# Double-difference/slope tomography by a variational projection approach (Abstract S33D-3583)

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## I - Context

• **Stereotomography** (slope tomography) (Lambaré, 2008), a **velocity macro-model building** method, exploits the horizontal component of the slowness vector at source and receiver positions. The **two slopes** associated with the **two-way traveltimes** define a **locally coherent event** in the data volume associated with a scatterer in the image domain.

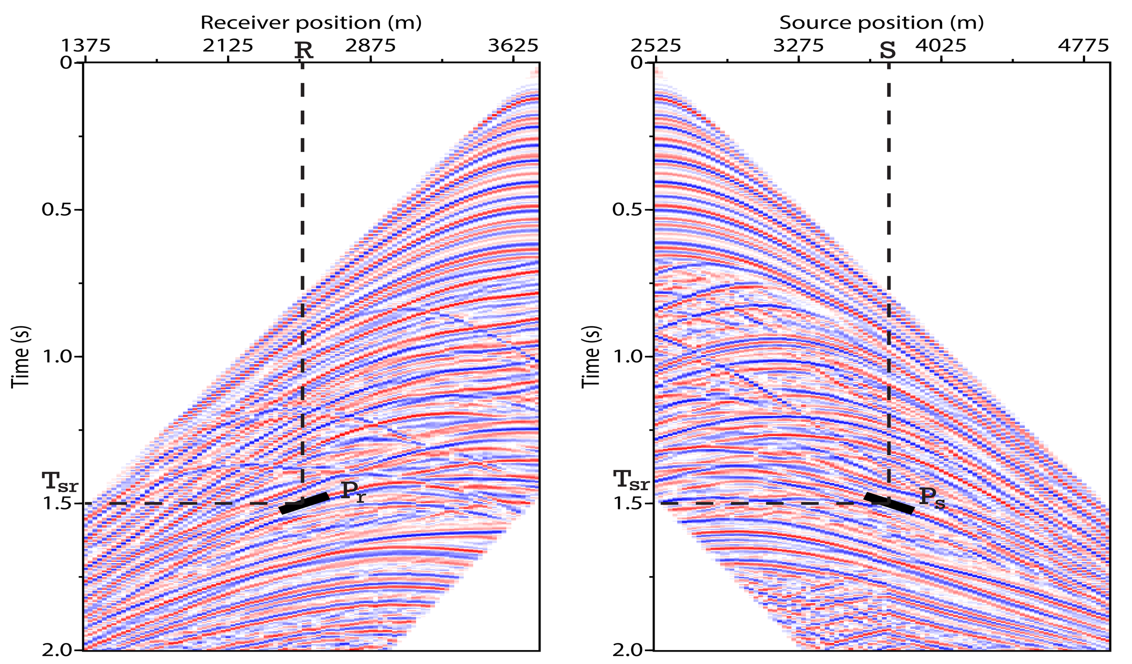


**Figure 1:** A locally coherent event picked in the data.

• **We address the issue of the ill-famed velocity-position coupling inherently present in reflection tomography. The strategy presented in this context draws perspectives to the analogous localization problem in earthquake seismology.**

## II - Method

• We opt for the **matrix-free formulation** of slope tomography (AST) (Tavakoli F. et al., 2017) based on the **adjoint-state method** (vs. Fréchet derivatives) for the gradient computation. The forward problem is performed with **eikonal solvers** (vs. ray tracing).

• Commonly, the chosen optimization strategy aims at fitting all objective measures (**two-way traveltime and both slopes**) per scatterer, in search of **the velocity field and the scattering position jointly**.

• We propose a parsimonious formulation (PAST) that reduces the problem to fitting **one slope** in seek of **the velocity field** through a variational approach.

• **How?** An identified event in the data volume can be mapped in the image domain through a **kinematic migration** by means of the **focusing equations** (Chauris et al., 2002).

• **So what?** We elaborate on this relationship and how it is implemented in the form of **enforced physical constraints** under AST's framework and its implications on the **velocity-position coupling**.

