**Broadband marine seismic – Breaking the limits**

*Robert Soubaras, Peter Whiting, Bruce Ver West, Roger Taylor; CGGVeritas*

**Introduction**

The importance of recording the full range of frequencies (low as well as high) is widely accepted. High-fidelity, low-frequency data provides better penetration for the clear imaging of deep targets, as well as providing greater stability in seismic inversion. Broader bandwidths produce sharper wavelets and both low and high frequencies are required for high-resolution imaging of important features such as thin beds and stratigraphic traps.

The industry has been facing many issues that have limited the performance of marine seismic surveys with respect to bandwidth. Among them, we find mechanical and acoustic noise, source and receiver ghosts and attenuation with depth. Until recently, conventional de-ghosting was found to be sub-optimal. Thanks to recent advances in technology and also in operational capabilities, we have seen several improvements, in particular with the use of solid streamers, deep towing and notch diversity.

We describe a different technique to achieve broadband marine streamer data. The proposed solution is a new combination of streamer equipment, novel streamer towing techniques, and a new de-ghosting and imaging technology. It uses receiver notch diversity to yield a broadband spectrum and takes full advantage of the low noise and low-frequency response of the new generation of solid streamers. As a result, the method creates an exceptionally sharp and clean wavelet for interpretation. It can be tuned for different water depths, target depths and desired output spectra.

**Improvements in streamer technology**

A key element of this towed streamer broadband seismic technique is the streamer itself. Dowle (2006) describe some of the recent improvements in streamer technology. The new generation of streamer electronics can record hydrophone signal as low as 2Hz, which adds an additional one or two octaves to the low-frequency end of spectrum. Another key element is the design of solid streamers which can significantly reduce noise (particularly sea-state noise) when compared to fluid-based (including gel) streamers (Figure 1). This is done by isolating the hydrophone sensing elements from the strain member to reduce vibration noise sensitivity (Figure 2) and using a solid foam fill which inhibits the transmission of noise wave modes along the streamer such as bulge waves.

This combination of low-frequency hydrophone recording and reduced noise make solid streamers an excellent platform for broadband recording. An additional advantage for this technique is that the solid streamer has a uniform density, stable buoyancy and is robust enough to operate at extreme depths (greater than 60m). This deep-tow capability facilitates streamer depth profiles which have significant ghost-notch diversity and optimal low-frequency recording.

**Novel De-ghosting approach**
Marine receiver deghosting has received renewed interest recently as a key component of broadband imaging. Different approaches for acquiring broadband marine streamer data such as over-under streamers, dual-sensor streamers or variable-depth streamers require their own deghosting methods which may include 2D propagation assumptions. We introduce a novel approach which leads to a deghosting method adapted to any acquisition method and which is optimal in terms of signal-to-noise ratio because it is not performed as a preprocessing stage. It is true amplitude, being able to extract the true deghosted reflectivity, i.e. the reflectivity that would be obtained should the water surface be non-reflecting.

The principle of this method is to perform a standard migration together with a mirror migration, and to perform a joint deconvolution using these two images as inputs. We refer to a mirror migration as one which migrates from receivers that are mirrored above the surface.

The normal migration stacks the primary events coherently, the ghost events being imperfectly stacked in such a way that the migration has a residual ghost wavelet that is causal (i.e. lags the primaries), Figure 3. The mirror migration stacks the ghost events coherently with their polarity reversed, whilst the primary events are imperfectly stacked in such a way that the mirror migration has a residual wavelet that is anticausal (i.e. the residual primaries precede the well-imaged ghosts), Figure 4.

The proposed deghosting method uses this dual imaging of the same reflectivity with two different viewpoints to extract the true amplitude deghosted migration.

In an intuitive way, we can say that we have a binocular vision of the reflectivity with the normal migration image coloured by a normalized minimum phase distortion, and the mirror migration image coloured by a normalized maximum phase distortion. To recover the reflectivity in true colour (i.e. without distortion) we propose a joint deconvolution. This is a well-posed problem, which means it has a unique solution, and makes no assumption (like a common white reflectivity assumption for example) about the underlying reflectivity spectrum. The method is a real true-amplitude process and outputs the reflectivity of the earth, which is arbitrary and unknown.

