A new wave in marine seismic source technology

Nicolas Tellier[1*], Julien Large[1], Shuki Ronen[1] and Jeremy Aznar[1] present two innovate marine sources intended to address current industry key expectations in terms of seismic signal generation.

Summary

While innovation in marine equipment has mainly concerned receiver technologies over the last few decades, a new focus within marine sources is drawing ever-increasing expectations in the industry to meet two key evolutions in offshore seismic acquisition. Reduced seismic signal energy in the audible bandwidth of marine mammals is becoming a must-have, either as a reflection of marine players' environmental awareness or as a way to meet ever-demanding regulations. On the other hand, low frequencies have become paramount – if not a standard – to achieve superior seismic imaging and reservoir characterization, all the more when deep targets or complex geologies are at stake. After several years of development, optimization and field validation, two innovative marine sources intended to address these new requirements are herein introduced. The Bluepulse, available either as a complete source or as a straightforward upgrade of existing inventories, scales down the high-frequency output of conventional pneumatic sources. In a more disruptive approach, the Tuned Pulse Source (TPS) yields unprecedented performance in low-frequency signal generation.

Introduction

The last 60 years have seen significant developments in receiver technologies for marine purposes, with a focus on bandwidth extension and preservation of the fidelity of the seismic data acquired. Decades ago, 24-bit recording and solid streamers were introduced. Solid streamers are quieter and provide higher signal-to-noise ratio enabling hydrophones with less aggressive RC analog-low-cut filters – less than 2 Hz instead of more than 7 Hz. Multi-sensor and slant streamers were introduced a decade ago (Tenghamn 2009, Mellier 2014) and enabled deployment of receivers further from the noisy surface of the ocean. Acquiring seismic data in quieter environments has been made further possible with ocean bottom cables and nodes that enable – albeit with higher operating costs – freedom from azimuthal and offset constraints. On the sensor side, 3C MEMS sensors for OBN guaranteeing true phase, amplitude, verticality and vector fidelity (Tellier 2020) extend the capability to record high–fidelity low frequencies. However, advances in marine sources have remained more limited in the meantime, with air guns, incrementally improved since their invention (Chelminski 1966), still being the standard.

As oil and gas become more difficult to find and produce, the need for low frequency signal increases. Lower frequency signal, acquired by broader band sensors, deeper streamers and OBNs have been a game changer in exploration and production. A good summary of the geophysical motivation of low-frequency signal is given by ten Kroode et al (2013). Low-frequency signal enables imaging under complex overburden such as basalt (Ziolkowski et al, 2003) and salt. To build blocky reservoir models, the impedance is integrated from the reflectivity. Blocky impedance causes spikey reflectivity. Without low-frequency signal, the spikes in the data have deep side lobes. If a spike is not a spike then a block is not a block. To fill in the low-frequency signal that is missing, well-log data is often used, but information from well-logs is unreliable far from the wells. Velocity models, built from the travel times rather than the reflectivity amplitudes, are used to provide low-frequency information. In recent decades significant development in data processing has been enabled by waveform inversion (FWI) methods (Tarantola, 1984). FWI methods build an earth model that best matches the data. They minimize the mismatch. A practical challenge in FWI is local minima, also known as cycle skips. Cycle skips happen when a side lobe of one reflection matches the main lobe of another reflection. Advanced FWI methods address the issue, but a full solution must rely on acquiring the low-frequency signal. With or without FWI, we also need low frequency to improve resolution. It may be surprising that to improve resolution we need not only high frequency signal, but also low frequency signal. Without low-frequency content, deep side lobes compromise resolution owing to interference from reflections at the top and bottom of a thin layer.

Another game-changer in marine acquisition technology arises from ever-increasing environmental awareness, and the associated concern with regard to the possible impact of offshore seismic acquisition on marine life (Southall, 2007 and 2019). Since the traditional mitigation approach – direct marine mammal observation – can now be smartly complemented or replaced by automated Passive Acoustic Monitoring (PAM) detectors (L'Her 2017), the environmental performance of marine sources has become a key industry focus. In this regard, miscellaneous approaches are being considered:

- The design of pneumatic sources can be modified so as to reduce their high-frequency energy output, while not compromising their efficiency at lower frequencies (e.g., Coste, 2014). The size of pneumatic source arrays can also be scaled down (e.g. Laws 2008, from a signal-to-noise ratio

