Seismic time-lapse image registration using amplitude-adjusted plane-wave destruction[a]

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ABSTRACT

We propose a method to efficiently measure time shifts and scaling functions between seismic images using amplitude-adjusted plane-wave destruction filters. Plane-wave destruction can efficiently measure shifts of less than a few samples, making this algorithm particularly effective for detecting small shifts. Separating shifts and scales allows shifting functions to be measured more accurately. When shifts are large, amplitude-adjusted plane-wave destruction can also be used to refine shift estimates obtained by other methods. The effectiveness of this algorithm in predicting shifting and scaling functions is demonstrated by applying it to a synthetic trace and a time-lapse field data example from the Cranfield CO_2 sequestration project.

INTRODUCTION

Over the past 25 years, time-lapse seismic monitoring has evolved into the standard method to detect spatial fluid changes in the subsurface (Lumley, 2001). In some locations, permanent stations have been installed for continuous time-lapse monitoring (Berron et al., 2015).

Many methods for analyzing time-lapse seismic data have been proposed. Cross-equalization includes spatial and temporal registration to compensate for different acquisition geometries and amplitude balancing to scale the data to the same amplitude (Rickett and Lumley, 2001). Hall (2006) proposed a 3D vectorial conditioning using a deformable mesh with sensitivity to image quality. Williamson et al. (2007) explained time shifts and amplitude changes by integrating classical warping and impedence inversion in the limit of small offset and dip and low frequency. Hale (2009, 2013) proposed an extension of the dynamic time warping algorithm developed for speech recognition and multidimensional local phase correlation scanning. Fomel and Jin (2009) proposed local similarity scanning, which was applied to time-lapse registration in Cranfield by Zhang et al. (2013, 2014). More recently, Khalil and Hoeber (2015) used the wave equation to compute shifts normal to reflectors. Baek and Keho (2015) proposed warping as an inverse problem where velocity changes are optimized to resolve events in time-lapse seismic images.

In this paper, we adopt and extend plane-wave destruction (Fomel, 2002; Chen et al., 2013a) for automatic estimation of time-variant shifts and rescaling functions between seismic images. In time-lapse seismic monitoring, sensitive acquisition and processing is required to detect small shifts induced by fluid migration. We show that the proposed amplitude-adjusted plane-wave destruction is particularly effective in measuring small shifts and test the proposed algorithm using synthetic and field data examples.

THEORY

We propose to estimate local scaling functions and spatially variable temporal shifts by modifying plane-wave destruction (Fomel, 2002) to include scaling. A scaling function is incorporated in the description of high-order plane-wave destructors. These filters are described in the Z-transform notation as

$$C(p, Z_1, Z_2) = B(p, Z_1^{-1}) - Z_2 B(p, Z_1) \tag{1}$$

where p is the local slope (corresponding to a time shift), Z_1 and Z_2 are local shifts in time and space, respectively, and B is a polynomial filter. We modify this formulation to incorporate a scaling function as follows:

$$C(a, p, Z_1, Z_4) = B(p, Z_1^{-1}) - a Z_4 B(p, Z_1) \tag{2}$$

where a is a scaling coefficient and Z_4 represents a shift between images. In the matrix-vector notation, equation (2) is expressed as

$$\mathbf{C}(\mathbf{a}, \mathbf{p})\mathbf{d} = \mathbf{B}_l(\mathbf{p})\mathbf{d} - \mathrm{diag}(\mathbf{a})\mathbf{B}_r(\mathbf{p})\mathbf{d} \tag{3}$$

where $\mathbf{B}$ and $\mathbf{C}$ denote the convolution operator with the filters B and C, respectively, and $\mathbf{d}$ is the time-lapse data. r and l denote the right and left hand side of the polynomial filter B in equation (2). Our goal for the warped and scaled monitor image is to match the base image, therefore

$$\mathbf{C}(\mathbf{a}, \mathbf{p})\mathbf{d} \approx 0. \tag{4}$$

The depedence of $\mathbf{C}$ on $\mathbf{a}$ is linear, however $\mathbf{p}$ enters in a nonlinear way (Chen et al., 2013a). We separate this problem into a linear and nonlinear part and use the variable projection technique (Golub and Pereyra, 1973; Kaufman, 1975).

We describe the algorithm below.