This is a well-posed problem, which means it has a unique solution, even when the minimum phase and maximum phase properties are marginally respected (meaning the operators have perfect spectral notches). No assumption is needed on the amplitude spectrum of the reflectivity, which is arbitrary and unknown. The joint deconvolution can be done in a least square sense in the case where there is noise in our data, and can also be done in a multichannel way.

Applications

This approach to towed streamer broadband seismic is particularly efficient, flexible and customizable for a range of environments and applications. The acquisition parameters such as variable depth streamer profile, maximum streamer depth and source depth can be tuned to provide the maximum possible bandwidth for a given geological setting and water depth.

In particular this technique can take full advantage of towing solid streamers at what are currently considered as extreme depths to benefit from the improved low-frequency response of the hydrophones and reduced sea-state noise. To date a variety of test lines have been acquired in different settings with streamer maximum depths as large as 60m.
In terms of acquisition geometries, the novel approach to de-ghosting is fully 3D. It makes no 2D assumptions and has no limitations in the cross-line direction making it suitable for wide-azimuth as well as 3D surveys.

This flexibility means that the technique can be used for a range of applications. The increase in penetration from the extension of the bandwidth at the low end will benefit the imaging of deep targets and those below complex overburdens. Shallow targets (such as shallow hazards) will benefit from the fully from the total bandwidth available and recordable. Recent trials have achieved usable bandwidths between 2.5 and 150 Hz.

The joint migration - mirror migration deconvolution technique is well-suited to deghost variable depth streamer acquisition but can cope with any acquisition geometry, so could be applied to other techniques such as dual-depth streamer spreads and dual-sensor recordings.

Data examples

A dataset was acquired with the variable-depth streamer technique offshore NW Australia and processed with the new de-ghosting scheme. The data was migrated in depth, just after source designature. Figure 3 shows the migration, Figure 4 the mirror migration. The residual causal ghost can easily be seen in the migration below the water bottom, as well as the anti-causal ghost on the mirror migration above the water bottom.

Figure 5 shows the deghosted output after application of the joint deconvolution, with no spectral shaping applied. The de-ghosted output shows the broadband nature of the final image with low frequencies down to 2.5 Hz and high frequencies up to 110 Hz and the intrinsic noise-free character of this approach. These results are compared to legacy data (Figure 6) over the same area to indicate the uplift in resolution possible with modern broadband acquisition and imaging techniques.

Conclusions

We have described an efficient and robust approach for recording and imaging broadband marine towed streamer seismic data by exploiting the ghost notch diversity of a variable-depth streamer profile which features extreme maximum streamer depths. The approach utilises the latest solid streamer technology to maximise the recording of both high- and low-frequencies (down to 2Hz) with high signal-to-noise. Central to it is a novel deghosting technique which is robust, true amplitude, fully 3D and suitable for wide-azimuth data.

This robust approach provides exceptional broadband seismic images with a clean, low-noise character, a wide frequency range (2.5 to 150 Hz, more than five octaves in a recent trial) and a sharp wavelet which facilitates the interpretation of fine subsurface details which were previously unresolvable.

References


Figures

Figure 1. Noise performance of the solid streamer section of a hybrid streamer compared to the fluid section in marginal weather. Typically the noise level of the solid streamer is 15dB below that of the fluid-filled section.

Figure 2 (a) Image of cut-away solid streamer showing the solid foam fill which isolates the hydrophone from the strain member. (b) Image of the cylindrical hydrophone assembly which is embedded in the foam flotation jacket and contains 32 noise-cancelling piezoelectric elements per group.

Figure 3 Depth migration stack image with residual ghost appearing as a causal minimum phase distortion.

Figure 4. Mirror migration stack image where the ghost is imaged at negative polarity to match the primaries in Figure 3, and the residual primaries appear as an anti-causal maximum phase distortion (visible above the water bottom).

Figure 5 Broadband stack image after de-ghosting by joint deconvolution

Figure 6 Comparison of legacy dataset over the same area compared to the new broadband image
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Figure 3. Depth migration stack image with residual ghost appearing as a causal minimum phase distortion (visible below the water bottom).

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Figure 5. Broadband stack image after de-ghosting by joint deconvolution.

Figure 6. Comparison of legacy dataset (left) with the new broadband image (right).