuring traveltime errors along "energetic" waves/rays traveling across the subsurface model (e.g., reflections, refractions, diffractions, etc.). After formulating linear relationships between the traveltime errors and unknown subsurface model errors, and after constructing these relationships as a set of linear equations (tomography matrix), the tomography uses a constrained inversion process to find the model errors.

Obtaining accurate and reliable traveltime errors is one of the most challenging parts in the tomography workflow, especially when working in geological areas where complex wave phenomena are involved. In principle, traveltimes (moveouts) can be directly picked in the time gather domain, where the aim of the tomography is to find model perturbations that minimize the discrepancy between the computed and picked time events. However, in complex structures, the reflection events in the time gathers can be very complex (chaotic) containing many triplications and cusps. This makes the picking process in this domain extremely difficult, if at all possible. In some implementations, the picking of traveltimes and their slopes is performed over pre-processed local coherent events (e.g., Lambare, 2002), which tends to stabilize the process to a certain degree. Alternatively, a more stable approach is to pick residual moveouts (RMOs) rather than moveouts, along depth domain common image gathers (CIGs) and then to transform the RMOs into traveltime errors within the tomography. In this case, the complex reflection events recorded on the acquisition surface in the time domain are migrated, with an approximated background velocity, into image depth gathers, where the migrated events become nearly flat. Although the automatic picking in this domain is much simpler, we will show that when using offset domain common image gathers, some severe ambiguities might occur, which make their use questionable.

In this study we refer to reflection tomography, where traveltime errors are computed from depth domain RMOs which are automatically picked along different types of CIGs. It is well known that rich or wide azimuth data are essential for resolving the isotropic/anisotropic velocity model parameters in complex subsurface models, especially below and in the vicinity of salt bodies. We therefore concentrate on the use of 3D CIGs that contain imaging information from wide angles and azimuths. These have the potential to provide optimal data for the extraction of accurate RMOs for the tomography. In particular, we show the advantages of using amplitude-preserved CIGs in the Local Angle Domain (LAD) to provide the most reliable information for angle/azimuth dependent RMOs, which are then uniquely transformed into traveltime errors along the specular rays.

After minimizing the RMOs and flattening the CIGs reflection events, and due to the amplitude preserving imaging in the LAD, the resulting angle domain CIGs become the most suitable and accurate data for amplitude inversion, such as AVA(Z).

Angle Domain Traveltime Errors

The tomography is designed to be independent from the imaging method used in the creation of the CIGs. Within the tomography, specular ray pairs are traced from dense subsurface "reflecting points" $M = x, y, z$ up to the surface, with a given range and density of opening angles θ and azimuths φ, in order to span the subsurface model points from rich directions. An example of a specular ray pair used in tomography is shown in Figure 1. Reliable traveltime errors $\delta t(M,\theta,\varphi)$ are then required to generate the tomography matrix. As noted above, these traveltime errors are usually obtained from depth domain RMOs extracted along CIGs. In order to compute the required traveltime errors along the ray pairs, the depth domain RMOs should be first transformed (interpolated) into the ray pairs' opening angle/azimuth. The traveltime errors are then given by (Kosloff et al, 1995),

$$\delta t(M,\theta,\varphi) = \delta z(M,\theta,\varphi)\left(p_z^i + p_z^r\right) \tag{1}$$

where p_z^i, p_z^r are the vertical slowness parameters of the incident and reflected rays at point M, respectively.

CIGs and RMOs

Three main types of 3D CIGs are commonly generated in exploration geophysics and can be used to provide offset/angle and azimuth varying RMOs:

1. LAD gathers (e.g., Koren and Ravve, 2011)
2. Surface offset vector tile (S-OVT) gathers which are generated by Kirchhoff migrations
3. Image offset vector tile (I-OVT) gathers which are generated by common shot wave equation migrations, like Reverse Time Migrations (RTM) and WEM (a one-way wave equation extrapolation method)

Depth domain RMOs are automatically extracted from these gathers using a high-fidelity automatic event picking procedure. The method we use is based on a direct solution of the Poisson equation (Bartana et al, 2010). The automatically picked RMOs are then transformed to traveltime errors along specular (reflection) ray pairs within the tomography.

Below we show how the traveltime errors are computed from the different types of CIGs/RMOs mentioned above.

