Industry-first deployment of simultaneous source acquisition using a Dispersed Source Array (DSA) with Tuned Pulse Source (TPS) and conventional airgun for a shallow water seismic survey offshore Malaysia

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Abstract
We present a shallow water case study offshore Malaysia where a Tuned Pulse Source (TPS) and Conventional AirGuns (CAG) were deployed simultaneously, in a Dispersed Source Array (DSA) mode, to acquire seismic data with Ocean Bottom Node (OBN) and borehole distributed acoustic sensor (DAS) receivers. Both TPS and CAG were deployed from a single source vessel, using a single compressor package in a single pass. This industry-first novel deployment was also the first time the TPS source and MEMS-based OBN had been deployed in tandem to ensure optimum low-frequency signal from the emission stage to 4C fidelity sensor recording.

Introduction
The first successful seismic acquisition and imaging project (Meritt et al, 2024) conducted with the Sercel TPS, a low-frequency and environmentally friendly seismic source, in the Gulf of Mexico validated the value of its pre-survey analysis tools (source configuration and planning), and the efficiency and reliability of its deployment in a production environment (full azimuth to 40 km offset and 60 km offset inline direction). Six weeks after retrieval of the last OBN, an unprecedented sub-salt full-waveform inversion (FWI) image was delivered, revealing deep geological features which had previously been invisible. This case study took place in deep water, with OBN recording and using only the TPS as a source over an area already covered by legacy full-azimuth (FAZ) towed-streamer data acquired with a CAG source.

Why deploy the TPS in DSA mode with a CAG array?
Some of the most challenging E&P projects are conducted in complex geological settings, involving chalks, basalt, carbonate or salt bodies which are responsible for wavefield scattering above targets of interest. In such environments, the lack of low frequencies combined with limited acquisition offsets and azimuths are the main factors that can reduce penetration of the useful seismic signal. When current data-driven inversion algorithms, such as FWI, are applied in these complex environments they are subject to local minima also known as cycle skips, and dependent on subjective a priori information. Inverted velocity and reflectivity models do not therefore accurately depict the subsurface. Limited seismic signal penetration impacts project life cycles, prospect identification, and well placement.

Seismic surveys that combine broadband sources starting from a very low frequency (1 Hz) and covering at least 7 octaves recorded over wide-azimuth and long-offset geometries are required for a robust inversion process with minimum a priori information. To efficiently address the long-offset, wide-azimuth requirements, OBN acquisition is the solution, and, in this Malaysia case study, Sercel GPR300 MEMS-based OBNs were used. To generate the valuable low frequencies, for a faster and more robust FWI (Meritt et al., 2024), a TPS source was deployed in addition to a CAG array. The TPS added one and a half additional octaves compared to the CAG alone. By enhancing the signal-to-noise ratio (SNR) in the low-frequency part of the seismic spectrum, TPS enables clear identification of subsurface structures at longer offsets. It also leads to a higher peak-to-side lobe ratio of the seismic wavelet, which results in higher-resolution mitigating interference caused by wavelet sidelobes. Here, we present a survey acquired with an efficient operational solution to combine the benefits of a CAG array (5 to 100 Hz) with the lower-frequency information from the TPS source (below 5 Hz) in a single pass with a single source vessel.

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DSA principles

Historically, marine seismic acquisition has used large arrays of impulsive sources with different volumes ranging from a few tens to a few hundreds of cubic inches (cu.in). In most seismic surveys, all the sources in an array are shot at the same time in a synchronized mode or with subtle delays between the sources to enable bubble tuning. Another approach, known as Dispersed Source Array (DSA) (Berkhout, 2012) is to shoot sources with different characteristics at intervals of a few seconds. Each source type is called a voice and this survey corresponds to multi-voice acquisitions. There are various geophysical and operational benefits to operating the different sources as a DSA as opposed to deploying all sources simultaneously. The first advantage of the DSA approach is the use of more compact arrays which can be reduced to point sources as is the case for the TPS source. Point sources emit an azimuthally isotropic source wavelet free of array-induced effects such as multiple arrivals affecting near- and mid-offsets. More importantly, single sources reduce the risk of overdrive or amplitude saturation often observed on near-offset sensors, especially in shallow water environments. Another important advantage of the DSA, covered in this paper, is the better use of air consumption with different shot intervals. Low-frequency sources which use a lot of compressed air and require longer listening times for deep targets can be deployed more sparsely than high-frequency sources that use small amounts of compressed air and require shorter listening times for shallow targets.

