Shot-based pre-processing solutions for wide azimuth towed streamer datasets

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Wide azimuth towed streamer (WATS) acquisition has been shown to provide improved seismic imaging, especially in areas with complex 3D structures. By making use of additional source vessels shooting into the streamer array from large lateral offsets, a dataset is created with a large cross-line aperture, higher fold, and a broader offset-azimuth distribution than conventional (narrow azimuth) streamer datasets.

The improved imaging provided by WATS acquisition geometry has been well illustrated as this method is being more widely adopted. An example which illustrates the superiority of WATS data for imaging was given by Michell et al. (2006). There, a straightforward depth migration of WATS data with limited pre-processing was shown to provide a significantly improved image compared to the results obtained with conventional streamer acquisition.

However, to realize the full potential of WATS data, pre-processing (the processing sequence prior to imaging) is essential, especially for applications which depend on the quality of the pre-stack gathers such as:

- Velocity model building and update
- Pre-stack time and depth imaging
- 4D/time lapse processing
- AVO analysis and reservoir characterization
- Quantitative analysis

With WATS data we move away from narrow azimuth (essentially 2D) gathers to 3D gathers with greatly increased cross-line aperture and a broad azimuth-offset distribution: see Table 1 and Figure 1 for a comparison. This has major implications on the pre-processing sequence which has traditionally used 2D...

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**Figure 1** Rose diagrams showing the offset-azimuth distribution for a conventional streamer acquisition (left) and the WATS super-shot field trial (right). Maximum offset is 10 km.

<table>
<thead>
<tr>
<th>Shot Gather</th>
<th>Inline Aperture</th>
<th>Crossline Aperture</th>
<th>Aspect Ratio</th>
<th>No. of traces</th>
<th>Data volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>8 km</td>
<td>0.8 km</td>
<td>1:10</td>
<td>~5,000</td>
<td>0.1 Gb</td>
</tr>
<tr>
<td>WATS</td>
<td>18 km</td>
<td>5.7 km</td>
<td>1:3</td>
<td>~104,000</td>
<td>2.5 Gb</td>
</tr>
</tbody>
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**Table 1** Comparison of shot gathers from typical 3D conventional streamer and the WATS pilot dataset used for this article.

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Figure 2 To build the entire swath, six different tiles are acquired using a streamer vessel and a single source vessel. Each tile is shot four times: a first pass in one direction and a second pass in the same direction but interleaving the six streamers (160 m spacing) in order to simulate a 12 streamers spread with 80 m separation; then the two passes are repeated from the opposite heading in order to obtain a 180 degrees azimuth sector. Note that tile 6 is shot with the source of the streamer vessel whereas tiles 1-5 are acquired with the source of the source vessel. The streamer length was 9 km and the shot spacing was 31.25 m.

algorithms, taking advantage of the pseudo-2D nature of the pre-stack data. So, there is a real need to develop a processing sequence which fully respects the 3D offset–azimuth distribution and preserves the 3D wavefield recorded in the WATS gathers.

As we consider the nature of the algorithms which are required for processing WATS data, it is also important to consider how the data should be sorted or organized for processing. It is vital for these large datasets with their super-sized gathers (see Table 1), that efficient flow of data through the sequence is achieved and that processing is easily parallelized at all stages.

WATS data: The processing challenge

Comparing the dimensions of conventional and WATS gathers provides a hint of the challenges ahead for data processing. If we now look at the acquisition scheme used to acquire the dataset (Figure 2) and the actual geometry of an example WATS super-shot gather (Figure 3) we get a much clearer idea of the potential complexity of the problem. The composite super-shot gather is obtained by combining 24 sail lines of six cables each, giving a total of 72 cables and 103,680 traces. It was formed after minor corrections for source mis-positioning between sail lines. In practice this mis-positioning did not exceed 10 m and was corrected using a differential NMO correction.

Looking at the super-shot gather, one is immediately struck by the dimensions involved. It is approximately 16 times the area of a typical conventional 3D marine gather. Also notable for this dataset is the large variation in the cable feather from one sail line to the next, leading to a super-shot gather with significantly irregular receiver sampling. From this example we can draw two important conclusions:

1) Although source position can be accurately controlled during WATS acquisition we cannot depend on a regular spatial

Figure 3 Composite WATS super-shot combining data from 24 sail lines, using 6 cables. The receiver locations are shown colour-coded to the cable number (1 to 72) to emphasise the cable feathering and position. The resulting common mid-point (CMP) locations are shown as white dots. The composite WATS super shot has an in-line aperture of 20 km, cross-line aperture of 5.7 km and contains 103,680 traces.
receiver distribution. As a consequence some of the current sail line based pre-processing will not be applicable.

