Stanford Exploration Project, Report 95, October 10, 1997, pages 195–204

An amplitude bias correction for 4D seismic cross-equalization

James Rickett[1], *David Lumley*[2], *and Harry Martin*[3]

keywords: *4D cross-equalization, time-lapse, monitoring, signal-to-noise*

ABSTRACT

Amplitude balancing is an important part of the 4D seismic cross-equalization process, which aims to suppress processing and acquisition differences between time-lapse 3D seismic surveys. The matched-filter approach to cross-equalization estimates an amplitude correction that minimizes the norm of the difference section. However, this correction will be biased by the presence of noise, and the amplitude of coherent events will not be equalized correctly. Similarly, a normalization scheme that is based on equalizing the energy in the two surveys, implicitly assumes that their random noise levels are equal. We illustrate the problem with a synthetic example, and present a method that correctly scales the amplitudes based on the relative signal-to-noise levels of each dataset.

INTRODUCTION

Seismic reservoir monitoring is a new technology that uses multiple time-lapse 3D seismic surveys to directly image fluid movements, pressure/temperature fronts or other effects of production in the subsurface (Lumley, 1995). Unfortunately, different generations of 3D seismic can exhibit seismic differences unrelated to reservoir production, caused by non-repeatability of seismic acquisition and processing artifacts. The aim of cross-equalization is to remove processing and acquisition differences between time-lapse seismic surveys, so comparison between them can be interpreted in terms of genuine fluid-related changes.

Cross-equalization of post-stack seismic datasets typically includes the following generic elements:

1. Survey realignment to a common grid.

[1]**email**: james@sep.stanford.edu
[2]Chevron Petroleum Technology Co., Consulting Professor at Stanford University. **email**: lumley@chevron.com
[3]Chevron Petroleum Technology Co. **email**: hlma@chevron.com

2. Amplitude balancing to scale the data to the same amplitude/energy level.
3. Bandwidth equalization to compensate for different source wavelets.
4. Phase matching to correct residual wavelet phase differences.
5. Spatial and temporal re-registration to correct the effects of geometry errors, differential statics, or different velocity functions used for NMO and migration.

In a previous SEP report, Rickett (1997) discussed the use of L_2 matched-filtering to simultaneously correct bandwidth, phase and static shifts between surveys. Unfortunately, the amplitudes of the L_2 filters are biased by the presence of uncorrelated noise differences between the surveys, and the amplitude of coherent events may not be equalized correctly.

Similarly, any scheme that is based on equalizing the energy in the two surveys, implicitly assumes that their random noise levels are equal, which may or may not be the case.

We present an approach that scales the amplitudes in two data sets based on their relative signal-to-noise levels, and test the approach on a synthetic example that has many features observed on 4D field datasets.

MATCHED-FILTER AMPLITUDES

Matched-filtering (Claerbout, 1991) can simultaneously estimate a correction for static, phase and spectral differences between surveys. A cross-equalization operator, $\mathbf{A}$, can be designed to minimize the norm of the residual,

$$\mathbf{r} = \mathbf{A}\mathbf{d_1} - \mathbf{d_2} \tag{1}$$

where $\mathbf{d_1}$ and $\mathbf{d_2}$ are the operator-design windows of the two data sets to be matched.

Rickett (1997) solved for $\mathbf{A}$ as a time domain convolution operator by minimizing the residual in a least squares (L_2) sense. The degree of spectral matching is then controlled by the length of the time domain operator. By working with a short operator of a similar length to the two wavelets being matched, the operator can provide the "right amount" of spectral shaping: a close enough spectral and phase match to compensate for differences in wavelets and statics between the two surveys, while avoiding over-match that can zero out differences in the data sets caused by petrophysical changes during reservoir production.

