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# Air Gun near the Sea Floor as Shear-wave Source?

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## SUMMARY

The feasibility of using an air gun near the sea floor as shear-wave source has been investigated. With an air gun near the sea floor, an evanescent P-wave in the water becomes a propagating S-wave in the sea floor, such that it seems that a pure shear-wave source has been used at the sea floor. This type of wave has been called a P*S wave. An experiment with such a set-up has been carried out at the Valhall field. For that case, modelling shows that shear-wave related event of the type of P*S waves can be expected with such a set-up. Especially at larger offsets, P*S waves can be expected. When analysing the field records and Constant-Velocity Stacks, it is hard to find P*S-wave reflected events. On the other hand, P*S-wave refracted events can be discerned in records. These events can be brought up to stack level and imaged, as shown in this paper.

## Introduction

P-wave imaging is often problematic when some gas is present in the overburden, directly affecting the P-wave velocity significantly. S waves do not have this difficulty as their propagation is independent of the pore content. Still, S waves also have some difficulties, one of them being that it is cumbersome (and therefore expensive) to generate these waves at the sea floor. Recently (Allouche *et al.* 2011, Drijkoningen *et al.* 2012) it has become clear that it is possible to create shear waves at the sea floor via an airgun that is deployed near the sea floor. The *propagating* part of the P wave in the water converting to a propagating shear wave at the sea floor is small in amplitude. However, the *evanescent* part of the P-wave in the water converting to a propagating S wave at the sea floor, is significant if not large in amplitude. This latter type of wave has been called a P*S wave.

This approach is appealing as it allows the use of only an airgun near the sea floor ("Deep Tow") to create S waves: this can be done in an efficient manner, in contrast to a shear-wave source deployed at the sea floor. In order to evaluate the possibilities of creating these P*S waves, an experiment is designed and carried out where the air gun is deployed at depth, just above the sea floor. This was executed over the Valhall field where 4C stations on the sea floor are actively recording. In the following analyses and processing, the first aim is whether P*S-wave type events could be detected in common-receiver gathers. Modelling study would aid in recognizing such events. The second aim consists of the imaging of these events.

## Acquisition

The aim of the acquisition part of this test was proving the concept of operating such a source in an efficient and safe manner. The Seismic Contractor for the Valhall LoFS Acquisition, WGP, was asked to develop such a source. Because of cost efficiency, real-time accurate positioning of the deep-tow source was limited to the surface buoy suspending the source. A double tow-point design was chosen, which minimized the overall risk to the operation. This design is essentially similar to the conventional LoFS source, with cannons hanging from a surface buoy. The key changes were reducing the number of sub-arrays to one, reducing the number of cannons in the sub-array to two (2x150 $in^3$ Bolt APG guns), increasing the length of the lines suspending the canons, adding a tow-point to the front of the canons, and replacing the umbilical with a stress member and electric and air-supply bundle. This led to deployment and retrieval operations very similar to those in a conventional LoFS acquisition, with only minimal modifications to current equipment or procedures.

The shooting  and turning area for the test was selected in order to keep a safe distance from any known subsea obstructions (pipelines, power cables, anchor chains, etc.) as well as surface obstructions, and with limited variations in bathymetry. The shot line was 5 km in length directly above one Valhall LoFS array cable. Shot lines were planned in both sail directions with recording in a continuous mode. The shot interval was 12.5 m firing guns independently in flip-flop mode, and shots in the 2 lines were offset with the intent of giving a 6.25 m shot interval when the lines were combined. The fly height was designed to be at 7 m minimum above any part on the sea floor.

The aim of the acquisition part of this test was proving the concept of operating such a source in an efficient and safe manner. The Seismic Contractor for the Valhall LoFS Acquisition, WGP, was engaged early-on to develop such a source. The acquisition contractor and operator decided not engineer a depth control mechanism or real time positioning of the source in the water, so that real-time accurate positioning was limited to the surface buoy suspending the source. This allowed delivery of a simple, cost efficient trial, and deferred development of a deep tow source with proper depth and positioning control until after the acquisition concept could be demonstrated.

The test was executed in June 2012 following the completion of Valhall LoFS#15. As expected, the control of source was challenging, being dependant on currents and vessel speed. Only the depth could be monitored in real time via a pressure sensor. The test was completed within 2 days. The average fly height was approximately 14 m, with a minimum of 8 m, and maximum of 16 m. Vessel speed in the water ranged from 2 to 3 knots, with clear inverse linear relationship between sail speed and source depth (within the same sail direction). 681 shots were fired, and 202 four-component stations of the corresponding receiver line were selected.

**Event interpretation on records**

At the processing centre, one of the first steps was the rotation of the data. Next, the geometry was defined: the analysis and processing was subsequently done completely as 2D. The data were analysed, via f-k spectra and their multi-component nature. A result was that the airgun source generated little energy in the desired frequency band for the P*S waves. For P*S events, the In-line component is the most important one and therefore chosen. A main observation is that the data start to look more like land data: the surface waves become more prominent, indicating that shear-wave related energy is becoming much more important. In order to enhance that energy, the data were:

- High-cut filtered (13-18 Hz) with a minimum-phase Butterworth filter
- Muted to remove direct P-wave arrivals and some early P-wave reflections

An example of such a record, part of a common-receiver gather, is given in Figure 1. For comparison purposes a regular shallow airgun-array-type record has been added to the figure: it can be seen that those shear/surface-wave related events are only very faintly present.