1. Set initial values as $\mathbf{p} = \mathbf{0}$ and $\mathbf{a} = \mathbf{1}$.

2. Hold the shift constant and compute the scaling weight **a** by the smooth division of the right and left side of the plane-wave destruction filter **C** in equation(3):

$$\mathbf{a} = \left\langle \frac{\mathbf{B}_r(\mathbf{p})\mathbf{d}}{\mathbf{B}_l(\mathbf{p})\mathbf{d}} \right\rangle \tag{5}$$

3. Scale the monitor image with the estimated weight.

4. Hold the scale **a** constant and compute the shift **p** using slope estimation by accelerated plane-wave destruction.

5. Shift the monitor image using the estimated slope.

6. Iterate until convergence (return to step 2).

This algorithm efficiently shifts and scales monitor images to match the base image. The estimated shifts and scaling weights are constrained to be smooth using shaping regularization (Fomel, 2007).

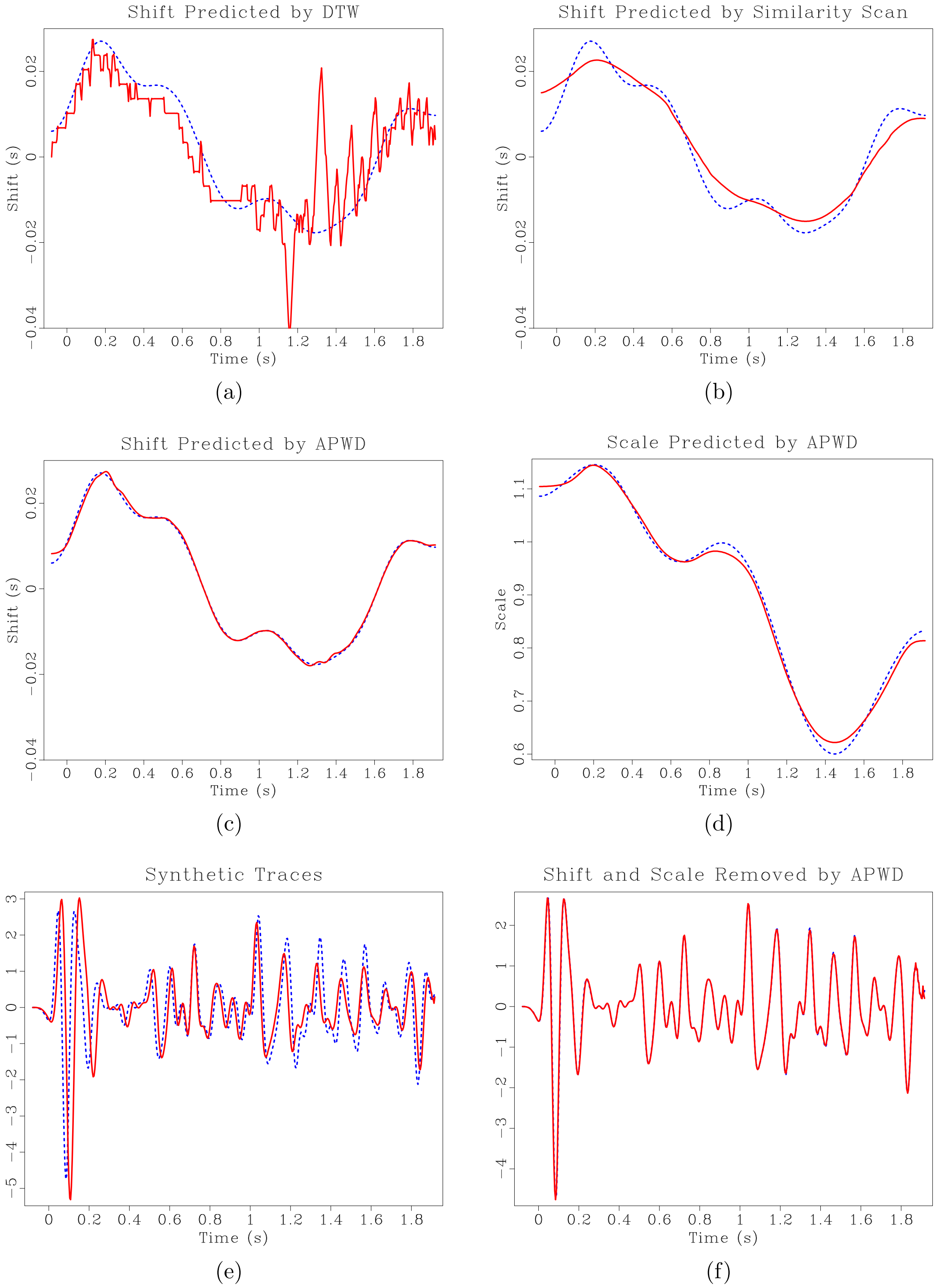
SYNTHETIC EXAMPLE

We first test the proposed algorithm by generating a random synthetic base trace, shifting function, and scaling function (Figure 1). The warping and scaling functions are applied to the base trace to create a synthetic monitor trace. We attempt to measure the shifting and scaling functions from the synthetic base and monitor traces using the proposed algorithm and compare the results with those from alternative algorithms.