The joint de-signature process involved in DSA has already been described in detail (Berkhout, 2012; Ronen et al, 2022; Allemand et al, 2023). De-signature can be performed either in the time or in the frequency domain as well as in the data or image space. In the data frequency domain, it can be described as follows,

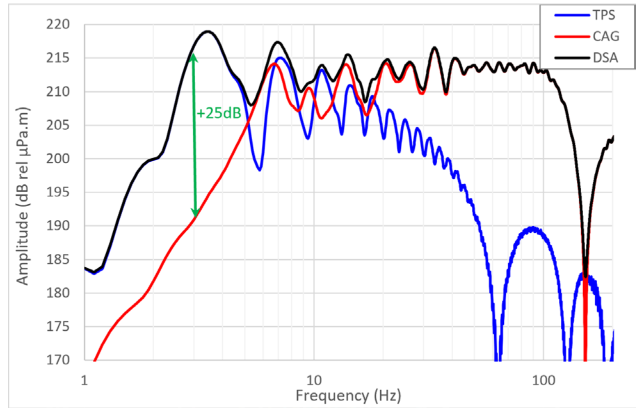

Figure 1 Spectrum of the pre-survey simulations (TPS spectrum, CAG array spectrum, combined DSA spectrum).

$$r(\omega) = \frac{d(\omega)\,\bar{s}(\omega)}{|s(\omega)|^2 + \epsilon} \tag{1a}$$

where r is the reflectivity, d is the data, s is the source signature (the upper bar ($^-$) stands for complex conjugate) and ϵ is the pre-whitening factor to prevent division by 0. ϵ is typically a constant value, or frequency dependent with $\epsilon(\omega) = \lambda|n(\omega)|^2$: $n(\omega)$: is