## III - Towards a velocity-position consistent formulation

In the proposed parsimonious approach we aim to solve the following minimization problem:

$$\min_{\mathbf{m}} J(\mathbf{m}) = \min_{\mathbf{m}} \sum_{s=1}^{N_\mathbf{s}} \sum_{r=1}^{N_r^s} \sum_{n_{s,r}=1}^{N_\mathbf{n}^{s,r}} \|(p_{s,n_{s,r}}(\mathbf{m}) - p^*_{s,n_{s,r}})\|^2,$$

where $N_s$ / $N_s^r$ / $N_{n_{s,r}}$ denotes the number of shots, receivers and events for a source/receiver pair $(s,r)$. The symbol $*$ denotes the observed data. The predicted slope $p_{s,n_{s,r}}(\mathbf{m})$ depends on the model parameters through a nonlinear forward problem operator $\mathcal{F}$ which gathers the eikonal equation, the finite-difference approximation of slopes and the **focusing equations (1) and (2) (figure below)**.

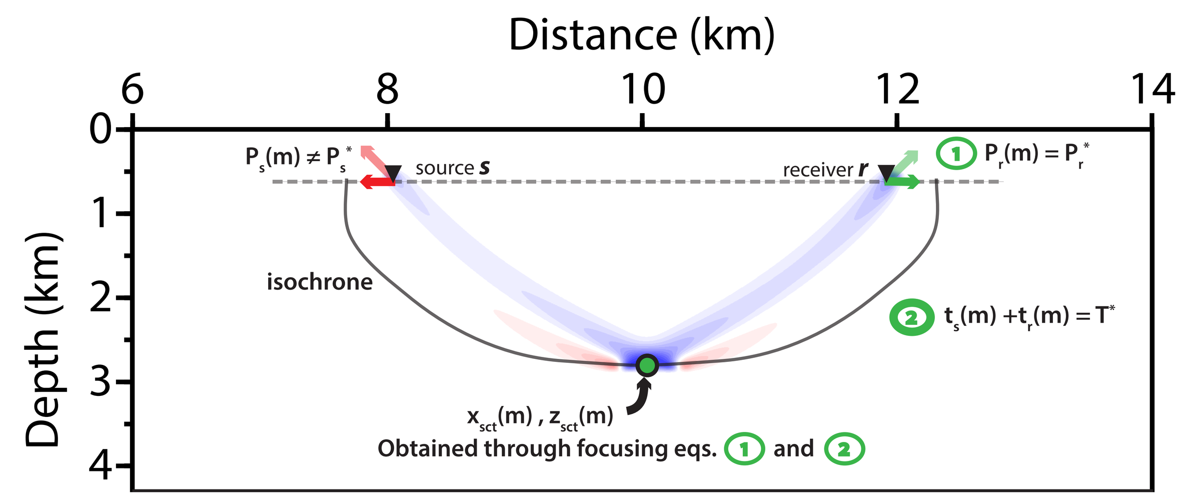


**Figure 2:** Focusing equations sketch superimposing a sensitivity kernel for a single scattering event.

We proceed under the reduced-space approach of the adjoint-state method (Plessix, 2006) for the gradient computation: $\mathcal{L}(\mathbf{m}, \mathbf{u}, \bar{\mathbf{u}}) = J(\mathbf{u}) - \left\langle \bar{\mathbf{u}}, \mathcal{F}(\mathbf{u}, \mathbf{m}) \right\rangle$, where $\langle ., . \rangle$ denotes the inner product, $\mathbf{u}$ gathers the state variables, $\bar{\mathbf{u}}$ the adjoint-state variables.

The projection of the scatterer position $\mathbf{x}_{n_{s,r}}$ out of the model space using the focusing equations implies a transmission of the positioning effect into the slope $p_{s,n_{s,r}}$ sensitivity with respect to $m$. The link is established while zeroing the derivative of the augmented functional with respect to $\mathbf{x}_{n_{s,r}}$:

$$\frac{\partial \mathcal{L}}{\partial \mathbf{x}_{n_{s,r}}} = \bar{\mathbf{u}}_1 \frac{\partial T_{s,r,n_{s,r}}}{\partial \mathbf{x}_{n_{s,r}}} + \Delta p_{s,n_{s,r}} \frac{\partial p_{s,n_{s,r}}}{\partial \mathbf{x}_{n_{s,r}}} + \bar{\mathbf{u}}_2 \frac{\partial p_{r,n_{s,r}}}{\partial \mathbf{x}_{n_{s,r}}}.$$