[1] Sercel

[*] Corresponding author, E-mail: nicolas.tellier@sercel.com

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perspective), possibly down to a single pneumatic source (e.g., Hegna 2018).
- The overall design of pneumatic sources can be thoroughly reviewed. This is the case with the Tuned Pulse Source (TPS, Ronen 2017): through an alternative balance of pneumatic source operating pressure and volume, the signal bandwidth is considerably extended towards the low frequencies, while the high-frequency energy is significantly reduced.
- Finally, the release of marine vibrators (e.g., Pramik 2015, Jenkerson 2018) at a commercial scale is expected by many to address environmentally sensitive areas. This is only once continuing efforts to improve their reliability, limit their maintenance requirements and ease the logistics and deployment associated with such cumbersome sources are completed.

Note that the reduction of marine source high-frequency output for environmental purposes does not contradict the industry expectation to record 'broadband' data, as most of this unexpected high-frequency signal is actually outside of the seismic bandwidth of interest for most analysis purposes. As the quality of a dataset is considered proportional to the number of exploitable octaves it contains, the remaining, useful high frequencies can be easily compensated by a limited bandwidth extension toward the low frequencies.

Two innovative and environmentally friendly pneumatic sources, now tested and available for acquisition, are herein presented and their performance discussed. The Bluepulse (Figure 1) generates signal similar to conventional sources in the seismic bandwidth of interest, but with a significant reduction in high-frequency energy. The Tuned Pulse Source (TPS, Figure 2) extends signal useful bandwidth down to 1.4 Hz, with Source Pressure Level (SPL) more than an order of magnitude below standard sources.

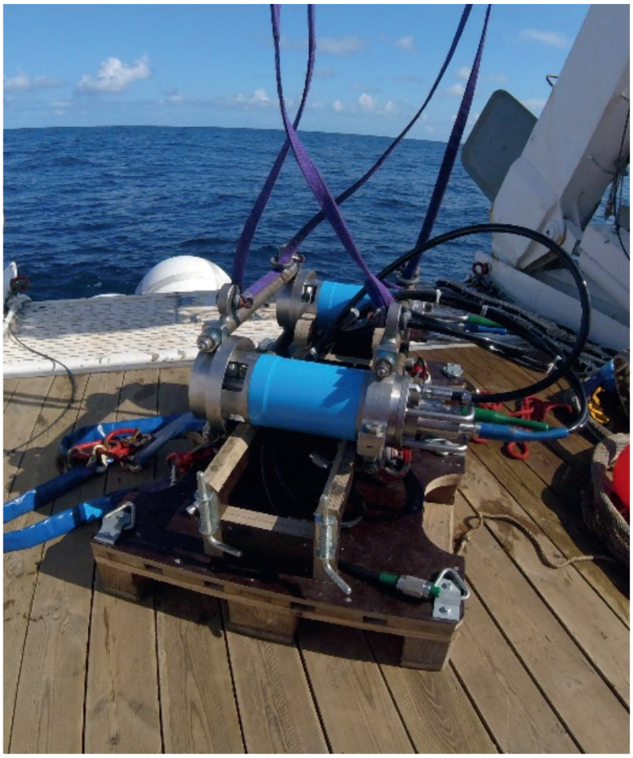

Figure 1 Bluepulse on vessel back deck, ready for sea calibration, Atlantic ocean, summer 2021.

The Bluepulse solution

An innovative, compact and agile pneumatic source has been developed to accompany the industry environmental effort with a state-of-the-art solution. After a description of the theoretical considerations that lie behind the design selected, the main outcomes of sea trials and acoustic calibration sorties are discussed. Simulation of the source signal generation when used in arrays is then presented, a mandatory consideration to address permitting processes. Finally, operational aspects are considered, in particular, maintenance and upgrade of current source inventory.

Modelling – Shuttle profile selection

The accurate transient multiphasic fluid dynamics modelling of a pneumatic source is a complex but mandatory computational problem that must be solved in order to understand and control the high-frequency emission levels of this technology of marine sources. We used computational fluid dynamics (CFD) in order to understand and evaluate the physics in action inside the pneumatic source and at the frontier between the water medium and the air jet. We have then validated these models on the basis of experimental results.

