Inverting for Reservoir Change: 4D image-domain tomography

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ABSTRACT

Adjoint-state methods (ASMs) have proven successful for calculating the gradients of the functionals commonly found in geophysical inverse problems. The 3D ASM image-domain tomography (IDT) formulation of the seismic velocity estimation problem highlights imperfections in migrated image volumes and, using appropriate penalty functions (e.g., differential semblance), forms an objective function that can be minimized using standard optimization approaches. For time-lapse (4D) seismic scenarios, the 3D ASM-IDT approach can be extended to multiple datasets and offers high quality estimates of subsurface velocity change. I discuss two different 4D inversion strategies: absolute and relative. The *absolute* approach uses the difference of independent 3D inversions to estimate a 4D model perturbation. The *relative* approach inverts for the model perturbation that optimally matches the monitor image to the baseline image - even where migrated energy is imperfectly focused. Both approaches yield useful 4D slowness estimates; however, we assert that the *relative* approach is more robust given the ubiquitous presence of non-repeatable 4D seismic acquisition noise and imperfect model estimates.

Key words: velocity, inversion, imaging, seismic, 4D/time-lapse

INTRODUCTION

Adjoint-state methods (ASMs) have been used with success for many years in seismic exploration as an effective tool for calculating the gradient of a functional. Whilst the majority of studies focus on data-domain implementations - in particular, full waveform inversion (FWI), a number of studies explore complementary image-domain tomography (IDT) strategies. Rather than posing an objective function (OF) based on differences between modelled and field data, IDT inversion approaches use OFs that measure observed imperfections in migrated images (i.e., poorly focused extended image gathers). Similar to the data-domain FWI approaches, these imperfections are back-projected using the ASM machinery to form gradient estimates appropriate for velocity model updating.

Because image-domain approaches do not match data amplitudes and thereby wavefield dynamics, they afford lower resolution than data-domain methods; however, they are less sensitive to the manifold factors affecting seismic amplitudes (e.g., attenuation, irregular illumination). While normally considered a negative trait, one corollary is that ASM-IDT inversions are more robust than data-domain ASM approaches because they satisfy less-demanding inversion criteria. This leads to an increased likelihood of converging toward correct - though necessarily more bandlimited - inversion results. Model perturbations derived from ASM-IDT analyses are thus useful when employed either outright as a final 3D migration velocity model or as the input to higher-resolution data-domain FWI analysis. Thus, there is great utility in further examining ASM-IDT methods for 2D/3D/4D velocity model building analyses.

METHODOLOGY

The 2D/3D ASM-IDT goal is to invert for the model slowness perturbation, $\Delta s_1 \approx s_1 - s_0$ (see Figure 1a), that optimally focuses the image and represents the difference between the true and background models, s_1 and s_0, respectively. A key decision in the ASM-IDT inversion procedure is to specify a judicious penalty operator that eliminates energy already optimally focused in the extended image gather volume at the zero correlation lag and upweights that poorly focused at non-zero correlation lags. One way to accomplish this is through a differential semblance operator (DSO) that cancels out a perfectly focused image at the zero correlation lag. Figure 2 shows the result of an ASM-IDT inversion procedure using DSO operators, including: (a) the depth migrated image using the incorrect background model s_0; (b) the inverted velocity perturbation Δs_1 using the 2D ASM-IDT strategy; and (c) the optimized image migrated using model $s_0 + \Delta s_1$.

The 4D ASM-IDT velocity estimation problem shares many similarities with - and may be regarded an extension of - 3D ASM-IDT inversion. Two key differences are that there are now multiple data sets to work with as well as multiple slowness perturbations to recover: (a) baseline Δs_1 in Figure 1a; (b) monitor Δs_2 in Figure 1b; and (c) the time-lapse Δs_{TL} difference shown in blue in Figure 1b). However, unlike the 3D problem where one seeks the *absolute* slowness perturbation that optimally focuses reflectivity at zero correlation lag, for 4D applications one can use either an *absolute* or a *relative* inversion strategy when estimating Δs_{TL}.

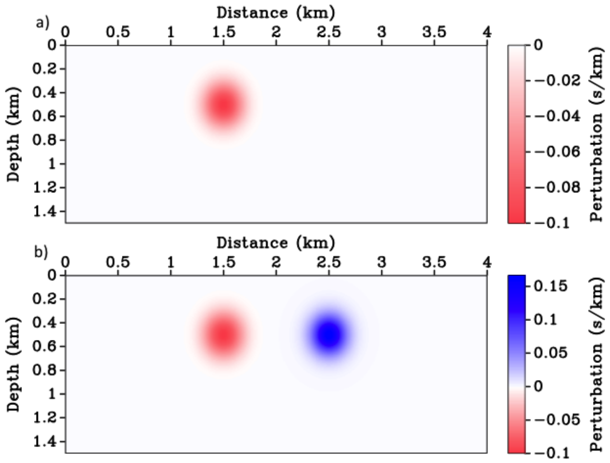

Figure 1. Slowness perturbations from the constant background s_0=0.5 s/km model. (a) Baseline Δs_1. (b) Baseline and monitor $\Delta s_1+\Delta s_2$.