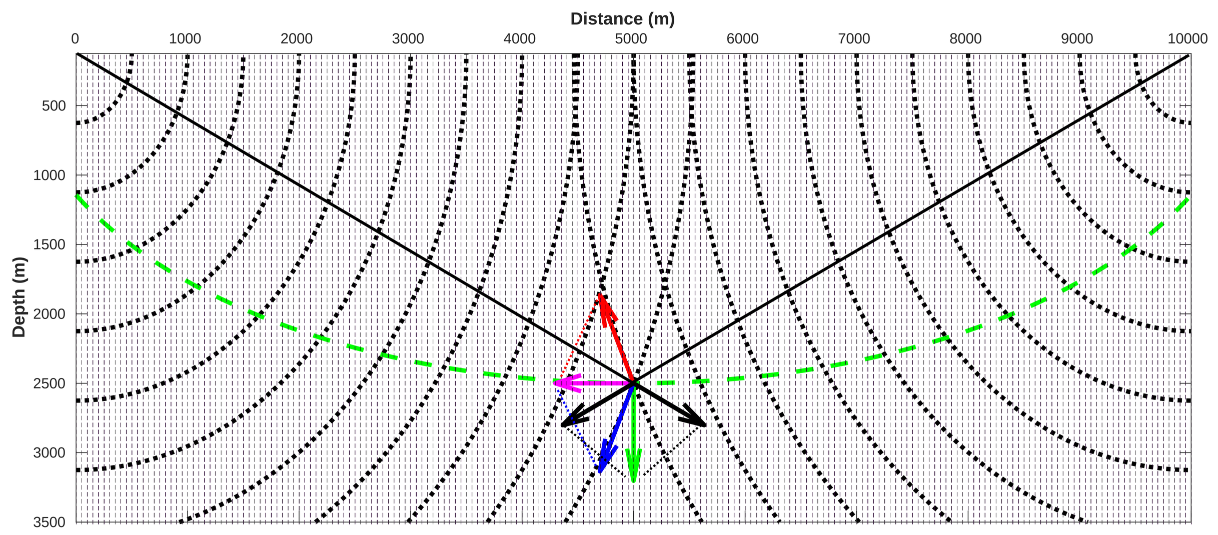


**Figure 3:** Three terms of $\partial \mathcal{L} / \partial \mathbf{x}_{n_{s,r}}$ with related colors. Added magenta arrow is the sum of blue and red arrows.

## IV - Synthetic and real data application

•**Marmousi case :** Tomography setup → 6708 scattering events, streamer acquisition, multi-scale approach. FWI setup → fixed-spread acquisition, frequencies [4, 6, 8, 10, 12, 14 and 16 Hz].

