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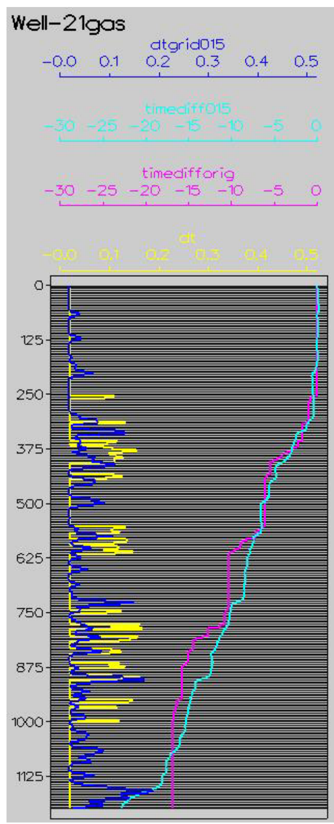
Note

Time match – a method for estimating 4D time shift



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Abstract

A method for estimating time shift in 4D seismic is presented. The algorithm we use matches the time in a new survey with the time in the original survey, providing a map from one to the other. This is done on a trace by trace basis. The algorithm is tested at synthetic seismic data, and performs well on the test case.

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Contents

1 Introduction

4D seismic involves 3D seismic surveys at different time instances. As a reservoir matures, the saturations in the reservoir are altered. Typically gas or brine replaces oil. The seismic response is affected by this trough a time shift because the seismic velocities are altered, and trough amplitudes since the reflection coefficients are altered. That is, both the mapping from depth to time and the strength of the signal changes between two surveys. In this note we describe an algorithm that estimates the time shift that has occurred between two seismic surveys. This is done in order to discriminate between the amplitude effects and time shift effects in a 4D survey.

The algorithm was developed in corporation with Hydro Oil and Energy, see Syversveen et al (2004), where it was tested on seismic data from the Njord field. The results were promising, but further investigation of the method was wanted. In this report, we describe the algorithm and test it on synthetic generated seismic, in order to better understand and document the strength of the method.

2 Time shift

The origin of the time shift is the velocity change in the reservoir. Let z denote the depth reference, $V_0(z)$ and $V_T(z)$ denote the seismic velocities at initial survey and repeated survey respectively. The time depth map for the two surveys are then given by the standard relations

$$t_0(z) = \int_0^z V_0(z)^{-1}\, dz$$

$$t_T(z) = \int_0^z V_T(z)^{-1}\, dz.$$

It is common to use the time map in the first survey as reference rather than the depth, since there is a one to one correspondence between these parameterizations,

$$z(t_0) = \int_0^{t0} V_0(t_0)\, dt_0.$$

The relation between the two time maps, t_0 and t_T is given by,

$$dt_T/dt_0 = dt_T/dz \cdot dz/dt_0 = V_0(z(t_0))/ V_T(z(t_0)) .$$

The time shift is defined as,

$$\Delta t(t_0) = t_T(t_0) - t_0.$$

2.1 Prior distribution of time shifts

The prior distribution of the time shift is defined by smoothing independent random measure, i.e.

$$\Delta t(t_0) = \int_0^{t_0} K(t_0 - t)\, dN(t).$$

The kernel K(t) is typically a smooth transition from zero to one, e.g. the cumulative distribution of a Gaussian variable, see Figure 1.

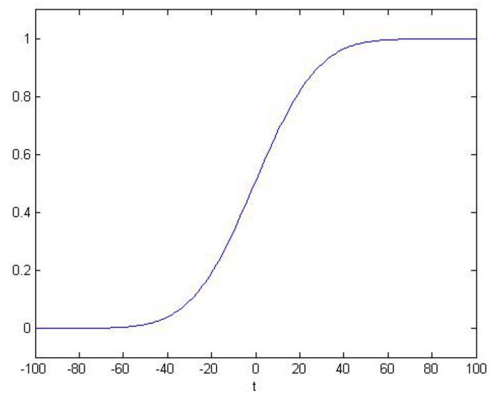

Figure 1: Integral kernel corresponding to a cumulative distribution of a Gaussian variable.

The continuous formulation above can be discretised, such that the time shift is a weighting of independent random variables,

$$\Delta \mathbf{t} = \mathbf{K}\,\mathbf{N}$$

where $\Delta \mathbf{t}$ is a discretisation of time shifts, $\mathbf{N}$ denotes a vector of independent variables, and $\mathbf{K}$ is a matrix of weight factors. A typical $\mathbf{K}$ that corresponds to the kernel in Figure 1 above is displayed in Figure 2.

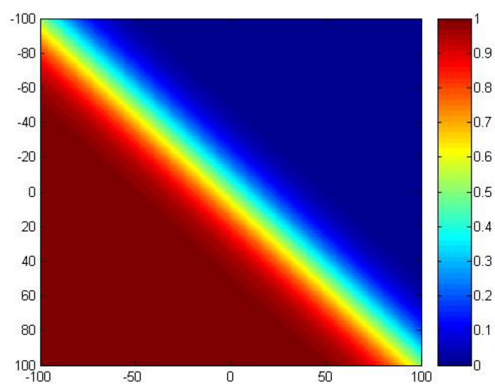

Figure 2: Matrix of weight factors which corresponds to the kernel in Figure 1.