We first apply the dynamic time warping algorithm (Sakoe and Chiba, 1978; Herrera and van der Baan, 2012; Hale, 2013). This algorithm is particularly effective when measuring large shifts, but it only computes integer shifts between samples on a pre-defined grid. In this synthetic example and many real examples from time-lapse monitoring, shifts are quite small and dynamic time warping is not always effective. Indeed, the shifting function measured with dynamic time warping does not effectively measure the small shifts in the synthetic trace and contains the unappealing “stair-stepping” artifact due to the algorithm’s inability to measure shifts outside of the predefined sampling grid (Figure 1a).

We then apply the local similarity scan (Fomel, 2007; Fomel and Jin, 2009) to measure the local shifting function. This algorithm scans through shifts, computing local similarity and picking the optimal warping path automatically. In our synthetic tests, this algorithm effectively measures the low frequency component of the synthetic shifting function, but fails to detect higher-frequency variations (Figure 1b).

Finally, we measure the shift using the proposed amplitude-adjusted plane-wave destruction algorithm. Compared to dynamic time-wapring and local similarity,



(a) (b)

(c) (d)

(e) (f)

Figure 1: (a-c) Exact shift (dashed) and measured shift (solid) using: (a) dynamic time warping, (b) local similarity scanning, and (c) amplitude-adjusted plane-wave destruction. (d) Exact scaling function (solid) and measured scaling function using amplitude-adjusted plane-wave destruction (dashed), (e) synthetic base trace (dashed) and monitor trace (solid), and (f) synthetic base trace (dashed) and shifted and scaled monitor trace (solid) using shifting and scaling functions measured by amplitude-adjusted plane-wave destruction.

plane-wave destruction proves to be particularly effective when measuring small, rapidly varying shifting functions. After only 5 iterations, the measured shifting function converges to the pre-defined synthetic shift (Figure 1c). We are also able to effectively measure the synthetic scaling function (Figure 1d). After applying the measured shifting and scaling functions to the synthetic monitor trace, the result is visually indistinguishable from the synthetic base trace (Figure 1f).

TIME-LAPSE DATA REGISTRATION

We then apply amplitude-adjusted plane-wave destruction to time-lapse field data from the Cranfield CO_2 sequestration experiment (Zhang et al., 2013, 2014). This dataset consists of a base and monitor image.

Plane-wave destruction is particularly effective for measuring very small shifts. Furthermore, rescaling the monitor image to match the amplitude of the base images allows local shifts to be measured even more precisely. Upon applying the algorithm, high resolution shifting (Figure 2a) and scaling (Figure 2b) functions are computed and applied to the previously shifted image to improve the match between the base and monitor image.