Using the LAD gathers with the corresponding in situ angle/azimuth depth domain RMOs, traveltime errors are **uniquely** obtained in a straightforward interpolation as,

$$\delta z\left(M,\gamma_1,\gamma_2\right) \Rightarrow \delta z\left(M,\theta,\varphi\right) \tag{2}$$

where, γ_1, γ_2 are the opening angles and opening azimuths of the angle domain CIGs, respectively.

Using the Kirchhoff based S-OVT or the RTM based I-OVT depth domain RMOs, the in situ angle/azimuth RMOs should be first computed using the traced specular ray pairs; i.e., mapping the surface or image offsets into subsurface angles. For the Kirchhoff S-OVT, the RMO ray-based transformation is symbolically given as,

$$\delta z(M,h_{s,x},h_{s,y}) \text{ or } \delta z(M,h_s,\varphi_s) \overset{\text{Ray Tracing}}{\Longrightarrow} \delta z\left(M,\theta,\varphi\right) \tag{3}$$

where $h_{s,x}$, $h_{s,y}$ or h_s, φ_s are respectively the x, y or radial and azimuth components of the surface source-receiver offsets. For the RTM I-OVT, the ray-based transformation is symbolically given as,

$$\delta z(M,h_{i,x},h_{i,y}) \text{ or } \delta z(M,h_i,\varphi_i) \overset{\text{Ray Tracing}}{\Longrightarrow} \delta z\left(M,\theta,\varphi\right) \tag{4}$$

where $h_{i,x}$, $h_{i,y}$ or h_i, φ_i are respectively the x, y or radial and azimuth components of the image offsets (horizontal distance between a given source and the image location). Once $\delta z\left(M,\theta,\varphi\right)$ is obtained, Equation 1 is used to compute the traveltime errors $\delta t\left(M,\theta,\varphi\right)$.

Multi-Pathing

Multi-pathing (or multi-arrival) phenomena are the main cause of problems when using the last two types of RMOs (S-OVT and I-OVT) in the tomography, making the transformation of the RMOs into traveltime errors non-unique.

In the case of S-OVT, several seismic events reflecting from the same location at the subsurface reflector, with the same surface offset and surface offset azimuth but with different CMP locations at different times, will be migrated into the same event in the CIG. Figure 2 schematically shows a situation where the two specular rays with the same offset and azimuth are mapped into the same bin in the S-OVT gather but into different bins in the LAD gather. In this case, when using S-OVT gathers, it will be impossible to know how to assign the RMO in that bin to the right ray pair.

In the case of I-OVT, a number of different incident rays can connect a given subsurface image point with a given source located on the acquisition surface (multi-pathing) where the corresponding reflected rays are obtained by tracing rays up with a take-off angle computing by using Snell's Law. Again, all these multi-arrival waves will be migrated (summed) by the RTM into the same event in the CIG. Figure 3 schematically shows three different specular ray pairs in which the incident rays connect the image point with the same source (multi-pathing). Their corresponding seismic event will be mapped into the same bin in the I-OVT gather. Again, we lose the connectivity between the RMO in that bin and the correct ray pair.

In both cases there are ambiguities regarding the assignment of a particular RMO with a certain ray pair. The connectivity between a given specular ray pair and its corresponding traveltime error is lost. Moreover, by assigning traveltime errors to wrong ray pairs, we can damage the subsurface velocity model, leading to divergence rather than convergence to a more accurate model.

Inward and Outward Specular Migrated Events in the Same Location

In complex areas with steep dips and a considerable velocity variation in the lateral and vertical directions, the contribution of specular energy to image points located along the steep horizons can come from two opposite specular directions: Inward (direction of the reflector's normal) and Outward (the opposite direction; + 180 degrees). An example of inward and outward specular ray pairs is shown for the BP TTI synthetic salt model (Figure 4). In some cases, only one of these directions will contribute to the image, since the specular rays associated with its reverse direction will not arrive to the acquisition surface. It is essential to decompose these two different imaging directions and their corresponding RMOs, since they are constructed from rays (waves) traveling through completely different parts of the model. As with the case of multi-pathing, assigning traveltime errors to wrong ray pairs can result in convergence to a wrong model.

Conventional migrations like Kirchhoff and RTM do not have the internal mechanism needed to distinguish between the different apparent directivities of the ray pairs (or wave pairs). However, the LAD imaging method (e.g., Koren and Ravve 2011) provides full control over the directivity and straightforward decomposition of these two different imaging directions.

