Introduction

Variable-depth streamer acquisition is a key solution for broadband marine seismic: an optimized receiver depth distribution results in a wide diversity of receiver ghosts thus increasing drastically the available frequency bandwidth, in both low and high ends frequency spectrum, from 2.5 Hz to source ghost notch. As a natural complement to this receiver-side solution, the same concept can be applied on the source-side, with a variability of gun depths. A multi-level source allows canceling of the source notches so extending the recorded bandwidth to 200 Hz, the current upper limit imposed by the 2 ms anti-alias filter. Thanks to accurate gun timing, the recorded data can be processed with the flow already developed for variable-depth streamer, where the receiver ghosts have to be rigorously taken into account through the sequence, to be used for the final image in the Joint Deconvolution algorithm (Soubaras, 2010). Obviously, some processing stages had to be adapted to better handle the extra high frequencies. A synchronized multi-level source combined with variable-depth streamer has been successfully tested and applied in various 2D and 3D cases, in both shallow and deep water environments.

Interests of combining a multi-level source to variable-depth streamer acquisition

During acquisition, the direct and ghost arrivals at the receiver side, creates a well-known interference pattern: the receiver ghost notch, whose frequency depends directly on the receiver depths. As a consequence, a clear strong notch will always occur with a conventional flat-streamer acquisition. On the contrary, varying the receiver depths along a streamer allows recording a wide diversity of receiver ghosts. Additionally, the sea-state noise level decreases as the cable is towed deeper: this technique thus benefits from towing solid streamers at what is generally considered as extreme depths (up to 50 meters), which allows recording more signals at low frequencies (Figure 1).

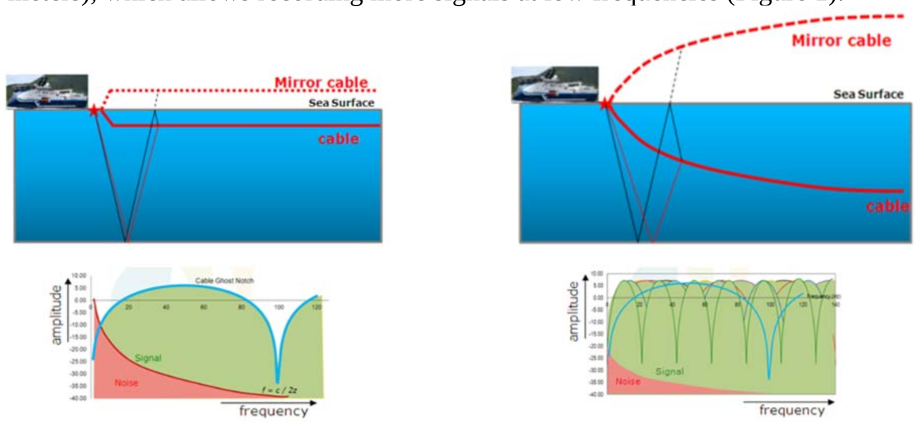

Figure 1 *Comparison of a schematic conventional (left) and variable-depth (right) streamer profiles, and their corresponding signal & noise amplitude spectra (bottom) which result from the interferences of the receiver ghosts.*

Rather than using a linear increase in streamer depth with offset (original slant streamer geometry), a custom profile is designed in order to provide a better receiver ghost diversity, particularly for shallow events, and can be tuned to provide the maximum possible bandwidth for a given geological setting and water depth. Nevertheless, this receiver-side technique is still limited by the source notch imposed by a one-level conventional source.

As a complementary solution to variable-depth streamer, the same model can be applied on the source-side, with a variability of gun depths. Based on variable gun depth geometry inside the three sub-arrays, this multi-level source allows the flip-flop mode for 3D acquisition. Synchronizing the gun timings allows the deeper guns to shoot when the down-going wave-front generated by the shallower guns reach them, creating a single synchronized down-going wave-front recorded by the cable later on, and thus defocusing both source ghosts. An optimized 3D distribution of airguns allows the generation of far field with a well-balanced directivity for all frequency bandwidth. Such a multi-level source generates similar low frequencies as a conventional source, while extending the spectrum to higher frequencies.