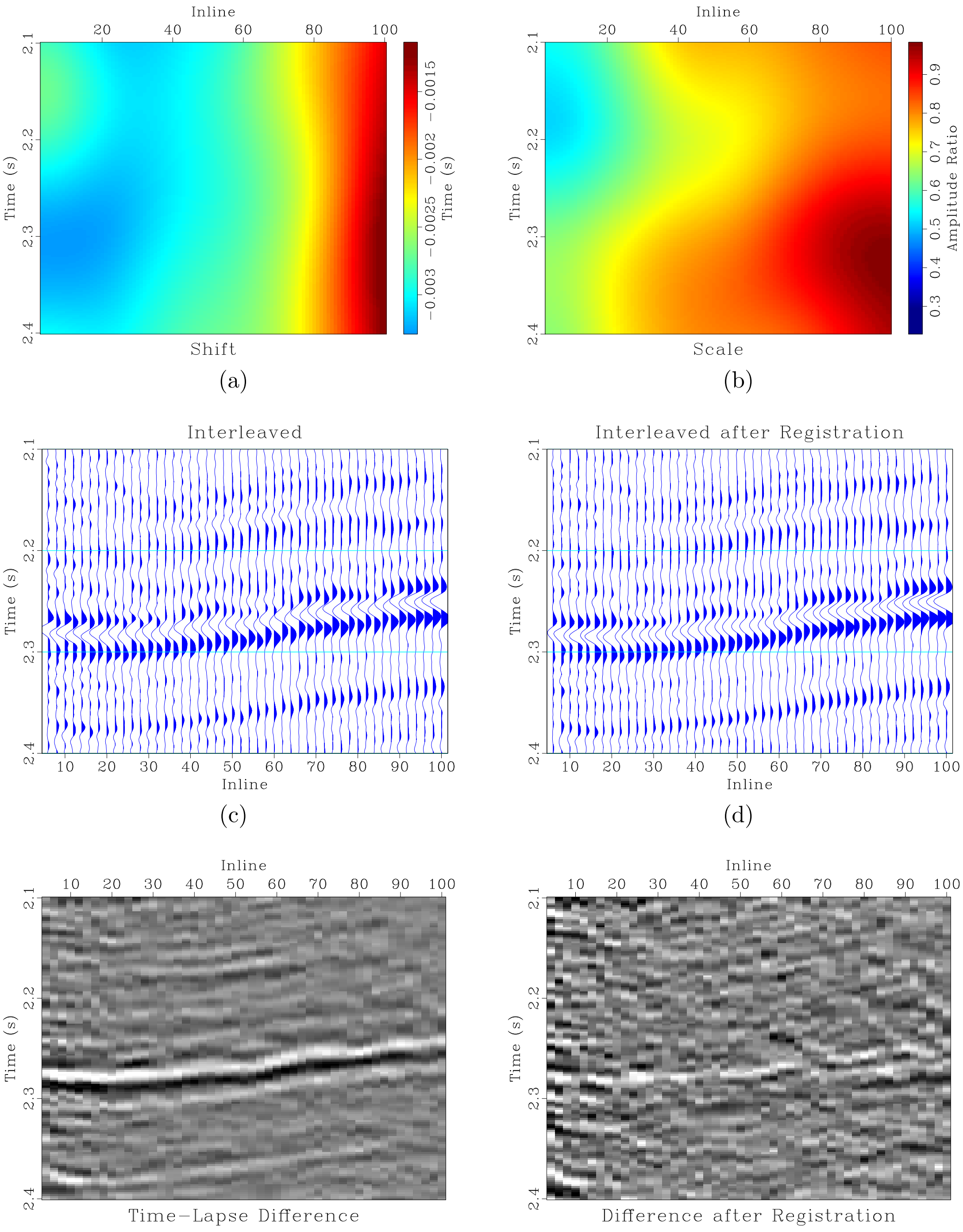
To display the results, we interleave a slice of the base cube with slices of the unaltered monitor cube (Figure 2c) and the shifted and scaled monitor cube (Figure 2d) and see that reflections become aligned effectively after applying the proposed algorithm, indicating that the shifting and scaling functions have been properly predicted.

We finally compute the time-lapse difference (Figure 2e) and the registered difference (Figure 2f). Coherent signal can be interpreted throughout the time-lapse difference due to the time shift between the images. Upon registering the images, the difference outside of the reservoir interval reduces to noise. The signal between 2.2 and 2.3 s corresponds to the reservoir where CO_2 injection took place between the surveys.

DISCUSSION AND CONCLUSIONS

The proposed amplitude-adjusted plane-wave destruction algorithm provides high resolution scaling and vertical shifting functions to be computed between time-lapse seismic images. In seismic image registration, vertical shifts are sometimes insuffiicent for matching the images. Lateral shifts may be required as well (Hale, 2009). In our future work, we will adapt the algorithm to measuring multidimensional shifts by incorporating amplitude-adjustment into omnidirectional plane-wave destruction (Chen et al., 2013b).

The proposed algorithm utilizes a modification of plane-wave destruction filters to acquire high-resolution shifting and scaling functions between monitor images and a base image. Plane-wave destruction is particularly effective for measuring small



(a) (b) (c) (d) (e) (f)

Figure 2: Image registration applied to time-lapse data from Cranfield CO_2 sequestration experiment. Slices of the (a) shift cube (b) scale cube, (c-d) the base image interleaved with the (c) monitor image and (d) shifted and scaled monitor image, (e) time-lapse difference, and (f) registered difference.

shifts. When shifts are small, amplitude-adjusted plane-wave destruction can be used as a standalone algorithm to efficiently measure shifting and scaling functions between seismic images. When shifts are large, the proposed algorithm can be used to refine shift predictions from other registration algorithms. Separating scaling and shifting allows local shifts to be measured more precisely. The proposed algorithm has immediate applications to processing data from time-lapse seismic monitoring experiments.

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