Triple-source seismic acquisition operations with a Tuned Pulse Source (TPS)

Julien Large[1]*, Shuki Ronen[1], Paul Wentzler[1], Maxime Benaniba[1] and Jeremy Aznar[1] describe an optimised survey design that encourages the industry to acquire data using a triple-source configuration with the TPS.

Introduction

Some of the most challenging E&P projects are conducted in complex geological settings, including chalk, basalt, carbonate or salt formations. These structures often cause wavefield scattering above target zones. In such environments, the absence of low-frequency content, combined with limited acquisition offsets and azimuths, severely impedes the penetration of the useful seismic signal. When modern data-driven inversion techniques, such as Full-Waveform Inversion (FWI), are applied in these complex settings, they are prone to convergence issues — most notably local minima, commonly referred to as cycle-skipping. This makes them heavily reliant on subjective prior information, resulting in inverted velocity and reflectivity models that often fail to accurately depict the subsurface. Moreover, it takes more time to process the data. Limited seismic signal penetration has significant impacts on project life cycles, from prospect identification to well placement. To overcome these challenges, seismic surveys must utilise broadband sources that generate very low frequencies (as low as 1 Hz), spanning at least seven octaves recorded over wide-azimuth and long-offset geometries. Such broadband data enable a robust inversion process with minimal dependence on prior information. A low-frequency source is a critical component of this solution to efficiently address the demands of long-offset, wide-azimuth acquisitions.

The first large-scale 3D long-offset, low-frequency (LOLF) seismic acquisition and imaging survey using the Sercel Tuned Pulse Source (TPS™) was conducted in the deep-water US Gulf. This survey (Meritt, 2024) demonstrated the value of the low-frequency signal emitted by the TPS, which proved essential for subsalt imaging. It also enabled the construction of a high-resolution blocky post-salt Earth model. Owing to the efficiency and reliability of deploying the TPS in a production environment, the survey achieved full-azimuth coverage with offsets of up to 80 km. The project was completed on schedule in just four months. By avoiding cycle skipping when performing Full-Waveform Inversion (FWI), data processing took only six weeks after last node recovery, to deliver a fast-track imaging product that unveiled subsalt images with detail never seen before with legacy data acquired with airguns and full-azimuth streamers.

A few weeks after retrieving the last TPS in the US Gulf, Sercel conducted additional low-frequency seismic surveys offshore Malaysia. These operations demonstrated the synergy of the TPS with airguns in Distributed Source Array (DSA) mode (Allemand, 2023) and revealed previously unseen deep geological features (Kaur, 2024).

This article describes an optimised survey design that encourages the industry to acquire data using a triple-source configuration with the TPS. This makes it possible to cover a wider survey area, decrease acquisition time and acquire higher-quality data. The TPS is a low-frequency source and has a large volume of 28000 cu.in.. When deployed in a triple-source configuration, it can provide a total volume of 84,000 cu.in. This significant volume could be challenging to fill for a seismic vessel designed for a triple conventional airgun (CAG) source of 3 x 5000 cu.in., totalling 15000 cu.in..

How to configure a source vessel for a TPS survey with high-density shot patterns?

The main objective is to demonstrate that the TPS can be deployed and triggered from a single seismic vessel in a cost-effective manner, for either hybrid TPS-CAG or pure TPS survey operations. CAG arrays and low-frequency TPS sources have complementary signatures, enabling delivery of the broadest possible bandwidth. Alternatively, a pure triple TPS source can be deployed to increase the shot density and improve the Signal-to-Noise Ratio (SNR). In such cases, the higher mid-frequency coverage provided by the CAG may become unnecessary. However, the operating pressures of these sources differ significantly — 2000 psi for the CAG arrays and 1000 psi for the TPS — which presents challenges in safely accommodating both systems without risking overpressure. To address this, an innovative Pressure Regulation System (PRS) integrated within the vessel's existing setup was developed (Benaniba, 2024). This PRS ensures that pressure inside the TPS remains below 1000 psi, while conventional sources are fed at 2000 psi. The onboard PRS includes regulators to decrease air pressure and a control valve as a safety device to bleed the umbilical, if needed. The hybrid survey presented by Benaniba successfully demonstrated the feasibility of deploying and operating CAG arrays in parallel with the low-frequency TPS, maximising the benefits of both sources. However, the onboard PRS revealed some limitations in

