Estimation of time and spatial shifts in 4D seismic surveys using mutual information and signal envelope

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Time and spatial shift estimation in time-lapse seismic data is usually achieved using cross-correlation. While this method works generally well and it is robust in dealing with real data, it has some drawbacks. We propose here two alternative methods based on mutual information and on the signal envelope, with the aim of getting an improved estimation of the temporal and spatial 4D shifts, even in the case of signal phase variations between base and monitor image. We quantify the performances of the proposed methods using synthetic examples, and we also show results of application to a real 4D dataset. From the analysed results, we conclude that the mutual information method gives better results than cross-correlation, but the larger improvements are obtained when computing the envelope of the signal, as it allows well estimating the time shifts in presence of 4D phase variations between base and monitor. Moreover, the results on field data obtained with the envelope-based mutual information method are more closely related to the expected dynamic changes within the reservoir.
Introduction

Changes in the seismic propagation velocities due to reservoir production and geo-mechanical effects above and inside the reservoir can be measured by estimating the apparent displacements between migrated images obtained from the recorded data of time-lapse surveys. Time-lapse image registration generally consists of stretching and squeezing (warping) the monitor image to align it with the base image in order to estimate and correct time shifts between time-lapse images. The anomalies observed in the difference between a warped monitor image and the base image are called 4D signal and are of high importance for monitoring fluid flow. Many methods for the estimation of the apparent displacements from time-lapse surveys have been proposed. A classical approach computes the time and spatial shifts between the two seismic datasets using cross-correlation (Rickett and Lumley 2001; Hale 2009). This method has proven to be easy to implement and robust for many real datasets. One of its drawbacks is the choice of the window length, that can affect the estimation of the seismic attributes that depend on the time-shift, e.g. the velocity change attribute (Stammeijer and Hatchell 2014; Pazetti et al. 2016). We propose two approaches based on mutual information and on the signal envelope, with the aim of deriving a novel method that can deal with phase variations between base and monitor images.

Time-lapse registration using mutual information

Image registration based on mutual information is a method appeared in the mid-90’s (Wells et al. 1996), which is now recognized as the leading technique in multimodal image registration and is particularly used in the context of medical image registration. Mutual information is well-known for giving good image registration results without need for image pre-processing and parameter tuning (Pluim et al. 2003). Therefore, we propose to adopt this measure with the goal of improving time-lapse image registration. The concept of mutual information is linked to that of entropy of a random variable, a fundamental notion in information theory. The mutual information quantifies the amount of information that can be obtained about one random variable, through the other random variable. The mutual information $MI$ of two random variables is a measure of the mutual dependence between the two variables. The assumption for using the mutual information in the context of image registration is that there is maximum dependence between the amplitude values of two seismic images when the images are correctly aligned. Given the images $X$ and $Y$, the mutual information $MI$ is defined as

$$MI(X,Y) = \sum_{x \in X} \sum_{y \in Y} p(x,y) \log \left( \frac{p(x,y)}{p(x)p(y)} \right),$$

where $p(x,y)$ is the joint probability distribution function of $X$ and $Y$, and $p(x)$ and $p(y)$ are the marginal probability distribution functions of $X$ and $Y$ respectively. Therefore, the mutual information measures the distance (or similarity) between two distributions of the images’ amplitude values: the joint distribution of the two images $p(x,y)$, and the joint distribution in case of independence of the images $p(x)p(y)$. Poor alignment (independence of the images) results into a decrease of the measure $MI(X,Y)$. In fact, if $X$ and $Y$ are independent, then $p(x,y) = p(x)p(y)$, and therefore $MI(X,Y) = 0$. Other properties of mutual information are of being nonnegative and symmetric: $MI(X,Y) = MI(Y,X) \geq 0$.

The implementation of the algorithm using the mutual information is very similar to the one using cross-correlation. We consider a window $w$ centered on a pixel of the base image, and for each temporal and spatial translation of the monitor image, we compute the mutual information. The maximum of the mutual information corresponds to the estimate of the temporal and/or spatial displacement between the two images. In Figure 1, we compare the normalized 2D cross-correlations (Figure 1a) and the equivalent function obtained with mutual information (Figure 1b). We can note that the functions found by the mutual information are much sharper, with a more resolved maximum.

We now analyze the performances of the mutual information method using different window lengths and we compare them with the cross-correlation method. Let us consider a base and a monitor images of 300x600 samples, with the monitor image being vertically and horizontally shifted with respect to
the base by the reference values shown in Figure 2b (left). In Figure 2a, we show the normalized root-mean-square error (NRMSE) for the estimation of the horizontal and vertical shifts using cross-correlation (blue lines) and mutual information (red lines), when varying the window length (standard deviation $\sigma$ ranging from 3 to 20 samples). The NRMSE is a measure of the estimation error with respect to the reference. From these results, we note that the mutual information method outperforms the cross-correlation for any window length, and especially in the case of large windows size. As an example, in Figure 2b, we show the displacement estimates obtained with the cross-correlation and the mutual information, when using a Gaussian window with $\sigma = 20$ samples, corresponding to a window length of about 240 ms.

