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A Regularization Algorithm Optimized for Time-lapse Processing

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SUMMARY

In time-lapse processing, independent regularization of each vintage is the typical approach. This disregards any geometrical limitations imposed by different surveys. Here we recast the regularization process as a minimization problem with model-space constraints. These constraints couple geometrical relations between surveys to improve repeatability. We also demonstrate how to solve the minimization problem using a practical and pragmatic approach. Results from a North Sea dataset show overall reduction of 4D noise, especially around less repeatable parts of the surveys including the undershoot zone.

Introduction

Interpretation of 4D seismic data aids in improving reservoir productivity and optimizing the planning of infill drilling. The key to successful time-lapse monitoring is repeatability in seismic surveys such that only the true subsurface changes are revealed (Calvert, 2005). Acquiring highly repeatable seismic data is challenging at the best of times, due to environmental factors such as weather conditions and sea state. The process is further complicated by new structures and rigs around the reservoir. All of these effects lead to suboptimal repeatability between time-lapse seismic surveys.

Processes such as 4D binning and regularization help in improving repeatability between 4D surveys. However, these may fail where base and monitor acquisitions are highly non-repeatable, for example around undershoot zones. These zones contain critical information as they are the closest to the wells. Better interpretation in these areas can bring considerable benefit to field productivity.

Traditionally, the regularization step is performed independently for each time-lapse vintage. This disregards any geometrical limitations imposed by different surveys. Here we recast the regularization process as a minimization problem with model-space constraints. These constraints couple geometrical relations between surveys to improve repeatability. We also demonstrate how to solve the minimization problem using a practical and pragmatic approach.

Theory

We start by recasting the regularization process into a minimization scheme. For two vintages we minimize two cost functions

$$E_1 = \left\| \mathbf{d}_1 - \mathbf{L}_1 \mathbf{m}_1 \right\|_\ell \quad , \quad E_2 = \left\| \mathbf{d}_2 - \mathbf{L}_2 \mathbf{m}_2 \right\|_\ell \quad , \tag{1}$$

where the subscripts $_1$ and $_2$ refer to the first and second vintages respectively, ℓ is the chosen norm, $E_{1,2}$ are the cost functions, $\mathbf{d}_{1,2}$ are the input irregular data, and $\mathbf{m}_{1,2}$ are the regularized datasets i.e. the solutions of the minimizations. $\mathbf{L}_{1,2}$ are geometry dependent operators which map regularized data back into their original irregular coordinates.

In an ideal time-lapse setting with good sampling on both vintages, the regularized data for any vintage should not depend on the original acquisition geometry; they should be a reflection of true subsurface properties taking into account other surveys' geometries. In such an ideal setting, this condition is stated mathematically by the operator $\mathbf{S} = \mathbf{L}_1^T \mathbf{L}_1 - \mathbf{L}_2^T \mathbf{L}_2$ as

$$\mathbf{S}\mathbf{m}_1 = [\mathbf{L}_1^T \mathbf{L}_1 - \mathbf{L}_2^T \mathbf{L}_2]\mathbf{m}_1 = 0 \quad , \quad \mathbf{S}\mathbf{m}_2 = [\mathbf{L}_1^T \mathbf{L}_1 - \mathbf{L}_2^T \mathbf{L}_2]\mathbf{m}_2 = 0 \quad , \tag{2}$$

where $\mathbf{L}_{1,2}^T$ are the adjoint operators of $\mathbf{L}_{1,2}$, i.e. the regularization operators.

Equation 2 states that the regularized data $\mathbf{m}_{1,2}$ should not change if it is mapped back and forth to either its original geometry or other vintages' geometry. This equation can be defined as a model-space constraint by introducing the time-lapse coupling cost function E_{4D}

$$E_{4D} = \left\| \mathbf{S}\mathbf{m}_1 \right\|_\ell + \left\| \mathbf{S}\mathbf{m}_2 \right\|_\ell \quad . \tag{3}$$

The full cost function is defined by the sum of each vintage's term and the 4D coupling term

$$E_{Total} = E_1 + E_2 + \lambda E_{4D} \quad , \tag{4}$$

where λ is weighting factor that controls the strength of the constraint.

Minimizing equation 4 to find the solution is a relatively simple operation if the operators $\mathbf{L}_{1,2}$ and $\mathbf{L}_{1,2}^{T}$ are linear; however in most cases they are not. The regularization process typically faces aliased data, and most regularization schemes have some non-linear aspects to overcome this issue, for example the anti-leakage Fourier transform as described by Xu *et al*. (2005).

