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CO-LOCATION OF SURVEYS IN SPACE AND TIME FOR IMPROVED ACCURACY AND SENSITIVITY IN 4D MARINE SURVEYS

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Abstract

Time lapse, or 4D, seismic surveys are designed to monitor changes in the seismic response of hydrocarbon reservoirs caused by production. In many reservoirs, the acoustic impedance changes induced by production are small and therefore we are looking for weak 4D signals. This means that 4D surveying requires a high degree of accuracy in order to detect a reliable 4D signal. In marine 4D surveys, variations in geometry caused by currents, variations in wave height and variations within the water column all combine to reduce the repeatability of the recording. Successful 4D processing must take account of these factors

Interpretation of 4D results has often been done on difference sections obtained by simply taking the difference between two vintages of data previously processed for 3D purposes. Variations in the individual survey results will be caused by variations in recording equipment and geometry, variations in feathering and infill, variations within the water column and variations in processing. In order to compensate for these differences, matching filters are applied to the datasets. In this method, it is assumed that matching the overburden will compensate for all of the above factors in a single filter (perhaps a single filter per trace) and thus reveal the true change at the reservoir level. Although this approach implies that the biggest difference between the two surveys will be outside the matching design window, it does not mean that these changes are only caused by reservoir production. Indeed, the difference between the datasets is often found to increase *everywhere* outside the design window. For example, data shot over the Oseberg field in 1989 and 1991 were normalised by applying scalars derived in a 150ms window around the water bottom for each trace. Equalising the amplitudes around the water bottom INCREASED the difference energy over a larger window from 0s to 3s, illustrating the dangers inherent in simply matching different datasets to optimise the 4D signal.

Since the differences between two datasets are caused by a number of factors, it is likely to be better to address each problem separately rather than attempting to do so with a single matching filter. The first, obvious step is to process both datasets simultaneously for 4D purposes. This eliminates differences in processing methods and algorithms and also testing of whether or not particular processing steps improve the 4D difference. Within this processing, variations in positioning (in space and time) should be addressed separately from, say, wavelet changes. Finally, matching filters may still be appropriate, but now they are addressing only residual differences in the seismic system

To examine how sensitive taking the difference between two datasets can be, consider two 40 Hz Ricker wavelets separated by a 1ms static shift. Figure 1 shows the two wavelets and the difference between them. The peak difference is about 25% of the peak value of each wavelet. Increasing the static shift to 4ms causes the peak value and the RMS of the difference to approximately equal the equivalent values for the individual wavelets. Static shifts greater than this cause the difference to have peak and RMS values up to twice that of the individual wavelets. This demonstrates that we will have to account for small timing and positioning shifts between vintages if we are to reduce the background difference 'noise' and detect true changes caused by hydrocarbon production. Moreover, many reservoirs require sensitivities of less than 25% in order for the production induced seismic changes to be detectable i.e accuracy to better than 1ms for the above synthetic wavelets.

POSITIONING IN TIME

Changes in water velocity and tidal effects are sufficient to cause problems for 4D. Tidal effects of 0.75m are not normally taken account of in 3D processing but they are equivalent to 1ms TWT. In a recent repeatability study conducted by Statoil (SEG, 1998), *tidal* changes of up to a maximum of 1m were recorded. During processing, accounting for these changes as static shifts halved the RMS of the difference data in the area of maximum tidal change. Figure 2 shows the effect of correcting for *water velocity* changes from another repeatability trial, this time from the W. Shetland region. This is a region of deep water and it is characterised by variations in water velocity caused by changes in water temperature. In this case, differential static shifts were computed by picking the water bottom times for stack traces from both surveys. Since it is known that the water velocity changes rapidly over short distances and times, it is likely that better results could be obtained by computing and applying the statics to prestack data. Nevertheless, it is clear that co-locating the surveys in time improves the sensitivity of the difference data.

