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Multi-realisation 4D Noise Attenuation

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SUMMARY

Weighted stacking can improve 4D difference volumes from multiple realisations of 4D difference data. Multiple realisations can be produced using wavefield separation (PZ summation or spectrally-shaped deghosting), data selection (rank-1 and rank-2 outputs from 4D binning), or diverging processing flows. However, stack weights based only on 4D difference data can only reduce noise that is incoherent across the 4D differences. More powerful noise-reducing data weights can be formulated using the 3D images as well as the 4D differences, enabling 4D signal to be separated from noise that is incoherent and also noise that is coherent across multiple realisations of 4D difference but not repeated in both baseline and monitor 3D images (e.g. residual multiple in the monitor). Examples using broadband towed-streamer base and monitor from the North Sea, and mixed-mode towed-streamer base and ocean-bottom monitor from deep water, show considerable uplift to the final 4D difference. This type of noise attenuation is an attractive option where the illumination and sampling of base and monitor cannot be matched accurately in processing and imaging.

Introduction

Much acquisition effort is put into repeating source and receiver positions to minimise 4D noise (Morice *et al.*, 2000; Kragh & Christie, 2002). Geometric repetition reduces differences in illumination and wavefield sampling of the two surveys, so that the eventual seismic images are similar and have low levels of 4D difference outside the region of petroleum production (Calvert, 2005). Recently, however, there has been rising interest in the use of legacy Towed-Streamer (TS) data as the baseline for new Ocean-Bottom Node (OBN) data. This might occur at the start of a planned OBN campaign. In these cases, it is not appropriate to match the source and receiver positions due to difference in acquisition datum. The match of illumination and sampling between these mixed-mode surveys can be improved in processing (e.g. Haacke et al., 2013). However, considerable 4D noise may still remain due to inaccuracies in processing and imaging. Where these inaccuracies cannot reasonably be addressed at source, an attractive remedy is to separate 4D signal and noise after imaging using signal-processing and statistical techniques, further enhancing the 4D image.

For decades, it has been common practice to improve an estimate of seismic signal ($\bar{a}_j$) from a set of N redundant measurements ($a_{i,j}$) by stacking (Mayne, 1962). Weighted-averaging schemes have also been widely used to better estimate signal and suppress noise using a stack of the form

$$\bar{a}_j(t) = \frac{1}{\sum_{i=1}^{N} w_{i,j}} \sum_{i=1}^{N} w_{i,j} a_{i,j}(t) \ , \qquad (1)$$

for weights w and where seismic traces a are functions of time t (Ulrych et al., 1999). The weights can be based on the signal-to-noise estimates of the redundant measurements (Robinson, 1970), or on coherency measures designed to identify similarity between signal realisations on the $i = 1, \dots, N$ redundant measurements at location j (Liu *et al.*, 2009). Hatchell *et al.* (2012) recently used a similarity-weighted stack of 4D-difference images created from wavefield separation of OBN base and monitor surveys (split into up and down wavefields then processed as different datasets). This method seeks to attenuate noise that is incoherent between the up and downgoing 4D differences, leaving energy (e.g. 4D signal plus residual multiple in both wavefields of the monitor) that is coherent between 4D differences. In this it is equivalent to the common seismic cube of Lecerf & Weisser (2003) as applied to two 4D differences.

A more powerful generalisation of Hatchell et al.'s approach is to process multiple realisations of baseline and monitor with a weighting scheme that can separate signal and noise based on the properties of the 3D images as well as the 4D differences. Multiple realisations of a survey can be generated using wavefield separation, by different selections of data (e.g. rank-1 and rank-2 selections in 4D binning),