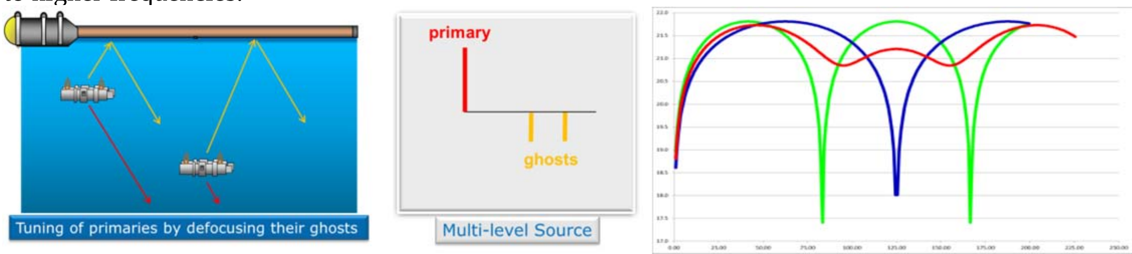

Figure 2 *Schematic multi-level source with synchronized gun timing (left). Theoretical sources signatures (right) generated by* ***a conventional source at 6m****,* ***a conventional source at 9m*** *and* ***a synchronized multi-level source****.*

Variable-depth streamer data processing

Thanks to the synchronization between the guns at different depths, only a notchless wave front will reach the cable, which means that the recorded data can be considered as standard variable-depth streamer data for the full source bandwidth and thus could be processed accordingly.

Processing variable-depth streamer data requires taking the receiver ghosts rigorously into account until the end of the sequence. The use of normal and mirror migrations (time or depth) allows the generation of causal and anti-causal receiver ghosts that a joint deconvolution algorithm is able to suppress pre-stack as well as post-stack. The deghosted image actually benefits from double fold effect, thanks to the use of both primary and ghost reflection energies to build the image. As the receiver ghosts are obviously a constraint for algorithms developed for flat streamers, a new sequence was set up, adapted from standard marine processing flow (Rebert & al, 2012). Nevertheless, acquiring with a synchronized multi-level source requires some processing stages have to be adapted for better handling of extra high frequencies up to 200 Hz, especially in denoising, designature and demultiple flows. Indeed, special attention should be paid to denoising parameters in order to accurately preserve the low and high ends of frequency spectrum. Concerning the deterministic source designature (debubbling & zero-phasing), improved results have been consistently achieved on a number of datasets by using a data-driven extracted source signature rather than a modeled one. The extraction of the source signature from the seismic requires appropriate conditions such as sufficient water bottom depth with lateral subsurface heterogeneities enabling the geology to stack out. Datasets satisfying those conditions have regularly produced source signatures which result in better zero-phasing and accurate debubbling. Among the existing demultiple tools, some standard methods, such as SRME, were adapted to handle variable receiver ghosts (Sablon & al, 2011). A further extension to the method developed for SRME is also used for Radon. For multi-level source data, those two developments in SRME and Radon are still suitable. Shallow water demultiple flow also required some changes, to overcome high frequency limitations in the multiple model computation.

2D & 3D Results in shallow and deep water environments

The combination of synchronized multi-level source with variable-depth streamer has been successfully tested in 2D acquisitions in both shallow and deep water environments, and compared to existing conventional and variable-depth streamer results (Figures 3 & 4). This combined Marine solution was then applied for two consecutive 3D surveys offshore Norway, respectively 300 km² and 2700 km². On these two datasets, the increased frequency bandwidth generated by the synchronized multi-level source from 2.5 Hz to 200 Hz is clearly visible in the shallow parts. The high frequencies are seen to decrease with depth as a result of the local absorption effect, although there is still a clear uplift down to 2 seconds below the water bottom, until it reaches strong absorbing layers of the basalt or chalk. Moreover, on the large 3D survey acquired offshore Norway, the current fast-track processing shows frequencies reaching 90 to 100 Hz below the chalk, with a similar vertical & spatial resolution (Figure 5).

In order to evaluate the potential of such a broadband dataset, a part of the survey has also been processed with a "site survey" type approach, with a denser bin size (6.25m x 9.375m) and near offsets only, which shows a general improvement in resolution and more detailed features, even in the deeper parts (Figure 6). The synchronized nature of the multi-level source maintains the penetration of low frequencies below the basalt (Figure 3) or chalk (Figures 4, 5&6) by proposing good resolution at deeper part as well as near water bottom. Shallow targets (such as shallow drilling hazards) will benefit from the total bandwidth available and recordable. Broadband seismic data is thus characterized by a clean sharp wavelet with minimal side lobes, which helps in resolving events and interpreting fine stratigraphic details. On the other hand, the increased low frequency content has a surprisingly powerful effect on the seismic images, providing strong discrimination of layers.