AVA(Z)

Obviously, a reliable analysis of AVA(Z) - amplitude versus angle (and optionally azimuth) - requires an amplitude preserved migration to construct the angle/azimuth dependent reflectivities at the target image locations. Unlike Kirchhoff and RTM-based migrations, LAD imaging provides this type of information in the most efficient and accurate manner possible (Koren and Ravve, 2011). AVA(Z) is applied to flat reflection angle events within the CIGs following tomography and a final flattening procedure which is normally based on automatic RMO correction. Since the resulting subsurface model is never perfect, and since the accuracy of the amplitude correction along the traced rays is somehow limited (high-frequency asymptotic ray method), it is important to refrain from mixing different families of specular events when constructing the migrated reflection events of the CIGs, which is the case in Kirchhoff and RTM migrations. Moreover, in the case of mixing (or flipping) inward and outward imaging contributions at the same subsurface location, the physical meaning of the resulting angle domain reflectivity is actually wrong. The proposed LAD migration is the only imaging tool that can efficiently provide accurate and non-conflicting migrated events which are reliable enough for amplitude analysis.

Conclusions

In this work we show that among the different types of CIGs generated by seismic migrations, only migration in the local angle domain provides CIGs that can be reliably used for kinematic velocity model updating (tomography) and for dynamic amplitude inversion (AVAZ). Moreover, when introducing the background directivity of the reflection surfaces within the imaging process, it is possible to distinguish between inward and outward directions in the same location representing the different imaging contributions from both sides of the target reflectors. The migration then becomes very efficient, since only controlled and limited directions are used in the data integration within the migration.

References

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Figures

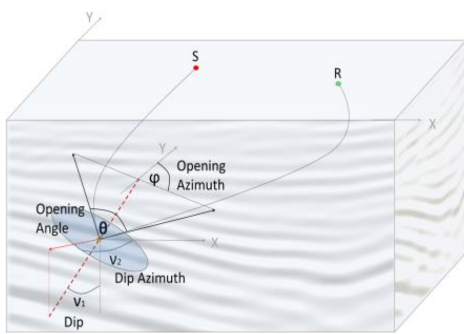

Figure 1. Example of a specular ray pair used in tomography

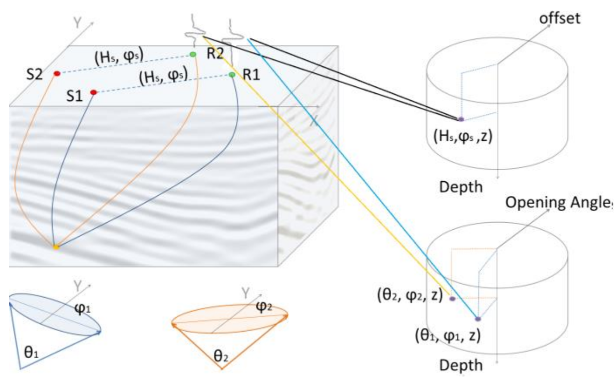

Figure 2. Two specular rays with the same offset and azimuth mapped into the same bin in the S-OVT gather but to different bins in the LAD gather

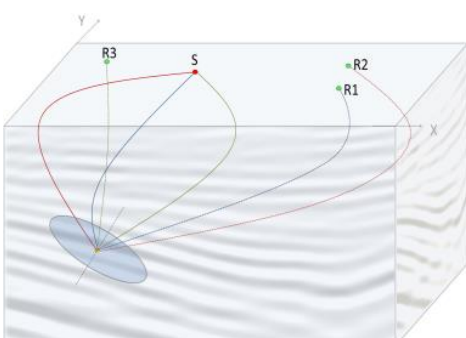

Figure 3. Three specular ray pairs showing shot domain multi-pathing. Their corresponding seismic event will be mapped into the same bin in the I-OVT gather.

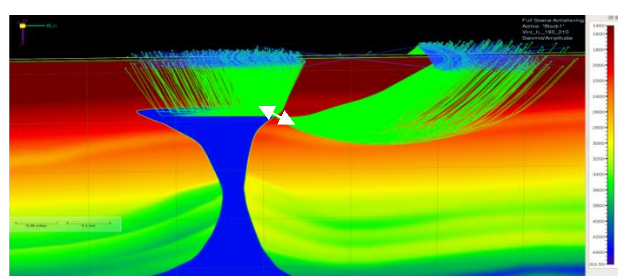

Figure 4. Inward and outward specular ray pairs from the same subsurface point (BP TTI synthetic salt model)