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Enhanced Velocity and Impedance Inversion via Full Waveform Inversion of OBN and DAS-VSP Data

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Abstract

We propose a workflow for high-resolution velocity inversion and seismic imaging that jointly utilizes OBN and DAS-VSP data. Because DAS-VSP data record axial strain rate and OBN data capture pressure, directly integrating these measurements into a Full Waveform Inversion (FWI) can be challenging. Conventional approaches convert DAS-VSP data into velocity components, relying on assumptions and approximations that may introduce errors. To address this issue, we present a novel method that directly simulates strain rate components using the acoustic wave equation with virtual dipole sources, explicitly accounting for the gauge length effect in DAS measurements. This approach precisely reconstructs the data and avoids errors associated with data conversion as well as gauge length effects. We applied the proposed method to a joint OBN and DAS-VSP survey conducted in the East China Sea. Our results demonstrate that the combined use of OBN and DAS-VSP data reduces parameter trade-offs, further constrains vertical velocity and anisotropy, and enables enhanced inversion of depth-dependent Q models. Building upon the anisotropic velocity and Q models derived via FWI, we performed impedance inversion on the raw data. The resulting impedance model effectively eliminates multiple crosstalks and compensates for high-frequency attenuation due to Q effects. These results highlight the potential of the proposed workflow to enhance FWI applications, mitigate inversion uncertainty, and provide substantial theoretical and practical benefits.

Introduction

Full Waveform Inversion (FWI) has proven highly effective for building high-resolution velocity models, particularly with Ocean Bottom Node (OBN) data. Sparse OBN surveys provide long offsets and rich low-frequency content, enabling robust and efficient FWI. However, relying exclusively on surface-based datasets, whether streamer or OBN, can limit the sensitivity of multi-parameter FWI particularly for anisotropy and attenuation. This constraint often requires multiple iterative rounds of FWI and tomography, increasing computational cost and complexity while reducing efficiency and interpretive clarity.

A promising solution is by integrating OBN data with Vertical Seismic Profile (VSP) data. While OBN data delivers broad spatial coverage, VSP data provides localized, high-fidelity measurements that help refine critical anisotropic and attenuation parameters. By combining these complementary datasets, we can significantly enhance the stability and reliability of multi-parameter FWI, reducing the trade-offs among velocity, anisotropy, and attenuation.

In this paper, we introduce a novel FWI workflow that incorporates OBN and VSP data acquired via Distributed Acoustic Sensing (DAS). Using datasets from a shallow-water region in the East China Sea, we jointly invert for velocity, epsilon, and attenuation models. The resulting models serve as a foundation for Full Waveform Impedance Inversion (FWII) (Chen et al., 2023) to generate an ultra-high-resolution subsurface image. Our results demonstrate that integrating OBN and DAS-VSP datasets within an FWI framework significantly improves the accuracy and robustness of multi-parameter inversions, thereby enhancing subsurface characterization in complex geological settings.

Theory

Our full waveform velocity inversion (FWI) and full waveform impedance inversion (FWII) jointly find optimal velocity model v and impedance model $I = \rho v$ to minimize the data misfit between the modeled data u and the field data d, which can be expressed using a least-squares misfit function:

$$E(v,I) = \frac{1}{2}\iiint (d - u(v,I))^2 dt d\boldsymbol{x}_s d\boldsymbol{x}_r. \quad (1)$$

The modeled data u with airgun sources and hydrophone recording is simulated using the following acoustic wave equation:

$$\left(\frac{1}{I(\boldsymbol{x})v^2(\boldsymbol{x})}\frac{\partial^2}{\partial t^2} - \frac{1}{v(\boldsymbol{x})}\nabla\frac{v(\boldsymbol{x})}{I(\boldsymbol{x})}\cdot\nabla\right)p(\boldsymbol{x};t;\boldsymbol{x}_s) = \delta(\boldsymbol{x}-\boldsymbol{x}_s)s(t), \quad (2)$$

where $s(t)$ denotes the source time function excited at the source location $\boldsymbol{x}_s$. Seismic data is the recorded pressure wavefield $p(\boldsymbol{x};t;\boldsymbol{x}_s)$ at receiver location $\boldsymbol{x}_r$. Data recorded by OBN hydrophones can be directly modeled using the above equation. For DAS-VSP data, a modified algorithm is needed to reproduce the strain rate recording. In our FWI framework, we use the following modeling equation to accurately model the DAS recorded data (Yang et al., 2025):

$$\left(\frac{1}{I(\boldsymbol{x})v^2(\boldsymbol{x})}\frac{\partial^2}{\partial t^2} - \frac{1}{v(\boldsymbol{x})}\nabla\frac{v(\boldsymbol{x})}{I(\boldsymbol{x})}\cdot\nabla\right)p(\boldsymbol{x};t;\boldsymbol{x}_s) = -[\frac{\partial\delta\left(\boldsymbol{x}-\boldsymbol{x}_s+\frac{\boldsymbol{\delta l}}{2}\right)}{\partial l} - \frac{\partial\delta\left(\boldsymbol{x}-\boldsymbol{x}_s+\frac{\boldsymbol{\delta l}}{2}\right)}{\partial l}]\int s(t)\,dt, \quad (3)$$