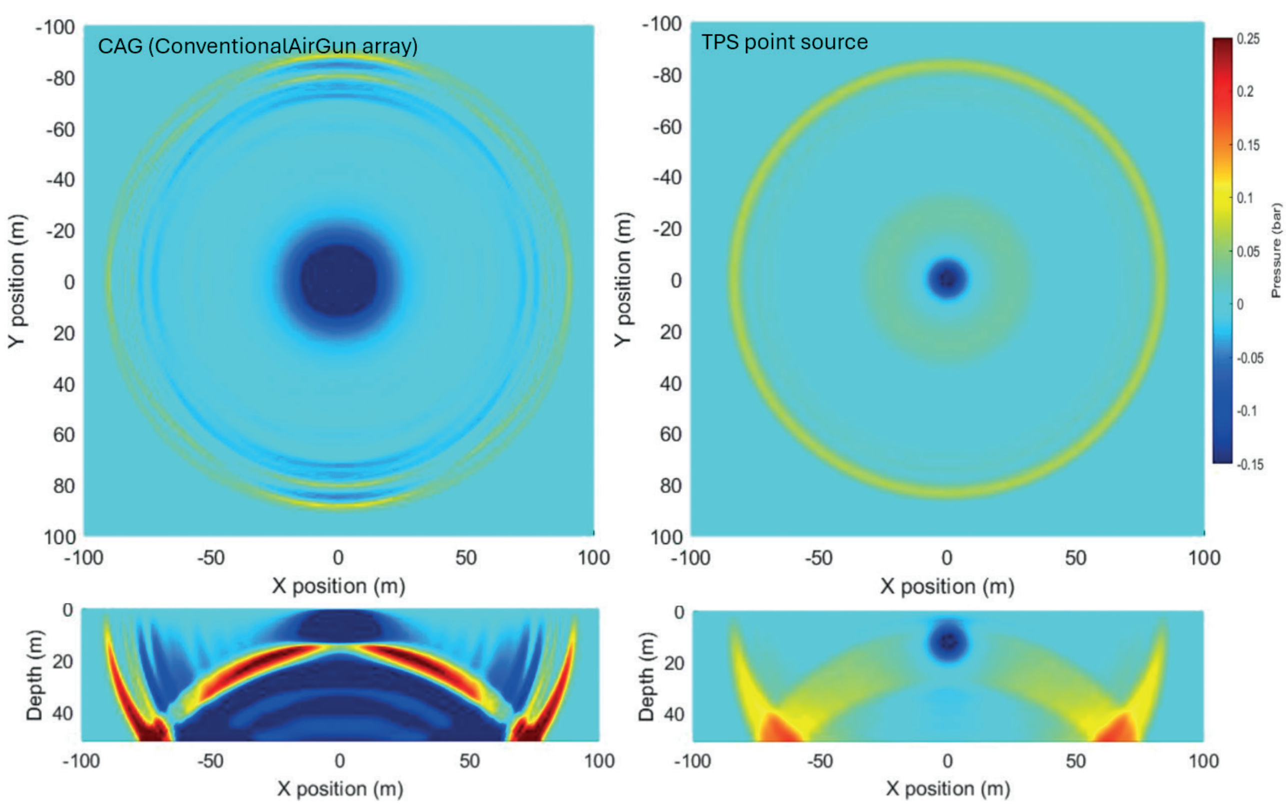

Figure 2 Pressure wavefield modelling. On the left, the CAG array with 14 airguns of different volumes, on the right, the TPS point source. We can see the time delay for the different pressure waves generated by the array, leading to a multi-arrival source wavefield with a strong azimuthal dependency. For the point source, the pressure map is simpler: single arrival, azimuthally invariant.

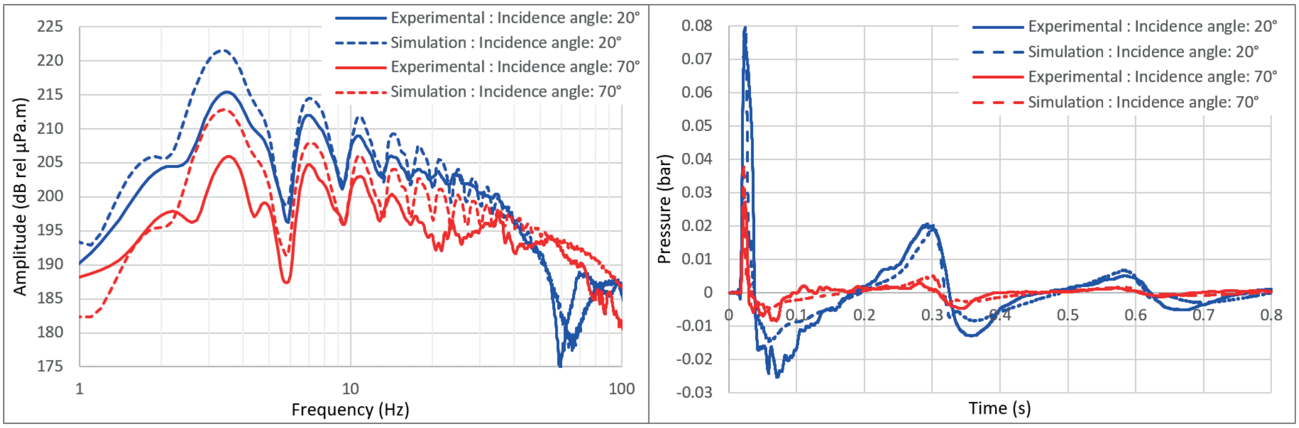

Figure 3 Signal from the TPS received by a node, plotted in the time domain, left-hand graph, and in the frequency domain, right-hand graph.

the average instrument and ambient noise and λ a constant factor. If we have two sources, then joint de-signature reads,

$$r(\omega)=\frac{d_1(\omega)\,\bar{s}_1(\omega)+d_2(\omega)\,\bar{s}_2(\omega)}{|s_1(\omega)|^2+|s_2(\omega)|^2+\epsilon} \qquad \text{1b)}$$

with two input data; d_1 and d_2, related to two source signatures s_1 and s_2.

From the above expression, we define the equivalent DSA source spectra as,

$$|DSA(\omega)|=(|s_1(\omega)|^2+|s_2(\omega)|^2)^{1/2} \qquad (1c)$$

The scheme can be extended to any number of sources.

TPS and CAG pre-survey source modelling

Our proprietary source modeling capabilities were used to model the 3D wavefield generated by a single TPS (28,000 cu.in, at 1000 psi) and the CAG array historically used in this area, see Figure 3.

From the simulation, the CAG array and TPS amplitude spectra are available to derive the DSA amplitude spectra (1c) as shown in Figure 2. The CAG array of ~3500 cu.in at 2000 psi emits a signal with a relatively flat spectrum between 6 Hz to 100 Hz. The TPS of 28,000 cu.in at 1000 psi provides a signal increase of 18 dB below 5 Hz. We can also note some peak and notch complementarity between the two sources within the 5-12 Hz bandwidth. DSA combines the best of TPS and CAG array sources with a robust handling of the point source notches. DSA is a flexible digital array offering an alternative to the conventional hard-wired CAG arrays. Pre-survey modelling is also useful to predict any signal saturation of the hydrophone and accelerometers. This is of particular interest in shallow water with OBN deployment close to the source. An accurate modelling can also be of use for QC or processing purposes such as the reconstruction of saturated samples and near-field hydrophone (NFH) modelling. One can see the good correlation between the simulation modelling and the real data recorded by the node for different angles of incidence (Figure 3). This highlights the ability of the simulations to model accurately the directivity effect for a point source.

