EFFECT OF VERTICAL ARRAYS ON NEAR-SURFACE VELOCITY AND STATICS UNCERTAINTY

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Summary

The near-surface velocity model estimated using first arrival tomography is often used for the computation of static corrections. In order to understand the uncertainty of these statics, we apply a Bayesian seismic tomography technique. First, we generate three different seismic datasets using the SEAM Arid model – a surface seismic survey and the same survey combined with vertical receiver arrays of 150 and 300 m depth. Then, we run the Bayesian tomography using the traveltimes obtained from the three surveys and analyze the uncertainty of static corrections in the stochastic models provided by the tomography. The results suggest that the introduction of vertical arrays significantly decreases the uncertainty of obtained static corrections. Joint tomography provides a unifying and powerful integration of surface seismic and simultaneously acquired vertical arrays or upholes.

Effect of vertical arrays on near-surface velocity and statics uncertainty

Introduction

The accuracy of near-surface velocity estimation strongly influences the resulting structural interpretation of seismic data, especially when mapping low-relief structures. To estimate these near-surface velocities, first arrival refraction tomography is routinely used. However, in the case of a complex near-surface with low-velocity layers and anomalies, the surface seismic acquisition often leads to inaccurate velocity estimation from first arrival traveltimes (Liu et al., 2010). However, such inaccuracies are challenging to detect directly from the data when single, or several deterministic inversions are run. Distributed acoustic sensor (DAS) systems in a smart DAS acquisition (Bakulin et al., 2017), e.g., simultaneous acquisition of surface seismic and DAS vertical arrays, were proposed to improve the accuracy of near-surface velocity estimations. Vertical arrays are, in essence, upholes, except they are simultaneously acquired with the surface seismic. Therefore, they listen to all the shots from the surface acquisition. As a result, the smart DAS dataset contains additional raypaths and traveltimes traversing through the near surface at all possible angles. Smart DAS acquisition was shown to improve velocity estimation accuracy by deterministic first arrival tomography (Alshuhail et al., 2019). Here, we evaluate the improvement of accuracy provided by DAS vertical receiver arrays using Bayesian tomography. Specifically, we analyze the uncertainty of velocity and static corrections computed from the tomography velocity models and contrast them to conventional surface seismic.

Bayesian solution of the seismic first arrival tomography problem provides the optimal subsurface velocity model and the velocity uncertainty. It is a suitable method for near-surface uncertainty estimation in exploration seismic. However, it is rarely applied to refraction seismic geometries (Ryberg and Haberland, 2018). Such tomography problem has been solved by various methods, including Markov Chain Monte Carlo (Bodin et al., 2012), Hamiltonian Monte Carlo (Fichtner et al., 2019), and variational inference methods (Zhang and Curtis, 2020). We apply the reversible-jump MCMC method (Bodin and Sambridge, 2009; Malinverno, 2002). In this method, the velocities are defined on a set of nodes. The velocities in the whole domain are acquired by interpolating and extrapolating the values defined on the nodes. The chosen parameterization defines the interpolation method, and several parameterizations exist for this problem (Belhadj et al., 2018; Hawkins et al., 2019). We apply the natural neighbor parameterization due to the inherent smoothness of its models (Egorov et al., 2021).

Method

We model a 2D smart DAS acquisition using a section of the SEAM Arid velocity model (Oristaglio, 2015). The surface acquisition consists of receivers with 25 m spacing and sources with 250 m spacing; the maximum offset is 1100 m. We consider two scenarios with vertical array depths of 150 and 300 m, respectively, for the combined surface and vertical array acquisition. For both cases, the spacing of vertical arrays is 500 m. After obtaining the seismic gathers with the finite-difference modeling algorithm, we pick the first arrivals and supply the identified first arrival traveltimes to the tomography algorithm.

The tomography for all three types of acquisition is conducted with the same parameters. Using the reversible-jump MCMC with natural neighbor parameterization (Egorov et al., 2021), we obtain 20,000 accepted samples for 56 Markov chains for each acquisition type. In addition, we apply coordinate scaling with a scalar of 4, as suggested by (Zhang et al., 2018). This provides stochastic models with more defined horizontal structures. Finally, we disregard the first 15,000 samples in each of the chains as burn-in and decimate the remaining samples for further analysis.

In addition to analyzing the velocities obtained by the tomography, we analyze the static corrections derived from these models. For each stochastic velocity model, we compute the static corrections as two-way vertical traveltimes to the selected datum of 150 m for each of the lateral locations. We then analyze the uncertainty of the static corrections and compare these statics to the statics computed in the true model.

Results

The mean velocities and standard deviations in Figure 1 suggest that the introduction of vertical arrays improves the accuracy of velocity estimation with depth. For the surface acquisition (Figures 1c-d), the velocities are estimated with high accuracy until the first low-velocity layer (at a depth of ~100 m in the middle of the model). This low-velocity layer is delineated with a sharp increase of standard deviation in Figure 1d. For the combined acquisition of surface receivers and vertical arrays in Figures 1e-h, the standard deviation of the estimated velocities quickly starts increasing below the maximum depth of vertical arrays.

