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Bandwidth-equalization and phase-matching of time-lapse seismic datasets

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ABSTRACT

Time and frequency domain methods for equalizing bandwidth and making phase corrections are tested on synthetic time-lapse data. Cross-equalization filters are primarily designed to equalize amplitude spectra by decreasing the bandwidth of the higher frequency survey to that of the lower frequency survey. I also tested approaches that tried to maximize the bandwidth of the difference between surveys, in such a way to avoid amplifying noise.

INTRODUCTION

Time-lapse (4D) seismic studies are becoming a useful tool for monitoring fluid movements in the subsurface. The technique is based upon the assumption that the only changes in the subsurface over time will be production related (e.g. saturation changes); therefore, with knowledge of the rock physics of the field, it may be possible to infer saturation changes from the difference between surveys shot at different times.

In the past, fields with steam injection have been considered the best targets for reservoir monitoring projects (Lumley, 1995) because of the sensitivity of velocity to temperature in common sedimentary rocks (Wang and Nur, 1989). However, there has been increasing interest in using 4-D seismic to monitor water-floods (Johnstad et al., 1992), where the seismic response is less sensitive to the fluid parameters.

A universal problem in reservoir monitoring projects, is how to best compare surveys, and identify the differences caused by fluid movements. Simple differencing will only work if the surveys are fully repeatable, and the only differences between them are fluid related. However, this is never the case, as other differences always creep in.

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There are ways to design surveys which maximize repeatability. For example, permanent geophone arrays can be used to reduce differences due to navigational errors. However, differences can appear from many sources, and so complete repeatability can never be achieved. Potential causes for differences include: environment problems such as weather conditions, cable feathering, sea-state, tides and seasonal temperature/salinity changes of the ocean; hardware problems such as equipment deterioration, source signature variability, misfires and geophone failure; and unavoidable survey design changes e.g. due to the position of a platform.

Given that unwanted changes do occur, it is natural to ask how they can be reduced. Cross-equalization is a catch-all term for methods that eliminate these acquisition and processing differences between surveys.

Cross-equalization is usually applied in the migrated-stack domain (Ross et al., 1996), where the signal-to-noise ratio is higher, and changes due to fluids are focused. In this domain, cross-equalization consists of corrections for the following elements, which are often applied sequentially:

1. Realignment of surveys to a common grid
2. Time shifts between surveys
3. RMS energy balancing
4. Bandwidth equalization
5. Phase rotations

A common approach to cross-equalizing is to take a region of the survey to use as a design window. This window should be a subsection of the survey in which there are expected to be no changes over time. It is also important that stationarity can be assumed between the design window and the target regions. This means that the statistics of the systematic differences within the design window are the same as those within the zone of interest. Cross-equalization parameters are chosen that eliminate the differences within the design window, and then applied on the zone of interest.

Often a field had a 3-D survey shot in the 1980's, and is being reshot with 90's technology. In these circumstances, there is a question as to whether the two generations of survey can be cross-equalized, and used to locate areas of bypassed oil. These surveys will have completely different acquisition parameters. In general, the more recent survey will be of considerably higher bandwidth. Ideally the cross-equalization algorithm should try to use the statistics of the newer survey to increase the resolution of the older survey.

In this paper, I consider the bandwidth equalization and phase corrections elements of cross-equalization in both the time and frequency domains. I present methods that if the surveys have different frequency content, try to raise the bandwidth of the lower resolution survey, while taking care to avoid amplifying noise. Algorithms are tested on synthetic post-stack data. This paper does not consider the other parts of the cross-equalization process.

SYNTHETIC DATASETS

A synthetic dataset can never fully capture the complexity of field data, and it is this complexity that causes many of the problems in the cross-equalization process. Synthetics, however, can provide useful testing ground for algorithm development, as they allow small parts of a larger problem to be tackled independently.

This paper is concerned with the problems of bandwidth equalization and phase matching. By working with synthetic data, these parts of the problem can be removed from the rest of the cross-equalization process.

4-D cube

To compare different cross-equalization algorithms, I created two 3-D cubes based on the 'Qdome' synthetic (Claerbout, 1994). Changes were introduced in an interval low in the section to simulate fluid movements. The two sections were the filtered by different non-zero phase filters to simulate different generations of seismic data. Finally Gaussian noise was added.