How to configure a source vessel for DSA surveys?

1/ Hybrid survey operations

The main survey objective was to demonstrate that TPS and CAG sources can be deployed simultaneously from a single seismic vessel on a commercial survey (Figure 4*)*. CAG arrays and low-frequency TPS sources have complementary signatures, which means that their combination delivers the widest bandwidth possible.

However, both sources operate at a different pressure: 2000 psi for the CAG array and 1000 psi for the low-frequency TPS due to the mechanical limitations of the firing chamber. This poses a number of challenges to accommodate the requirements

Figure 4 TPS ready to be deployed from the source vessel back deck (full TPS installation video).

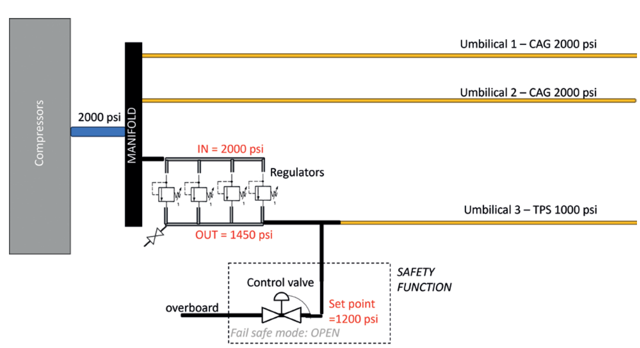

Figure 5 Schematic of the pressure regulation system installed on the seismic vessel to conduct an hybrid survey.

of both systems and allow safe operations using both seismic sources without the risk of overpressure.

The TPS solution was integrated within the existing vessel setup and a pressure regulation system was added to the vessel's high-pressure lines. The pressure regulation system ensures pressure inside the TPS remains below 1000 psi while conventional sources are fed at 2000 psi. The system has regulators to decrease air pressure and a control valve as a safety device to bleed the umbilical if needed (Figure 5).

This survey has successfully demonstrated that it is possible to deploy and operate CAG arrays in parallel with the low-frequency TPS to get the best out of both sources. The graph below (Figures 6a and 6b) illustrates the TPS firing pressure and the manifold pressure where we can observe the ability of the pressure regulation system to keep the TPS below its maximum operating pressure (1000 psi). During this survey, the firing pressure was set at 900 psi to safely absorb excess pressure related to slowdown in navigation speed which implies more charging time to reach the next predefined firing position. This would not be needed in the case of a firing strategy on pressure.

2/ Simulation and model

In addition to this operational deployment of a hybrid source from a single vessel, Sercel has developed the tools and expertise to accurately simulate the airflow rate from the compressors to the source (Figure 7). This knowledge has been used to build a model that can predict minimum refilling time for hybrid surveys (Table 1). Our tool is key to designing the shot grid with complex

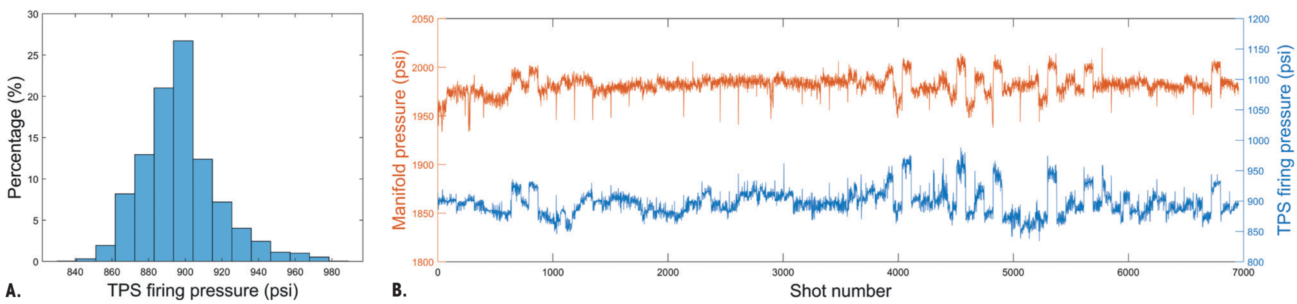

Figure 6 A. TPS firing pressure distribution (+ 99% within a firing window of +/- 50 psi). **B.** Manifold and TPS firing pressure graphs during the hybrid survey.