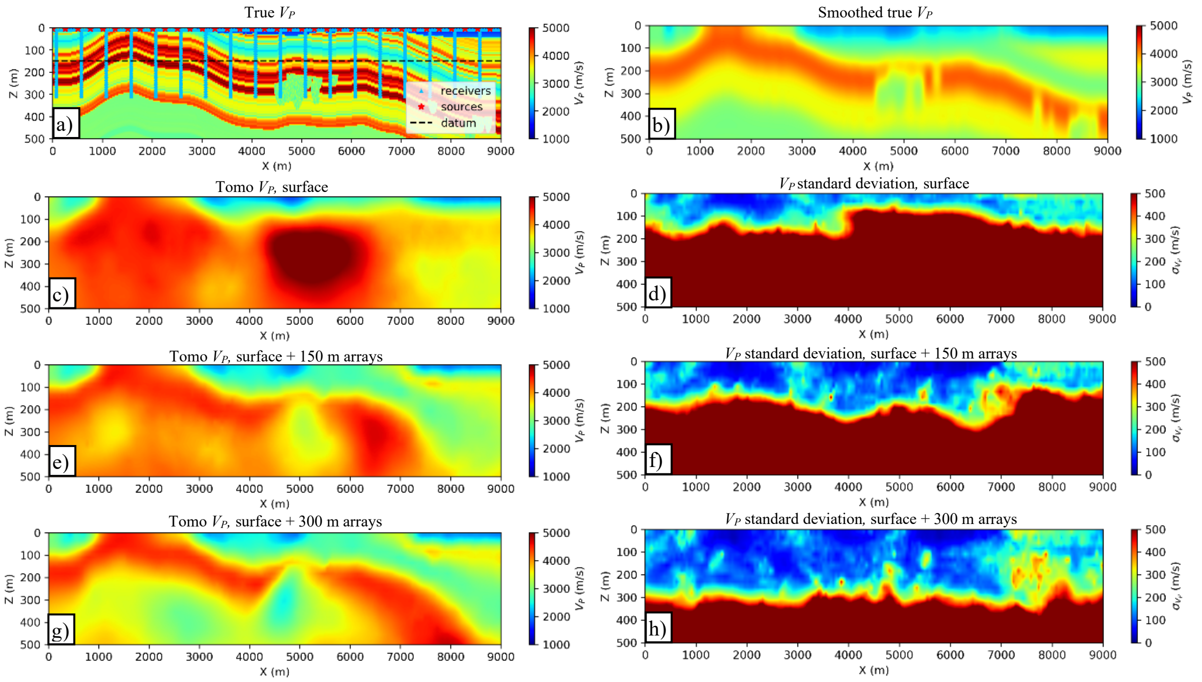

Figure 1 *True (a) and smoothed (b) section of the SEAM Arid velocity model; mean estimated velocities (c,e,g) and standard deviations (d,f,h) for surface acquisition (c-d) and surface acquisition combined with 150 m (e-f) and 300 m (g-h) vertical arrays. Figure 1a displays the datum used for statics and the acquisition geometry for the dataset with 300 m deep vertical arrays.*

The interpretation of the resulting static corrections in Figure 2 is complicated. Plots in Figure 2a-c compare the true static corrections for the chosen datum of 150 m (green line) with the static corrections in the stochastic velocity models obtained by the tomography. Static corrections in the mean velocity models are shown as red lines, the PDFs of the statics corrections are plotted as the background image. We estimate the uncertainty as 99% symmetric confidence error bars taken from the PDFs and shown as dashed red lines. As the datum of 150 m is below the described low-velocity layer, the static corrections for this datum have high uncertainty in the case of surface acquisition (90 ms maximum uncertainty in Figure 2a). The true statics stay within the error bars, suggesting that the uncertainty estimates are meaningful.

Introducing the vertical arrays of 150 m depth (Figure 2b) decreases the uncertainty significantly. Still, surprisingly, the uncertainty remains relatively high for the locations with lateral coordinates higher than 6500 m, and it still stays at approximately 40 ms when 300 m upholes are used (Figure 2c). This may be related to the survey boundary being close to this location and the datum being directly located in the low-velocity layer. The velocities in the low-velocity layer are less accurately identified even with receivers inside and below it, which leads to errors in static corrections. Such higher uncertainty in the low-velocity zone is obtained in a synthetic test by Galetti et al. (2015), even when the receivers are all around the anomaly. However, if the datum is below the anomaly, as for the displayed examples for X < 6500 m, the statics are relatively accurate, as the traveltimes through the low-velocity anomaly are constrained by the picks supplied by the vertical arrays. These results suggest that the datum should not go through low-velocity layers and anomalies if possible.