Two slices were extracted from each cube: a slice with no fluid changes to use as a design window, and a slice with fluid changes to test the success of the algorithms.

CROSS-EQUALIZATION

Frequency domain

In the frequency domain, the problems of bandwidth equalization and phase matching are orthogonal, since they are concerned with the amplitude and argument of a complex signal.

The steps I applied to equalize the bandwidth were: Fourier transform the training windows, S_1 and S_2, on the time-axis, and calculate their spectra, $\hat{S}_1$ and $\hat{S}_2$, where

$$\hat{S}_i(\omega) = \sum_{\mathbf{x}} |S_i(\omega, \mathbf{x})|^2 \tag{1}$$

I then designed the desired spectrum of the output, $A(\omega)$, by simply taking the minimum of the two spectra at each frequency.

$$A(\omega) = min\left(\hat{S}_1(\omega), \hat{S}_2(\omega)\right) \tag{2}$$

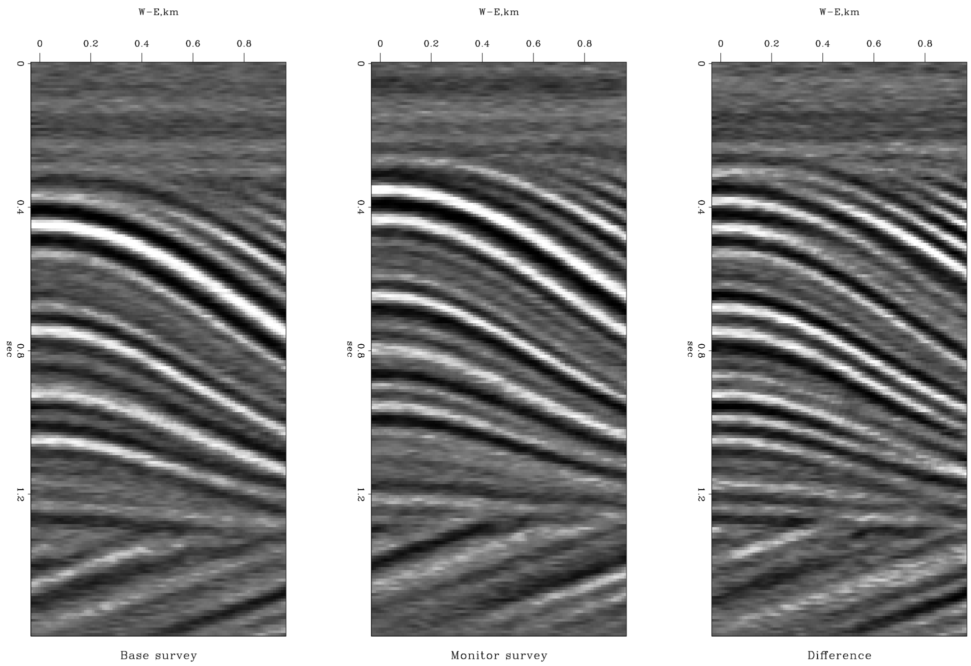

Figure 1: Slices through synthetic cubes with no fluid movements. The panel on the left shows the base survey, the center panel shows the monitoring survey and the panel on the right is the raw difference. james1-train [ER]