As well as matching wavelets and static shifts, a matched-filter also has an associated amplitude correction. However this amplitude correction is biased by the presence of noise in $\mathbf{d_1}$. For example, if $\mathbf{A}$ is decomposed such that $\mathbf{A} = a\mathbf{A_w}$, where

$\mathbf{A_w}$ is a wavelet correction that matches the spectrum in $\mathbf{d_1}$, and a is a scale factor, then

$$a\,\mathbf{A_w}\mathbf{d_1} = ab\,\mathbf{s} + a\,\mathbf{n_1} \tag{2}$$

$$\mathbf{d_2} = \mathbf{s} + \mathbf{n_2} \tag{3}$$

where $\mathbf{s}$ is the common signal due to the geology that we are trying to remove from the difference image, $\mathbf{n_1}$ and $\mathbf{n_2}$ are the uncorrelated noise components, and b is a scalar that quantifies the different signal amplitude present in the two data windows. Ideally the operator scalar should be

$$a = \frac{1}{b}$$

and then the residual will be simply the difference of the (scaled) uncorrelated noise fields. However if the residual, $\mathbf{r}$ is minimized in an L_2 sense then

$$\frac{\partial}{\partial a}\left|ab\,\mathbf{s} + a\,\mathbf{n_1} - \mathbf{s} - \mathbf{n_2}\right|^2 = 0 \tag{4}$$

and if the noise fields are largely uncorrelated with the geology and each other, $\mathbf{n_1}\cdot\mathbf{n_2} = \mathbf{n}\cdot\mathbf{s} = \mathbf{0}$, then

$$a = \frac{b\,\mathbf{s}^2}{b^2\,\mathbf{s}^2 + \mathbf{n_1}^2} \tag{5}$$

which will only be unbiased if $\mathbf{n_1} = \mathbf{0}$. Note that as the energy of the noise field $\mathbf{n_1}$ increases, the L_2 estimate of a will be biased increasingly lower than the optimal value $1/b$.

The low value of a manifests itself in the low amplitude of $\mathbf{Ad_1}$. This was first noted while matched-filtering field data, and was corrected empirically by a trace renormalization to equalize the energy in traces between surveys.

AMPLITUDE BALANCING

Whether an AGC window or a more careful geometric spreading correction has been applied, two generations of seismic survey will, in general, have different time-varying gain functions applied to them. If not compensated for correctly, this may lead to a systematic leakage of non-reservoir events into the difference section. Although an amplitude correction may need to be time and space-varying, it should be constrained to vary very slowly, so it is not influenced by changes in the reservoir zone.

The simplest approach to amplitude balancing is to scale the data based on the r.m.s. energy in the two surveys. However, this assumes that the energy present in the noise fields are the same in both datasets, or of much smaller magnitude than the signal energy. Following a similar model to that used to describe the failings of matched-filtering we can consider the two normalized datasets, $\mathbf{d_1}$ and $\mathbf{d_2}$, to consist of some shared signal, $\mathbf{s}$, and uncorrelated "noise" components, $\mathbf{n_1}$ and $\mathbf{n_2}$, which include the reservoir difference anomaly we seek:

$$\mathbf{d_1} = \frac{1}{|\mathbf{s}+\mathbf{n_1}|}(\mathbf{s}+\mathbf{n_1}) \tag{6}$$

$$\mathbf{d_2} = \frac{1}{|\mathbf{s}+\mathbf{n_2}|}(\mathbf{s}+\mathbf{n_2}) \tag{7}$$

In order to rescale the signals to the same level, we need to apply a scale factor, ν to $\mathbf{d_1}$, such that

$$\nu = \frac{|\mathbf{s}+\mathbf{n_1}|}{|\mathbf{s}+\mathbf{n_2}|} \tag{8}$$

or again assuming the noise fields are weakly correlated with the geological signal

$$\nu \approx \frac{\sqrt{\mathbf{s}^2+\mathbf{n_1}^2}}{\sqrt{\mathbf{s}^2+\mathbf{n_2}^2}} = \sqrt{\frac{1+\frac{1}{(s:n_1)^2}}{1+\frac{1}{(s:n_2)^2}}} \tag{9}$$

where $s:n_1$ and $s:n_2$ are the signal-to-noise levels in the two datasets.

The value of ν applied to $\mathbf{d_1}$ has a large effect on the amplitude of coherent events in the difference section, and consequently may significantly affect the interpretation of the 4D data. Unfortunately, the value of ν cannot be obtained directly from the data without an *a priori* assumption about the nature of the noise. Also the optimum value of ν may be time and space varying, which further complicates its determination.