In order to observe any *reflective* P*S-wave events, extensive filtering has been done, such as removing the surface-wave cone by dip-filtering, but still it remained hard to see any. Modelling has been done to aid the interpretation but that also did not help. On the other hand, P*S-wave *refracted* events can be discerned: a clear event can be observed directly in the Deep-tow record in Figure 1: the event starting near X = 0 (T = ~ 0.2 s), and ending at X = 1600 m offset at T = ~ 3.8 s. Further analysis shows that more refractors are present.

**Processing, leading up to the image**

The next stage is the processing of these data leading up to an image. A main item in this processing sequence is the stacking, to see whether P*S wave events can be enhanced, being either reflections or refractions. Since the interest is in SV-wave reflections/refractions, the main focus has been on the in-line-component data. An important issue for the stacking of gathers is the shear-wave stack: for positive and negative offsets, the polarity of the SV waves changes, and therefore data for positive and negative offsets need to be subtracted rather than added. Shear-wave stacking enhances SV-wave information and cancels/suppresses P-wave information.

A main interest of the experiment was to see whether *reflections* could be discerned. Especially the stacking should aid in recognizing these events. After filtering as described above including dip-filtering to remove the surface waves, CMP bins (up to 454 traces per bin) were made which were good for Constant-Velocity Stacks (CVS) using NMO. Also here after extensive analyses, no reflective P*S-wave reflections were recognized. Some coherent energy started to emerge for velocities that were too high for shear-wave velocities for the depths concerned. After comparison with data from a regular shallow-airgun array, it turned out that the coherent energy was “regular” PS-wave energy, not emerging from an evanescent-wave but from a propagating P-wave part in the water.

Another focus was on the *refractions*: already in the records they could be discerned so it was expected that they could also be imaged. The same data, up to the CMP binning, were used here. From there, a Linear Move-Out (LMO) correction was applied. And then a stack was applied for each LMO velocity, resulting in Constant Velocity Stacks. An example of such CVS is shown in Figure 2: it shows that good lining ups can be discerned, hence a good velocity model can be constructed. The velocities obtained have expected values for regular S-wave velocities in the shallow subsurface.

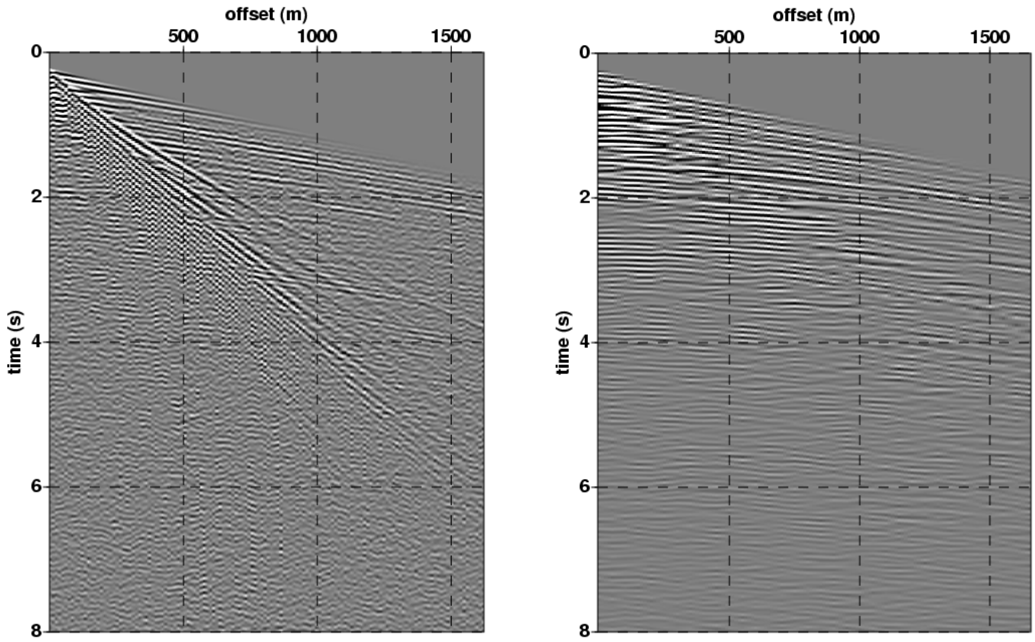


***Figure 1*** *Common-receiver gather for In-line component. Left: Deep-towed airgun. Right: Regular shallow-airgun array.*

Based on the obtained velocity model, the final processing steps applied to the CMP gathers were:

- For each velocity (in range of LMO):
  - Dip-filter CMP's (selecting data around velocity)
  - LMO
  - CMP stacking, including shear-wave stack
  - Prediction-error filtering
  - Time-windowing around refraction(s)
- Stack constant-velocity LMO stacks (time windowed)
- Convert time section to depth

So for each velocity, a set of processing steps was applied to the CMP gathers. First, dip filtering to remove energy which would otherwise show up as noise in the stack. After LMO and stack, some "ringiness" was observed, probably due to remnants of the surface waves, hence prediction-error filtering was applied. And finally, a time window around the refracted event was applied: this step emerged when the LMO stacks for different velocities were added together, to get a "full" refraction image. The final image became noisier when the LMO stacks were not windowed.

