# Near-surface traveltime tomography with long-wavelength statics optimization

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**Summary**

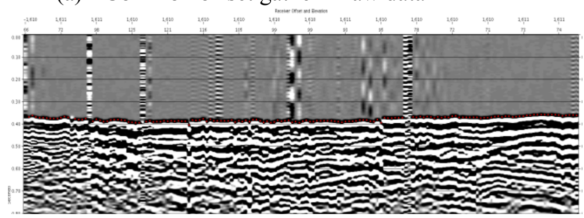
The first-arrival traveltime tomography has been applied to resolve near-surface complex structures, which are used to calculate long-wavelength statics corrections for reflection imaging. However, such tomographic imaging results cannot guarantee the statics solutions effective. This is because the traveltime tomography solutions are nonunique, and making effective statics corrections is not any part of the tomographic objective function. After calculating long-wavelength statics, we often apply that to raw data and observe the changes of the first arrivals in the common offset domain for a quick QC examination. An effective statics solution should help to smooth the first arrivals. In this study, we explicitly include this QC approach in the tomographic objective function by assuming virtual sources and receivers at the intermediate datum. Traveltimes from the surface sources or receivers to the virtual receivers or sources are calculated after each inversion iteration, and the results are subtracted from the first arrivals. The lateral variations of the remaining quantities along the surface are explicitly minimized in the tomographic objective function. This approach will ensure that the long-wavelength statics solution effectively removes the near surface variances by using traveltime data alone.

**Introduction**

Applying turning-ray traveltime tomography or first-arrival traveltime tomography can help to reconstruct the near surface velocity structures (Zhu et al., 1992; Zhang and Toksöz, 1998), which can be used to calculate long-wavelength statics. The fundamental assumption of the approach is such that the traveltime tomography method should accurately reconstruct the near surface velocities, and the subsequent statics calculation is then accurate as well. However, geophysical inversions are nonunique, and there are many situations that the traveltime data are perfectly fit but the resulted velocity model is not necessarily close to the true model enough for making effective statics corrections. Certain complex velocity structures such as thin beds, low-velocity layers, small objects, and many others may not be fully resolvable by any traveltime method. Thus, statics values calculated using the solution model for seismic data processing may not be correct. Our intention is to develop a traveltime tomography method that explicitly constraints long-wavelength statics such that the velocity model solution with optimal statics is favored among nonunique velocity model solutions.

There are a number of ways to do quality control for statics corrections. We intend to include a statics quality control process in traveltime tomography executed in an automatic fashion. The quality control methods include stacking image with statics applied, which should justify the statics values. Another approach is to observe the first-arrival traveltimes over several common offsets across the survey line before and after the long-wavelength statics is applied. If statics corrections are effective, it should remove large variations in the common-offset traveltimes along the profile. Figure 1 shows an example of raw data without and with effective long-wavelength statics applied.

(a) Common offset gather – raw data



(b) Common offset gather with statics applied

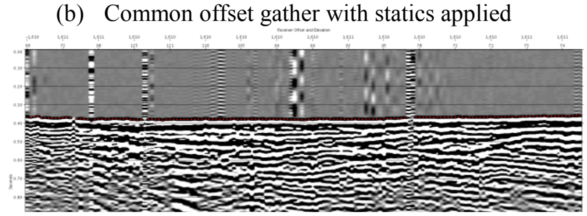


Figure 1: (a) Raw data in the common offset display; (b) Raw data after statics applied in the common offset display.

Connecting our traveltime tomography with the stacking process directly is difficult, since it requires accessing wavefield data. However, including statics QC in the common-offset traveltime domain in the traveltime tomography is straight-forward since traveltime data are already available and accessed. Therefore, we want to solve a first-arrival traveltime tomography that fits the traveltime data and also minimizes the traveltime variance in the common-offset domain after statics correction is applied.