Conclusions

We apply Bayesian refraction traveltime tomography to evaluate near-surface velocity uncertainty on a synthetic dataset computed in the SEAM Arid model. This model contains alternating high- and low-velocity layers with large contrast that are pretty typical for desert environments. When mapping a low-relief, medium- and long-wavelength errors in statics can mask real structures or even create a false structure. While supplementing surface seismic with vertical arrays was proposed before, the uncertainty of such configurations was not studied. Here we analyze and contrast velocities and statics derived from surface seismic and surface seismic with DAS vertical receiver arrays of various depths. Bayesian tomography validates the improved accuracy provided by the vertical arrays in the presence of low-velocity layers and anomalies. The stochastic velocity models provided by the Bayesian tomography are used to estimate static corrections' uncertainty. The introduction of vertical arrays decreases the uncertainty of static corrections from 90 ms to 40 ms in the worst-case scenario.

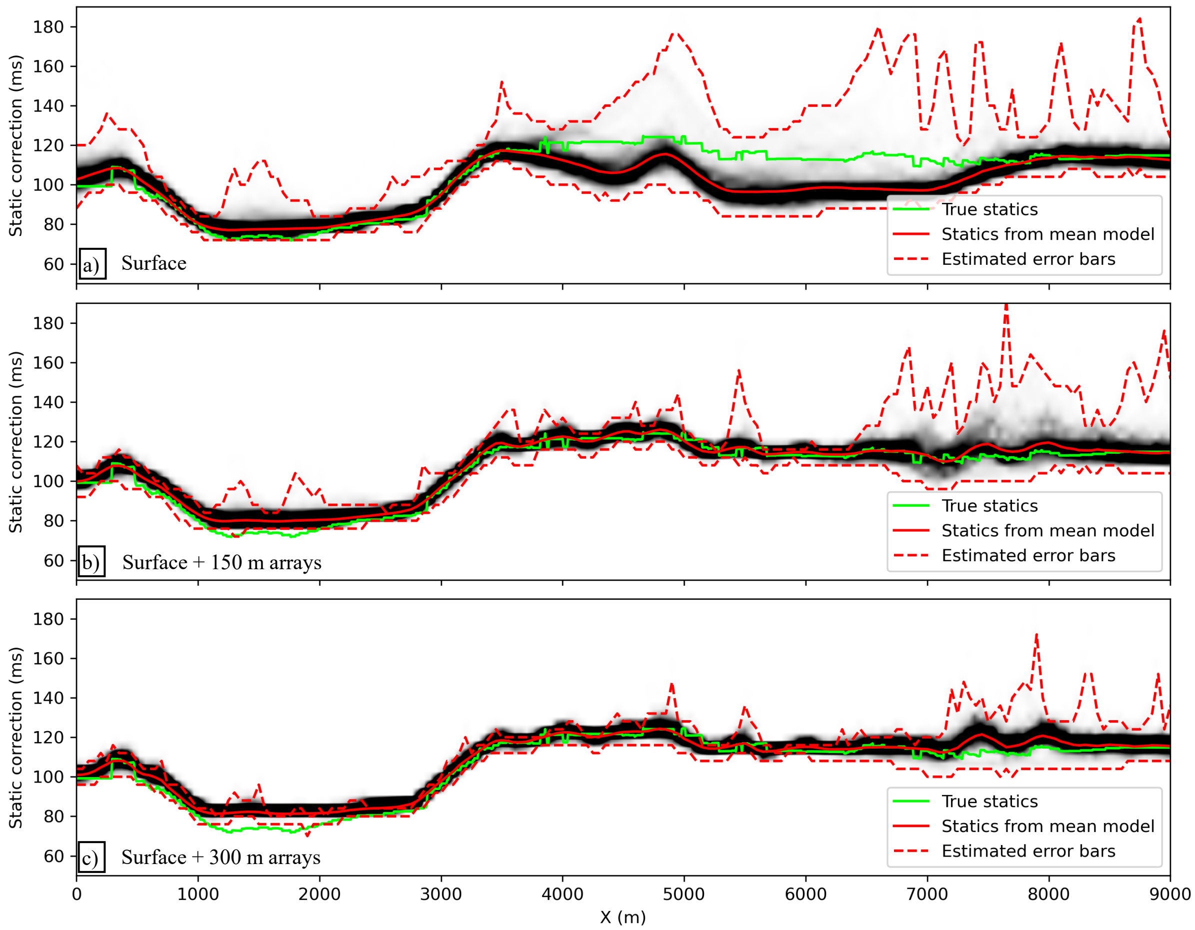

Figure 2 *Analysis of static corrections' uncertainty estimated from the stochastic velocity models of Bayesian tomography for surface acquisition (a), surface acquisition with vertical arrays of 150 m (b), and 300 m (c) depth. The datum is at 150 m.*

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