where l is along the VSP trajectory and $\boldsymbol{\delta l}$ is the half gauge length perturbation along the well. It is equivalent to two dipole sources separated by gauge length and simultaneously injected in opposite directions along the fiber. This approach precisely reconstructs the DAS data and avoids errors associated with data conversion as well as gauge length effects. With equation (2) and (3), OBN data and DAS-VSP data share a similar formulation, with only differences appearing in the source terms. Thus, both datasets can be integrated seamlessly into the FWI workflow.

The gradient of velocity and impedance can be calculated by applying perturbation theory with a velocity perturbation δv and impedance perturbation δI in equation (2). Applying Taylor expansion and computing the pseudo-inverse of equation (2), the gradient formula is derived as follows (Zhang et al., 2014):

$$sin^2\theta\frac{\delta v}{v} + cos^2\theta\frac{\delta I}{I} = -32\pi\iiint\frac{v(\boldsymbol{x})}{sin\,\theta'}cos^2\theta'\,\delta(\theta'-\theta)\frac{p_F(\boldsymbol{x};\omega;\boldsymbol{x}_s)p_B(\boldsymbol{x};\omega;\boldsymbol{x}_s)}{i\omega}d\boldsymbol{x}_s d\theta' d\omega, \quad (4)$$

where p_F and p_B are the forward and backward wavefields, respectively, and θ represents the subsurface reflection angle. Here, the impedance perturbation $\delta I/I$ can be predicted using near angle images while the velocity perturbation $\delta v/v$ can be estimated using the far angle images. This approach allows us to separate the velocity and impedance effects and could potentially invert them simultaneously in each iteration.

Results

We implemented the proposed methodology to a joint OBN and DAS-VSP survey conducted in a shallow water region of the East China Sea, where the water depth varies from 70m to 110m. The dataset comprises two DAS-VSP well logs, each extending to a depth up to 3km. These well logs were acquired simultaneously with the OBN data, providing a unique opportunity to integrate both data types for enhanced subsurface imaging. The primary goal of this study was to construct a reliable velocity model and get a high-resolution imaging. In this study, both the hydrophone data from the OBN survey and the DAS-VSP data were utilized to construct a reliable visco-acoustic vertical transverse isotropy (VTI) model.

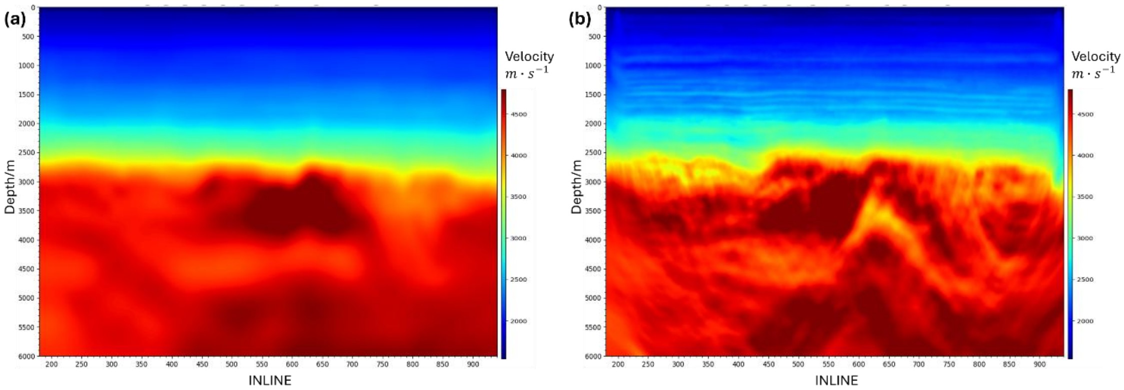

Figure 1: (a) initial model for FWI and (b) 15Hz FWI model.

Data preprocessing included denoise and debubble for both OBN and DAS datasets. To ensure compatibility between two datasets, we accounted for the DAS-specific measurement of true ground strain rate (Lindsey et al., 2020) by convolving the geophone instrument response with the DAS recordings. This adjustment enabled both datasets to be treated as originating from the same airgun source. The debubble filter was estimated using OBN data, benefiting from its clear separation of direct arrivals from other events, and was then applied consistently to both datasets. Similarly, the source wavelet was also derived from the OBN data.