[1] Sercel, a Viridien Business
* Corresponding author, E-mail: julien.large@sercel.com
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refill time and pressure stability. To overcome these challenges, Sercel leveraged its engineering and operational expertise to accurately model airflow rates from the compressors to the source. This insight was used to develop a refined solution that minimises refilling time and stabilises TPS chamber pressure at 1000 psi. The solution was to move the PRS from onboard, between the compressor outlet and the umbilical inlet, to the water, between the umbilical outlet and the TPS inlet. From a more general perspective, both solutions can be used to build multiple configurations, combining TPS with any other type of marine seismic source to achieve the geophysical imaging objectives. This article presents several simulations showing the minimum compressor capacity a vessel must have to achieve a triple-source TPS survey with a dense shot carpet (Figure 1). The results demonstrate that most available source vessels would be able to meet these specifications.

A TPS triple-source configuration can be described with the following metrics: for a volume of 28000 cu.in (= 0.459 m³) and an operating pressure of 1000 psi (= 69 bar), the required Free Air Delivery (FAD) is calculated as $0.459\ m^3 \times \frac{69\ bar}{1\ bar} = 31.67\ Nm^3$. A typical vessel may have three compressors with a FAD of $62\ \frac{m^3}{min}$ which is 2200 CFM (cubic feet per minute) each.

The feasibility of a shot point interval (SPI) of 25 m is considered. This implies running the three TPS units sequentially so that each unit fires every 75 m. With a vessel speed of 4 knots (i.e. 2.06 m/s), available refill time in between two shots will be $T_{refilling} = \frac{75}{2.06} = 36$ s. The compressor will deliver in the meantime a FAD of $62 \times \frac{36}{60} = 37.2\ m^3$. This means that if a single compressor is operated at $\frac{31.67}{37.2} = 85\%$ of its capacity will be able to supply one TPS unit at the targeted 36-second refilling period. If these results are extended to the complete source, it can be concluded that three compressors at an 85% load are able to feed a triple TPS source with a 25 m SPI. This simple calculation is also supported by our multi-physics modelling tool that we use to design surveys. This modelling includes both vessel pressure losses and air remaining in the chamber after a shot.

Another challenge that needs to be assessed is whether our refilling period $T_{refilling}$ is achievable with umbilical flow restriction and friction losses. Let us assume a typical 500 m – 1” umbilical for this purpose to check if our target of 36 seconds is achievable. To perform this calculation and estimate the minimum refilling time achievable, we use in-house calibrated multi-physics modelling tools. A quick look at the specification (Figure 2, top), confirms that a 36-second refilling period at 1000 psi is not achievable with a 1” standard umbilical – a 1.25” umbilical is therefore required instead (Aznar 2022).

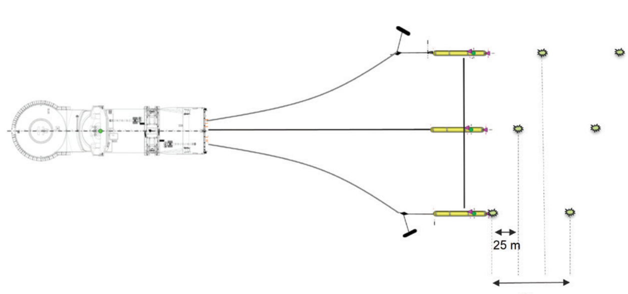

Figure 1 Example of a TPS triple-source configuration.

Inlet pressure = 1000 psi (69 bar)		Umbilical length (m)					
		200	400	500	600	800	1000
Umbilical diameter (inch)	1	35 s	51 s	59 s	66 s	75 s	84 s
	1,25	23 s	31 s	36 s	40 s	48 s	55 s

Inlet pressure = 2000 psi (138 bar)		Umbilical length (m)					
		200	400	500	600	800	1000
Umbilical diameter (inch)	1	11 s	15 s	17 s	18 s	21 s	23 s
	1,25	8 s	9 s	10 s	11 s	13 s	14 s

Figure 2 Minimum refilling time achievable with respect to umbilical specifications (length and diameter).