The final steps were then adding the refraction-windowed constant-velocity stacks, and converting time to depth. The conversion was based on the velocity profile that came out of the velocity analysis via constant-velocity-LMO stacks. No extra factor due to the angle of incidence has been taken into account (this is an unsolved issue and needs to be tackled), which makes the depth estimates approximate and therefore only indicative. The final refractor image is then as shown in Figure 3.

For comparison purposes, the processing sequence has also been applied to the data shot with regular shallow airgun arrays. That result can be seen in Figure 4. A surprising result is that although events were faint in common-receiver gathers (see Figure 1), they still stack up. When comparing the result with the section from the deep-towed airgun as given in Figure 3, it can be seen that the shallower part of the deep-tow data is of superior quality. The deeper parts seem of equal quality but are a bit different in character; the section from the regular airgun-array looks somewhat ringy again, while the deep-tow section does not. In that sense, the deep-tow section looks better.

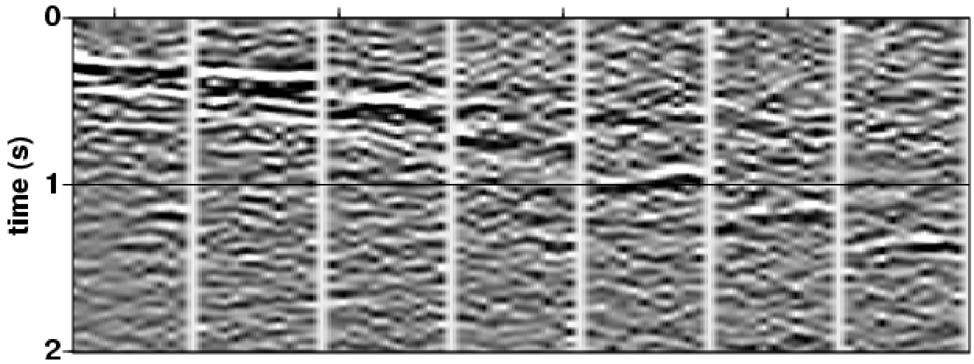


***Figure 2*** *Constant-Velocity panels from 10 adjacent CMP's, with LMO velocities from 400 to 700 m/s, with steps of 50 m/s.*

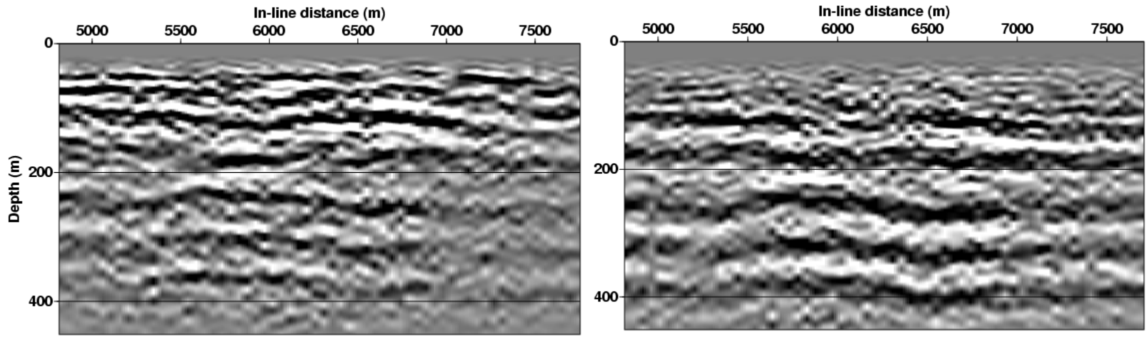


***Figure 3*** *Depth sections, based on LMO processing of refractions. Left: Deep-Tow data. Right: Regular shallow airgun-array data (LoFS15) data.*

## Conclusions

When an airgun is towed deeply near to the sea floor, P*S waves are generated. An experiment was carried out at the Valhall field to investigate whether these P*S waves were present, in what form and how they could be used for imaging. The source generates little energy in the frequency band of interest, but could by enhanced by proper filtering and muting. For these data, it is hard to find any P*S-wave *reflected* events in (pre-processed) records, possibly due to being drowned by the surface-wave cone. Also in the data up to and including CMP stacking, and comparison with the regularly shallow airgun-array data, no evidence has been found for pure P*S-wave *reflective* information. However, in the pre-processed records P*S-wave *refracted* events can be discerned. Also in the data up to and including CMP stacking, P*S wave *refractions* are evidently present in the LMO-corrected constant-velocity stacks. After cleaning up by processing, significant P*S wave refractors have been identified and imaged.

## Acknowledgements

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