A number of publications present a traveltime tomography method that simultaneously solves a velocity model and source and receiver residual statics (Tryggvason et al., 2009; Squires et al., 1992; 1994; Simmons and Backus, 1992; Bergman et al., 2004, 2006). Their approach is robust, and is proven by both synthetics and real data. However, their problem and the approach are different from this study. They are dealing with residual statics due to partial traveltime misfit that cannot be represented by any long-wavelength velocity model, while we are dealing with long-wavelength statics associated with a near surface velocity model. Our tomography does not directly invert any statics since it only constrains relative statics variances rather than absolute values. We will still need to calculate the long-wavelength statics using the final velocity solution.

## Method and theory

In our Statics-Optimized Traveltime Tomography (SOTT), we want to minimize the following objective function that includes three terms:

$$\Phi(m) = \left\| d - G(m) \right\|^2 + \alpha \left\| D_x (d_{off} - T_s(m) - T_r(m)) \right\|^2 + \beta \left\| L(m) \right\|^2 \qquad (1)$$

Where $d$ is the picked traveltimes, $G(m)$ is calculated traveltimes using model $m$, $d_{off}$ is the common-offset traveltime data, $T_s$ and $T_r$ are the down-going source and receiver statics associated with model $m$, $D_x$ is a first-order derivative operator over distance, $L$ is a Laplacian operator. $\alpha$ and $\beta$ are the scaling factors for the second and third terms.

We apply a wavefront method to calculate traveltimes and raypaths. For inversions, we apply a conjugate gradient method to solve a Gauss-Newton inverse problem.

The above equation (1) follows a schematic plot shown in Figure 2:

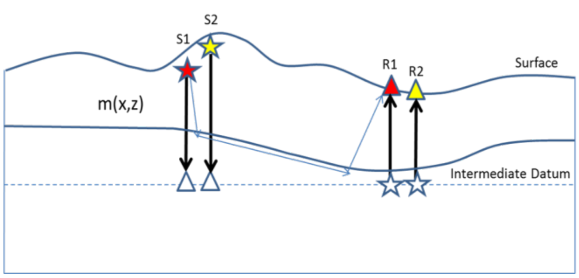



Figure 2: The difference between traveltime S1 to R1 and S2 to R2 corrected by down-going traveltimes (statics) is minimized in tomography.

We should define an intermediate datum, and place virtual sources and receivers on the datum. Virtual receivers are placed right below actual sources, and virtual sources are placed right below receivers. For any given model, we can calculate the vertical times from sources to virtual receivers and from receivers to virtual sources. These vertical traveltimes are the major components of the long-wavelength statics, since the up-going vertical times in statics are calculated with a constant replacement velocity.

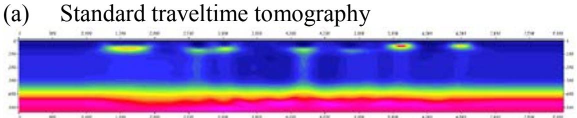
In equation (1), we do not have real data of the vertical times, but we know that the variances should be minimized while fitting traveltimes. Since down-going and up-going raypaths of refraction are near vertical, applying statics corrections to the first arrivals is going to smooth the traveltime variance in common offset domain due to the near surface structures. This is the basis for the second term in the objective function.

In principle, this new approach intends to produce a tomographic solution that ensures the magnitude of lateral statics variations large enough so that statics corrections could remove the relative trace shifts due to near surface velocity variations.

## Synthetic example

We design a synthetic experiment with a near surface velocity model that consists of a flat refractor and seven high velocity anomalies above the refractor. The true model is fairly simple, and is not shown in figure. Figure 2a) shows the result from a standard traveltime tomography (TT) that minimizes data misfit and regularizes model as well. Figure 2b) shows the result from statics-optimized traveltime tomography (SOTT) imposed by the objective function (1). Both results do not perfectly recover the true velocity model but resolve the major features. However, SOTT results show much sharper lateral variations in the velocity model and the large magnitude of vertical traveltime variation over distance is maintained. That is essential for making proper statics corrections.