The components of $\mathbf{N}$ are independent and identically distributed. The law of the i^{th} component, N_i can in practice be any law. We model the distribution as a convolution of a threshold transform of a normal variable and normal variable, i.e. let X_i and Y_i be standard normal then $N_i = sd \cdot (p_1 X_i \cdot I(X_i > 0) + p_2 Y_i)$, where p_1=0.99 and p_2=0.01 in the experiments described later, and *sd* is called the standard deviation of the prior (which is not exactly correct). One example of a resulting distribution is displayed in Figure 3. The rationale behind such a distribution is that that time shifts are skewed and tend to have larger positive shifts than negative shifts.

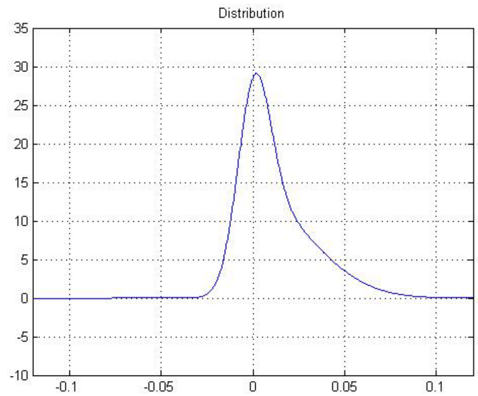

Figure 3: Distribution of independent random variables.

3 Time match method

We have developed a method to extract 4D time shifts from two seismic 3D surveys. We consider this as a problem of nonlinear pairwise alignment of seismic traces. The problem of nonlinear pairwise alignment of seismic traces is discussed in Liner and Clapp (2004). They formulate the problem as an optimization problem. In this respect our approach is similar to the one by Liner and Clapp (2004). The optimization algorithm and the application we consider is however different.

3.1 Algorithm

The algorithm matches the time in a new survey with the time in the original survey, i.e. it estimates the time map $t_T(t_0)$. The algorithm works on a trace by trace basis. The matching is done by locally compressing and stretching the time axis in order to minimize the squared difference between amplitudes. The optimization algorithm we use is simulated annealing. This is an iterative algorithm. In each iteration a perturbation of the current state is proposed. This new state is accepted or rejected with a probability based on the difference in fit. As the algorithm progresses, the probability of accepting a worse fit tends toward zero.

Formalize this by denoting the seismic from the original survey by $s_0(t_0)$ and the repeated seismic by $s_T(t_T)$. Let the target region for the match be $t_0 \in [T_B \ \ T_E]$. The algorithm can be stated as follows:

1. Initialize: $t_T^0(t_0) = t_0$, compute the residuals, $r^0(t_0) = s_0(t_0) - s_T(t_T^0(t_0))$

2. Sample change center proportional to the absolute difference at the location, i.e. $\tau^{Prop} \sim p^i(t_0) = | r^i(t_0) | / \int_{T_B}^{T_E} | r^i(t_0) |$

3. Sample $N_{\tau Prop}$ according to the prior distribution, i.e. resample the component in the random vector which corresponds to the change center. Compute the proposal for the new time map $t_T^{Prop}(t_0)$ according to the relation between the time shift and the random vector, see Section 2.1 above. Note that the perturbation influences a region around the

change center and all times after, see Figures 4 and 5. Alternatively, swap current time shift with the closest time shift below in the trace.

4. Compute the residuals of the proposed time map, $r^{Prop}(t_0) = s_0(t_0) - s_T(t_T^{Prop}(t_0))$, and the change center proposal distribution $p^{Prop}(t_0) = |r^{Prop}(t_0)| / \int_{T_B}^{T_E} |r^{Prop}(t_0)|$

5. Accept the proposal with probability
$$\alpha = \max\{ p^{Prop}(\tau^{Prop})/p^i(\tau^{Prop}) \exp[\lambda^i(\|r^{Prop}\|^2 - \|r^i\|^2)], 1\}.$$

6. If accepted, set $t_T^{i+1}(t_0) = t_T^{Prop}(t_0)$, else set $t_T^{i+1}(t_0) = t_T^i(t_0)$.

7. Increase the iteration number *i*, and go to step 2 if maximum number of iterations is not reached.

The constant λ in step 5 is larger than one. When *i* becomes large, the exponential term dominates the expression, and only proposals which improve the fit are accepted.

The maximum number of iterations is crucial for convergence, but since the algorithm is very time consuming, we have to limit the number of iterations.