Previously, several studies were dedicated to similar objectives and are described e.g. by Coste (2014). We pushed the analysis further to assess instability at the air/water interface and the supersonic conditions observed at shuttle opening (Figure 3). This Figure shows, for different shuttle positions, the dimensionless Mach number fields, which reflect the sonic level observed on a vertical plane passing through the centre of the pneumatic source. From these results, we used a method for determining the discharge coefficient for supersonic flows. As a result of this modelling, an optimal shuttle profile was selected. Indeed, the selection of a 'S' profile for the shuttle reduces the risk on machining tolerances at the manufacturing stage, and enables very stable and repeatable acoustic signatures. We have therefore chosen two 'S' profiles to maximize the pressure of the acoustic

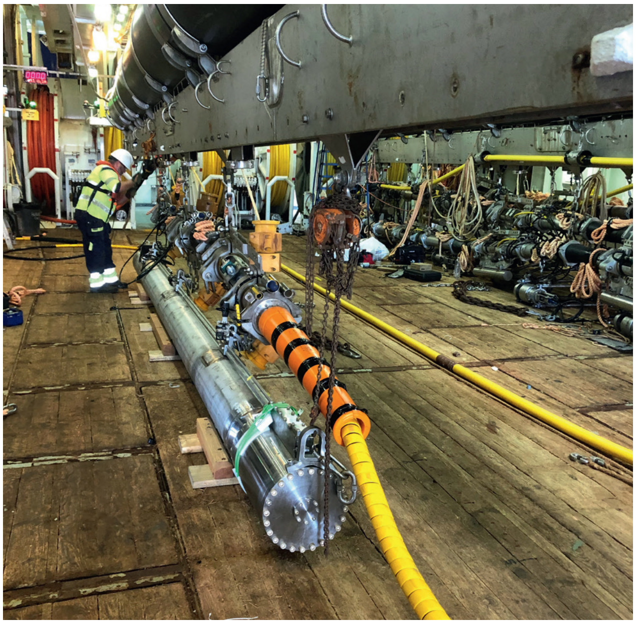

Figure 2 Tuned Pulse Source (TPS) on the back-deck of Sanco Atlantic, Gulf of Mexico, 2020.

Figure 3 Mach number (dimensionless), for three shuttle positions critical for the source performance and reliability.

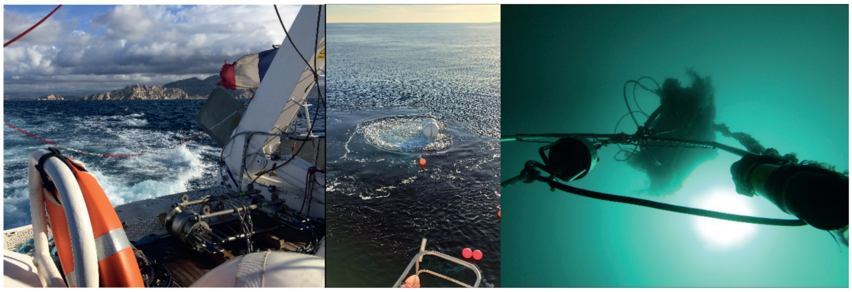

Figure 4 Samples of pictures from 2019, 2020 and 2021 sea trials, dedicated mainly to calibration and validation.

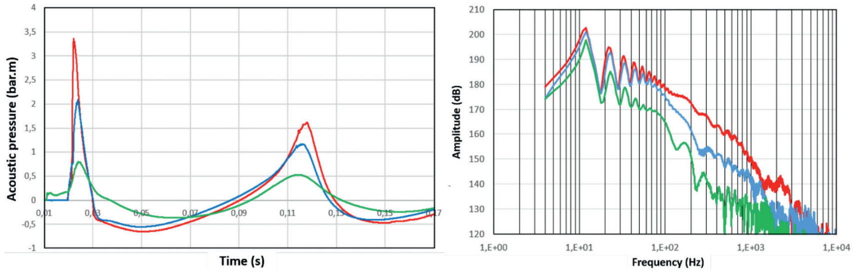

Figure 5 Near-field performances for three pneumatic sources: standard G-Source II (red), Bluepulse 200 Hz (blue) and Bluepulse 100 Hz (green). Note the significant difference in slopes at high frequencies that is directly related to marine life potential disturbance.

peak while scaling the cut-off frequency down to about 100 Hz for the first profile, and 200 Hz for the second. The accurate choice of these two cut-off frequencies was done to suit industry expectancies in terms of signal high-frequency content.