A simple pragmatic alternative to direct solution of Equation 4 proceeds by generating and comparing multiple realizations of each vintage; each realization is generated by one term of the $\mathbf{S}$ operator in Equation 2. The first vintage is regularized, acting as realization 'one'. The second realization 'two' is created by mapping the regularized data to other vintages' geometry and regularizing back again. The two datasets 'one' and 'two' carry the same subsurface information; differences are only due to geometrical limitations of any particular acquisition geometry. To enforce the action of Equation 2, the difference between the two realizations is treated as noise and removed, for example using the method described in Huang *et al*. (2014). The process is safe in terms of genuine 4D signal as the noise removal process is performed only using data from a single vintage. Only the geometries of the other vintages are engaged in the scheme.

A North Sea example

Figure 1 shows the sail-line geometry of a two-vintage time-lapse project from the North Sea. The base dataset has a regular acquisition direction with only minor deviations. The monitor has been acquired eight years after the base has been shot, during which time a rig was placed resulting in the under-shoot zone visible on the monitor geometry.

The two vintages have been regularized through a standard uncoupled Fourier based regularization algorithm (Poole and Lecerf, 2006) and then reprocessed with the time-lapse optimized scheme outlined above using the same core components and parameters from the standard regularization.

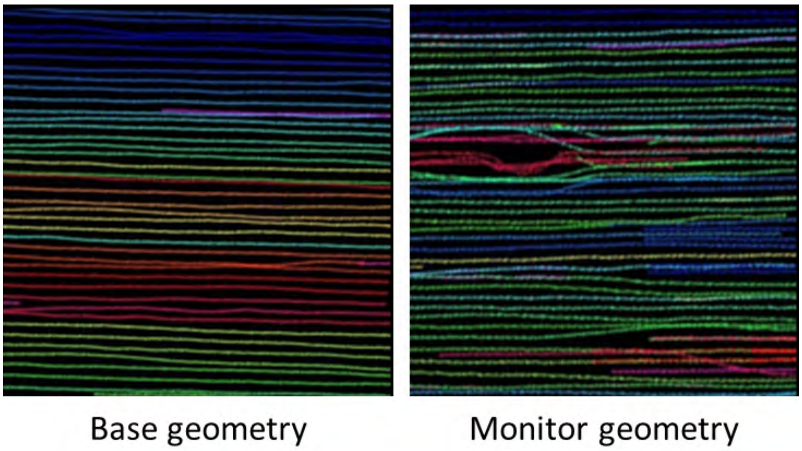

Figure 1 *Sail-line geometry of the base (left) and monitor (right) surveys. The erected rig forced the visible undershoot zone in the monitor survey.*

Figure 2 shows the results for the two approaches. The 4D difference displays show relatively good repeatability on the right side of the section; in this area, the acquisition is well repeated. The undershoot area on the left hand side of the data is characterized by a fair amount of noise and geological leakage into the difference sections. The monitor survey is clearly affected by the suboptimal acquisition around the rig so that the two vintages are rather different around the undershoot zone. However, the time-lapse optimized regularization (bottom row) removes a significant amount of non-repeatable energy in the base survey making it more comparable to the monitor. While standard regularization (top row) leaves the 4D section overwhelmed with noise around the undershoot area, the time-lapse optimized approach significantly improves repeatability and reduces leakage. A zoomed section is displayed in Figure 3. The 4D QC maps in Figure 4 reveal the uplift gained by the algorithm in a more global sense. The RMS ratio and NRMS attributes around the less-repeatable parts of the survey is significantly enhanced. The average RMS ratio and NRMS are improved by more than 45% in these areas. The global median NRMS excluding the undershoot zone is improved by around 5%.