Fortunately, for seismic data with high signal-to-noise ($s:n_1, s:n_2 \gg 1$), the equal energy ($\nu = 1$) balancing will be valid since $\Delta\nu \equiv \nu - 1$ will be very small.

$$\Delta\nu \approx \frac{1}{2}\left(\frac{1}{(s:n_1)^2} - \frac{1}{(s:n_2)^2}\right) \ll 1 \tag{10}$$

In the past we have been estimating a value for ν by eye from difference sections by sweeping through a range of scalar values and finding one that minimizes the non-reservoir coherent energy in the difference sections. This is unsatisfactory in that it can be overly subjective. However an alternative approach is to make *a priori* estimations of the signal-to-noise ratio's, and use Equation 9 to calculate ν.

For the synthetic example described below, three independent "eyeball" estimates of ν were 0.77, 0.81 and 0.80. Knowing the noise fields exactly, the value obtained with the formula above was 0.808.

In production environments we expect to use an F-X decon method to estimate noise levels present in the two surveys. Alternatively, the amplitude of a marker horizon above the reservoir could be used to scale the datasets to the correct level.

SYNTHETIC EXAMPLE

Figure 1 shows inline sections through two synthetic surveys, which were created to test 4D seismic processing algorithms. Although they were modeled post-stack, they contain many features derived from actual 4D field datasets, including different wavelets, random noise, spatially varying static and phase shifts, different time-varying gain functions, and different mute and dead-trace zones. The two surveys have different bandwidths and signal-to-noise levels to simulate multi-vintage 3D seismic.