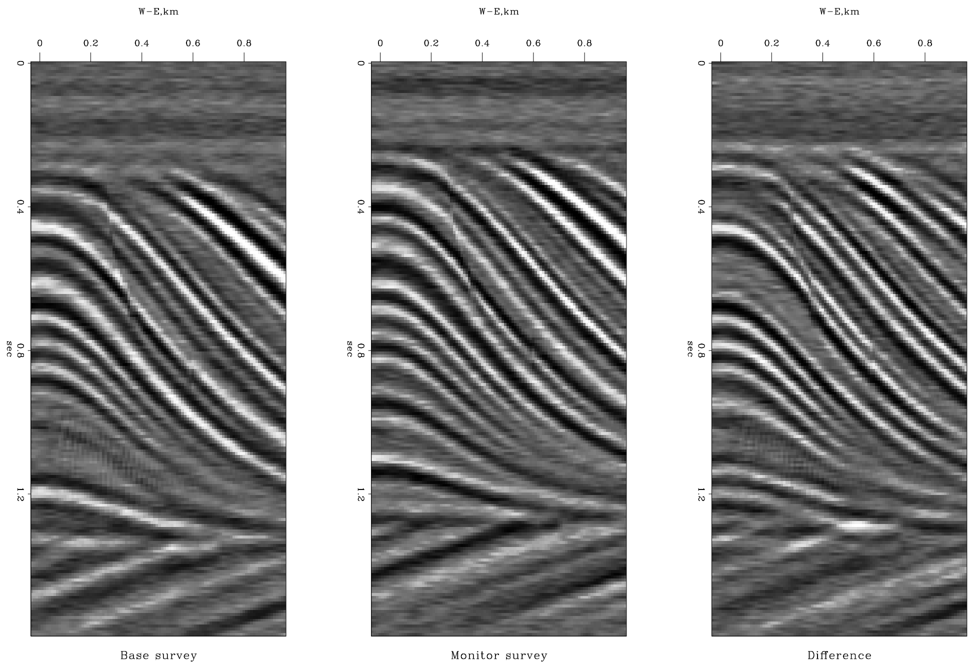

Figure 2: Slices through synthetic cubes containing fluid movements. The panel on the left shows the base survey, the center panel shows the monitoring survey and the panel on the right is the raw difference. james1-real [ER]

I applied this filter to shape the spectra of the regions of interest

$$S_i(\omega, \mathbf{x}) = S_i(\omega, \mathbf{x}) \frac{\sqrt{A(\omega)}}{|S_i(\omega)| + \epsilon} \tag{3}$$

The ϵ in the denominator is purely for the event $S_1(\omega) = S_2(\omega) = 0$, since in this formalism $A(\omega) \leq S(\omega)$.

As well as calculating a spectral operator, $A(\omega)$, I calculated the average difference in phase between the training windows for each frequency, $\Theta(\omega)$.

$$\Theta(\omega) = arg\left\{\sum_{\mathbf{x}} S_1(\omega, \mathbf{x})\right\} - arg\left\{\sum_{\mathbf{x}} S_2(\omega, \mathbf{x})\right\} \tag{4}$$

This was then applied to map S_2 onto S_1

$$S_2(\omega, \mathbf{x}) = S_2(\omega, \mathbf{x})\; e^{-i\Theta(\omega)} \tag{5}$$

Although the phase and bandwidth are orthogonal, in this approach it does matter the order in which the corrections are applied. This is due to the fact I calculate the average phase as the phase of the average value, as opposed to the average of the phases. With my approach it is correct to apply the bandwidth correction before the phase correction, although this is unlikely to be very important.

The results of the frequency domain cross-equalization are displayed in Figure 3. The differences due to the fluid movements are clearly visible, and the signal-to-noise level is high.

Time domain

In the time domain, the bandwidth and phase problems are not as easily separable, since it is difficult to constrain the phase of a time domain filter. However, the two steps can be tackled together by designing a filter on the training window that maps the monitor survey, s_2, onto the base survey, s_1, minimizing the regression:

$$\mathbf{A s_1} - \mathbf{s_2} \approx \mathbf{0} \tag{6}$$

This approach effectively looks for components of s_1 that are present in s_2. If there are none, then A will equal 0, and the difference, $\mathbf{A s_1} - \mathbf{s_2} = \mathbf{s_2}$.

The results of match-filtering in the time-domain are shown in Figure 4. The approach was at least as successful as the frequency domain approach, although there were only 12 free coefficients in the filter compared to several hundred in the frequency domain approach. Another advantage of this approach is that the random noise is naturally attenuated in the filtered monitor survey.