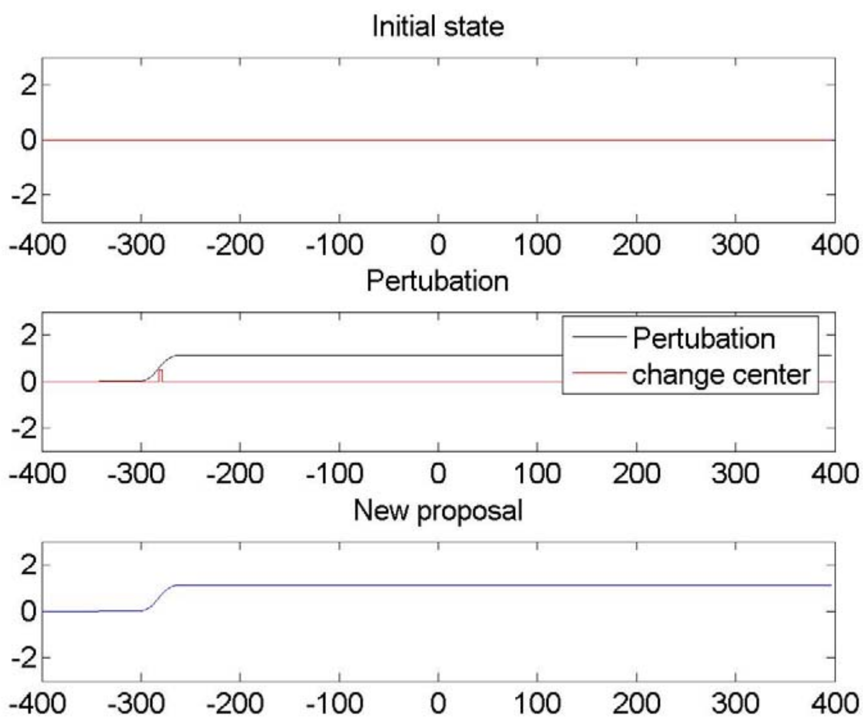

Figure 4: Possible first step in the time match algorithm.

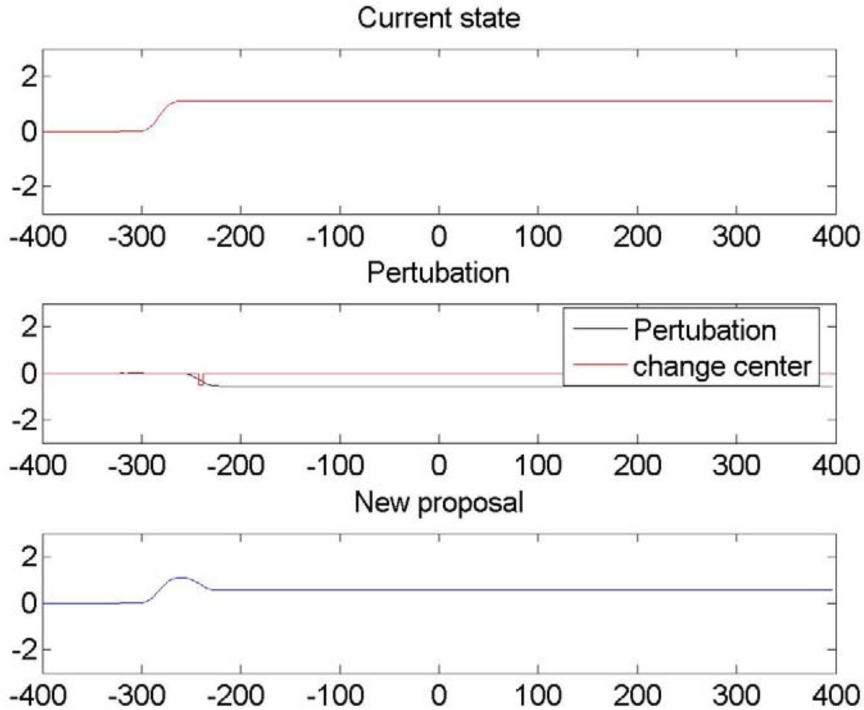

Figure 5: Possible step two in the time match algorithm.

Time match of a whole cube can be very time consuming if the cube is large. In order to save time, we propose to match only a part of the traces, and interpolate over the cube. The algorithm used is as follows:

1. Choose a parameter k, a small integer, for example 3 or 4.

2. In each lateral layer, do a convolution with the Gaussian kernel with $2\sigma = k$.

3. Do the time match on every k'th trace in x- and y-direction.

4. At last, the time matched traces are interpolated over the whole grid using a bilinear interpolation of length k in both directions.

In addition to saving time, we get smoother cubes after time shift.

4 Test case

A synthetic test case was built for testing of the time match algorithm. A synthetic reservoir with 100*100*300 grid cells was constructed. Fluvial channels of sand were generated in a homogeneous background of shale, and zones with only background were placed on top and bottom of the reservoir, see Figure 6. We assume that the channels are filled with oil at time 0 and gas at time T. Synthetic reservoir variables Vp, Vs and Rho are generated by Gaussian random fields at time 0 and T , see Figure 7. The z-axis is now the time reference at time zero, i.e. t_0. In the cells containing shale, the petrophysical variables are equal at time 0 and T. The time shift introduced by this model is calculated as follows. The local time shift is found by inserting the simulated Vp for time zero and T into the relations in Section 2. The time reference for the second reservoir is then computed and the reservoir variables at time T are shifted to the natural time reference, i.e. t_T.