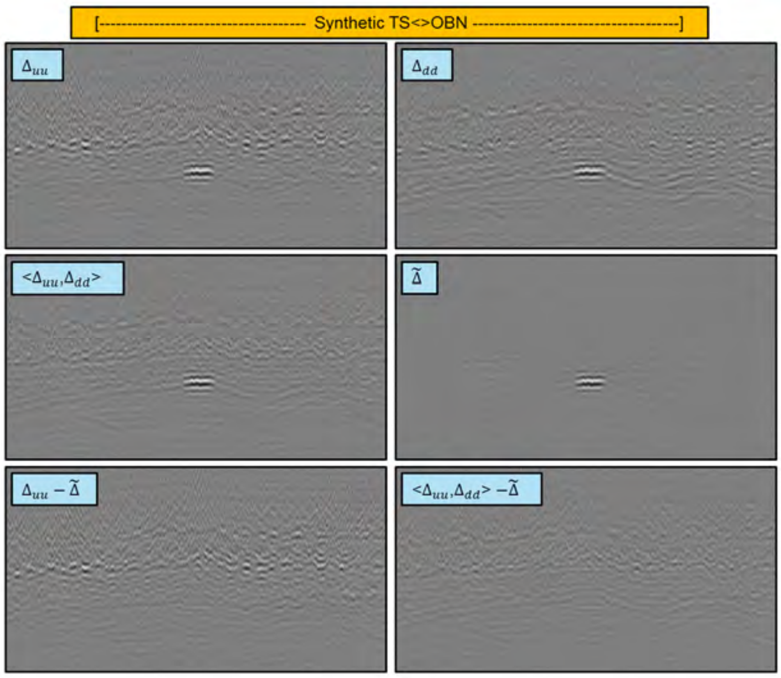

Figure 1 *Synthetic TS base and OBN monitor. 4D difference stacks are shown for the upgoing (Δ_{uu}), downgoing (Δ_{dd}), average of Δ_{uu} and Δ_{dd} ($<\Delta_{uu},\Delta_{dd}>$), and the weighted average in eq 3. Differences of these illustrate very low levels of signal damage.*

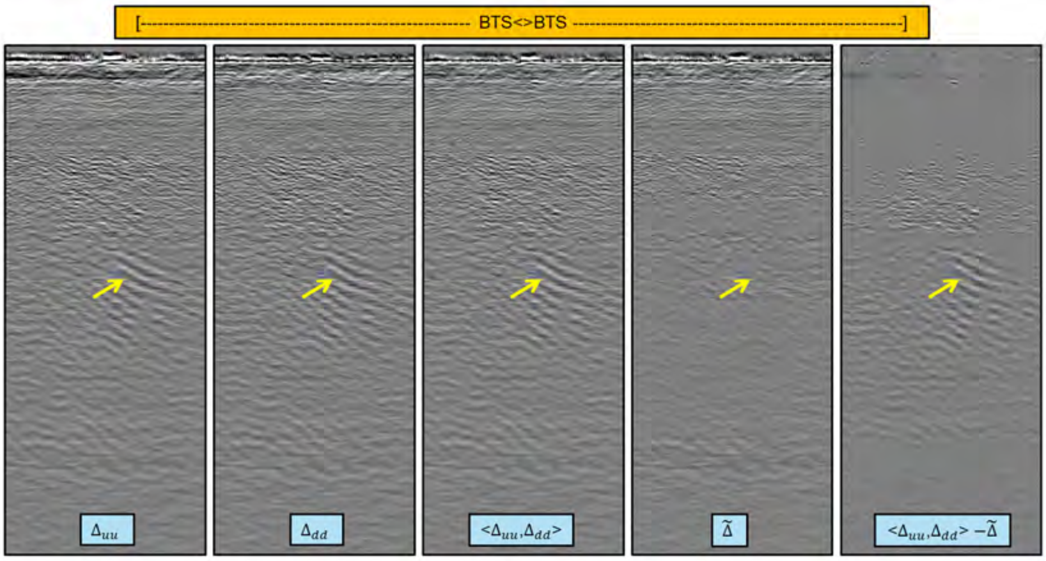

***Figure 2** Deghosted Broadband Towed-Streamer (BTS) data from back-to-back baseline and monitor surveys (there is no 4D signal from intervening fluid production) show significant attenuation of coherent noise (yellow arrows) present in both Δ_{uu} and Δ_{dd}.*

or by deliberately diverging processing flows. Using multiple image realisations, the method described in the following sections proves able to distinguish signal from noise that is incoherent between realisations of the 4D difference, and also from noise that is coherent in the multiple realisations of 4D difference but not repeated on both base and monitor. This is made possible using properties of both 3D and 4D images in the analysis.

Method

Neidell & Taner (1971) describe various similarity or coherence measures, which are included here as a generic similarity operator $\psi\{x,y\}$ for seismic datasets x and y. For $i,j = 1,\dots,M$ realisations of the baseline image I_i and the monitor image I'_j, a matrix of 4D differences can be created $\mathbf{\Delta} = [\Delta_{ij}] = [I_i - I'_j]$. A matrix of 3D similarities can also be created, $\boldsymbol{S}^{3D} = [S_{ij}^{3D}] = [\psi\{I_i, I'_j\}]$, and a matrix of 4D similarities can be created from the 4D differences, $\boldsymbol{S}^{4D} = [S_{ijkl}^{4D}] = [\psi\{\Delta_{ij}, \Delta_{kl}\}]$, where $i,j,k,l = 1,\dots,M$. S_{ijkl}^{4D} has symmetry $S_{ijkl}^{4D} = S_{klij}^{4D}$ (i.e. $\psi\{y,x\}$ is the same as $\psi\{x,y\}$) and comes with the condition $i \neq k$ if $j = l$ (the symmetry and conditions leave only $ijkl =$ 1112, 1121, 1122, 1221, 1222, 2122 for $M = 2$). Subsequently, a set of weights

