Improved 4D Seismic Processing: Foinaven Case Study
Henning Hoeber*, Suhail Butt, Daniel Davies, CGG c/o BP Exploration, Aberdeen, UK, and Steve Campbell, Trevor Ricketts, BP Exploration, Aberdeen, UK.

Summary
Using a case history from West of Shetlands, we study the combined impact of improved acquisition and improved processing on 4D time-lapse repeatability, as well as on 3D imaging. We show how, following a carefully planned 4D acquisition, new processing technologies improve the repeatability and interpretability of our three seismic vintages.

In the first part of this paper we compare the repeatability of two vintages acquired in a non-4D friendly fashion to that of 4D-purpose data. We show how processing these vintages with an improved 4D sequence, i.e. better regularization and 4D binning, with pre-stack time Kirchhoff imaging, increases the repeatability. In the second part of the paper we also show comparisons of data processed with the new Kirchhoff imaging based 4D sequence to the same data analyzed with a 4D DMO sequence from four years ago.

Introduction
Our paper shows how both improved acquisition and refined processing enhances the quality of the 4D repeatability. The data are from the Foinaven field, which is part of three BP-operated fields from West of Shetlands. Early 2004, a careful acquisition planning study was carried out for this field, in order to improve the 4D signal previously measured, based on the 1993 baseline and the 2002 monitor (Campbell et al., 2005). We thus have three vintages of data, two of which (‘93 and ‘04) were carefully designed to give a high quality 4D signal, with the other pair (‘93 and ‘02) considered less suited for 4D.

Time-lapse processing has several key components all aiming to progressively equalize the different vintages: firstly, we use deterministic processing whenever possible, e.g. for zero phasing and for tidal statics. Secondly, progressive cross-equalisation is enforced by using repeatability metrics, such as NRMS or cross-coherence, to drive the processing. Finally the use of simultaneous processes, such as 4D binning and co-filtering techniques, ensures that the vintages are progressively equalized. In addition, there are several processing techniques, more generally viewed as 3D processes, which are key to obtaining reliable 4D signals above the noise-floor. Our improved regularization methods, presented below, are an example of this.

Acquisition
Figure 1 shows the differences in acquisition geometries between the three vintages. The 2004 vintage was acquired on a dense basis in order to match the source and receiver locations of the 1993 data (Campbell et al., 2005). The 2002 vintage was not a dedicated time-lapse acquisition, which explains the geometry differences relative to the 1993 baseline.

4D processing
All three vintages of Foinaven data were analyzed with an improved 4D processing sequence centered on Kirchhoff pre-stack time imaging. Only the 1993 and 2002 data had been previously analyzed with a DMO style sequence.

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Source Depth</th>
<th>Cable Depth</th>
<th>Source Sep</th>
<th>Source Gain</th>
<th>Cable Sep</th>
<th>Gain</th>
<th>Shoot Dir</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>2 source</td>
<td>8m</td>
<td>8m</td>
<td>50m</td>
<td>120m</td>
<td>18.75m</td>
<td>12.5m</td>
<td>48/228</td>
<td>200-3200m</td>
</tr>
<tr>
<td>2002</td>
<td>2 source</td>
<td>7m</td>
<td>8m</td>
<td>50m</td>
<td>100m</td>
<td>18.75m</td>
<td>12.5m</td>
<td>48/228</td>
<td>200-3200m</td>
</tr>
<tr>
<td>2004</td>
<td>2 source</td>
<td>7m</td>
<td>8m</td>
<td>57.5m</td>
<td>55m</td>
<td>18.75m</td>
<td>12.5m</td>
<td>48/228</td>
<td>200-3200m</td>
</tr>
</tbody>
</table>

Figure 1: Acquisition parameters of the three vintages. Red marks the most significant differences.
Important processing components in the sequence prior to data regularization and imaging are: deterministic zero phasing of all vintages using measured far field signatures; global amplitude matching; high resolution Radon demultiple (Herrmann et al., 2000) using initial velocities; deterministic tidal statics; cold water statics corrections. For the cold water statics corrections, which affected mainly the 1993 data, we use a method based on high-resolution picking of water bottom velocities, followed by layer replacement, where all water velocities are set to a fixed and constant reference value. This method is deterministic and therefore intrinsically 4D friendly.

### Regularization and 4D Binning
Regularization is a key component of 4D processing and it significantly reduces the NRMS on this project (figure 3). The sequence we applied consisted of: inline regularization, 4D binning (see below), crossline regularization and interpolation to 12.5x12.5 meter grid. Figure 2 shows the marked reduction in striping and noise on a single offset 4D difference section due to the crossline regularization. This is performed using a high resolution Radon transform. Figure 3 shows the improvement (reduction) in NRMS on a single offset class, after the imaging step, due only to the crossline regularization.