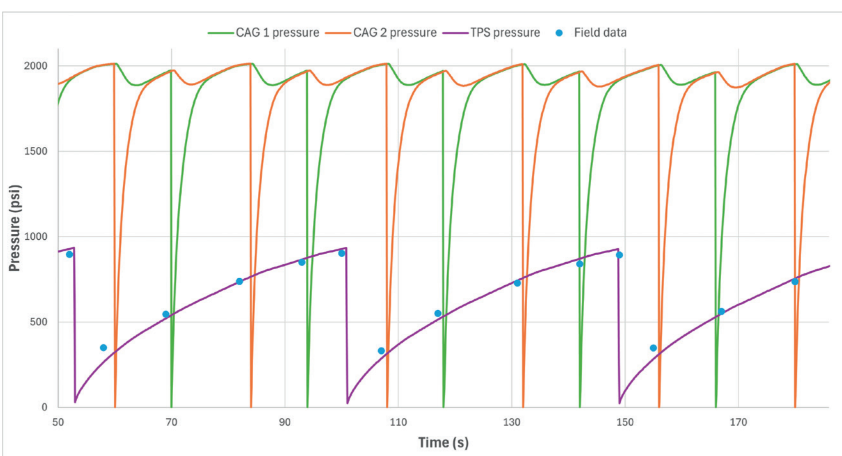

Figure 7 Comparison between field data and simulation model prediction (source: TPS 28 000 cu.in + CAG 2 x 3460 cu.in. Note the good match between modelled TPS refilling purple curves and TPS chamber pressure data (blue dots).

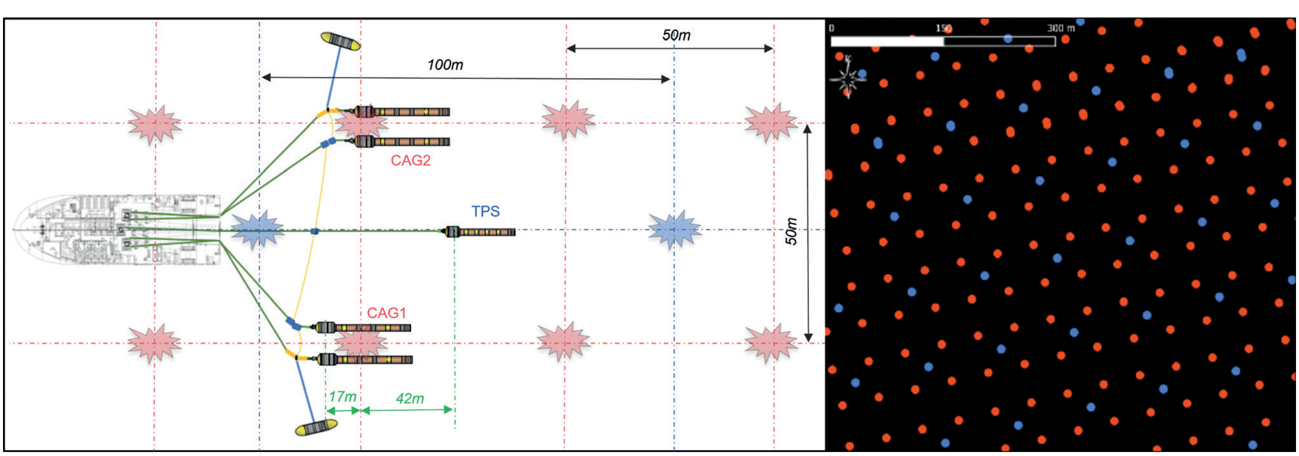

Figure 8 DSA shot carpet illustration for the hybrid survey (TPS 100 m x 100 m in blue, CAG 50 m x 50 m in red).

source setups such as hybrid configurations. Figure 7 compares field data with a simulation for a triple source design consisting of one TPS 28 000 cu.in source and two CAG arrays of 3460 cu.in.

From a more general perspective, our prediction model can be used to build a table for a range of configurations, with umbilicals from 100 m to 400 m and a diameter of 1” and 1”1/4.

The table below shows refilling times and related SPIs (Shot Point Intervals) for source vessel speeds of 3 knots and 4 knots for various umbilical configurations. The source used to build this table is a triple source with:

- TPS 28,000 cu.in (@ 1000 psi)
- 2 x CAG 3460 cu.in (@ 2000 psi) firing every 12 s

Umbilical length / Umbilical diameter	100 m	200 m	300 m	400 m
1-1/4”	**30 s**	**44 s**	**59 s**	**74 s**
SPI @ 3 knots	46 m	68 m	91 m	114 m
SPI @ 4 knots	62 m	90 m	121 m	152 m
1”	**32 s**	**44 s**	**62 s**	**79 s**
SPI @ 3 knots	49 m	68 m	96 m	121 m
SPI @ 4 knots	66 m	90 m	123 m	162 m

Table 1 TPS refilling times and shot point interval simulation for a hybrid survey with triple source.