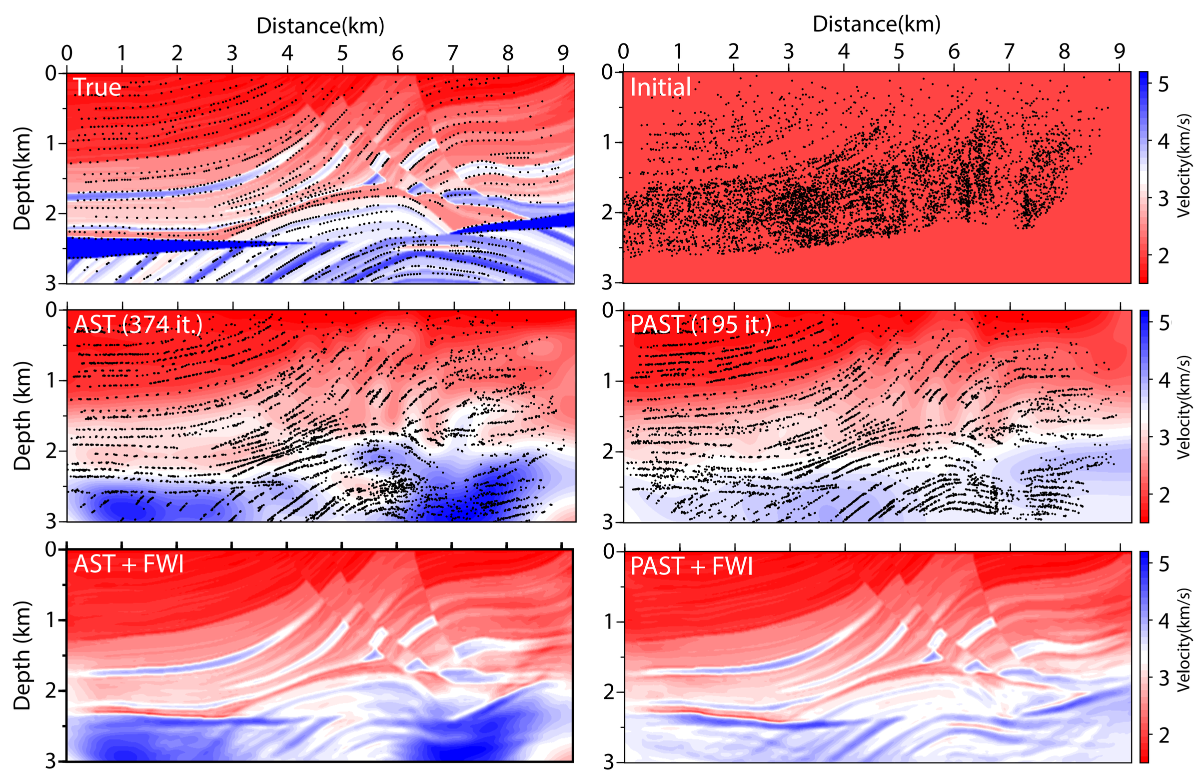


**Figure 4:** AST and PAST inversion results and their FWI.

✓ Good velocity reconstruction in the reservoir.
✓ Improved convergence with respect to AST.

•**Real data application :** Broadband streamer acquisition, 50000 scattering events, multi-scale approach, passive anisotropy (TTI) parameters.

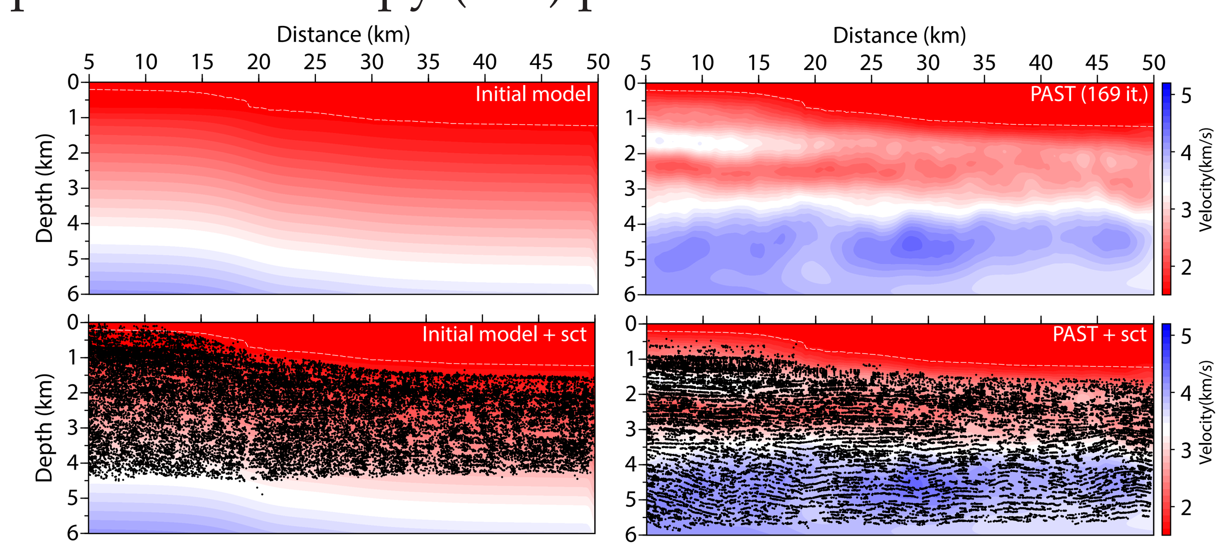


**Figure 5:** PAST inversion results after 169 iterations.

✓ Velocity model validated with well logs.