As a remark, Landrø has shown that a source array can generate additional high frequencies as a consequence of cavitation (Landrø 2011). This cavitation is mainly due to the reflexion of the acoustic wave at the sea surface: with a -1 reflection coefficient, the down-going source ghost induces a drop in pressure that can go below the saturation vapour pressure of water. This phenomenon, also known as ghost cavitation, is however much lessened with the new pneumatic source design, owing to its accurate optimum control of the energy released.

Sea trials and performances

In 2019, 2020 and 2021, field experiments (Figure 4) were organized with two main objectives. First, the validation of our hypothesis regarding the mechanical shapes chosen, followed by the validation of the overall acoustic behaviour and performance of the entire source. Then, the calibration of the full range of sources (three casing volumes for each of the two profiles) when used at the extreme of the specified pressure and depth. During the source development, we have calibrated and validated several designs, thus providing added knowledge and trust in our computational models.

These acoustic measurements were used to validate the CFD model's predictions of the pneumatic source itself and the bubbles' interaction with the surrounding water. A full range of volumes and shuttle designs were calibrated and validated, providing added confidence in the model's predictions. Two optimum profiles were eventually selected (around 110 and 210 Hz, further referred to as '100 Hz' and '200 Hz'), enabling different shapes in the decay of high frequencies to suit particular industry needs (Figure 5).

Near- and far-field acoustic signatures were then acquired with calibrated state-of-the-art acquisition system and hydrophones, suitable to high-frequency analyses. This enabled us to assess and validate the source performance and have them included (release pending) in the most-used source array simulation software.

Model of an environmental array

One of our customers requested we evaluate the feasibility and benefit of moving to a full environmental source for one of their surveys in an area subject to strong regulatory constraints. The signature of an array consisting of 28 Bluepulse (total volume of 4,180 cu in. at 2,000 PSI, Figure 6) was modelled using an in-house simulation program. For an array, as for a single source, the low-frequency seismic bandwidth of interest for imaging (< 100 Hz) is preserved while the high-frequency content is greatly attenuated.

Sound Exposure Level (SEL, Figure 7, a) and Sound Pressure Level (SPL, Figure 7, b) are the two main metrics used to evalu-

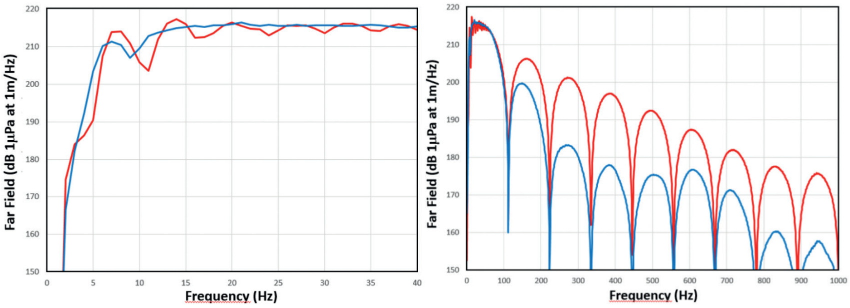

Figure 6 Far Field reconstruction of Bluepulse 200 Hz (blue) and conventional G-Source II (red) for an array of 4180 cu in at 2000 psi.

