Toward 4C FWI: Distributed acoustic sensing and 3C as complementary datasets

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Summary

Full waveform inversion (FWI) is a powerful tool for obtaining high resolution estimates of subsurface parameters. However, when applied to land datasets its success is generally limited by undesirable consequences of the practical limitations imposed on seismic acquisition. Ideally, seismic data acquired for elastic full waveform inversion would provide three component data, that is densely sampled with a wide aperture, having a wide bandwidth, especially at low frequencies. The mechanical limitations of standard geophones, and the practical constraints placed on seismic acquisition results in datasets lacking the information required for successful elastic full waveform inversion. Distributed acoustic sensors (DAS) have shown promise as a practical means of supplying the information that we currently cannot obtain using standard acquisition techniques. However, DAS fibres only supply one, tangential, component of strain, meaning on their own they are not appropriate for elastic FWI. Distributed acoustic sensors and geophones share complementary aspects that when taken together have the potential to provide a more robust FWI result. In September of 2018, the Consortium for Research in Elastic Wave Exploration Seismology (CREWES) in partnership with the Containment and Monitoring Institute (CaMI) acquired a large 3D vertical seismic profile into 3C accelerometers, straight DAS fibre, and helical DAS fibre. This dataset will be used to develop a FWI workflow that jointly inverts 3C and DAS data to provide robust information about elastic subsurface properties. This paper focuses on the forward modeling of the datasets as a first step toward four-component FWI and discusses the complementary aspects of the two datasets.

Introduction

Full waveform inversion seeks high resolution models of subsurface properties by updating the model such that the predicted data is driven towards the observed data (Lailly, 1983, Tarantola, 1984, Pratt et al., 1998, Virieux and Operto, 2009). This is accomplished by minimizing an objective function that is dependent on the L_2 norm of the data residuals. However, when applied to the land data the result is not always desirable due to physical limitations of standard geophones and the practical constraints on seismic acquisition geometry. Standard geophones are generally less sensitive to low frequency seismic waves due to their inherent resonant frequency, and therefore do not record the low frequencies crucial to FWI. Additionally, practical and financial constraints imposed on seismic exploration programs results in data lacking the dense spatial sampling required for surface wave inversion, and lacking the wide aperture required for elastic FWI.

A relatively new, and rapidly expanding technology, known as distributed acoustic sensing (DAS) has the potential to remedy some of the challenges that geophones present with respect to FWI. Employing standard, cost-effective, and readily deployable telecommunications optical fibres to sense seismic strain, DAS provides the ability to sense the seismic wavefield along the entire length of the borehole offering much denser spatial sampling. Laboratory and field studies have shown that distributed acoustic sensors also provide data with the low frequencies that are crucial for successful full waveform inversion (Jin and Roy, 2017; Becker et al., 2018). Optical fibres tend to only be sensitive to wavefields that cause strain along the fibre axis, and thus only provide one tangential component of the strain field (Kuvshinov, 2016). Distributed acoustic sensors also provide wavefields with a lower signal to noise ration then geophones.

On their own, neither geophones or DAS fibres provide an ideal dataset for elastic full waveform inversion. When taken together and viewed as a four-component dataset they share complementary aspects that should combine to provide a more robust dataset for elastic FWI. In September of 2018, CREWES in partnership with CaMI acquired a 3D walkaway-walkaround vertical seismic profile at the field research station in Brooks, Alberta (Lawton et al., 2014). This dataset was acquired into 3C accelerometers, straight DAS fibre, and helically wound DAS fibre to explore the complementary aspects of the datasets as they relate to FWI. This paper will focus on the forward modeling of the two datasets and will discuss how they complement each other from and FWI perspective.

3D Walkaway-Walkaround VSP

In September of 2018 CREWES acquired a 3D walkaway-walkaround VSP using a vibroseis sweep from 1-150 Hz. Figure 1 shows the source geometry for the 3D-VSP survey. Shots were centered on what is known as the geophysics observation well, represented by the green circle in figure 1 and taken every 15 degrees along concentric circles with radii of 60 meters. The shot spacing reduced to 10 meters every 45 degrees.

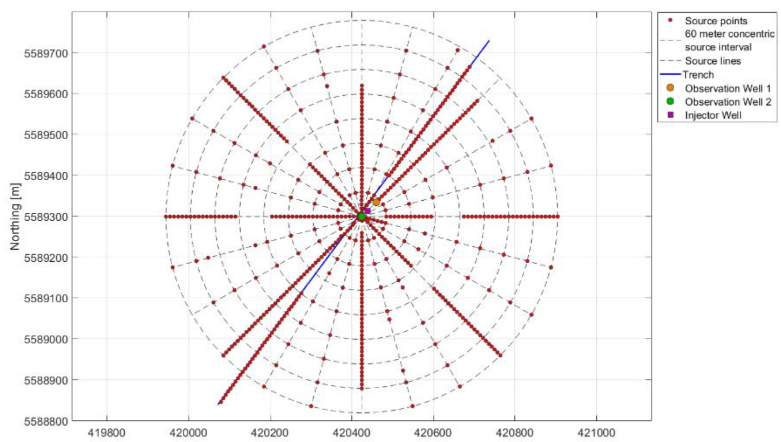

Figure 1: *Source geometry for 2018 walkaway-walkaround 3D VSP survey. Shot locations, shown by red circles, were taken every 15 degrees along concentric circles with radii increasing by 60 meters. Shots centered on observation well 2 (green circle). Also shown are the positions of the injector well (purple square), and observation well 1 (orange circle).*

The shots from figure 1 were recorded into 324 levels of vectorseis accelerometers at 1-meter intervals, a loop of straight DAS fibre over the length of the well, and a loop of helically wound fibre with a radius of 1 cm and a pitch of 30 degrees, all of which were deployed in observation well 2.