To overcome the limitations associated with the use of non-standard umbilicals (i.e of 1.25” diameter), the minimum refilling time allowed by the air supply chain needs to be decreased. This is the purpose of our in-sea PRS (Figure 3), which allows a supply pressure that is higher than the operating pressure of the source. By comparing the 1000 psi and 2000 psi tables in Figure 2, it is possible to assess the expected improvements with increased supply pressure.

Higher inlet pressure has a significant impact on refilling capability. The minimum refilling time achievable with a 500 m – 1” umbilical would be around 17 seconds using our PRS solution with a 2000 psi inlet pressure, well below our targeted 36 s.

The Sercel in-sea PRS allows the TPS to be fed up to 2000 psi while the shooting pressure remains at 1000 psi.

Finally, the analysis and modelling confirmed the capability of standard compressors to supply a triple TPS source for an SPI as low as 25 m, with either a specific 1.25” umbilical, or a standard 1” umbilical combined with an in-sea PRS. This confirms that the TPS can be configured as a triple source on most seismic source vessels using their standard source ancillary equipment in combination with our in-sea PRS.

To reach compressor consumption, is it better to reduce the pressure or the volume?

To go further in our investigations of survey configurations in very challenging conditions where compressor capacity is limited, we studied the impact on TPS acoustic signature if there has to be a compromise on the firing pressure or the source volume.

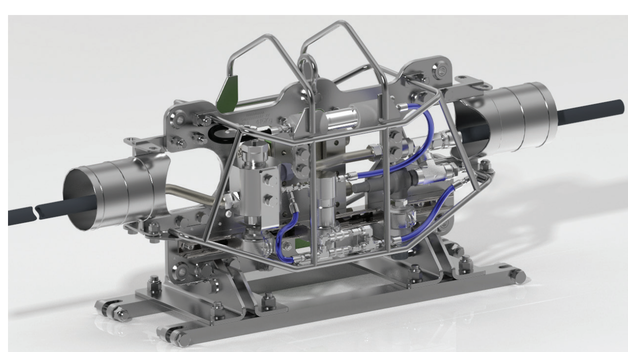

Figure 3 The pressure regulator system (PRS).

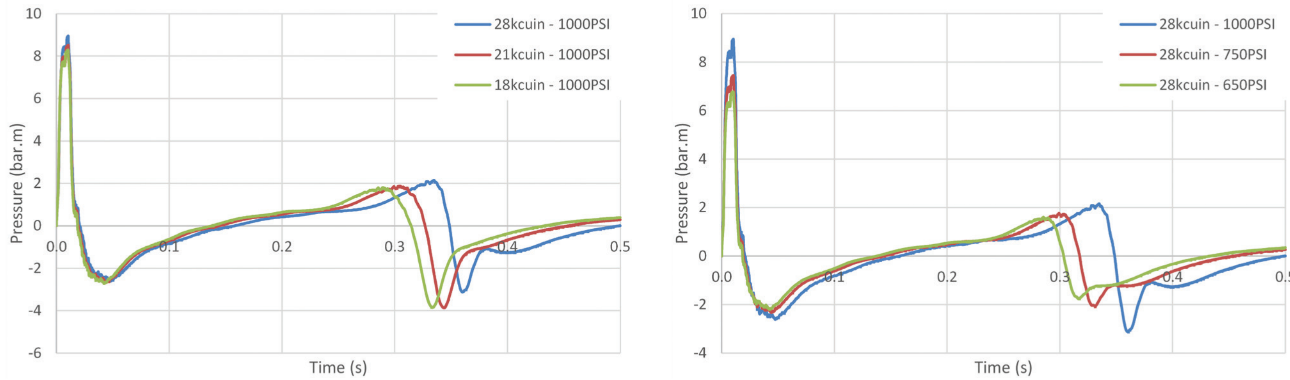

Figure 4a TPS signatures in time domains for several configurations. The reference (blue curve) is a 28 kcuin TPS operated at 1000 psi, with a 8 m depth. It is compared with (top): 21 kcuin (red) and 18.5 kcuin TPS (green), both operated at 1000 psi, and (bottom) with a 28 kcuin TPS, operated at 750 psi (red) and 650 psi (green).