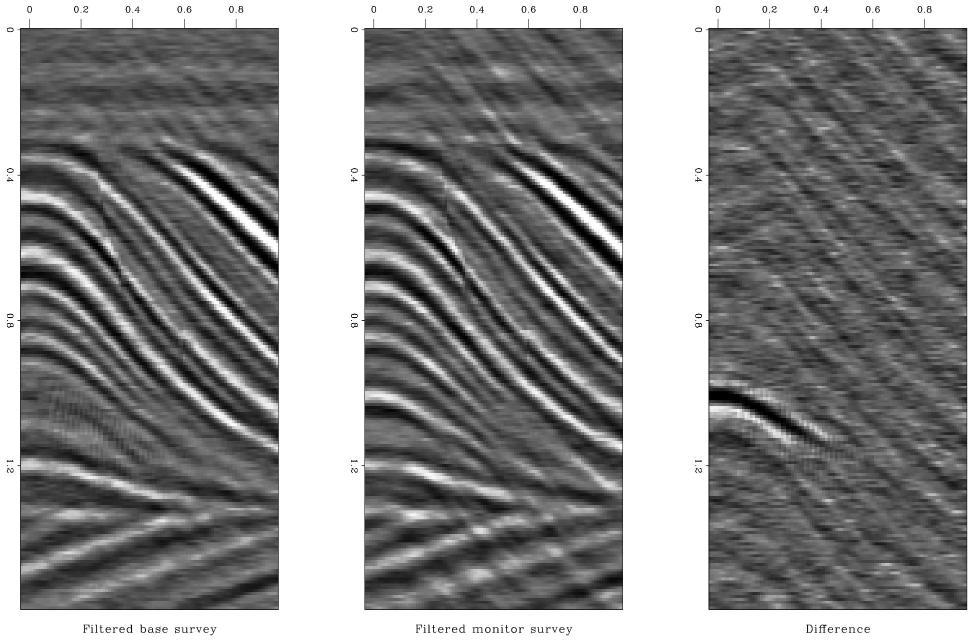

Figure 3: Results of frequency domain cross-equalization. Left is filtered base survey, center is filtered monitor survey and right is the difference. The synthetic fluid layer is clearly visible in the difference section. $S/N = 9.14$. james1-freq [ER]

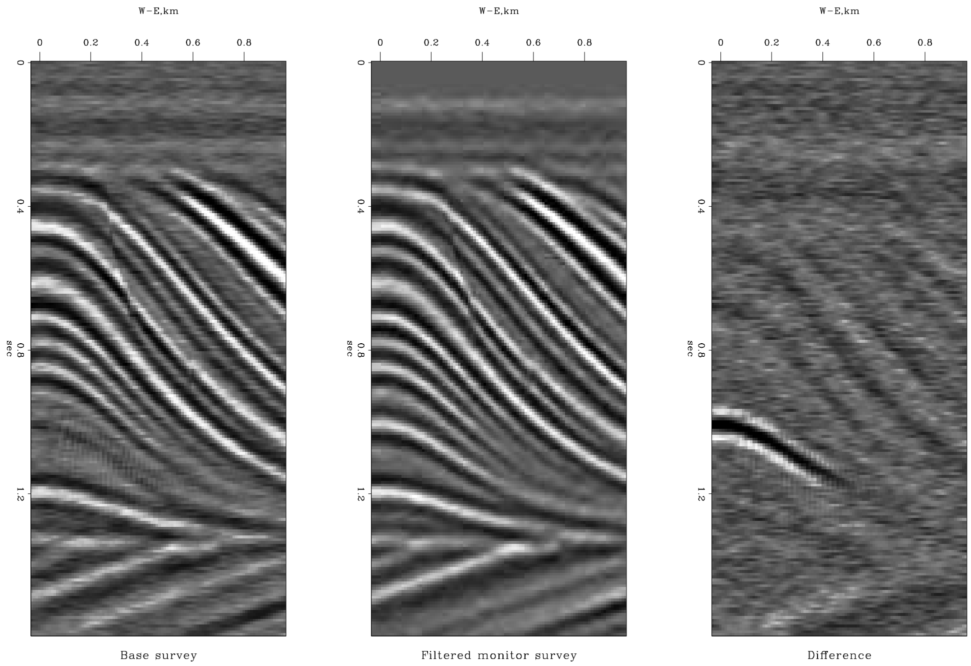

Figure 4: Results of time domain match-filtering. Left is filtered base survey, center is filtered monitor survey and right is the difference. $S/N = 9.54$ james1-time [ER]

A mixed domain approach

It is possible to have the best features of both domains by using a mixed domain approach. Figure 5 shows the results after bandwidth equalization in the frequency domain and phase-matching with a 12 point time filter. Tackling the problem in this way, you have control over the spectra, and do not need to worry about constraining the wildly oscillatory phase of an all-pass filter.