POSITIONING IN SPACE

It is apparent that changes in position are equivalent to timing changes for constant amplitude, dipping events. For example, if two traces are at opposite sides of a CMP bin, they have a timing difference of 1ms for a dip of 1ms per trace. For data of greater dip, this implies we need to position the two surveys to an accuracy of less than the bin size.

Variations in currents cause marine surveys to have prestack traces that are scattered pseudo randomly over the survey area. Processing typically collects these traces into regular bins, which imposes variations in fold of coverage and offset distribution and also assumes that all traces fall at the bin centres. Flexible binning is then applied to try to normalise the fold of coverage and offset distribution. The flexible binning involves eliminating duplicates and replication to infill missing traces. This process does not allow for dip or lateral amplitude variation. No account is made of the scatter of traces away from the bin centre. Prestack interpolation both to fill in gaps and also to interpolate data to the bin centres in both the inline and crossline directions can better account for geometry variations between two vintages of data.

Figure 3 illustrates the effect of interpolating traces to the bin centre in the INLINE direction. Figure 3a shows a CROSSLINE through a 4D synthetic with 10ms/trace dip in the INLINE direction. A 10ms static shift has been applied before differencing to mimic 4D. Alternate inlines have traces systematically at one edge of the inline bin, then the other edge etc. This leads to 'jitter' in the crossline direction since alternate traces are up dip or down dip relative to the bin centre. As can be seen in figure 3a, this gives the appearance of 4 events instead of 2 on the crossline and also appears to reduce the signal-noise of the event. After interpolation to the bin centre, as shown in figure 3b, the double event is more easily and accurately detected.

Repeatability studies on 3 datasets, including the Oseberg data, show benefits from prestack interpolation. In all 3 cases, replacing flexible binning by interpolation improved the repeatability and interpolation to bin centres provided a further uplift.

NAVIGATIONAL ERRORS AND UNCERTAINTIES

We have seen that deterministic prestack interpolation of irregularly sampled data onto a regular grid can improve the repeatability of seismic data. However, this is limited by the accuracy of the navigation data. Modern navigation data has an accuracy of several metres for mid-point position. Older vintages of data, used as a baseline survey for 4D purposes, may well have lower positioning resolution. The navigation information from two different vintages with possible differing systems may have systematic as well as trace to trace differences. The redundancy of information in stacked data may be used to detect and minimise systematic positioning changes between two surveys, thus improving the co-location of the two datasets in a statistical manner.

A systematic navigational error between two 3D surveys can be factorised into two components: an error in the orientation and an error in translation. We have also seen that timing and spatial shifts can have similar effects. The solution we suggest uses a method which separates rotational, translational and timing effects, thus allowing us to tackle each component separately. This allows an efficient and reliable solution to be found. The inconsistency in orientation is first measured. A re-orientation of the data is applied before each of the time and translation components are computed and applied. This enables a minimisation of systematic differences in navigation. For these calculations, equivalent timeslices from each 3D survey are required from a time window of the data not expected to exhibit reservoir induced changes.

The relative orientation between two equivalent timeslices is determined by calculating a *rotation overlap*, with one timeslice rotated in a number of possible orientations. The rotation overlap gives a measure of correlation between two timeslices, using origin-invariant functions to give a measure of orientation only. The maximum value of the rotation overlap corresponds to the relative orientation between the timeslices. Once this is known, orientation problems can be eliminated by a suitable rotation.

Once inconsistencies in orientation are eliminated, a "temporal overlap" is calculated. The temporal overlap gives a measure of equivalence between timeslices that is independent of spatial location. The temporal overlap is calculated with a range of static shifts applied to one vintage, where the maximum value will give the relative time shift to be applied.

The solution to the translation problem is then solved using a *translation overlap*, with one timeslice translated by a number of possible vectors. The translation overlap acts like the rotation overlap, though giving a measure of translation rather than orientation. The maximum value of the translation overlap will give the relative translation between the two 3D surveys. Systematic navigation differences can now be minimised in the 4D study.