(a) Standard traveltime tomography



(b) Statics-optimized traveltime tomography

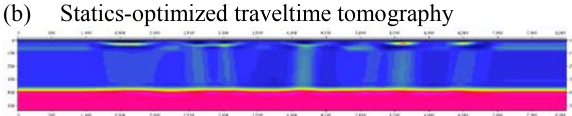


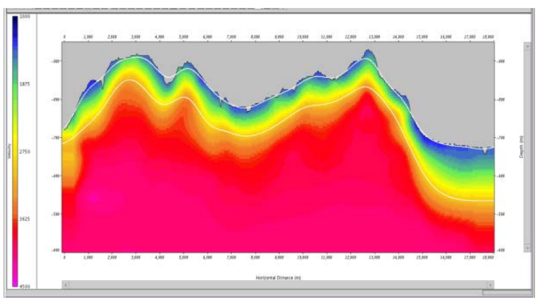
Figure 3: Synthetic test with a few velocity scatters. (a) Standard traveltime tomography result; (b) Statics-optimized traveltime tomography result.

The synthetic experiment suggests that fitting traveltimes with or without statics optimization produces different velocity models, although both models fit data equally well. Statics optimization ensures that the common offset traveltimes after statics corrections are smooth and continuous. We favor the statics-optimized velocity model even though it does not fully reconstruct the true model, but it fully reconstructs the long-wavelength statics.

**Real data example**

We also apply the method to a real 2D dataset and invert for a near surface velocity model that is optimized for statics solutions. This dataset is acquired over a mountain area with rough topography. Figure 3a) shows the velocity model inverted from applying standard traveltime tomography, and Figure 3b) presents the velocity model inverted from applying statics-optimized traveltime tomography. Their model differences are small, however, significant for making statics corrections. Again, SOTT produces larger magnitude of statics values due to shaper later velocity contrasts.

(a) Standard traveltime tomography



(b) Statics-optimized traveltime tomography

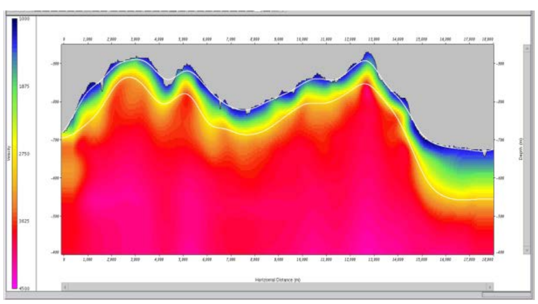
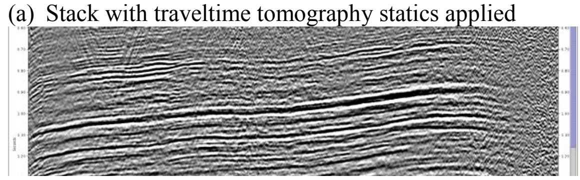


Figure 4: (a) The near surface velocity model is resolved from applying a standard traveltime tomography; (b) the near surface velocity model is resolved from applying statics-optimised traveltime tomography.

The following figure shows constant-velocity stacks by applying statics calculated using the model inverted from applying a standard traveltime tomography and by using a model inverted from applying statics-optimized traveltime tomography.

(a) Stack with traveltime tomography statics applied



(b) Stack with optimized tomography statics applied

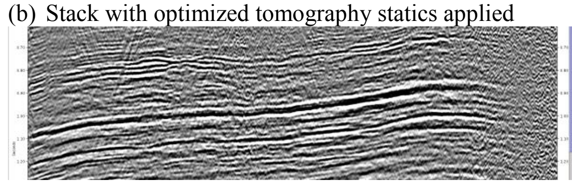


Figure 5: (a) A constant-velocity stack with standard traveltime tomography statics applied. (b) A constant-velocity stack with optimized statics applied.

It appears that SOTT helps to produce better event continuity as shown in Figure 4b). The shallow events are broken in Figure 4a), while they are continuous in Figure 4b).

**Conclusions**

I present a statics-optimised traveltime tomography method for the near surface imaging. The objective function of the traveltime tomography problem explicitly includes a term that optimises the long-wavelength statics across the model. Therefore, it helps to produce better stacking images. The method does not require much additional computation cost. It requires defining an intermediate datum prior to running SOTT. Other than that, the execution of SOTT is similar to TT. Current implementation and testing are limited to 2D. The method can be extended to 3D as well. Since this is a traveltime method, it still requires accurate traveltime picks. Further modification could include residual statics for sources and receivers as well.

**Acknowledgments**

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