$$\boldsymbol{S}^{w} = [S_{pq,ijkl}^{w}] = [\psi\{S_{pq}^{3D}, S_{ijkl}^{4D}\}] = \left[\psi\left\{\psi\{I_p, I'_q\}, \psi\{\Delta_{ij}, \Delta_{kl}\}\right\}\right] \quad (2)$$

are created, where $p,q,i,j,k,l = 1,\dots,M$ and the rules for $\boldsymbol{S}^{4D}$ apply to i,j,k,l. Equation (2) is a similarity of a pair of similarities, and represents weights that can be computed in any domain (for example in time, frequency, depth, or a dip-decomposed domain) as long as the realisations remain independent.

The 3D similarities, $\boldsymbol{S}^{3D}$, are large in regions of signal (including 4D signal) that appear with similar kinematics in the images (e.g. if they are located on reflecting interfaces), but low in regions of noise that are not fully repeated, such as residual multiple in the baseline or monitor. Where 4D time-shifts are present, these are usually small (of the order of milliseconds or less) and their effect can be mitigated with high-cut filters applied before the ψ operator, or using time-shifted similarity measures in ψ (e.g. Inderwiesen, 2014). Conversely, the 4D similarities, $\boldsymbol{S}^{4D}$, are large in regions of 4D signal and large in regions of coherent noise (e.g. the residual multiple again), while low in regions of incoherent noise. Thus, the similarity of similarities in equation (2) is able to differentiate between the cases of 4D signal ($\boldsymbol{S}^{3D}$ and $\boldsymbol{S}^{4D}$ are both high, so $\boldsymbol{S}^{w}$ is high), incoherent 4D noise ($\boldsymbol{S}^{3D}$ is high and

$\boldsymbol{S}^{4D}$ is low, so $\boldsymbol{S}^{w}$ is low), and coherent 4D noise not repeated in baseline or monitor ($\boldsymbol{S}^{3D}$ is low and $\boldsymbol{S}^{4D}$ is high, so $\boldsymbol{S}^{w}$ is low). The weighted stack of 4D differences is then

$$\widetilde{\Delta} = \sum S^{w}_{pq,ijkl} \Delta_{pq} \,/ \sum S^{w}_{pq,ijkl} \,, \qquad (3)$$

where $p, q, i, j, k, l = 1, \ldots, M$ and the summation spans the entire allowed space of p, q, i, j, k, l (with the rules specified above for $\boldsymbol{S}^{4D}$).

Results

The weighted-stack outlined above is illustrated first using synthetic data simulating a TS baseline with a sparse OBN monitor (Figure 1). After wavefield separation of OBN and 4D binning to create two realisations of TS and OBN data, regions of 4D noise are successfully attenuated in the weighted stack. There is little 4D signal damage evident in the difference of the weighted stack against the average of the upgoing and downgoing 4D differences.

A second example using Broadband Towed-Streamer (BTS) baseline and monitor (Figure 2), undergoing wavefield separation with a deghosting technique (Poole, 2013), shows similar success with the additional attenuation of coherent noise not repeated in the monitor.

Two final examples are from mixed-mode cases with TS baseline and OBN monitor acquired in deep water. The data are processed with the flow outlined in Figure 3, comprising wavefield separation, redatuming and 4D binning (see Haacke et al., 2013). In the first example (Figure 4), the weighted stack clearly attenuates energy not common to both upgoing and downgoing images. The last example (Figure 5) shows significant noise attenuation in an amplitude extraction from a producing interval, bringing clarity to the interpretation of 4D signal on that extraction.

Conclusions

Using multiple realisations of 4D difference it is relatively straightforward to identify and attenuate noise that is incoherent. However, noise that is coherent across multiple realisations of baseline or monitor, but not repeated in both base and monitor, is harder to separate from 4D signal since it is present as a repeated feature of all 4D differences. Nevertheless, by incorporating weights derived from the similarity of similarities of 3D and 4D images, it is possible to separate and attenuate this type of noise also. Results show considerable uplift to 4D differences produced from data with residual multiple in the monitor, and with poor matches of illumination and sampling