Figure 4 shows timeslices from two synthetic 3D surveys containing an elliptical structure embedded within random noise. These surveys are defined on a grid of 100 by 100 bins with a bin size of 25 by 25m. The same signal was created for each synthetic, but with 5 degrees rotational difference between the two. A translation of 25m in x and 10m in y was also introduced. Figure 5 shows the result from calculating the rotation overlap. This is a clear, sharp result where the maximum occurs at 4.98 degrees. After correcting for the orientation error, the translation overlap was then calculated. This is shown in Figure 6. Again this is a good result with a clear solution, accurate to within a CDP bin. Figure 4c shows the difference between the first synthetic and the second synthetic before correction for the rotational and translational differences, whereas figure 4d shows the same difference after the computed corrections have been applied. The '4D' repeatability has clearly been improved by measurement of and correction for the systematic positioning differences.

Another test of the techniques involved using a single, real 3D dataset and a second copy of the same data with a deliberate rotation and translation introduced. Figure 7a shows the time slice difference after the mis-positioning has been introduced, while figure 7b shows the difference after statistical co-location. The computed rotation overlap peaks at 7.45 degrees, very close to the true value of 7.5 degrees. Applying the computed correction to the misplaced copy of the data reduced the RMS of the '4D difference' by a factor of 8

CONCLUSIONS

Simple matching of two surveys is insufficient (and possibly incorrect) for detection of many 4D signals. Deterministic co-location of surveys can improve the repeatability of the seismic surveys. Limits on navigation accuracy imply that statistical methods may be necessary to further improve repeatability. One method of statistical co-location that separates rotational, translational and timing effects has been proposed. Once these effects have been accounted for, residual differences can be addressed with matching filters if necessary.

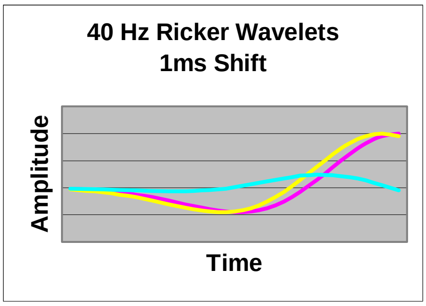

Figure 1. 40Hz Ricker wavelets separated by 1ms plus the difference of the two wavelets

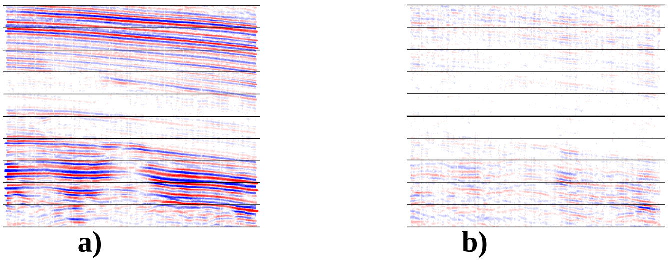

Figure 2. Difference section from W. Shetland a) before water velocity static shift and b) after water velocity static shift

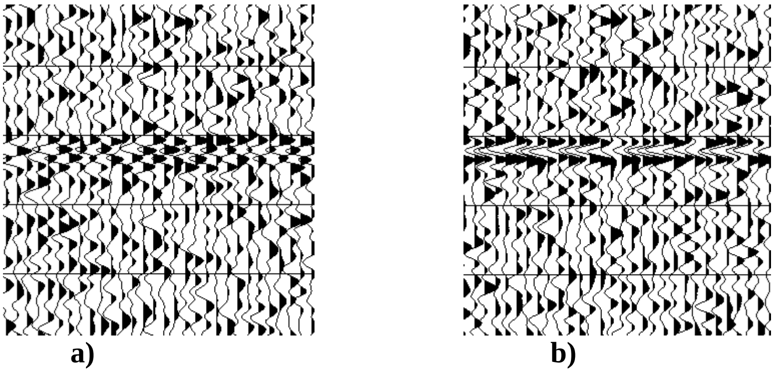

Figure 3. Synthetic inline difference section of two events 10ms apart which dip in the crossline direction. In 3a, alternate traces are at opposite sides of the bins whereas in 3b they have been interpolated to the bin centres.