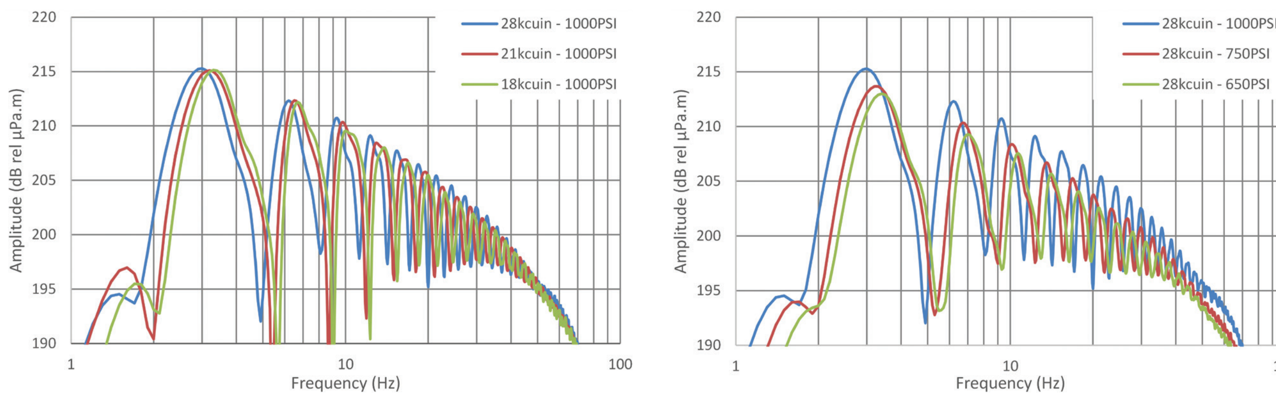

Figure 4b TPS signatures in spectral domains for several configurations. The reference (blue curve) is a 28 kcuin TPS operated at 1000 psi, with a 8m depth (top). It is compared with (top): 21 kcuin (red) and 18.5 kcuin TPS (green), and (bottom) with 28kcuin TPS, operated at 750 psi (red) and 650psi (green).

The period of the bubble and its peak pressure are defined by the two following formulae:

$$T = K.V^{\frac{1}{3}}p^{\frac{1}{3}}(1+\frac{h}{10})^{-5/6},$$
$$P_{Peak} = K.V^{\frac{1}{5}}p^{\frac{2}{3}}$$

The Willis formula of the period (T) implies that the pressure (p) and the volume (V) are both to the exponent 1/3. A 35% reduction in the volume is therefore equivalent to a 35% reduction in the pressure. This effect of equivalence can be observed on variations in the first harmonic (Figure 4b). For the peak pressure, the volume is usually exponent 1/5 and the pressure exponent 2/3. So, the peak pressure is more sensitive to pressure variations than to volume variations (Figure 4a).

At low frequencies, the combined effects of frequency and amplitude shifts can be represented by the amplitude at 2.5 Hz.

Notably, for the same compressor power consumption, the amplitude at 2.5 Hz is higher in the reduced-volume configuration compared to the reduced-pressure configuration. Specifically, at 2.5 Hz, the configuration with a reduced volume (18 kcuin @ 1000 psi) results in a peak amplitude of 206 dB, whereas the configuration with a reduced pressure (28 kcuin @ 650 psi) produces 204 dB. This indicates a 2 dB increase when the volume is reduced while maintaining higher pressure.

Field trial results: refilling a triple TPS source

A triple TPS source configuration was successfully tested at sea with Viridien and TGS at the end of the Laconia Phase III survey. Each TPS was fitted with a PRS regulator and deployed with a 133 m lateral source separation. Separation was limited by the vanes available onboard. The vessel was equipped with three compressors SAPS 62 $\frac{m^3}{min}$ delivering (2200 CFM) each.