The *absolute* 4D inversion approach is achieved by solving two separate tomographic inversions that independently estimate Δs_1 and Δs_2 and then taking their difference. Figure 3a shows the concatenation of penalized image gathers, subject to an *absolute* penalty operator, that show the time-lapse image difference supposed caused by Δs_{TL}. The corresponding ASM-IDT result (Figure 3c) shows a fairly diffuse model perturbation that is not spatially compact.

Alternatively, one may estimate a *relative* 4D slowness difference by coupling the baseline and monitor datasets in an inversion procedure that finds the slowness perturbation that optimally matches the monitor image to the baseline image. Figure 3b shows concatenation of penalized mage gathers, subject to a *relative* penalty operator, that shows time-lapse image difference again supposed caused by Δs_{TL}. We note that the residual energy is more compact in Figure 3b than 3a. The inverted ASM-IDT result (Figure 3d) shows a much more compact model perturbation than Figure 3c, indicating that the relative approach is more robust and leads to improved 4D ASM-IDT results.

CONCLUSIONS

I extend 3D ASM-IDT inversion to 4D scenarios and discuss absolute and relative inversion strategies. Because the relative inversion strategy couples the baseline and monitor datasets by incorporating the baseline image into the monitor penalty operator, this allows consistently - though not necessarily optimally - imaged reflectivity to be removed leading to more robust 4D seismic velocity inversion result.

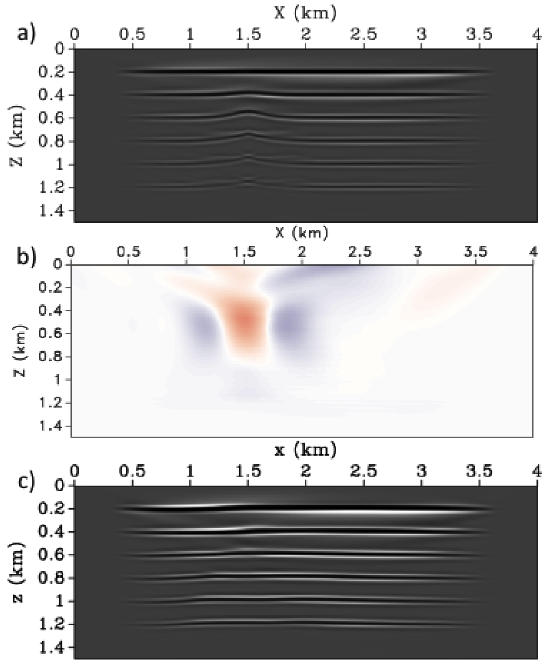

Figure 2. (a) Baseline image using background model s_0=0.5 s/km. (b) Inverted perturbation estimate Δs_1. (c) Baseline image using migration slowness $s_0+\Delta s_1$.

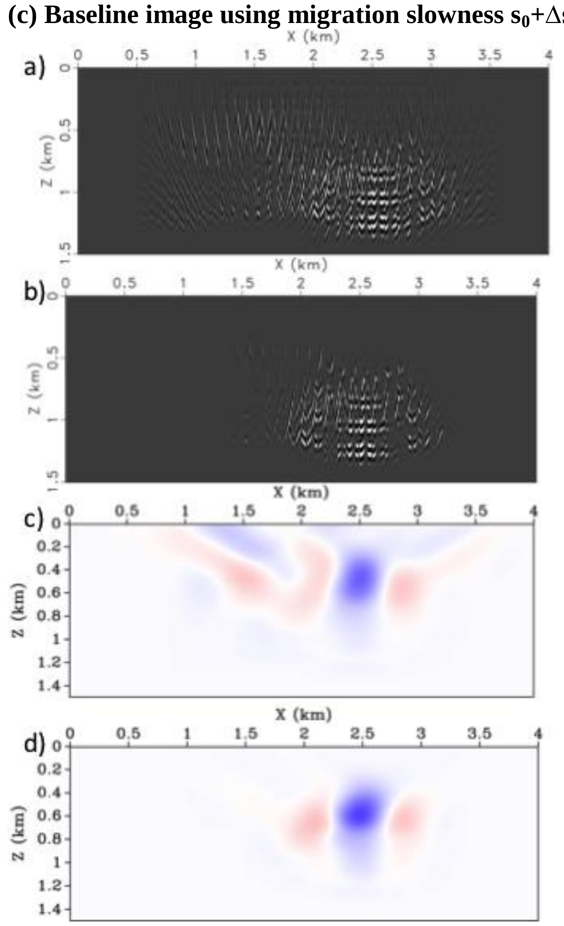

Figure 3. Monitor images and inversion results using slowness profile $s_0+\Delta s_1$. (a) Horizontal concatenation of penalized correlation gathers for *absolute* penalty. (b) As in (a) but for *relative* penalty operator. (c) Estimated *absolute* perturbation $\Delta s_{2\lambda}$. (d) Estimated *relative* perturbation Δs_2.