Synthetic seismic can now be generated for the oil and gas case, see Figure 8, and this seismic will be used for testing the time match algorithm. The Crava program, developed by The Norwegian Computing Center, is used for generating synthetic seismic. Buland et al (2003) describe the theory behind Crava. The angle in the synthetic seismic is set to 0 degrees.

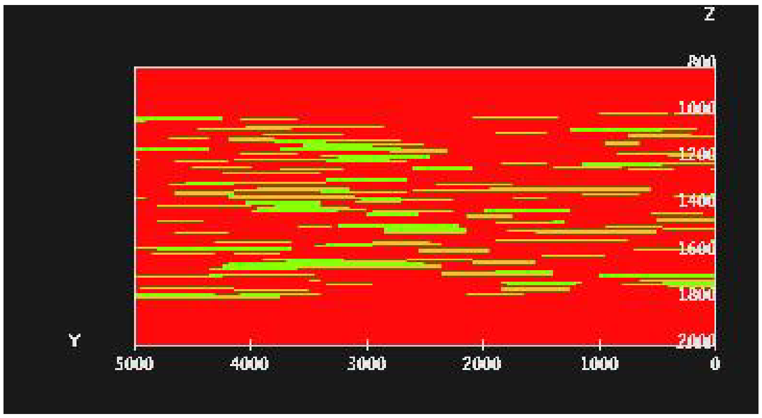

Figure 6: Facies model used in the test case.

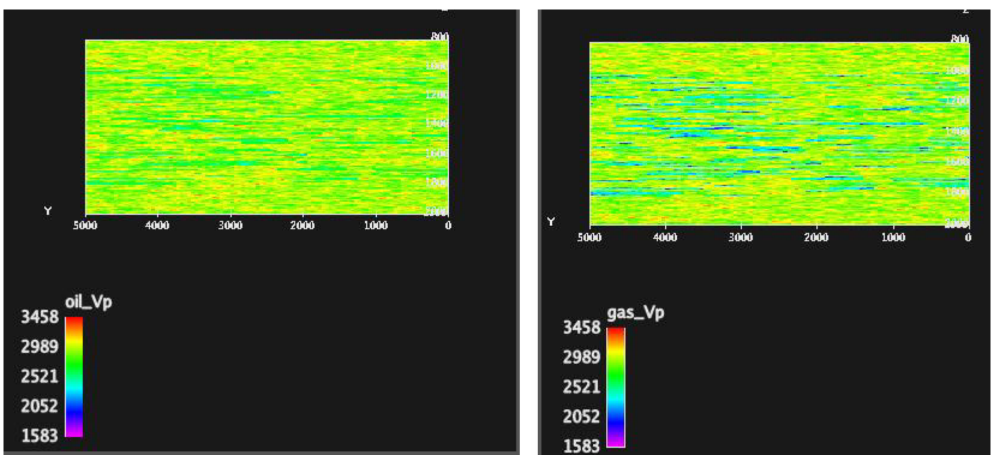

Figure 7: Vp in oil (left) and gas (right). Z-axis is deep.

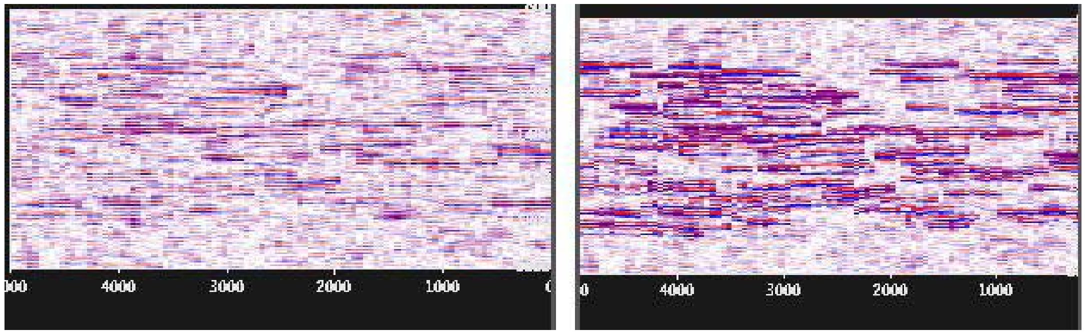

Figure 8: Synthetic seismic for oil case (left) and gas case (right).

The maximum time shift observed in the data is 32ms. Therefore the maximum time shift in the time match algorithm is set to 35ms. We do a match of every third trace in x- and y-direction before smoothing. The kernel in the prior, K(t), is the cumulative distribution of a Gaussian variable with variance 4 ms and range 10 ms. The elements of **N** are multiplied with a weight 1.5 ms in the first experiment below, later referred to as the standard deviation of the prior.

