A key objective in 4D projects is to acquire and process seismic data in such a way that the differences between base and repeat surveys only reflects changes in the state of the reservoir.

In search of the reservoir's 4D signal we frequently face the problem that monitor and baseline surveys do not have the same survey configurations and are differently affected by feathering. We consequently have to compare two or more surveys with varying source-receiver azimuths and different sampling in inline and crossline directions. Differences in azimuth imply different ray paths through the overburden and different illumination of the target.

The acquisition-related effects on the seismic may be further enhanced in processing because many basic operations applied in multi-channel 3D processing are of 2D nature. Changes in azimuth can therefore lead to degradation of the repeatability and large differences in source-receiver azimuths between the base and monitor surveys may obscure the 4D difference.

PGS' strategy for acquisition of optimal 4D surveys (both base and monitor surveys) is comprised of:

1. Acquisition with overlap configurations, i.e. the seismic vessel is towing more streamers (additional outer streamers) than nominally required according to the sail line separation. In other words, the vessel is steered as if it had fewer streamers than actual. This gives oversampling of the surface fold, making it possible to select matching source-receiver azimuths during processing.

2. The vessel is steered for repeating-shot positions and sailing direction for all lines.

3. Dense streamer separation.

By using this strategy source-receiver azimuths can be repeated very accurately. The repetition of vessel/source positions in future monitor surveys can be more efficient if today's baseline surveys are also well conditioned.

This means that for baseline surveys, infill shooting is minimized and the vessel closely follows the survey's pre-plot sail lines. Again, overlap shooting allows us to achieve this.

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A Strategy for Optimal Marine 4D Acquisition

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**Dense Streamer Sampling**

In order to investigate the optimal strategy for 4D acquisition we first analyze synthetic navigation data. We assume that we have 2-degree and 10-degree constant feathering in the base and monitor survey, respectively. Shot positions are repeated exactly. Thus, changes in azimuth depend on the receiver positions only. The denser we sample in the cross-line direction the less exposed we are to azimuth errors.

In our first example, base and monitor datasets are acquired by a dual-source/8-streamer configuration with 100m streamer separation, i.e. 25m spacing between inlines. In the second example, the 4D surveys are acquired by an equivalent single source configuration, i.e. 16 streamers with 50m separation. Figure 1 shows a map with azimuth mismatches for traces in a nominal offset bin at circa 1100m offset after 3D binning. The single source configuration offers better azimuth preservation due to the increased number of streamers deployed with a denser separation. In both cases the feathering leads to large azimuth mismatches between base and monitor data along adjacent sail lines.

**Overlap Shooting**

We can use the overlap technique to minimize the strong 4D azimuth mismatches observed at the sail line boundaries in Figure 1, provided that shot positions and sailing directions are repeated. Figure 2 shows that overlap helps to repeat source-receiver azimuths. Since the critical areas around the sail-line boundaries are oversampled, we can select traces from base and monitor surveys with minimum azimuth differences. Over-sampling here is meant relative to the nominal surface fold. However, the over-sampled traces are unique with respect to azimuth. In Figure 2 we compare azimuth differences for a nominal single source, 8-streamer configuration (50m streamer separation, 200m sail line separation) with an overlap configuration (12 streamers on an 8-streamer pre-plot). Again, feathering is assumed to be 2 degrees (base) and 10 degrees (monitor).

**Repetition of Shot Lines**

Repeating shot lines is important for optimal azimuth preservation. The good match in Figure 2 (right) was achieved by combining overlap shooting with shot line repetition. Since marine-streamer acquisition is much sparser sampled on the source side than on the receiver side, it is more important to repeat the shot lines than repeating the receiver positions in order to get a good azimuth match. Steering for shot positions in the presence of feathering may cause holes in the surface coverage, especially at large offsets. Therefore, it is important to use overlap when repeating shotlines. The effect of not repeating shot positions is illustrated in Figure 3. In this case the monitor sail lines are moved by 1/2 sail line separation in the crossline direction. We observe that the match in source-receiver azimuths is significantly degraded.