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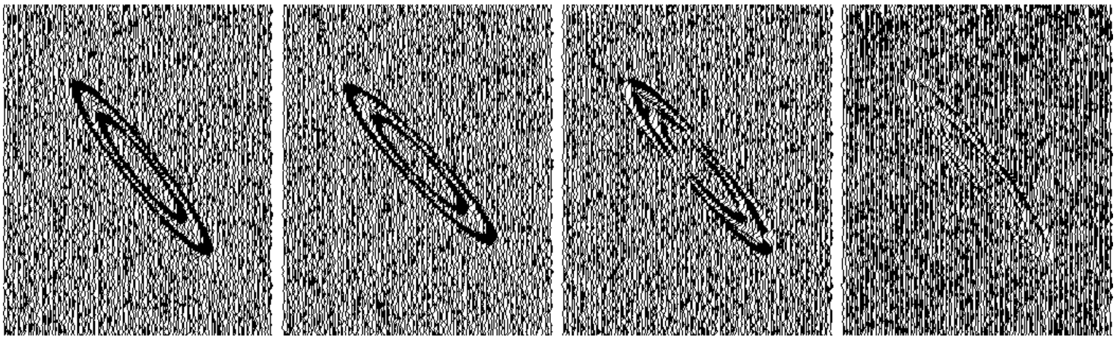


a) b) c) d)

Figure 4: Synthetic timeslice a) in original position, b) after rotation and translation and c) difference section after correction of positioning errors.

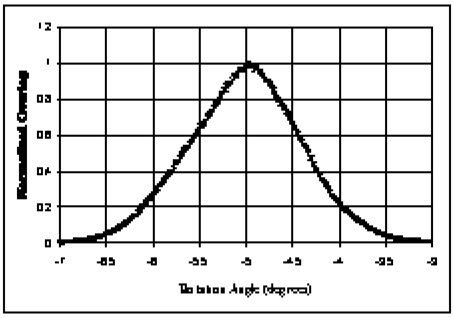


Figure 5: Graph of Rotation Overlap between synthetic 1 and synthetic 2.

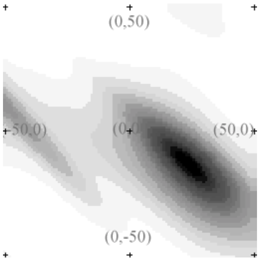
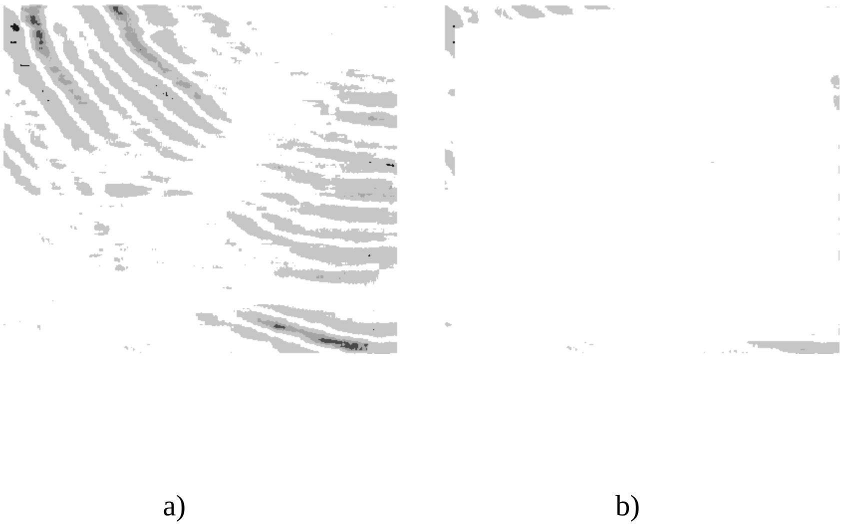


Figure 6: Contour plot of Translation Overlap between synthetic 1 and synthetic 2



a) b)

Figure 7. Difference time slice a) before correction of rotation and b) after correction of rotation.

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