Forward modeling the 3D-VSP data

The velocity-stress finite difference method utilizes a staggered grid and alternates between solving he elastodynamic equation of motion for particle velocity, equation (1-**i**), and the time derivative of Hooke's Law for stress, equation (1-**ii**) to propagate the wavefield.

$$i.\ \rho\frac{\partial^2 u_i}{\partial t^2} = \nabla \cdot \sigma + f_i \qquad ii. \frac{\partial \sigma_{ij}}{\partial t} = c_{ijkl}\dot{\boldsymbol{\epsilon}}_{kl} \tag{1}$$

The term $\dot{\epsilon}_{kl}$ is the strain rate which can be computed through the time derivative of the expression for strain. Solving equation (1-**i**) supplies the particle velocity in the x,y, and z directions, providing a method of directly computing all three components of the 3C geophone data in observation well 2. The strain rate field in cartesian coordinates can be computed through spatial derivatives of the particle velocities according to the standard expression for strain. To acquire the strain rate along the tangent of the fibre, we rotate the strain rate in cartesian coordinates into a tangential, normal, and binormal coordinate system that varies along the fibre by invoking the rotation formula for a rank 2 tensor.

$$\dot{\epsilon}_{tnb} = \boldsymbol{R}\dot{\epsilon}_{xyz}\boldsymbol{R}^T \tag{2}$$

The strain rate provided by the (1,1) element of equation (2) and the particle velocity supplied by equation (1-**i**) compose the model for 4C dataset of the 3D-VSP. Eaid et al., 2018 and Eaid et al., 2017 provide more details about considerations for the fibre geometry and the forward modeling.

Results

A shot was modeled from the northeast portion of the survey in figure 1 at approximately (420650 E, 5589700 N). The p-wave velocity model was computed from the first breaks of the vertical component of geophone motion. The s-wave velocity and density were then computed with a vp-vs ratio of 2.1 and a using Gardner's relation respectively. Noise was then added to both the DAS and 3C geophone datasets to highlight their signal to noise ratios. The geophone data was then band passed filtered from 10-150 Hz to simulate the field geophone data. The DAS data was not filtered as the literature suggests millihertz sensitivity with DAS. The results of the modeling are shown in figure 2. The top row shows the particle velocity, simulating the geophone measurements, for the vertical component (a), radial component (b), and transverse component (c). The bottom row shows the strain-rate DAS measurements for the straight fibre (d), and helical fibre (e).

Figure 2 highlights some important differences between the DAS and 3C data that when taken together should be complementary. The geophone data supplies three components which is necessary for elastic multiparameter FWI, while the DAS only supplies one component. Additionally, the geophone data supplies data with a higher signal to noise ratio, and enhanced signal continuity, especially in the first breaks. When the wavefield is broadside to the DAS fibre the recovered signal becomes weak. The DAS data however provides better spatial sampling over the length of the well, and also provides lower frequency data which is crucial to recover long wavelength aspects of the model, especially at early iterations.

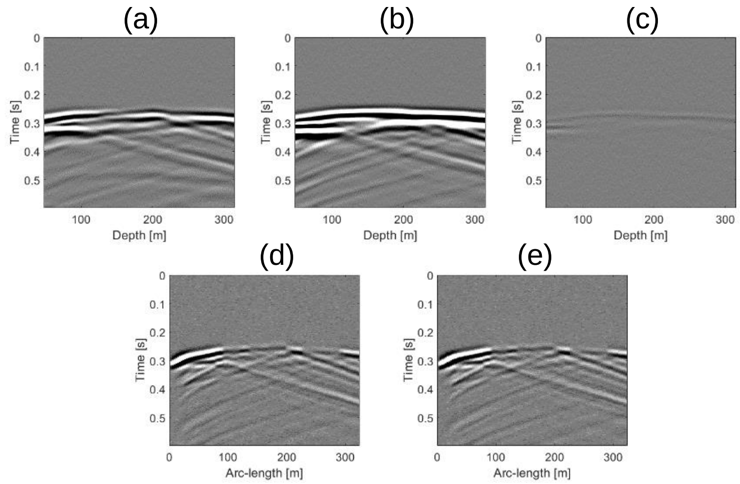

Figure 2: *Modeling results using source geometry from figure 1 and equations 1-**i** and 2. (a) Vertical component of particle velocity, (b) radial component of particle velocity, (c) transverse component of particle velocity, (d) strain-rate straight DAS fibre, (e) strain-rate helically wound DAS fibre.*

Discussion

Distributed acoustic sensors and geophones provide individual datasets that are missing information required for robust inversions. However, taken together the datasets complement each other in a way that should be beneficial to FWI. This paper presents a one of a kind 4-component dataset acquired in the fall of 2018 that will be used to explore the complementary aspects of DAS and 3C recording, and discusses the forward modeling of these datasets as the first step towards a more robust 4C full waveform inversion.

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