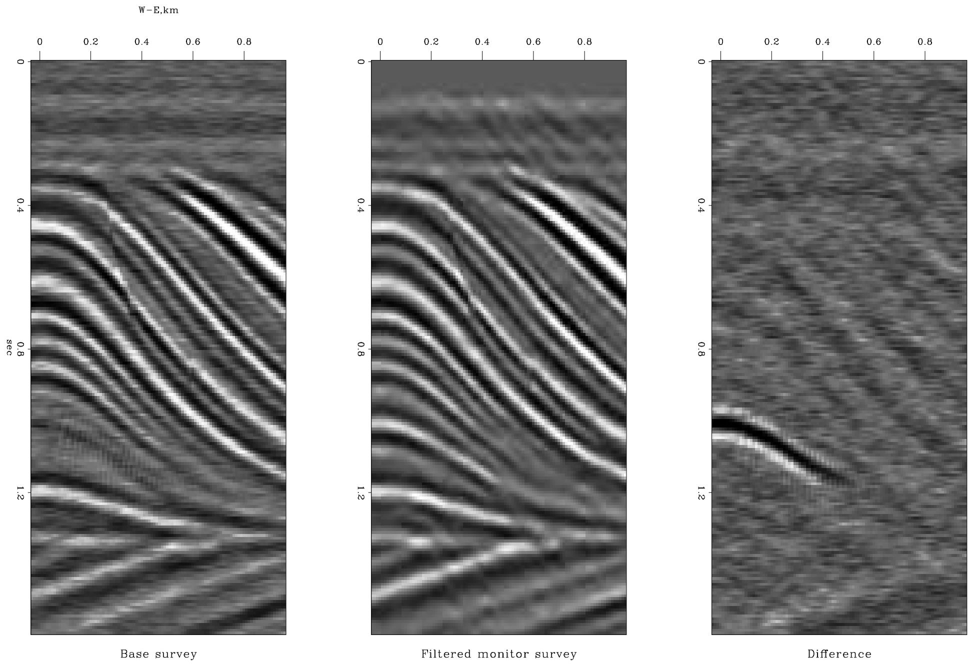

Figure 5: Results of mixed domain match-filtering. Left is filtered base survey, center is filtered monitor survey and right is the difference. $S/N = 9.50$ james1-mixed [ER]

OPTIMAL FILTERING

The three methods outlined above all cross-equalized the two surveys well. However, they all worked by effectively low-pass filtering the monitor survey to the bandwidth of the baseline survey. This is a safe strategy as there is no danger from noise blowing-up. An interesting question is whether it is possible to use the information contained in the high frequency survey to boost the bandwidth of the lower frequency survey. This is similar to deconvolution, and is very dangerous because there is always the danger of amplifying noise.

Mixed domain method

Instead of taking the minimum of the two surveys, as in equation (3), I took the lower value if it was below some threshold, B_1, and the higher value if it was greater than another threshold, B_2. For values in between I took a scaled linear combination:

$$A(\omega) = \left(\frac{S_{lower}(\omega) - B_2}{B_1 - B_2}\right) S_{lower}(\omega) + \left(\frac{B_1 - S_{lower}(\omega)}{B_1 - B_2}\right) S_{higher}(\omega) \qquad (7)$$

For the example shown in Figure 6, I used $B_1 = 10\%$ and $B_2 = 80\%$ of $max\{S(\omega)\}$. The bandwidth equalization was done in the frequency domain and the phase matching in the time domain. Figure 7 shows the spectra of the difference sections for this approach and the standard mixed domain approach. The bandwidth has been increased by a small amount, while the noise level has remained constant, so this approach has worked to a small extent.