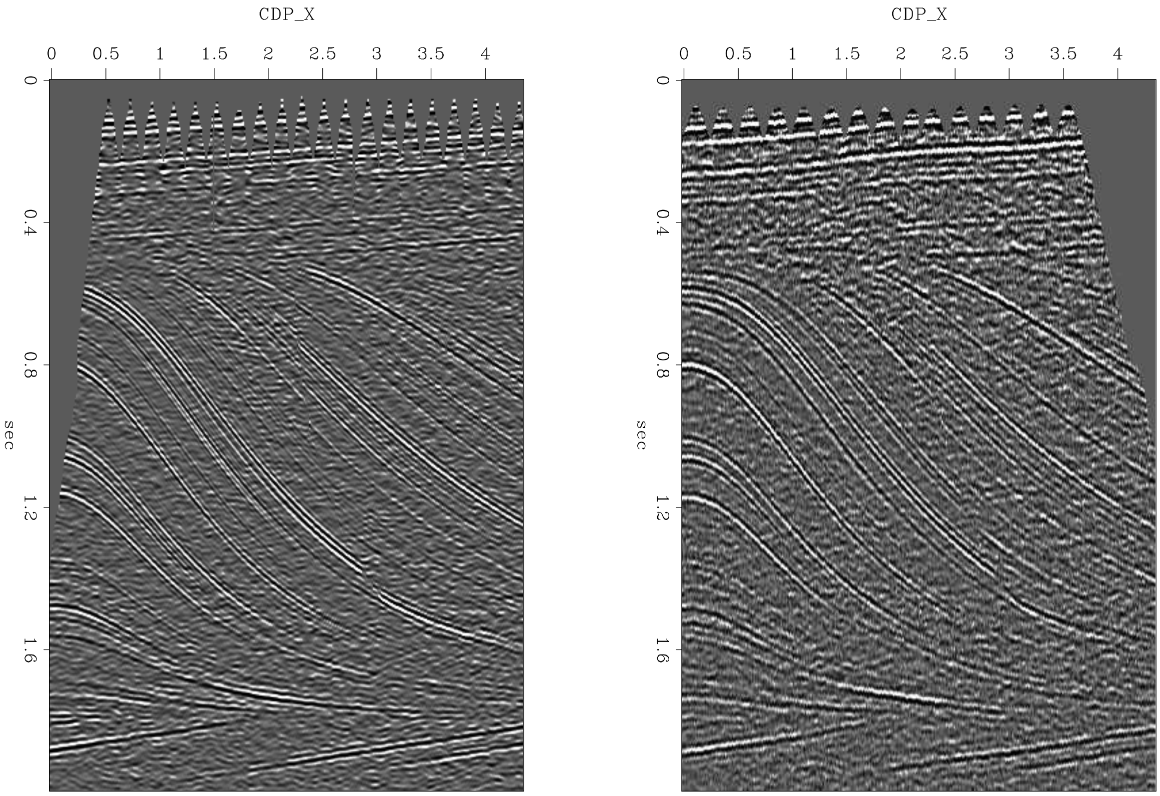

Figure 1: Inline sections through two synthetic datasets. d_1 is on the left and d_2 is on the right. james-raw [CR]

To simulate the effect of production changes, we created base and monitor reflectivity functions by introducing changes along a 'reservoir' interval. The best achievable result is shown in Figure 2. This contains only the coherent fluid changes and residual random noise.

A simple cross-equalization flow consists of matched-filtering and amplitude balancing. For this synthetic example, we designed the matched-filters on a trace-to-trace basis, in order to best estimate the spatially-varying static and phase shifts.

Figure 3 shows the filtered survey, $\mathbf{Ad_1}$ at the same scale as $\mathbf{d_2}$. The low amplitude of the figure on the left illustrates the characteristic low value of a due to the noise in $\mathbf{d_1}$. The result of the low value of a is coherent geological signal leaking through into

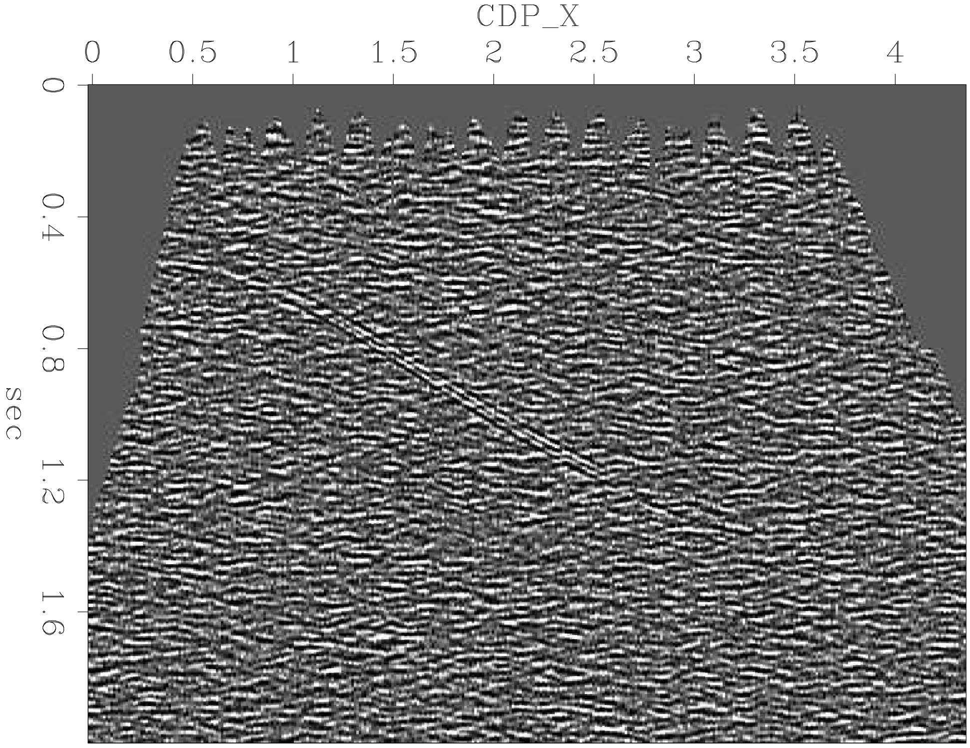

Figure 2: Best achievable cross-equalization difference result james-perfect [CR]

the difference plot, which is shown in Figure 4. The amplitude of $\mathbf{Ad_1}$ are equivalent to those obtained by renormalizing the data and scaling by $\nu = 0.61$.

Equalizing the energy in this case (using $\nu = 1$), produces the poor result shown in Figure 5. The brightest event in this image is no longer the reservoir interval, but rather the event below it. This would cause problems for interpretation.