**Envelope-based time-lapse image registration**

One important element to consider when implementing time-lapse image registration is the case of 4D signal variations that are related to the reservoir modifications (due to production and geo-mechanical changes). Let us consider that between the base and the monitor images there is a variation of the signal phase, which is a 4D effect due to the reservoir dynamic changes. The shortcoming of the cross-correlation method in this case is that it would interpret the phase variation as a time displacement. In Figure 3c, we show the results of the cross-correlation method when a phase shift of 30 degrees is applied to the monitor signals (in time). From this figure it is visible that the cross-correlation method estimates the phase shift as a vertical displacement, as the background color is yellow (corresponding to a displacement of about 1 sample) rather than green (corresponding to no displacement) as in Figure 3b, where we have used the cross-correlation method without applying the phase shift. The results obtained with the mutual information are very similar to the results with the cross-correlation (Figure 3c), because the phase shift modifies the image amplitude values, and therefore also the mutual information would estimate the phase shift as a vertical displacement.

To avoid this erroneous estimation, we propose to compute the displacements after computing the envelopes of the base and monitor images. The envelope of a signal is the magnitude of its analytical signal. A very important property of the envelope is that it is invariant to the phase variations of the original signal: the envelope of a signal does not vary when varying the phase of the signal. Therefore, by applying the cross-correlation and the mutual information methods after computing the signal envelopes (on the temporal axis), we expect that the estimation will be robust with respect to 4D phase variations between the base and monitor images.

In Figure 3d and 3e, we compute the vertical and horizontal shifts using the cross-correlation and the mutual information methods, respectively. For the results of these figures, a phase shift of 30 degree was applied to the monitor image, and the estimation algorithms have been computed on the envelopes of the data (in the time axis), rather than on the original data. The estimation results have improved. The result obtained with the 2D cross-correlation method (Figure 3d) is much more similar to the initial result without the applied phase shift (Figure 3b), except for few residual artifacts which are related to the shape of the seismic events of the considered base and monitor. The best result is obtained with the mutual information method (Figure 3e) for which we get a result that is very close to the one that we would obtain without phase shift. This result is due to the fact that the mutual information method analyzes the similarity between two images by comparing the distributions of the image values, therefore the results do not vary much if we consider a signal or its envelope.

![Figure 1](image.png)

**Figure 1** Example of one normalized 2D cross-correlation (a) and the same function obtained by mutual information (b), computed for a single sample of the base and monitor images from a synthetic dataset, considering time and space lags of ±7 samples.
Field data results

We compare the proposed methods in an inline section of the Norne field dataset, considering the 2001 and 2006 seismic surveys. We focus our analysis on the reservoir area, with the dashed black lines denoting the top and base of the reservoir. Figure 4a presents the time shifts computed using the cross-correlation method. This result is very similar to the one obtained with the mutual information (not shown here). The time shifts estimated with the envelope-based cross-correlation and with the envelope-based mutual information are shown in Figures 4b and 4c, respectively. We can note that the results with and without envelope are very different. In particular, the result without envelope shows a compact positive time shift estimation (corresponding to a decrease of the seismic velocity with time) all over the reservoir area. The results with the envelope-based algorithms show a larger time-shift on the left-side of the reservoir concentrated around the injector well (due to pore pressure increase), and a time-shifts decrease towards the producer well (due to competing effects of fluids and pressure changes). Overall, the results obtained with the envelope-based algorithms better match with the expected results, given the locations of injection and production wells.

Conclusions

The mutual information is a well-known method for image registration as it gives good image registration results without need for image pre-processing and parameter tuning. From the analysed results, we can conclude that, in the context of seismic time-lapse image registration, the mutual information method performs better than the cross-correlation method, but the results of these two methods are not so different. This might be due to the fact that the base and monitor images are already very similar, at least in the considered inline data, therefore the performances of the cross-correlation algorithm are already good. We have also proposed to compute the envelope of the data before estimating the time shifts (either with cross-correlation or mutual information). The use of the data envelope allows well estimating the time-shifts in presence of 4D phase variations between base and monitor. The results on the Norne field dataset show that the envelope-based methods give an interpretation of the reservoir variations that is closer to the expected outcome, given the locations of injection and production wells.

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References


**Figure 2** (a) NRMSE for the vertical and horizontal displacements using the 2D cross-correlation method (in blue) and the 2D mutual information method (in red), using different window sizes. (b) Reference and estimates of vertical (top) and horizontal (bottom) displacements using the 2D cross-correlation method (XCORR) and the 2D mutual information method (MI), with a Gaussian window with \( \sigma = 20 \) samples.

**Figure 3** Estimates of vertical (top) and horizontal (bottom) displacements: (a) exact reference, (b) result of the 2D cross-correlation method, (c) result of the 2D cross-correlation method when a 30 degrees phase shift is applied between the base and the monitor images, (d) result of the envelope-based 2D cross-correlation method when a 30 degrees phase shift is applied between the base and the monitor images, (e) result of the envelope-based 2D mutual information method when a 30 degrees phase shift is applied between the base and the monitor images. A Gaussian window with \( \sigma = 5 \) samples is used for these results.

**Figure 4** Time shifts estimated using (a) cross-correlation, (b) envelope-based cross-correlation, and (c) envelope-based mutual information, with a window of length 200 ms.