The impact of a bigger conventional source is quite marginal and would be + 1 s per additional 1000 cu.in. Note: 1 knot = 0.514444 m/s or 1.852 km/h

Field data recorded by ocean bottom nodes

From the above analysis and taking into account imaging sampling requirements (denser for mid to high octaves, sparser for low octaves), a DSA shot carpet was designed and acquired with a 100 x 100 m TPS grid and a 50 x 50 m CAG grid (see Figure 8). To address the need for the long-offset and full-azimuth acquisition, GPR300 OBN nodes were deployed on the seafloor at a depth of 50 m. The 3C MEMS (micro-electromechanical systems) were selected for their 3C sensing fidelity, especially in low frequencies. Figures 9 and 11 nicely illustrate how effective the TPS source is at generating the low-frequency seismic Earth response: the hydrophone data, in a common receiver gather (CRG), for two source lines, chunked according to TPS firing times over an extended time window [- 25 s,+20 s]; low-velocity sea bottom surface waves clearly stand out (high SNR) with the TPS source compared to the CAG source.

The additional robust subsurface information brought by the TPS source can also be illustrated on the first break (FB) data. Figure 10 displays low-frequency (1.5 Hz and 5 Hz) phase rings (for each source position (x_s,y_s) the phase at a given frequency

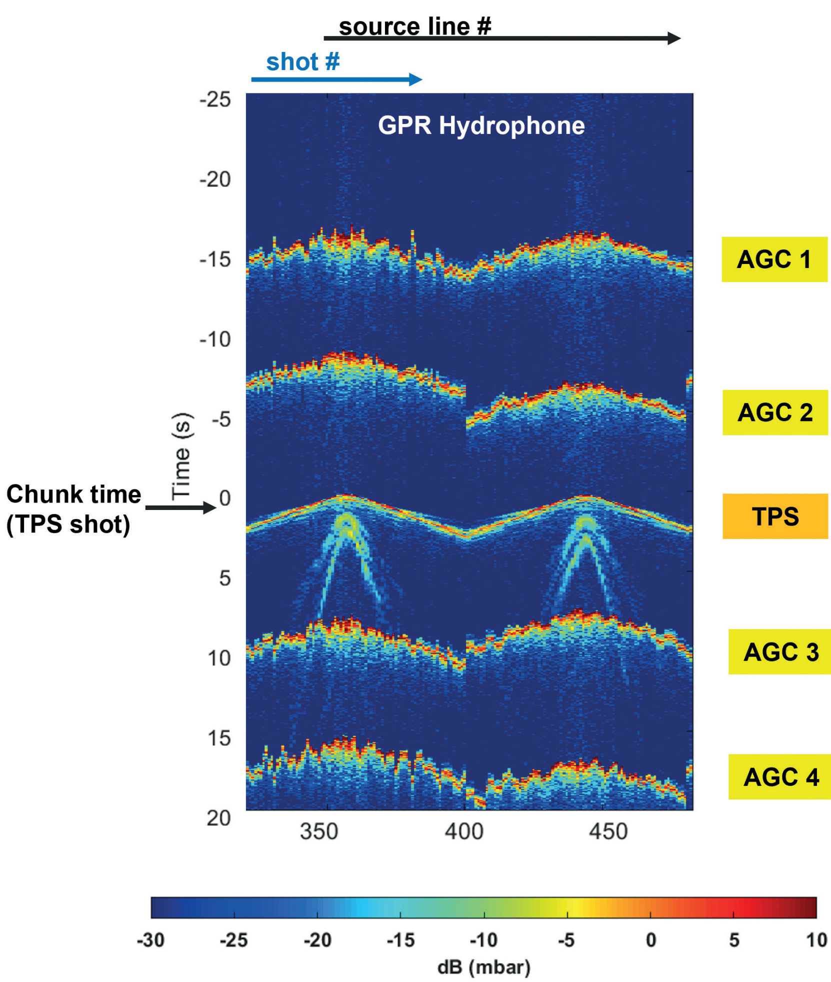

Figure 9 Hydrophone continuous record aligned on TPS firing time [-25 s:20 s] for one node and two source lines. The data are chunked with the TPS shot times. Hence, the TPS appears continuous while the four CAG shots are not continuous due to variations in vessel velocity. Note the stronger Scholte waves that are induced by the longer wavelength of the TPS compared to the depth of the seabed.

is displayed). The phase continuity around the rings is related to the SNR of the information. Continuity indicates that the signal is dominant. Discontinuity indicates that the noise is dominant. As expected, the FB phase rings show a significantly higher SNR with the TPS source compared to the CAG array. The final purpose of the DSA approach is to combine the best of the TPS and CAG sources to emulate a rich multi-octave source starting from very low up to very high frequencies. Figure 11 displays the TX CRG for one source line, Figure 12 displays the FX amplitude spectra for the TPS, the CAG source and the combination (TPS+CAG).