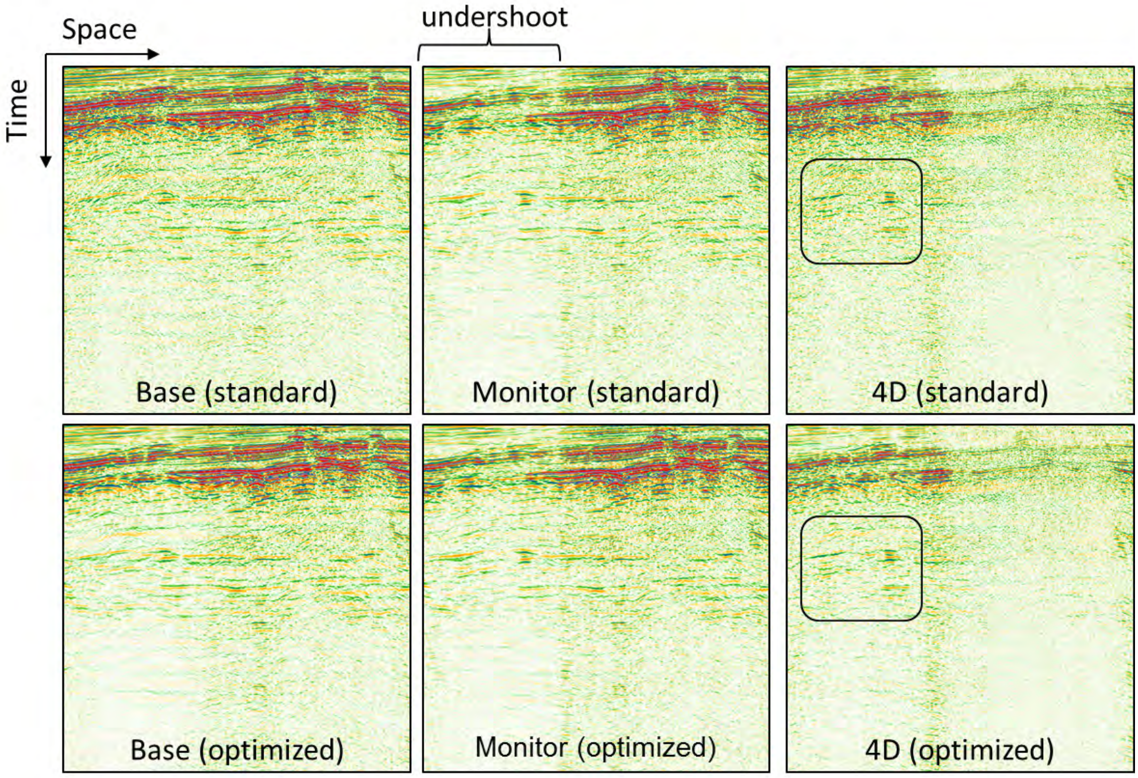

Figure 2 *Base, monitor and 4D difference sections after standard regularization (top) and time-lapse optimized regularization (bottom).*

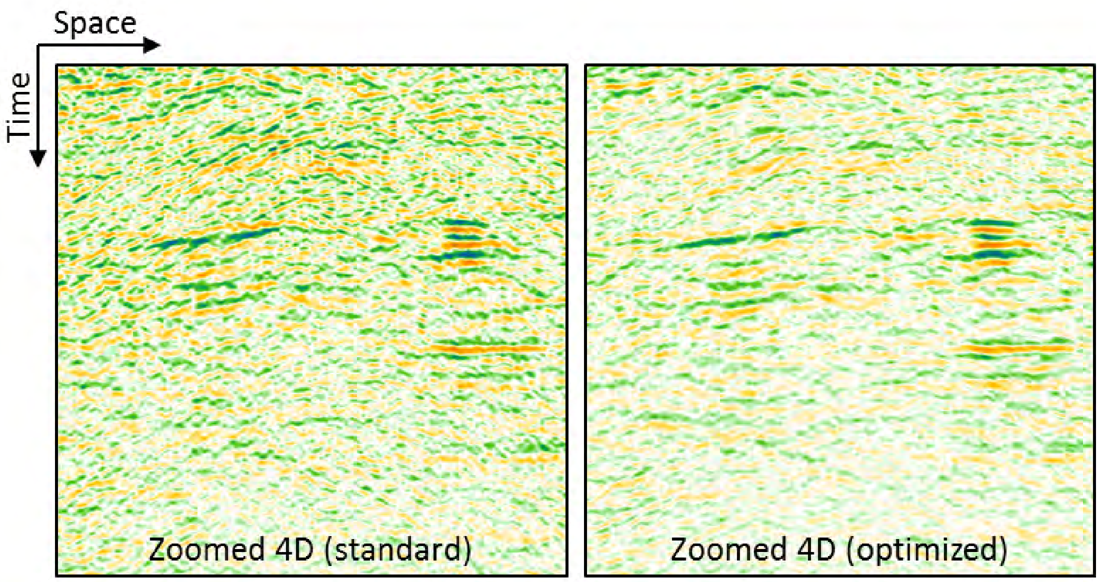

Figure 3 *Zoomed 4D sections after standard regularization (left) and time-lapse optimized regularization (right).*