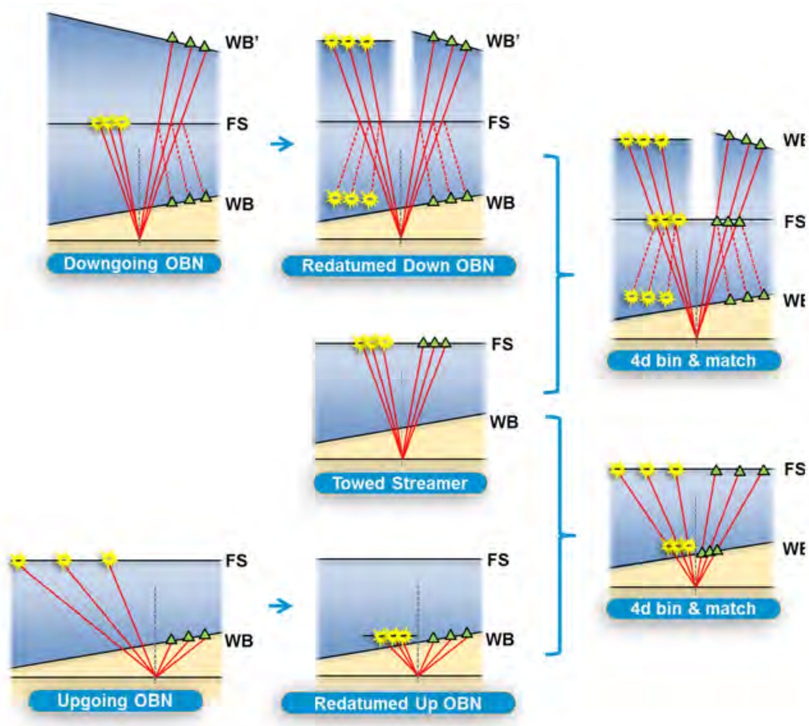

Figure 3 *Redatuming and 4D binning flow for TS baseline and OBN monitor. Redatuming moves shots from the free surface (**FS**) to the average waterbottom (**WB**), or the average mirror waterbottom (**WB'**) for the downgoing. Redatumed up and down wavefields produce different realisations of TS data in 4D binning.*

due to significant non-repeatability of source and receiver positions in mixed-mode acquisitions.

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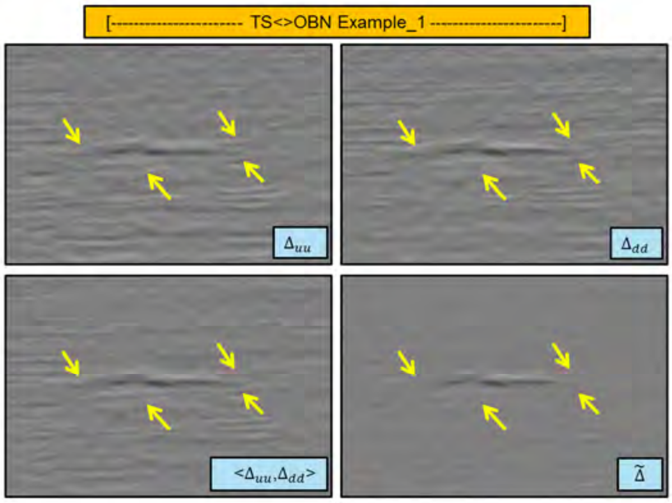

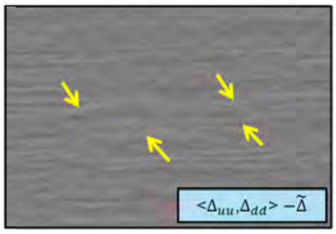

Figure 4 *Deep-water TS baseline and OBN monitor. The average 4D difference (<Δ_{uu},Δ_{dd}>) is improved by the weighting method, and removes energy not present in both up and down.*

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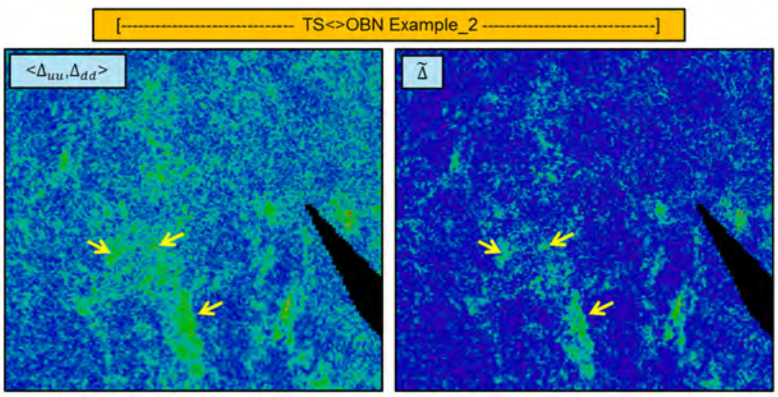

Figure 5 *Second example of TS baseline and OBN monitor from a different deep-water location. Amplitude extractions taken through the average 4D difference and weighted 4D difference around areas of known fluid production (yellow arrows).*