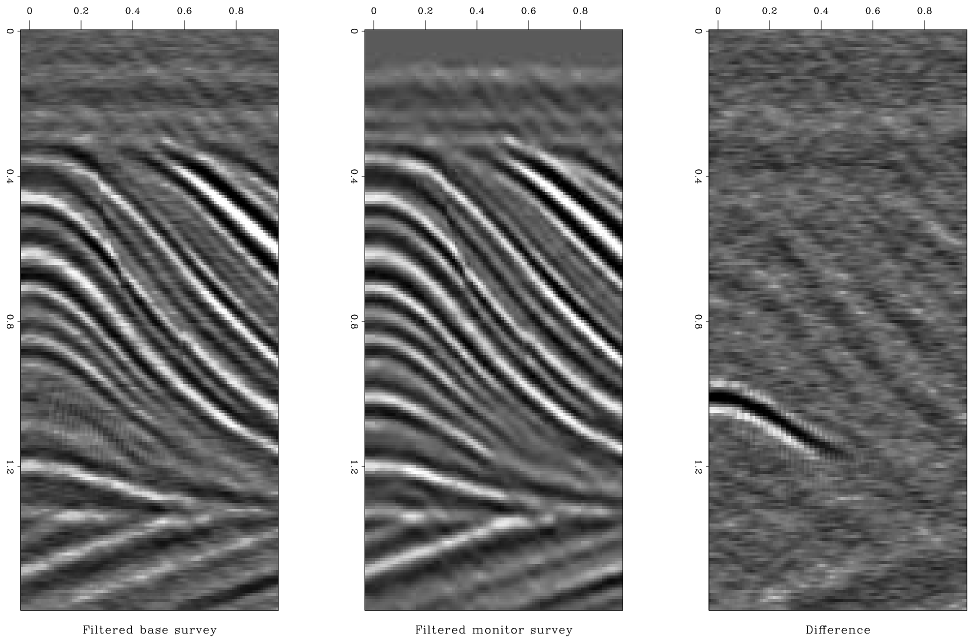

Figure 6: Cross-equalization while maximizing bandwidth of difference signal. Left is filtered base survey, center is filtered monitor survey and right is the difference. $S/N = 9.24$ $\boxed{\text{james1-optimal}}$ [ER]

Cross-equalization via an intermediate model

It is possible to construct many other operators which try to maximize the frequency content of the difference section.

For example another approach may be to find filters, A_1 and A_2, that when applied to unchanged areas of the two datacubes, s_1 and s_2, give the same result, m. In

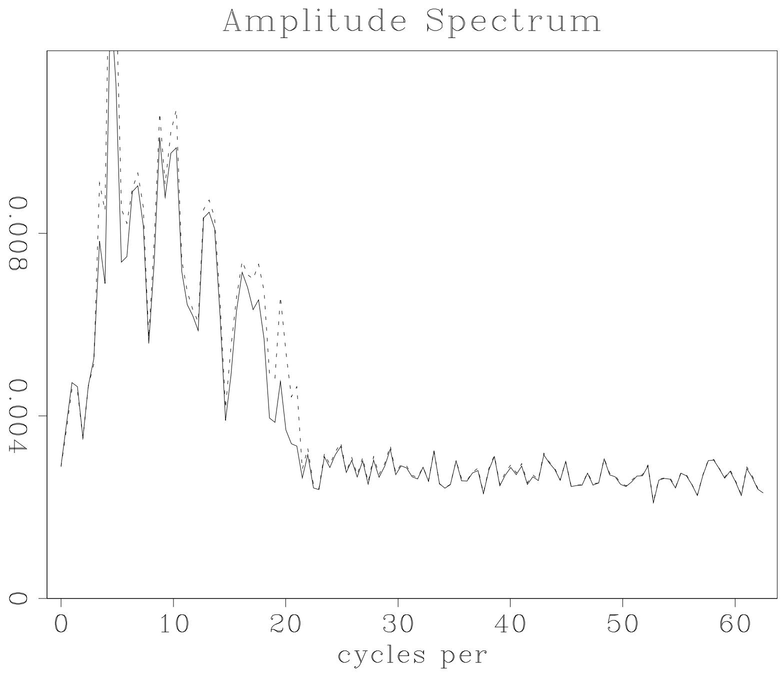

Figure 7: Spectra of difference plots. Solid line is standard mixed domain approach, and dashed line is 'optimal' mixed domain approach. james1-opt.spec [ER]

addition we wish the survey with the higher bandwidth to remain as unchanged as possible. These constraints are contained in the regression equations:

$$\mathbf{A_1 s_1} - \mathbf{m} \approx \mathbf{0} \tag{8}$$

$$\mathbf{A_2 s_2} - \mathbf{m} \approx \mathbf{0} \tag{9}$$

$$\mathbf{m} - \mathbf{s_2} \approx \mathbf{0} \tag{10}$$

The unknowns, $\mathbf{m}$, $\mathbf{a_1}$ and $\mathbf{a_2}$ can be packed into a single vector, allowing the above equations to be rewritten in matrix form:

$$\begin{pmatrix} -\mathbf{I} & \mathbf{S_1} & \mathbf{0} \\ -\mathbf{I} & \mathbf{0} & \mathbf{S_1} \\ \lambda\mathbf{I} & \mathbf{0} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \mathbf{m} \\ \mathbf{a_1} \\ \mathbf{a_2} \end{pmatrix} - \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \lambda\mathbf{s_2} \end{pmatrix} \approx \mathbf{0} \tag{11}$$

where λ controls the relative weights of the regression equations, and has to be chosen by the user.