In order to reduce differences between the three vintages we performed simultaneous 4D binning. This is a process by which all pairs of traces between two vintages within a certain radius, such as a single bin, are compared with respect to navigation attributes as well as seismic repeatability. For example, we can choose to select traces that have the smallest sum of source and receiver separation or we may wish to pick those two traces which have the highest cross-correlation or NRMS. Our 4D binning can also combine these attributes so that a cost-function can be built that contains elements of the navigation and of seismic repeatability.

As a binning criterion, we choose the minimum of source and receiver separation. We find this to give the best combination of low repeatability and structural imaging.

In order to bin and regularize the three vintages, which all have different bin sizes to start, we use a cascaded approach: first, the 1993 and 2002 are binned and regularized onto a 12.5x25 meter grid. The procedure is then repeated between the binned 1993 and the 2004 data.

### Imaging and gather pre-conditioning for AVO
Prior to imaging, all data is interpolated to a 12.5x12.5 meter grid since we find that a square grid reduces migration noise. Following Kirchhoff time-migration the data are output onto a 25x25 meter grid, as we observed no deterioration compared to a 12.5x12.5 meter output grid. After the imaging we perform residual moveout correction on every bin using a simultaneous two-parameter picking based on semblance (Silici et al., 2003). Figure 4 shows residual normal moveout, before and after final velocity picking. Velocity analysis is followed by another pass of demultiple using the high resolution Radon transform algorithm. For optimal AVO analysis we apply residual noise removal and spectral offset balancing (see figure 5).
Finally, we apply residual trim statics and Q amplitude compensation.

**Improvement of repeatability**

Figure 6 shows the progressive reduction in NRMS through various stages of the processing. Step 2 is after Kirchhoff imaging, step 3 encompasses dense residual velocity picking as well as demultiple. Step 4 is timing corrections and steps 5 and 6 are residual denoise techniques. After imaging, no particular step in the processing stands out, i.e. nearly all processing steps lead to a similar reduction in NRMS. Both at the reservoir, as well as at the top Balder horizons, the final NRMS between surveys 1993 and 2004 is lower by around 0.06 to 0.08 (20-25%) than that of the 1993 and 2002 vintages. Figure 7 compares NRMS maps extracted around the reservoir at the very start and the very end of the processing. These maps confirm that the acquisition of the 2004 data has improved the repeatability relative to the 1993 data, and that the processing preserves this improvement. These plots clearly highlight the importance of both carefully planned 4D acquisition and careful 4D processing.

**Improvement of imaging**

We now turn to a comparison of the old and new processing sequences. Although a 4D parallel processing sequence may not be optimal with respect to 3D imaging, it is instructive to compare the quality of the data at the end of the new 4D pre-stack time Kirchhoff sequence that we have shown above, relative to a DMO based sequence from around four years ago. Figure 8 shows a crossline comparison and we see a marked improvement in quality with our new Kirchhoff sequence. Recall in particular that the new processing includes improved regularization and 4D binning, as well as dense one-pass two-parameter velocity picking, as explained above. Figure 8 shows that there is a clear increase in resolution, with a better delineation of faults. Events are imaged more continuously and there is more pinchout clarity. Residual static errors, evident with the old processing, have also been removed.
Foinaven 4D

Conclusions
We have shown that a carefully planned dense 4D acquisition, followed by careful 4D processing, can improve the final repeatability (NRMS) by 0.06 to 0.08 (20-25%). This paper has also shown the impact of improved regularization techniques and of 4D binning on 4D repeatability. Finally, we have shown the improvements in the image of a 4D vintage processed with a state of the art 4D parallel processing pre-stack time Kirchhoff processing, versus the same data processed four years ago.

References
Campbell, S. et al., Improved 4D Seismic Repeatability – a West of Shetlands Towed Streamer Acquisition Case History, submitted for publication, SEG 2005.


Acknowledgements
This paper is being published with kind permission of the Foinaven partners Marathon and Marubeni North Sea Ltd. The authors would like to thank their colleagues at CGG and BP, particularly everyone involved with CGG’s in-house processing center in BP Aberdeen, and the collaborative technology development effort. Particular thanks are due to Gordon Poole and Celine Lacombe, of CGG Technology, London.

References
Campbell, S. et al., Improved 4D Seismic Repeatability – a West of Shetlands Towed Streamer Acquisition Case History, submitted for publication, SEG 2005.


Acknowledgements
This paper is being published with kind permission of the Foinaven partners Marathon and Marubeni North Sea Ltd. The authors would like to thank their colleagues at CGG and BP, particularly everyone involved with CGG’s in-house processing center in BP Aberdeen, and the collaborative technology development effort. Particular thanks are due to Gordon Poole and Celine Lacombe, of CGG Technology, London.