Figure 9 and Figure 10 show true and estimated time shift for the first test case. We see that the estimate is quite close to the truth. The estimate is smoother than the truth because we invert only a part of the traces and do a smoothing. In Figure 10, we see some areas where the true time shift is very small, but the estimated time shift is large. Elsewhere, the algorithm does a quite good job. In Figure 11, we see the derivative of the time shift for true and estimated case. This figure does not show such good reproduction of the time shift as the previous figures. Inspection of the well log shown to the left in Figure 12 can explain why. The figure shows the true and estimated time shift (pink and green), and match is relatively good. But when we look at the estimated derivative (blue), and compare to the yellow truth, there are too large and few changes in the time shift. This can be corrected by reducing the variance of the prior. A new time match with standard deviation reduced to 0.15 was run. To the right in Figure 12, we see the logs for this match, and we get a much better match of the derivative of the time shift.

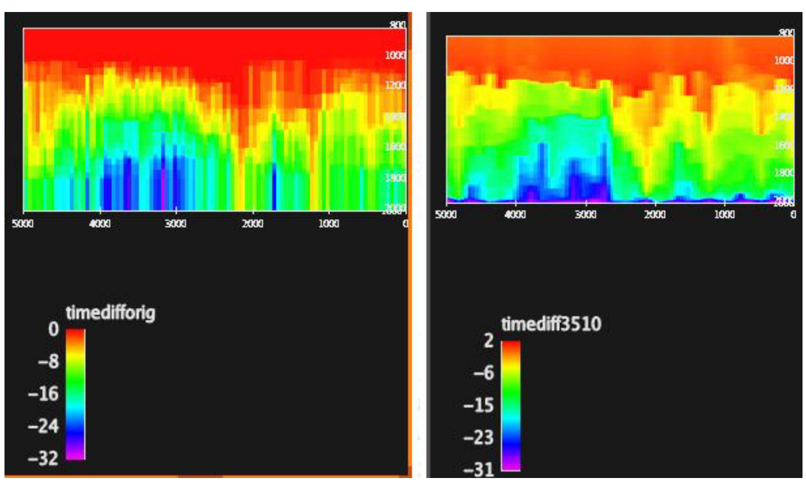

Figure 9: True and estimated time shift, side view. Standard deviation in prior is 1.5.

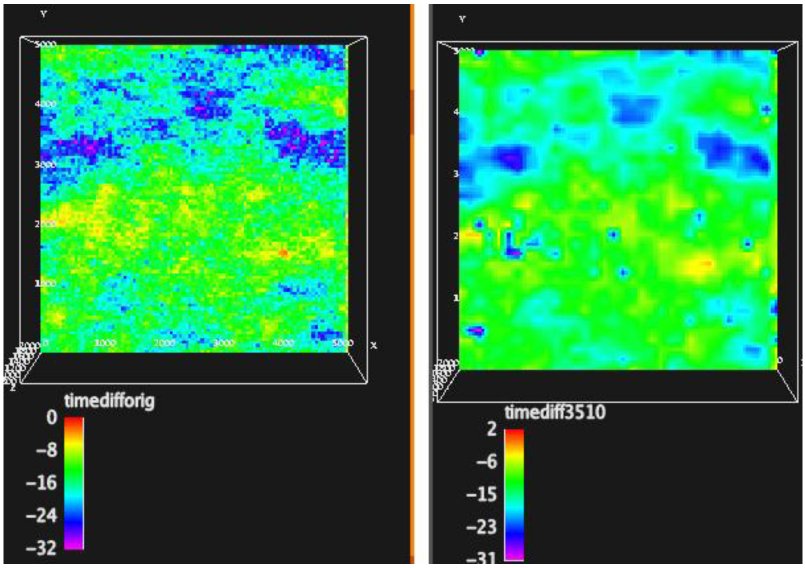

Figure 10: True (left) and estimated (right) time shift at bottom of the reservoir.