2) Given the broad offset-azimuth distribution within a super-shot gather, the conventional processing sequence involving common offset cubes is also no longer applicable. We must look for another more suitable domain for the data in which the cross line offset dimension is not ignored. We would have to adopt common offset-azimuth cubes, or preferably common inline offset - crossline offset cubes. However, for both of these domains, a significant proportion of missing traces (gaps) are to be expected due to cable feathering.

Now we have a good understanding of the potential problems and complexities of WATS datasets, we are in a position to propose a processing sequence which is robust and flexible enough to cope with them.

**Shot-record approach for WATS**

Based on the previous considerations, we propose a shot record approach, where the 3D nature of the recorded wavefield is preserved in its natural 3D shot gather domain for the full processing sequence. Shot-based pre-processing solutions also address the most general situations, without any dependency related to the spatial distribution of the WATS shots or receivers from one gather to the next. As well as satisfying our need for flexibility, the shot domain will allow us to efficiently parallelize all the processing steps (with gathered processed independently and in parallel), and will remove the need for the unnecessary and costly re-sorting of large datasets into different domains.

In this article we will demonstrate how 3D, one-pass, pre-stack, pre-processing solutions in the shot domain fully exploit the 3D nature of the recorded wavefield in a practical, efficient, and flexible manner. These solutions will be valid not only for WATS data, but any dataset with a broad, or full offset-azimuth distribution. We provide examples here for data regularization and de-multiple.

**Data regularization**

Data regularization has a significant role to play in the migration process. Kirchhoff-based methods depend upon the constructive interference of the migration operator at the reflector, and the destructive interference of the migration operator away from the reflector (or outside the Fresnel zone) to build the image (Poole et al., 2006). Whilst weights can be used to ensure that the amplitude at the reflector is preserved when acquisition geometry is irregular, it is more difficult to ensure optimal destructive interference away from the reflector. This results in what are commonly known as migration smiles which contaminate the migrated image. These ‘smiles’ are residual energy from the tail of the migration operator which has not been cancelled out by destructive interference, due to the irregular acquisition geometry resulting in irregular spatial positioning of the operator. Making the acquisition geometry more regular promotes the destructive interference away from the reflector and results in a cleaner, smile-free image.

The most commonly applied regularization process consists of bin centring the pre-stack data, i.e. shifting the common mid-points (CMPs) of the traces to the centre of the bin. When applied on a common shot gather, this process consists of the interpolation of the recorded 3D wavefield at receiver positions so that the CMP position for a given source-receiver pair occurs at the corresponding bin centre.

We demonstrate this one-pass bin centring regularization, which uses an irregular 2D Fourier transform, on our WATS super shot shown in Figure 4a. The white dots represent the raw CMP positions for the entire WATS super shot, and in Figure 4b
the bin centred CMPs are shown after regularization. This process can also be combined with missing trace reconstruction to fully populate our bins, as shown in Figure 4c. Notice how the gaps in CMP coverage due to the cable feathering and around the shot location have been filled.

Figures 5 and 6 illustrate the quality and effectiveness of the 3D, shot-based data regularization procedure on selected time slices and in-line sections on the WATS super-shot gather. With a one-pass 3D approach, large gaps along a single axis can easily be filled, and therefore significant migration artefacts can be avoided, whilst still preserving the character of the data.

3D surface related multiple attenuation

Multiple attenuation is a key pre-processing step, and 3D surface related multiple elimination (SRME) has been widely adopted where complex multiple wavefields contaminate the data. The shot-based wavefield modelling approach developed by Pica et al. (2005) is effective against peg-leg and shifted-apex diffracted multiples, and lends itself naturally to our shot record WATS processing sequence.

This two step approach consists of the generation of a 3D multiple model followed by an adaptive subtraction of the model from the recorded data. Following the ‘Delft’ approach, a multiple model (M) is obtained by taking the recorded wavefield (D) and giving it an extra bounce in the subsurface, represented by the Primaries (P). This gives us the following relationship:

\[ M = -D \ast P \]

Where the minus sign takes account of the negative reflection coefficient at the water surface. In a purely data driven approach, such as the one developed by Verschuur and Berkhout (1997) and Biersteker (2001), the extra bounce off the primaries (P) is driven solely by the pre-stack data using a surface consistent convolution scheme.