Conclusions and way forward

This case study validates the possibility of efficiently operating the TPS source with a CAG array source simultaneously using a single source boat with existing compressor capacity in DSA mode. This combination efficiently produces an effective broadband seismic source starting from low frequencies over several octaves (+25 dB at 3 Hz compared to the CAG array alone). In the pre-survey analysis phase, simulation tools were essential for the design of the activation sequence for each source to safely optimise productivity. The post-survey analysis confirmed the accuracy of Sercel modelling solutions.

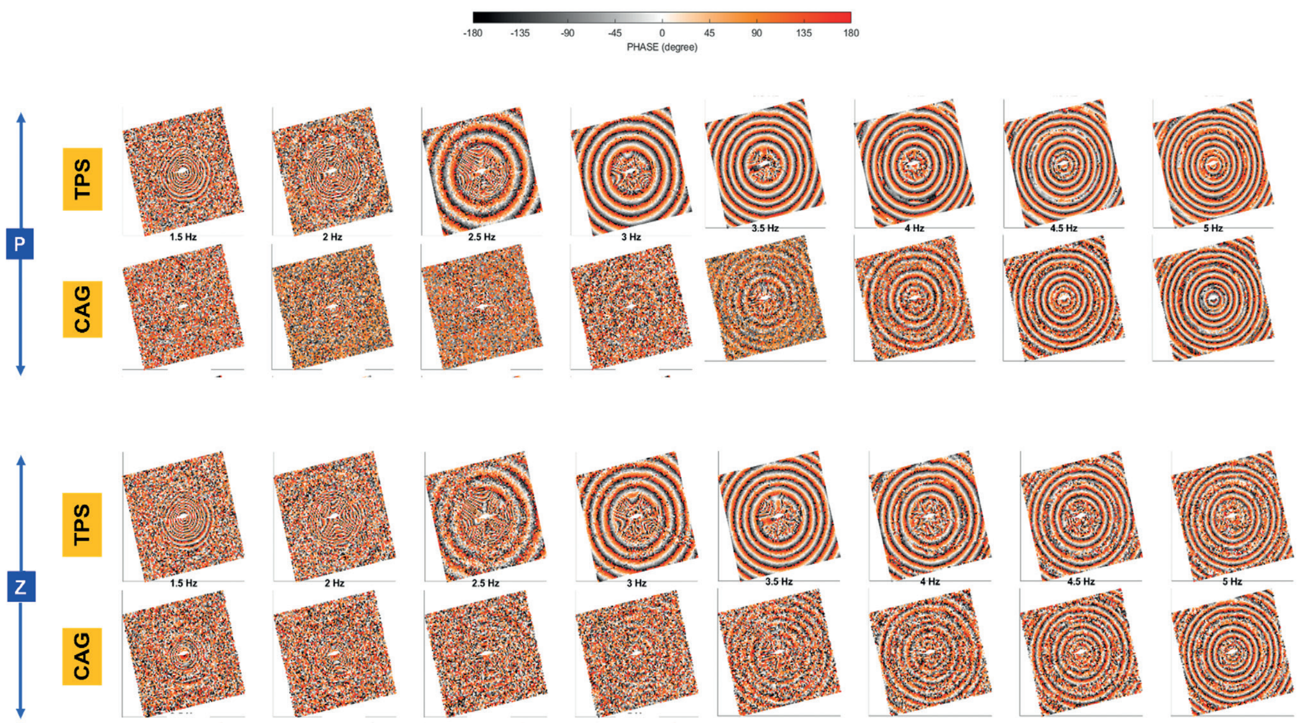

Figure 10 For a single node, hydrophone (P) and vertical acceleration (Z) phase rings at 1.5 Hz to 5 Hz for TPS and CAG over a 7 x 7 km source carpet. Inner small spatial wavelengths correspond to the slow-velocity surface waves, outer longer spatial wavelengths correspond to high-velocity first breaks.