**Case Studies**

In the following we analyze and compare the azimuth match for 4D surveys at two different fields in the North Sea. In both cases, PGS has acquired the most recent monitor surveys in collaboration with Shell. At Field_A, a 6-streamer dual-source vessel operated in overlap mode by steering as if 4 streamers were deployed. The base survey was acquired with 4 streamers. The vessel steering during the monitor survey was based on surface coverage without any attempt to repeat the shot lines of the base survey. At Field_B, a vessel towing 10 streamers acquired monitor data with overlap.
In addition, the shot lines of the base survey were repeated as closely as possible. The base survey was a normal 8-streamer survey.

An overview on the acquisition parameters is given in Table 1. Note that the 4D survey at Field_B, due to its wider towing spread, is much more exposed to azimuth errors than the Field_A survey. However, the following analysis shows that azimuths at Field_B have been better preserved because of the improved acquisition strategy.

A subset of the navigation data covering approximately 20,000 CMP locations at Field_A and Field_B has been arbitrarily chosen for a quantitative 4D azimuth comparison.

The navigation data have been sorted into offset bins with a nominal fold of 1. Figures 4 and 5 show fold maps for an offset bin at circa 1100m. Both base and monitor surveys show over-sampled areas, i.e. areas with a fold higher than 1. The over-sampled areas for both base surveys result from a combination of feathering, vessel steering for surface coverage and infill shooting, and appear to be randomly distributed. The fold maps for the monitor surveys, however, show a characteristic; regular increase of fold at the sail-line boundaries due to the overlap geometry. It can be demonstrated for Field_B (repetition of shot lines combined with overlap shooting) that the additional data in the critical zones between the sail lines allows searching for trace pairs with almost perfect azimuth match in the base/monitor survey.

4D Friendly Binning

A 4D - friendly binning procedure is necessary to take full advantage of the acquisition strategy outlined above. The surplus of data in the overlap zones makes it possible to achieve a better match by using selective binning schemes. Three binning approaches are discussed here:

1) Independent binning using distance to bin center as the trace-selection criterion for the monitor survey. The corresponding trace in the base survey is selected based on minimum difference in source-receiver azimuth.

2) Azimuth-dependent binning using azimuth closest to sail-line azimuth as the trace-selection criterion for the monitor survey. The corresponding trace in the base survey is selected based on minimum difference in source-receiver azimuth.

3) Simultaneous 4D binning using minimum difference in source-receiver azimuth between the base and monitor trace as the selection criterion.

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Table 1: Configurations for two 4D case studies.
Figure 6 shows azimuth-difference maps (offset bin at 1100m) resulting from these three methods. Flexing has not been applied to any of the examples.

Figure 6 (left) is based on independent binning of base and monitor. The observed azimuth differences are generally large. Azimuth dependent binning of the same 4D data results in an improved match, but azimuth mismatches at the sail-line boundaries are still visible (Figure 6, middle). Simultaneous 4D binning (Figure 6, right) reveals the real repeatability potential of this 4D data set. It proves that the acquisition applied on Field_B (shot-line repetition combined with overlap) resulted in proper over-sampling which minimizes the azimuth-difference footprint. The remaining azimuth differences in cross-line direction in Figure 6 (right) are related to the large streamer separation (100m) as illustrated in Figure 1 (left).

The advantage of this acquisition strategy becomes even clearer when comparing the azimuth-difference map from Field_A (overlap only) with the one from Field_B (shot-line repetition combined with overlap). Figure 7 shows that the acquisition performance with respect to the preservation of source-receiver azimuths at Field_B is superior. Statistical analysis of the azimuth differences confirms this observation (Figure 8).

The Ideal Base Survey

The base surveys of the two case studies were not acquired with the overlap approach. Thus, we can optimize the azimuth match by better conditioning the base survey. A base survey acquired with overlap allows the streamer vessel to follow the survey’s pre-plot with significantly reduced crossline deviations. This gives more complete surface coverage and reduces infill shooting. A well-conditioned base survey simplifies and optimizes the repetition of vessel/source positions in a future repeat survey.

Figure 7: 4D azimuth differences [degree] for Field_A (left) and Field_B (right). At Field_B overlap shooting combined with repetition of shot lines has been used in the monitor survey.

Figure 8: Histograms for azimuth differences at Field_A (red) and Field_B (blue). Results for the near-offset bin and the far-offset bin are shown on the top and bottom, respectively.

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