Since we are estimating an intermediate model simultaneously with the pair of filters, a good initial model speeds convergence. The initial models chosen were $\mathbf{m_0} = \mathbf{s_2}$ and $\mathbf{A_1} = \mathbf{A_2} = \mathbf{I}$.

With two sets of regression, a good choice of λ is important. A choice of λ that is too large results in $\mathbf{m} = \mathbf{s_2}$ and does not do a good job of match-filtering. Alternatively, a choice of λ that is too small does a good job of match-filtering, but a lot of the resolution is lost and the result approaches that of the simple inverse filtering above. Unfortunately an intermediate choice of λ is the worst of both worlds, as it does a poor job of match-filtering and the bandwidth of the signals are reduced. The results of the inversion with $\lambda = 0.1$ are shown in Figures 8. By playing around with different values of λ and different filter lengths, I was not able to get a successful result. Although this approach looks like it may be successful on paper, I believe

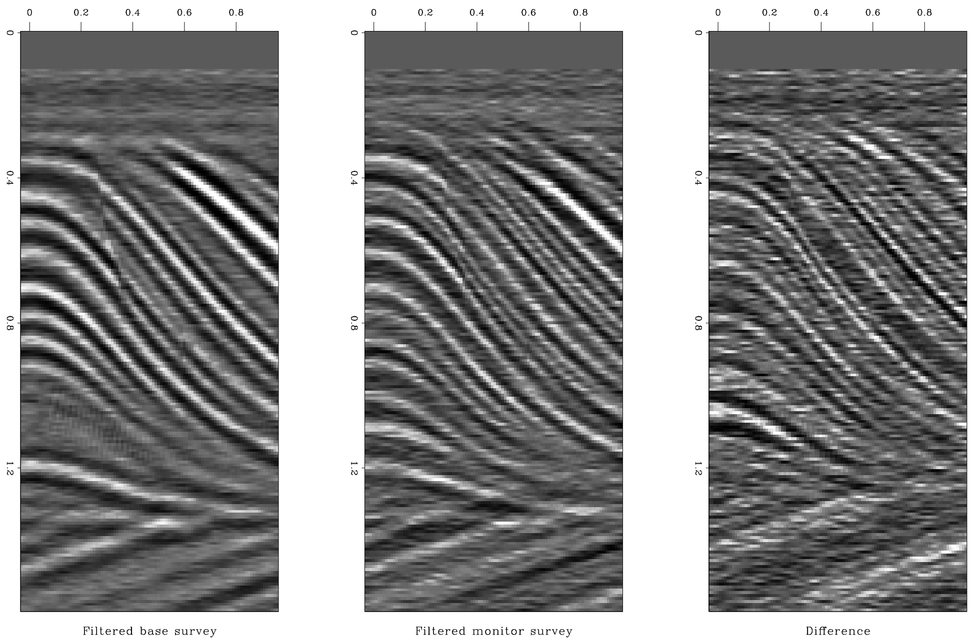

Figure 8: Unsatisfactory attempt at 'optimal' cross-equalization via an intermediate model - result with $\lambda = 0.1$. james1-inter [ER]

its failure stems from the size of the model space. Although time domain match-filtering uses a similar least squares formulation, it has only about a dozen elements in the model space, as opposed to a model the size of the data space which has to be estimated in this intermediate model approach.

CONCLUSIONS

In this paper, I have tested several approaches to the bandwidth equalization and phase matching steps of the cross-equalization process. Working in the frequency domain gives a large degree of control over the spectra and phase of the equalized data; however there is a danger of over-parameterizing the problem. Working in the time domain, provides a simple way of reducing the number of degrees of freedom. The best results were obtained by performing the bandwidth equalization in the frequency domain and phase matching in the time domain. An 'optimal' cross-equalization method was tested following this procedure, which successfully increased the bandwidth of the difference section.

Working with synthetic data, it is hard to simulate the problems faced while cross-equalizing field data. Specifically, there will be problems in the assumption of stationarity that will need to be addressed, and the noise will never be nicely

Gaussian. In these cases it may be possible to work under the assumption that the statistics although not stationary, are at least spatially slowly varying.

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