For this synthetic, we can calculate a value for $\nu = 0.808$ based on the known signal-to-noise levels in the two surveys. This gave us the results shown in Figure 6. Considerably less coherent energy is present in this image than in Figures 4 and 5.

CONCLUSIONS

Although L_2 matched-filters can remove bandwidth and phase differences between time-lapse surveys, the filter amplitudes may be biased by the presence of random noise in the surveys. If a further step of amplitude equalization is not taken after matched-filtering, then artifacts may appear in difference images that are not related to genuine production-related changes.

Matched-filtering aside, the aim of amplitude balancing is to equalize the amplitude of the non-reservoir related seismic signal between surveys, so that the difference image consists of only production-related changes and a small amount of background

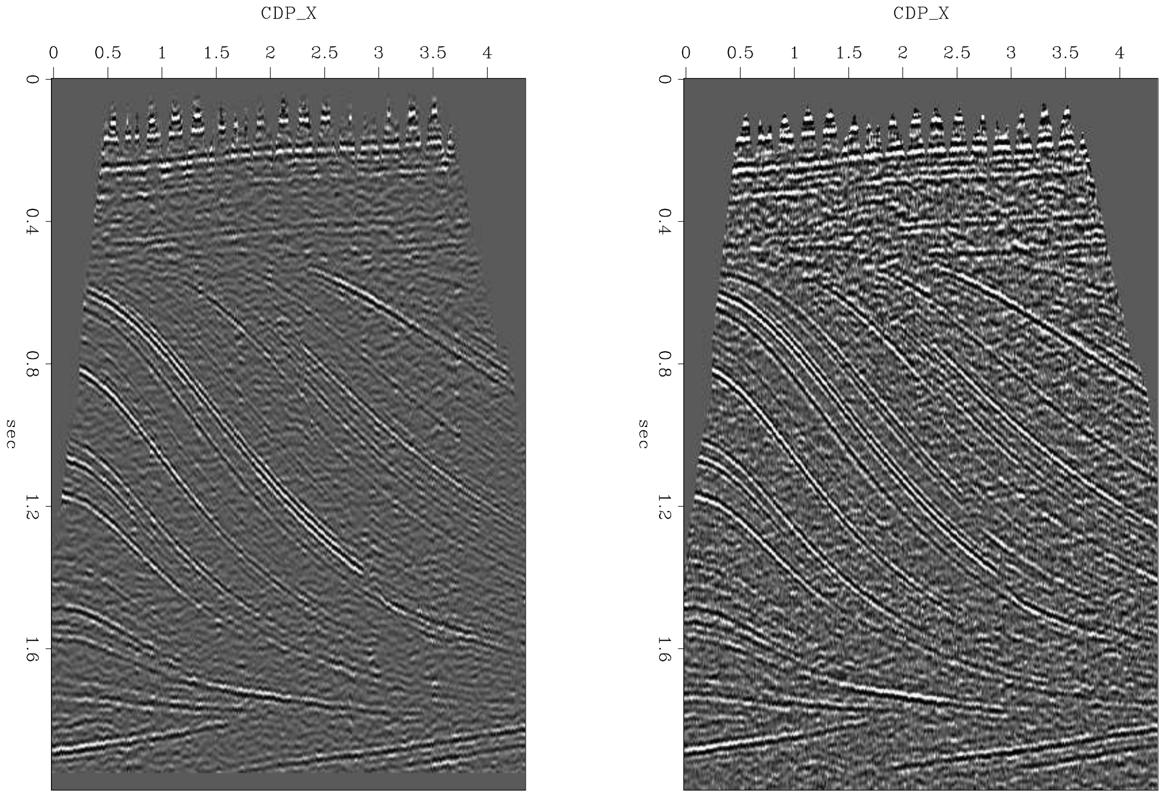

Figure 3: $\mathbf{Ad_1}$ (left) and $\mathbf{d_2}$ (right) plotted at same scale james-matchamp [ER]

noise. Matching energy between surveys will only achieve this goal if the signal-to-noise levels are approximately equal in both cases, or the noise levels are very low.