An initial isotropic velocity model was constructed using tomography, followed by isotropic FWI with the OBN dataset. Using OBN data alone provides limited constraints on anisotropic parameters. The synthetic data generated from the isotropic FWI model can match the observed field data well. However, modelling using DAS-VSP dataset based on this isotropic FWI model revealed deviations in diving waves as receiver depth increasing, highlighting the need for anisotropic model updates. Consequently, we refined the epsilon model using DAS-VSP data while keeping the horizontal velocity constrained by the OBN-based isotropic FWI. After this update, the diving waves from the inverted model showed a good match with the field data for both datasets.

Building on this foundation, VTI FWI was performed with the OBN data to further update the velocity model, using the inverted epsilon and a scaled initial delta model. This was followed by another round of tomography to refine the delta model. A final pass of VTI FWI, extending to 15 Hz, was then conducted to finalize the anisotropic velocity model. Up to this stage, all FWI processes were guided by a phase-driven objective function.

Synthetic DAS-VSP data from the inverted model revealed stronger amplitude decay with increasing receiver depth in the field data, prompting the incorporation of attenuation into the model building process. Using the 15 Hz VTI FWI results, we implemented visco-acoustic FWI with DAS-VSP data to update the Q model, leveraging both phase and amplitude information. This was followed by an additional visco-acoustic FWI pass to refine the velocity model with the OBN dataset (Figure 1). After this stage, modeling QC for both DAS-VSP and OBN datasets indicate near perfect match with the inverted models.

Finally, with the final inverted QVTI model, we performed QFWII to update the impedance model up to 60 Hz. The impedance imaging initially exhibited contamination from multiples and acquisition footprints due to raw data usage. However, the iterative updates of FWII effectively attenuated these artifacts, yielding an accurate impedance model. The inclusion of the Q model within FWII compensated for amplitude and frequency decay, enabling the reconstruction of a high-fidelity impedance model (Figure 2).

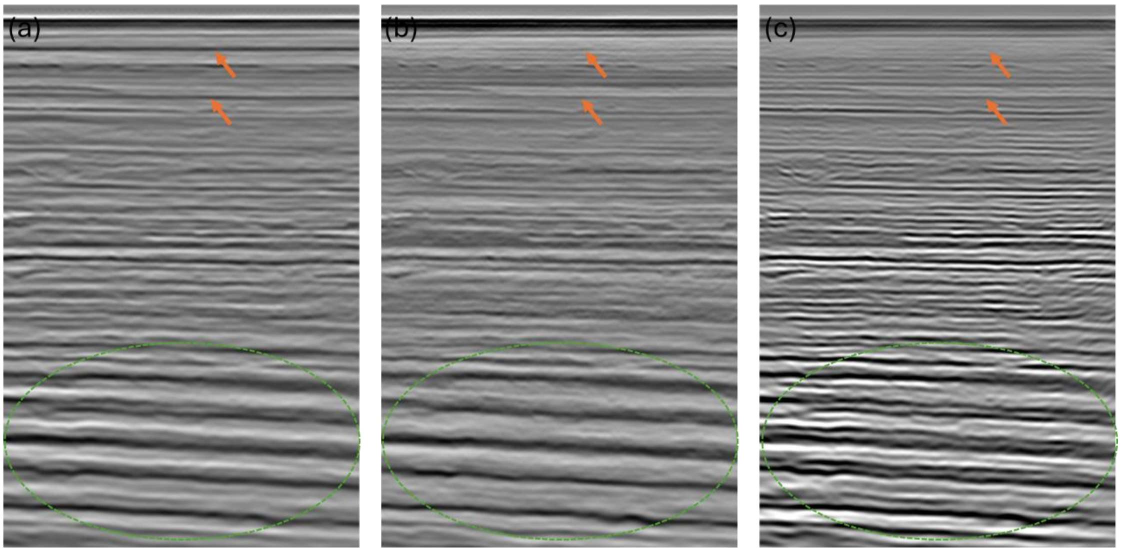

Figure 2: Comparison of 60 Hz impedance perturbations from (a) RTM, (b) FWII, and (c) QFWII using the final FWI models. Orange arrows highlight the attenuation of multiples after inversion. The green ovals indicate improved amplitude and frequency content from QFWII.

Conclusions

This study demonstrates the effectiveness of the proposed methodology for integrating DAS-VSP data directly into the FWI framework. By leveraging the complementary nature of OBN and DAS-VSP datasets, we have shown that inversion uncertainties, particularly those related to velocity and anisotropy trade-offs, can be significantly reduced. This joint approach provides crucial depth-varying constraints, which play a vital role in refining the attenuation (Q) model. Accurate Q estimation is essential for compensating for energy dissipation effects, ultimately leading to improved imaging and subsurface characterization.

Future research will focus on enhancing model fidelity by incorporating fully elastic effects into the inversion process. While the current methodology has shown effectiveness in improving velocity and attenuation estimates, a comprehensive elastic framework would allow for more detailed characterization of lithological variations and fluid effects. Additionally, continued advancements in fiber-optic sensing technology and data processing techniques will further refine the integration of DAS-VSP with other seismic datasets, paving the way for even more robust subsurface imaging solutions.

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