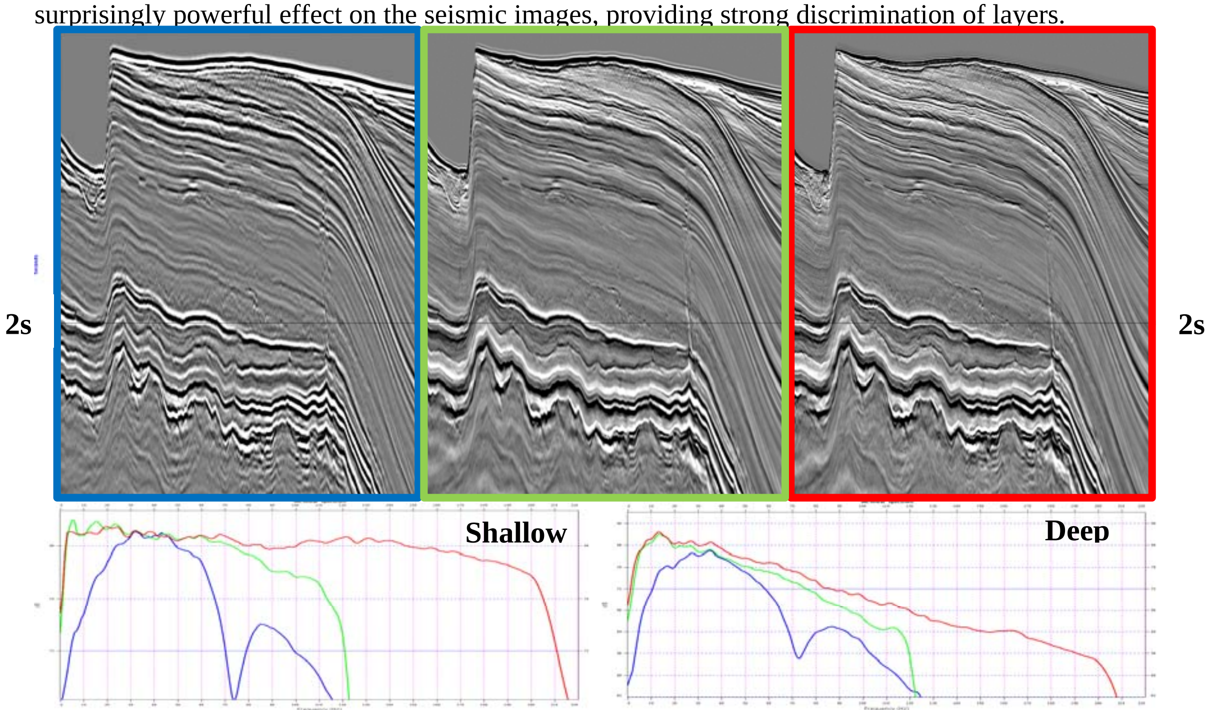

Figure 3 *Comparison of deep water 2D results from West of Shetlands:* ***Conventional flat-streamer acquisition with standard source****,* ***Variable-depth streamer acquisition with standard source*** *&* ***Variable-depth streamer acquisition with multi-level source****, with their corresponding amplitude spectra for shallow (left) and deep (right) windows*

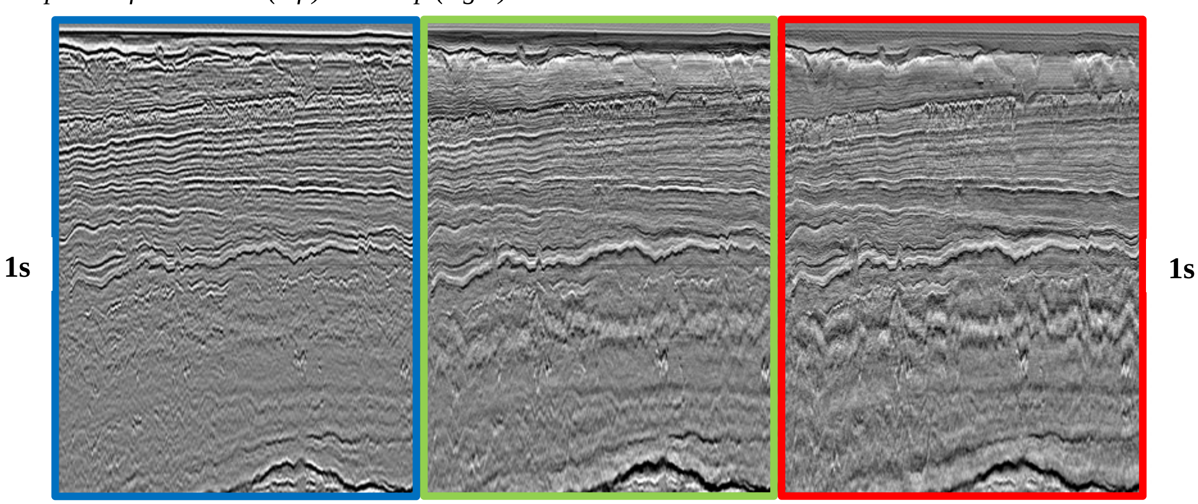

Figure 4 *Comparison of shallow water 2D results from offshore Norway:* ***Conventional flat-streamer acquisition with standard source****,* ***Variable-depth streamer acquisition with standard source*** *&* ***Variable-depth streamer acquisition with multi-level source****. Data courtesy of Lundin*