We have demonstrated these amplitude problems on a realistic synthetic example, and shown that by calculating the signal-to-noise levels before cross-equalization, the correct scaling factor can be applied to suppress the amplitude bias.

ACKNOWLEDGMENTS

James Rickett would like to thank everyone at Chevron Petroleum Technology Company in La Habra, especially David Lumley, Harry Martin, Greg Surveyer and the rest of the 4D Seismic Reservoir Monitoring Team, for a very enjoyable and stimulating summer.

REFERENCES

Claerbout, J. F., 1991, Earth Soundings Analysis: Processing vs Inversion: SEP–**71**.

Lumley, D. E., 1995, Seismic time-lapse monitoring of subsurface fluid flow: Ph.D. thesis, Stanford University.

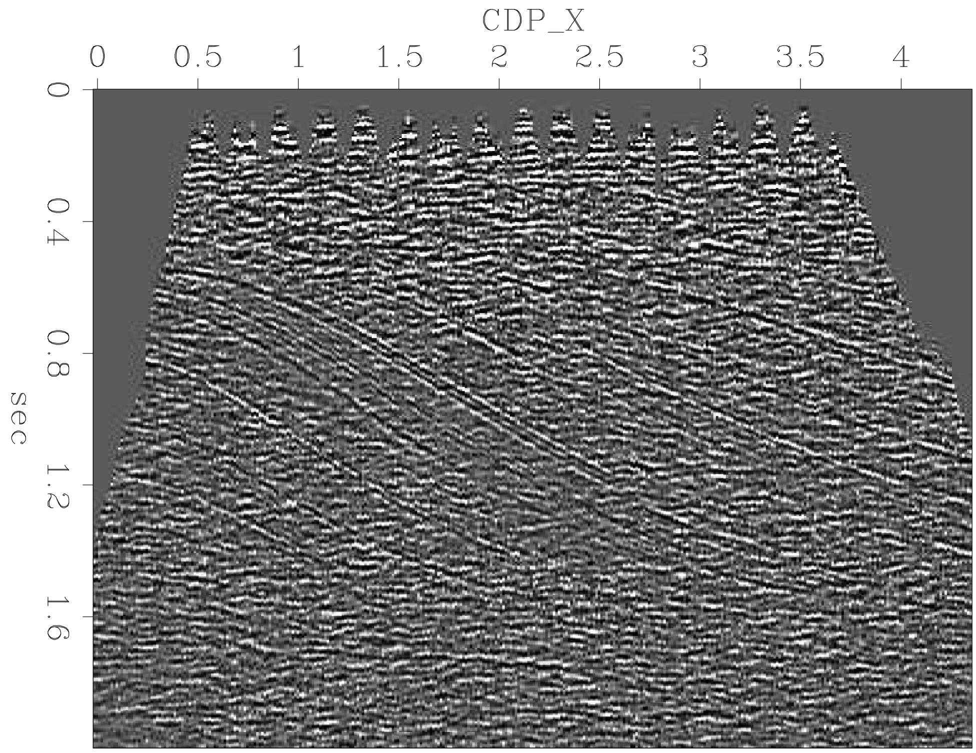

Figure 4: Difference using matched-filter amplitudes, $\nu \approx 0.61$. james-matchdiff [ER]

Rickett, J., 1997, Bandwidth-equalization and phase-matching of time-lapse seismic datasets: SEP–**94**, 33–43.