In our wavefield modelling approach, the extra bounce is modelled by downward wavefield extrapolation (W↓) of the recorded wavefield (D) into the subsurface, followed by a reflection (R) at each seismic reflecting boundary, and upward wavefield extrapolation (W↑) back to the surface. This hybrid method involving data and a model gives us an equivalent relationship:
In wavefield modelling 3D SRME, the multiple model is obtained by adding an additional “bounce” to the recorded data. Simplified ray paths for our shot record wavefield are shown in blue to represent the recorded data (D), with the shot point shown in red and the inline aperture of the gather represented by the black line. The bounce is modelled by downward extrapolation (W↓) of the recorded wavefield, then a reflection (R) at each seismic reflecting layer (from migrated section), followed by an upward wave field extrapolation (W↑) back to the surface, as illustrated by the orange ray paths.

**Figure 7b** Inline section through WATS composite super-shot gather before demultiple, corresponding to the location of cable 66.

\[
\begin{align*}
M &= -D \ast (W \downarrow \ast R \ast W \uparrow) \\
M &= -D \ast P
\end{align*}
\]

Where the extra bounce which comes from the wavefield extrapolation step \((W \downarrow \ast R \ast W \uparrow)\) is analogous to convolution with the primaries \((P)\). This approach requires a velocity model for the wavefield extrapolation and a migrated section to use as the reflectivity section \((R)\). The velocity model used depends on the complexity of the multiple wavefield and can simply be water velocity, or a variable velocity model if required, although the mixed data and model driven approach relaxes the dependency on an accurate velocity model. The reflectivity model can be quickly generated for a window of data around the water bottom (and main multiple generators) with pre-stack time migration of the near-offsets.

This approach, already successfully illustrated on streamer (Weisser et al., 2006) and node data (Pica et al., 2006), is now illustrated on WATS data without any decimation of the super-shot gather. Figure 7a displays the reflectivity (migrated) section used in the wavefield modelling. The impressive spatial extent of the WATS gather is shown on the display, and one can observe that it is comparable in scale to the salt structures, with our example shot location sitting between two salt domes. The blue lines illustrate simplified recorded data ray paths \((D)\), and the orange lines represent the multiple ray paths which we could expect to model. Looking at the multiple model, Figure 7c, we observe that the kinematics of the model perfectly fit with the recorded arrivals in Figure 7b, at offsets as large as 10 km from the source. The model is useful for identifying multiple arrivals from primary events in the WATS shot gather, and with some rudimentary interpretation it is interesting to see that the largest amplitude multiples in the section occur at the far offsets and are generated by the steep salt flanks. More importantly, this model is used to remove these surface related multiples from the WATS super-shot gather by adaptive subtraction as shown by the results in Figure 7d.

**Figure 7c** Inline section through wavefield modelling 3D SRME multiple model.

**Figure 7d** Inline section through WATS composite super-shot gather after subtraction of the wavefield modelling 3D SRME multiple model.
We have demonstrated that 3D SRME can provide excellent results for WATS super-shot gathers when applied in the shot domain where it can also be efficiently parallelized for full-scale production processing, without any need for data decimation.

Conclusion
The aim of WATS marine acquisition geometries is to record a dataset with a broad offset-azimuth distribution which provides improved reservoir illumination and signal-to-noise ratio, yielding a superior image. These new surveys involve long offsets with a significant cross-line component that cannot be ignored during data processing. The resulting 3D wide azimuth super-shot gathers challenge current pre-processing practices, generally performed in the sail line or common offset volume domain, which would have to be applied in an azimuth-sec- tored, multi-pass fashion to the WATS data.

To realize the maximum benefit of the 3D wavefield recorded in wide azimuth datasets, an efficient true 3D processing approach is required. We propose a one-pass, shot-based processing sequence as an effective and flexible processing solution. This approach will fully honour the 3D nature of the recorded wavefield and properly take into account all the effects related to the complexity of the acquisition, such as cable feathering, without any dependency on the spatial distribution of WATS shot or receivers.

Elements of the shot record processing sequence have been successfully illustrated on two important pre-processing steps: data regularization and 3D SRME. If we consider that we can utilize existing shot-based 3D noise attenuation solutions for random and impulsive noise, seismic interference (Gulunay, 2004), and diffractions (Gulunay, 2005), we may conclude that the entire WATS pre-processing sequence could be performed efficiently in the shot domain. When combined with existing shot record wave equation imaging and new tools for azimuthal velocity model building, it is easy to envisage a complete shot record processing and imaging solution for wide azimuth data which makes full use of the recorded 3D wavefield. We feel that this would be instrumental in realising the full potential of wide azimuth data and represent another significant step in the evolution of 3D seismic processing.

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References