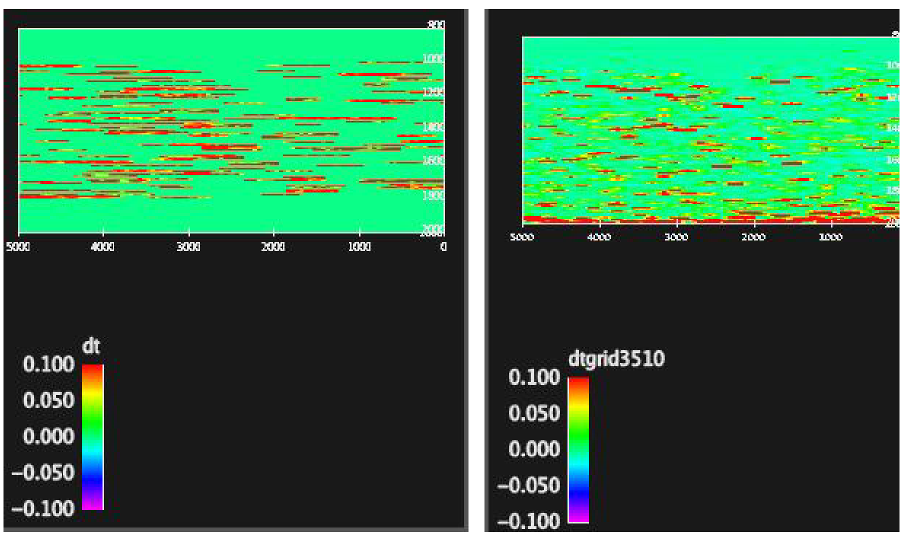

Figure 11: The derivative of time shift, truth (left) and estimated (right), side view.

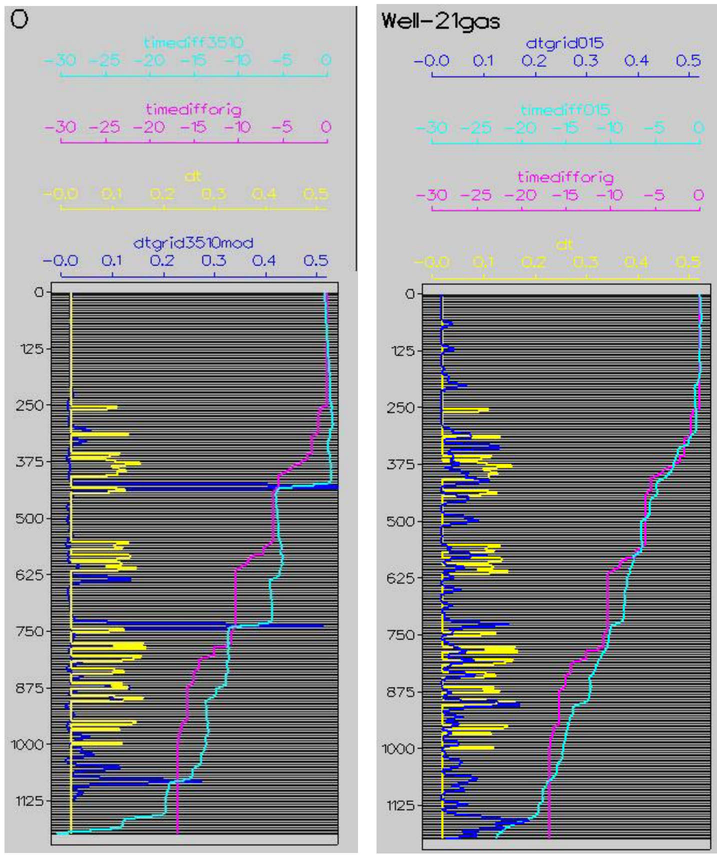

Figure 12: Well logs of true (pink) and estimated (green) time shift, and their derivatives (yellow and blue). To the left, prior variance is 1.5, to the right, prior variance is 0.15.

Figure 13 and Figure 14 contain further results from the time match with prior standard deviation set to 0.15. Again, the time shift is very well estimated, and the estimate of the derivative is better than in the first case. The time shift at the bottom of the cube will never be correct, because of the accumulation effect in the algorithm. Therefore we see too many large negative values in the bottom of Figure 13, and too large positive values in the bottom of Figure 14.

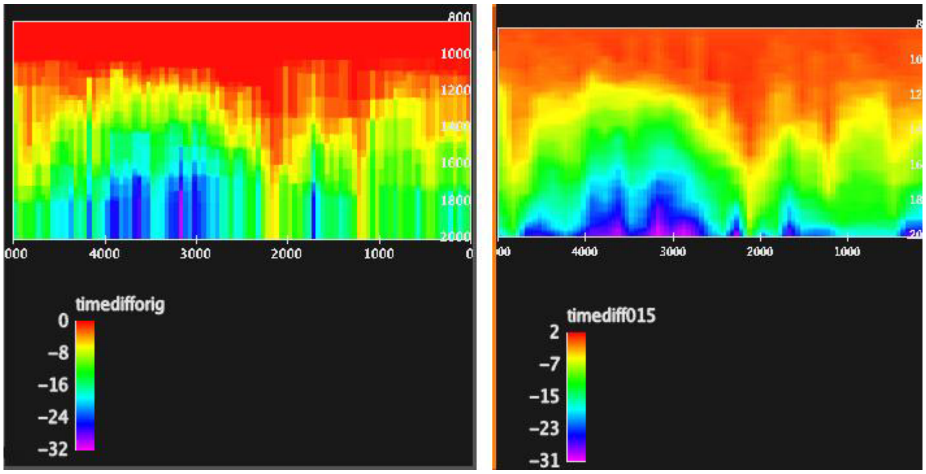

Figure 13: True and estimated time shift, side view. Prior variance is 0.15.