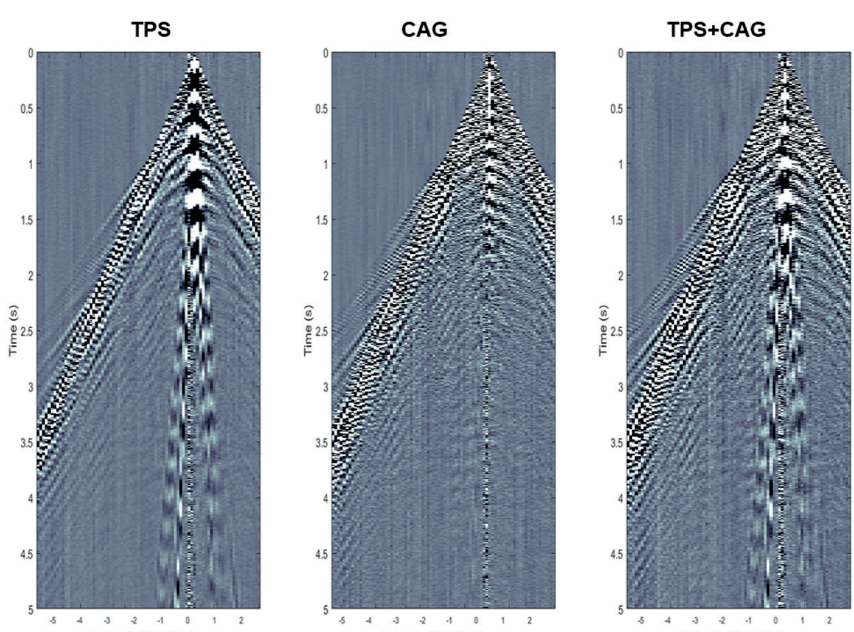

Figure 11 Common receiver gather in the TX (time, offset) domain for one source line: TPS point source (left), CAG array (center), and TPS +CAG (right). Note the lower-frequency content of the TPS and stronger Scholte waves that are induced by the longer wavelength of the TPS compared to the depth of the seabed. The Scholte waves are aliased with 100 m shot intervals.

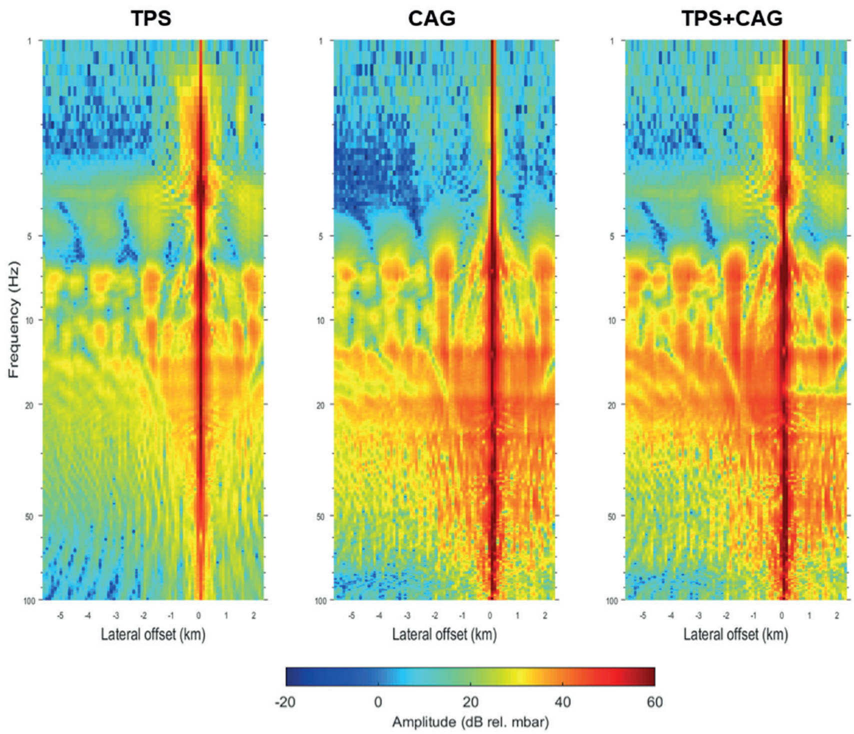

Figure 12 Common receiver gather in the FX (frequency, offset) domain for one source line: TPS point source (left), CAG array (center), and TPS+CAG spectrum (right). The variation in signal level as a function of frequency relate to the respective TPS, CAG and DSA source spectra, while the offset variations relate to the offset-dependent reflectivity. Note that below 5 Hz the TPS source is driving the signal. The DSA brings together the best of the two sources.

The next step could involve the deployment of multiple source boats, with simultaneous firing on irregular grids and with some level of source encoding.

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