All three compressors operated at a maximum output of 186.8 m³/min with 1.25'' air line umbilicals of 402 m, 650 m and 500 m. The test included two parts: Part 1 in flip-flap-flop mode

	Volume (kcuin)		
	28	21	18
Pressure (PSI)	**Frequency of the first harmonic (Hz)**		
1000	3,0	3,2	3,3
750	3,2	3,5	3,6
650	3,4	3,6	3,8
Pressure (PSI)	**Peak pressure (bar.m)**		
1000	8,9	8,5	8,3
750	7,5	7,1	6,9
650	6,8	6,5	6,3
Pressure (PSI)	**Amplitude @2.5Hz (dB rel µPa.m)**		
1000	213	209	206
750	207	200	195
650	204	195	194

Figure 5 TPS first harmonic, peak pressure and amplitude at 2.5 Hz comparison.

without dither, and Part 2 in Flip-Flip (synchronised +/-2 s dither) shooting mode.

The main goal of Part 1 was to determine the minimum shooting time needed for a full and sustainable refill of the TPS sources. Equipped with the PRS and 1.25" umbilical airline, the capacity of the compressors became the limiting factor. The compressors could deliver an airflow rate of 3.1 m³/s, resulting in 27.9 m³ of air in 9 seconds. Combined with roughly 3.1 m³ of air remaining in the chamber after each shot, this resulted in a complete refill of 31.1 m³ of air (28000 in³ at 1000 psi). Shooting faster than 9 seconds prevented the manifold pressure from being stabilised, meaning that compressors cannot provide enough air to the source (see Figure 7). Additionally, at 9 seconds, no air was venting from the manifold Fisher valve, indicating that the source was using 100% of the delivered air without back pressure from the air lines. The absence of air vented also confirms the 9-second limit is driven by compressor capacity and no longer by umbilical specifications. It was possible to overcome this umbilical limitation with our PRS which pushes back the umbilical limitation far more after the compressor limitation.

This field test was also an opportunity to confirm the validity of our refilling simulation tool as the 9 seconds achieved are in

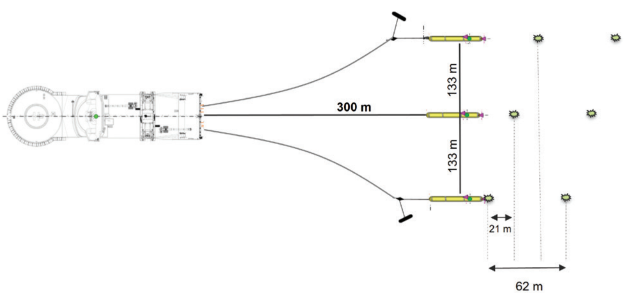

Figure 6a Source layout and shot carpet for flip-flap-flop mode (Laconia test Part 1).

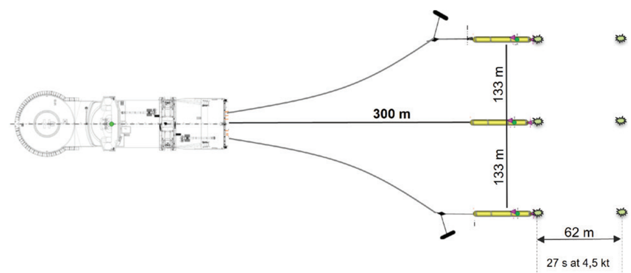

Figure 6b Source layout and shot carpet for synchronised shooting with +/- 2 seconds dither (Laconia test Part 2).