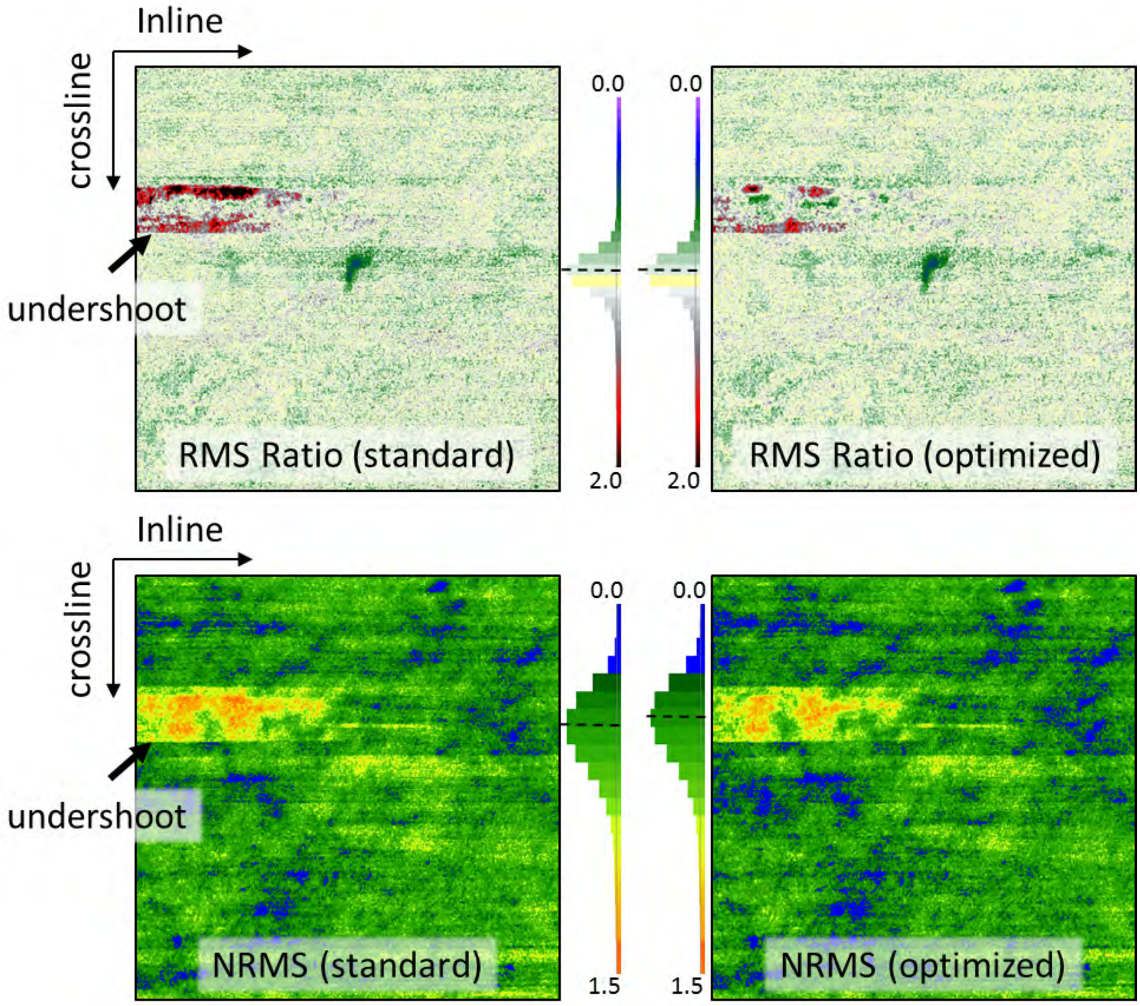

Figure 4 *4D QC maps after standard regularization (left) and time-lapse optimized regularization (right). Outliers on the RMS ratio map (top row) are reduced and NRMS is decreased on average.*

Conclusions

A new time-lapse optimized regularization scheme is introduced. The method improves global 4D repeatability across vintages. The method is most effective in areas where the acquisition is non-repeatable, for example around undershoot areas. The uplift on 4D sections and QC maps demonstrates the success of the method.

Acknowledgments

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