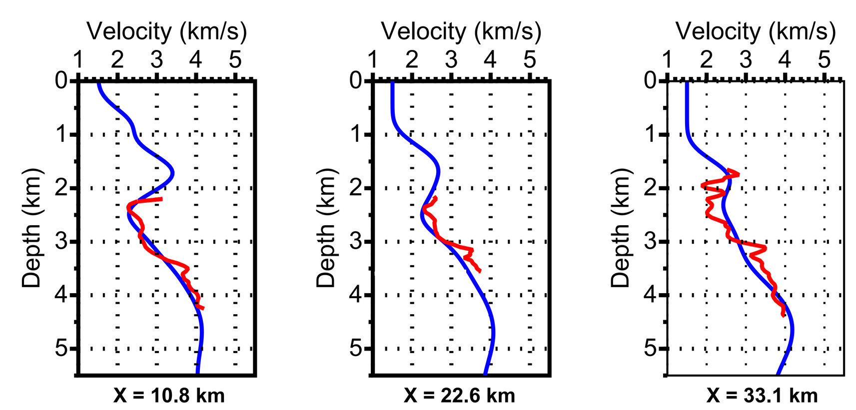


**Figure 6:** Comparative logs with respect to well data (red).

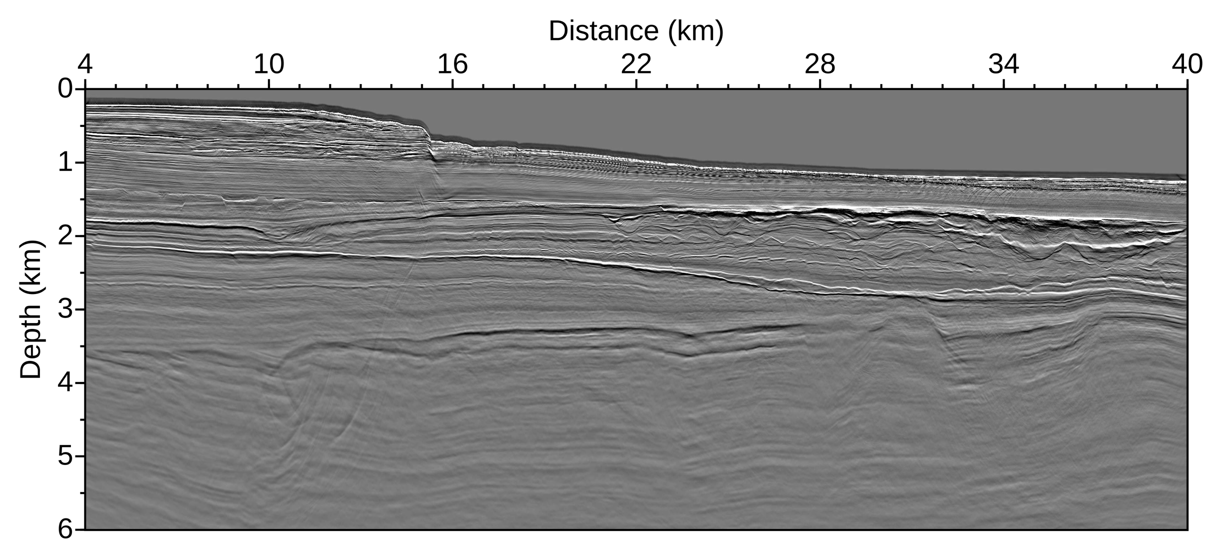


**Figure 7:** Image obtained through TTI Kirchhoff migration.

✓ Well focused image and coherent result with respect to previous studies.
✓ Flat events in the Common Image Gathers.

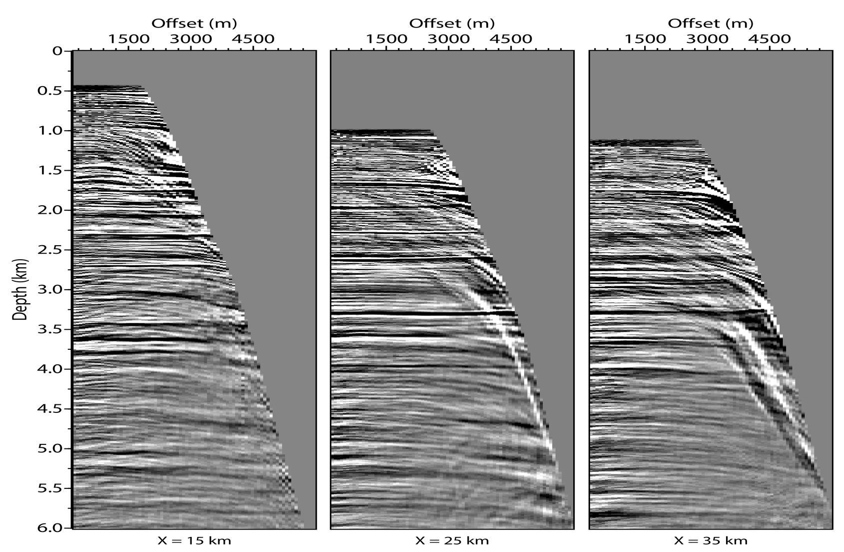


**Figure 8:** Common Image Gathers (CIG)

## Conclusion

We present a strategy to tackle the velocity-position coupling in the context of slope tomography. An induced consistency between the scatterers position and the background velocity field is achieved through a variational projection approach. We benchmark our method and validate it on a real data case. The results exhibit an improvement under this formulation with respect to a joint inversion.
A similar approach could be employed in other contexts like the hypocenter-velocity problem.

## References

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