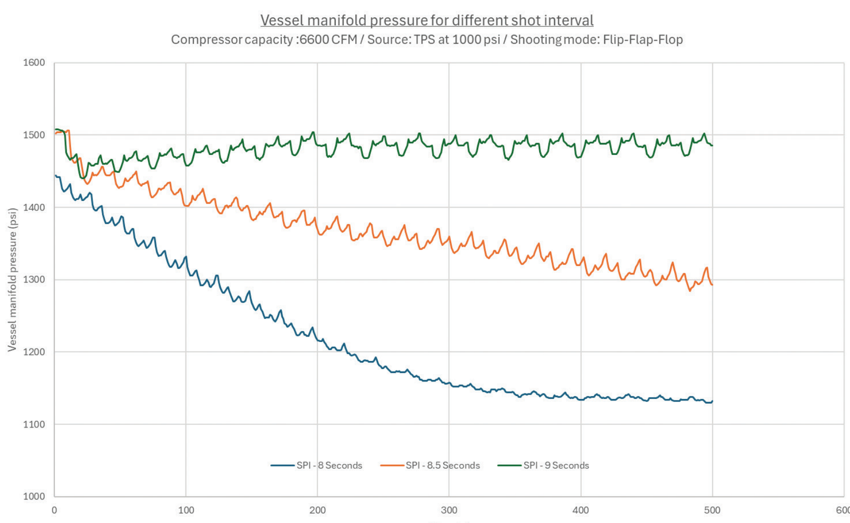

Figure 7 Manifold pressure for a 8, 8.5 and 9 second SPI.

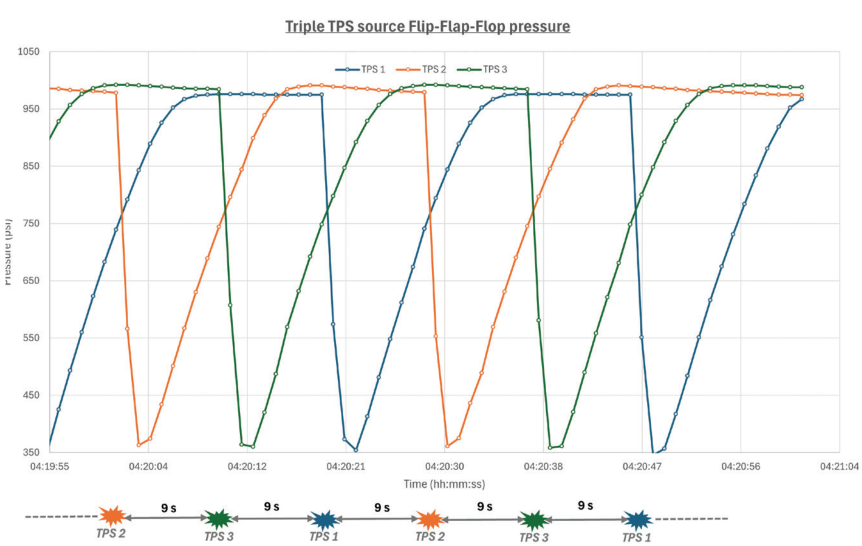

Figure 8 TPS chamber pressure during triple-source acquisition showing a shot every 9 seconds (3 x SAPS 62 compressors at full load).

line with the 10 seconds computed by our simulation tool (see Figure 8).

The vessel was travelling at 4.5 knots (i.e 2.31 m/s), resulting in an SPI of approximately 20.9 m. This precisely matched Part 2, the flip-flip test, which had an SPI of 27 seconds and 62.7 m.

Finally, this field test demonstrates that a triple TPS source enables an efficient survey with a 28000 cu.in shot every 25 m. The refill time of approximately 11 seconds pushes compressor load to 85%, resulting in a SPI of 25 m at 4.6 knots which is within normal operating ranges. When equipped with larger vanes, a 200 m source separation could significantly increase the distance between sail lines and hence lower survey costs by reducing the number of lines required to image an area.

Conclusion

This article presents a case study that validates the feasibility of efficiently operating the TPS in a triple source configuration using a single-source vessel with the current compressor capacity, while maintaining high productivity levels. This configuration effectively produces a robust broadband seismic source. During the pre-survey analysis and design phase, simulation tools played a critical role in designing the activation sequence for each source to safely and efficiently optimise productivity. The in-water Pressure Regulator System (PRS) now enables deployment of a triple TPS configuration on a source vessel with a 25 m shot point interval. All the above calculations can be adjusted for the purpose of a seismic survey and must be assessed by a full survey design analysis to comprehensively evaluate the performance of low-frequency source technology and its potential for further surveys.

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