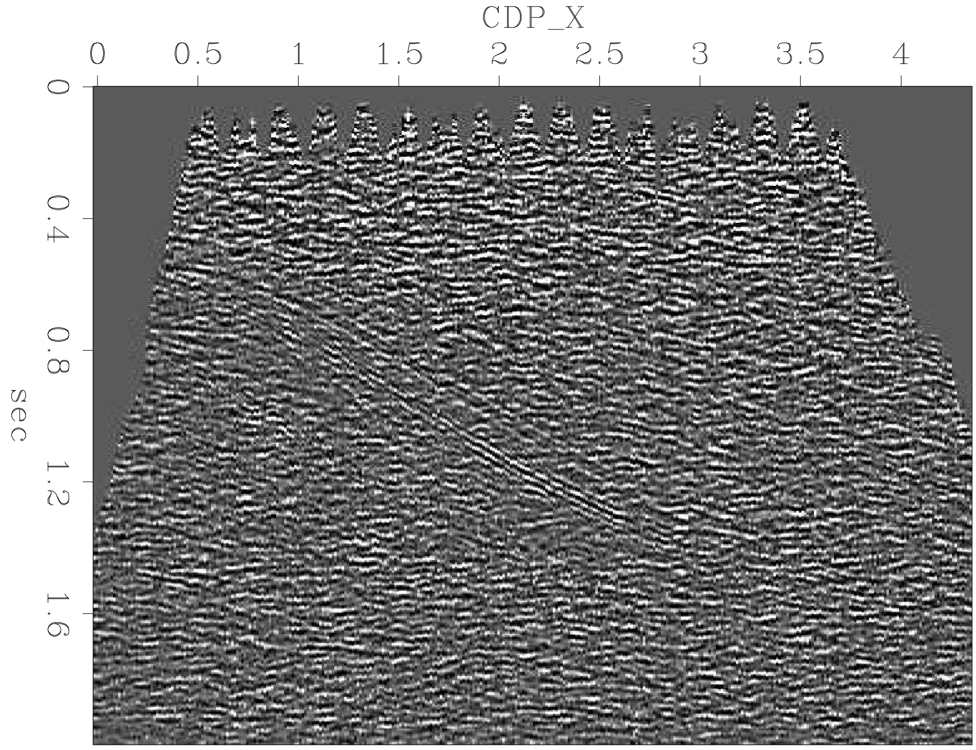

Figure 5: Difference after equalizing the energy between surveys, $\nu = 1$. james-eneqdiff [ER]

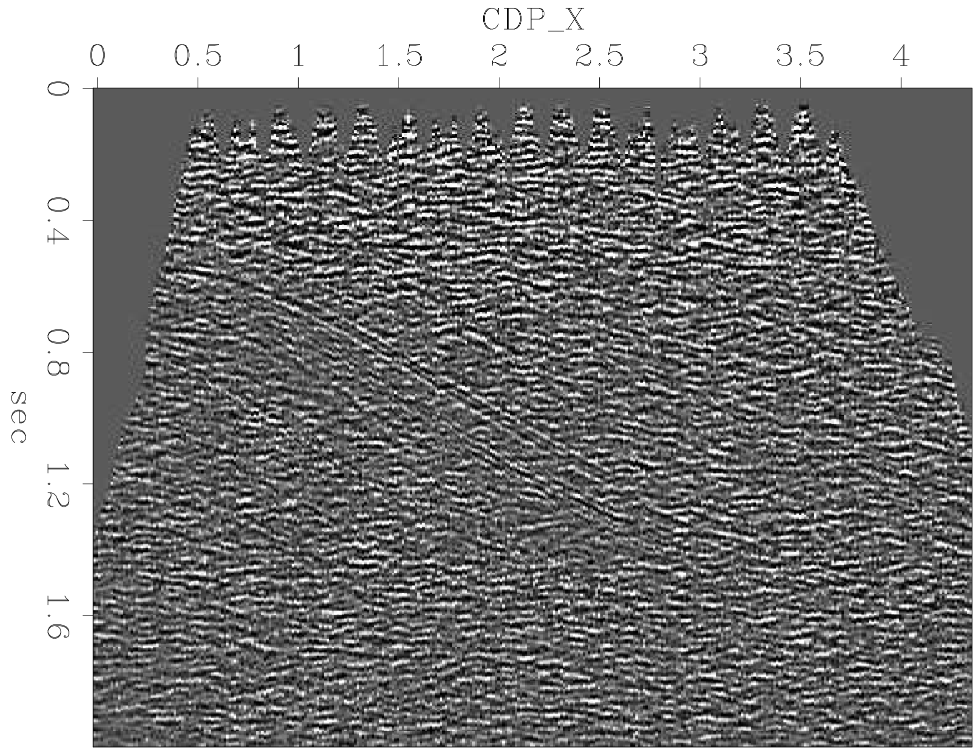

Figure 6: Difference using $\nu = 0.808$. james-bestdiff [ER]