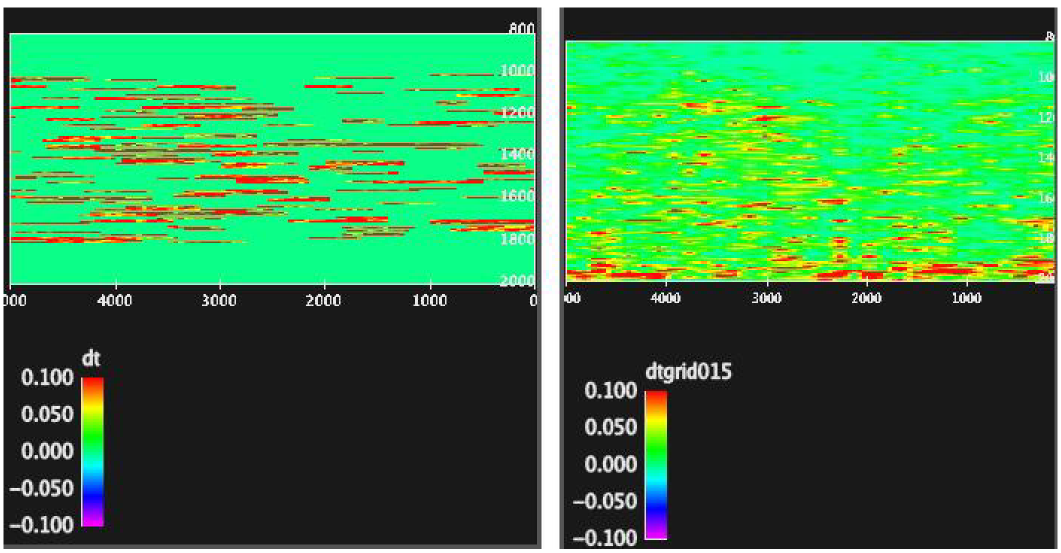

Figure 14: Derivative of time shift, true values (left) and estimated values (right). Prior variance is 0.15.

4.1 Inversion test

An interesting test is to see if inversion of the synthetic seismic data will give back the data we started with. An additional set of seismic cubes at 30 degrees is generated before the inversion. The seismic inversion program, Crava, is used both for generating synthetic seismic and for inversion. Four vertical wells are drilled in the true reservoirs, and these data are used as input to Crava and for generating background models.

Inversion is very sensitive with respect to the background model used. The background model for the oil case is created by kriging of four smoothed well logs with data from the true oil reservoir. For the gas case, the Vs background is the same as for oil. Vp and Rho are found by multiplying the oil background by dt_0/dt_T (=Vp(gas)/Vp(oil)), that is, one minus the derivative of the time shift, except for the 20 last grid layers below the reservoir, where the oil values are kept unchanged. We use the time shift from the last experiment above.

The inversion is done for the oil and gas case, and Vp for gas is time shifted. For the 20 last grid layers in the cube, the time shift is kept constant, because the estimated values in this area are not polite. Then the derivative of the time shift is estimated as 1-Vp(gas)/Vp(oil), and the time shift is calculated from its derivative. The results are shown in Figure 15, Figure 16, and Figure 17. Again, the time shift is better estimated than its derivative. The derivative contains negative values, which are not present in the true data.

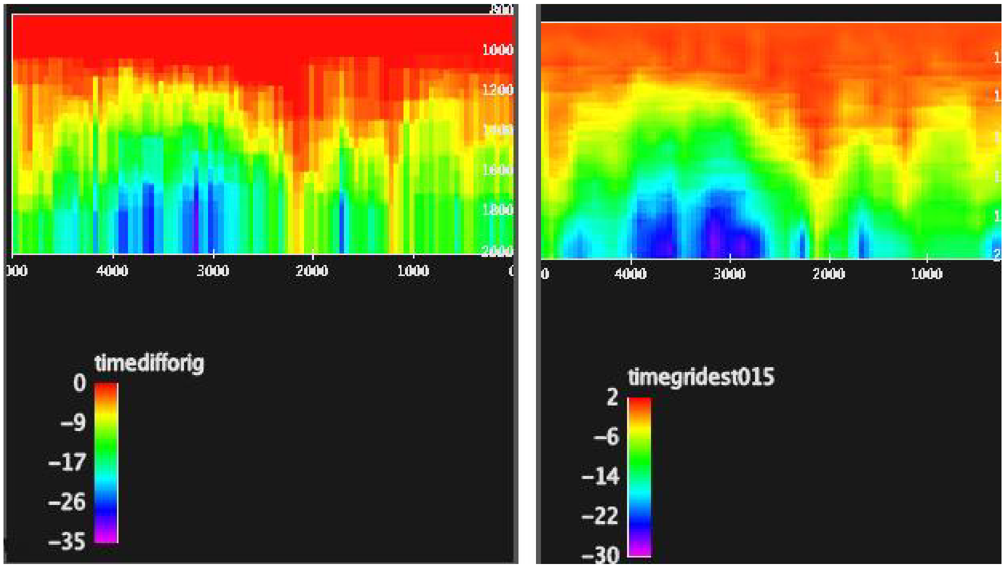

Figure 15: To the left, true time shift, to the right, time shift estimated from inverted Vp. Side view.