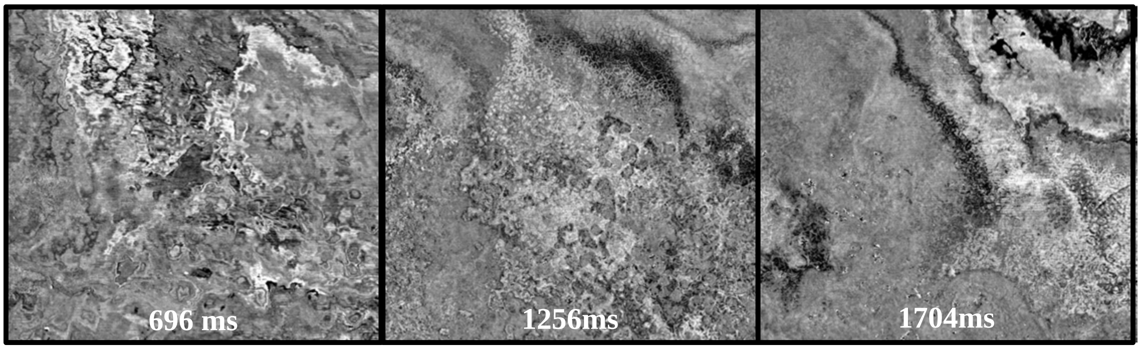

Figure 5 *Time slices from a 3D Shallow water dataset offshore Norway (2700 km²), with a Fast-track processing. Data courtesy of Lundin.*

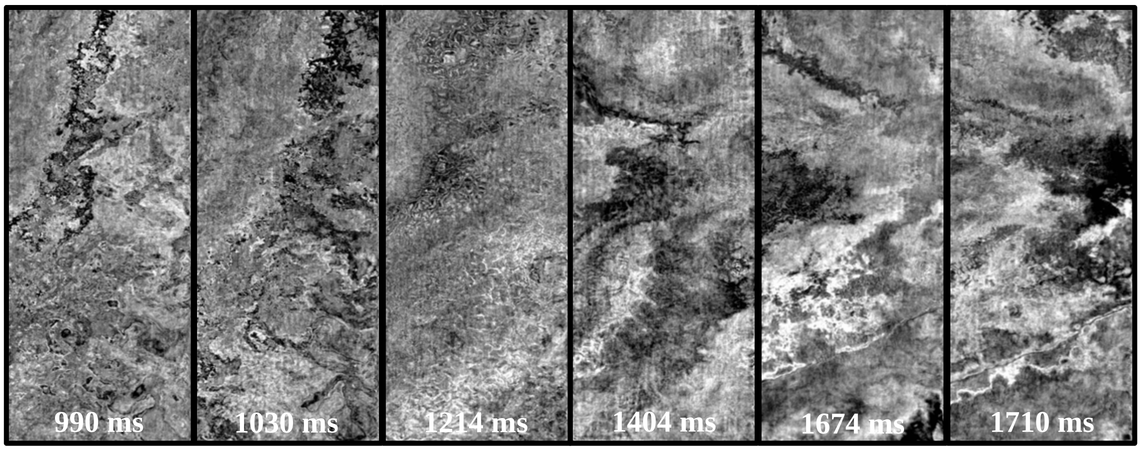

Figure 6 *Time slices from a 3D Shallow water dataset offshore Norway (300 km²), with a Site survey processing. Data courtesy of Lundin.*

Conclusions

A synchronized multi-level source unlocks the source ghost limit allowing variable-depth streamer acquisition to provide broadband seismic data reaching 200 Hz without compromising the low frequencies. This compact approach to ghost-free sources is operationally compatible with any 3D acquisition patterns. One key advantage of this combined source & receiver solution is to provide seismic data which could be processed with sequences already developed for variable-depth streamer, with the necessary updates required by better handling of extra high frequencies, in denoising, designature or demultiple. Characterized by a sharp wavelet with minimal side lobes, the imaging of such broadband data will provide more resolution thanks to the full bandwidth in the upper part while more low frequencies are critical in difficult environments like sub-basalt or sub-chalk.

Acknowledgements

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References

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