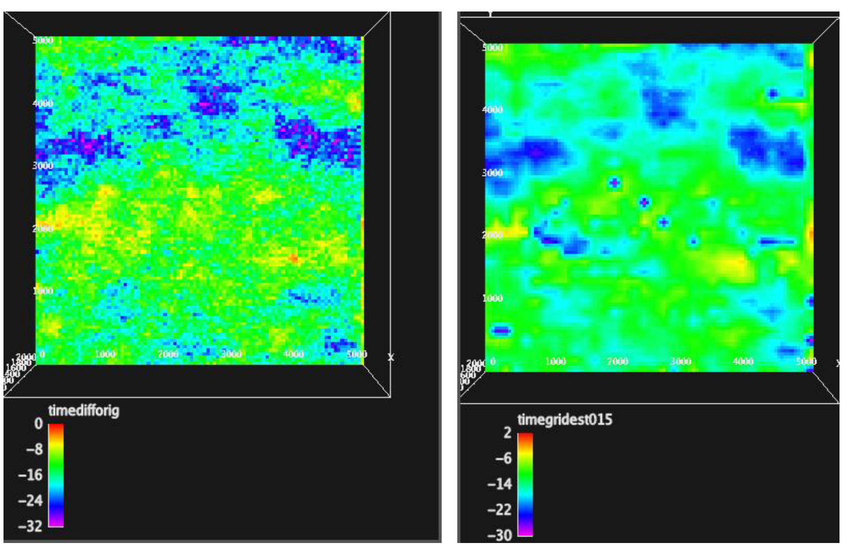

Figure 16: To the left, true time shift, to the right, time shift estimated from inverted Vp. Bottom reservoir.

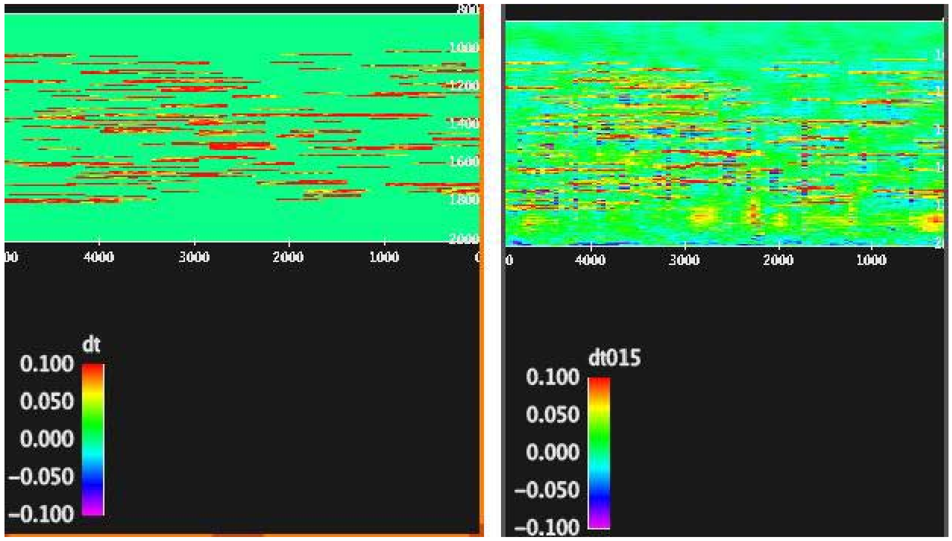

Figure 17: Derivative of time shift. To the left, true values. To the right, estimated from inverted Vp.

5 Concluding remarks

The time match algorithm performs well on the test case, proper choice of model parameters improves the match.

The estimated time shift can be used to construct better background models for new surveys, if the base survey has a good background model.

6 Ideas for further work

There are still some refinements that could be done with the algorithm. The accumulation effect in the bottom of the cube can be reduced by not suggesting changes in the area below the reservoir. This will also give a speed up of the algorithm.

A linear interpolation between neighboring grid cells is used to interpolate seismic values between sample points in the seismic trace. An interpolation scheme which uses more nodes (e.g. 6 or 8) will give a smoother appearance of the sub-sampled seismic. This is important to include before selling the idea to geophysicists, who consider this an important issue. It is however not clear whether this will significantly improve the time match.

A more efficient proposal scheme is thought to give the most significant improvement of the current algorithm.

Refinement schemes where the time maps that already have been estimated in the 3D cube are used to construct good starting points for the algorithm, can improve the convergence when several traces are considered.

In the current scheme we use an annealing term which increases the importance of the data for each step and the optimum fit is sought. An alternative is to sample the posterior distribution of the time shift with a fixed level of the tolerance of the residuals and report the conditional expectation in place of the optimum of the objective function. The conditional expectation tends to be a more stable estimate than the maximum posterior.

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