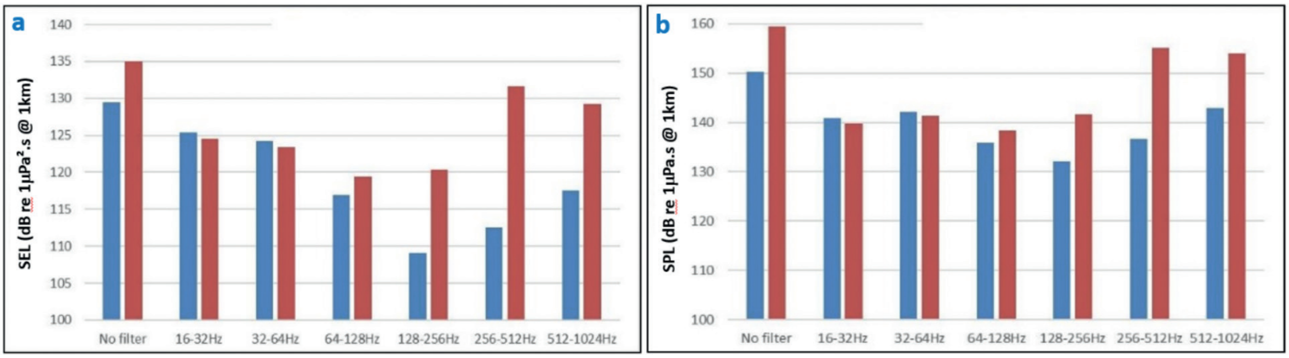

Figure 7 comparison of SEL (a) and SPL (b) between the conventional source array (red) and the Bluepulse (200 Hz profile) array (4180 cu in at 2000 psi for both arrays).

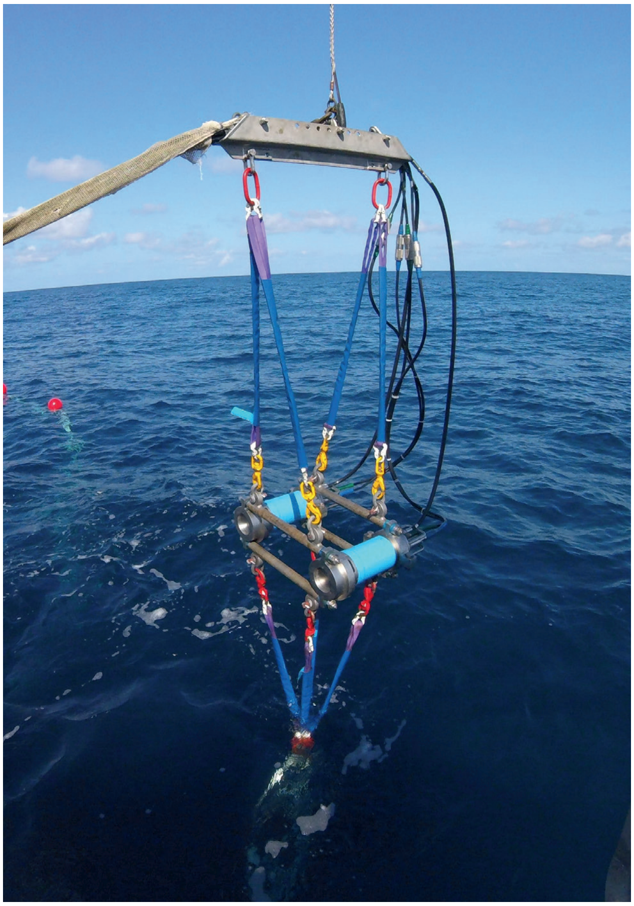

Figure 8 Cluster of Bluepulse 150 cu in @100Hz, sea calibration sortie (Atlantic Ocean, July 2021).

ate the auditory effect of impulsive sources on marine mammals (Southall 2019). For each group of mammals, an acceptance threshold is associated with a frequency band. We note that for frequencies above 128 Hz the SEL and SPL of the environmental source drop by 10 to 20 dB when compared to the conventional one. Consequently, the radius of the exclusion zone for mammals around the source can be decreased.

The operational perspective

A new pneumatic source intended to accompany increasing environmental awareness has been designed, and is fully calibrated and qualified (Figure 8). Its innovative, patented mechanical profile limits the disturbance associated with the high-frequency signal generation when compared with conventional pneumatic sources, and reduces the mechanical stress on both the source itself and its peripheral equipment.

The Bluepulse is the most compact and lightweight pneumatic source of its class, 30% lighter and smaller than current best-in-class industry solutions. It is available as a new source, or as a straightforward upgrade (three parts to swap in about 30 minutes) to the existing large installed base of G-Source II. The flexibility in source upgrade, together with dedicated volume reducers and shuttle profiles (Figure 9) enable high scalability in source configuration so as to adapt to the requirements of each survey, while optimizing maintenance and cost of spare parts. From an operational perspective, it is fully compatible with the most common array sub-harnesses, and with existing equipment inventories such as standard Mechanical Time Break (M-TB), or Sercel advanced Electronic Time Break (E-TB) and the Solenoid Valve (SV) used to trigger the source.

The TPS solution

The Tuned Pulse Source (TPS) is a pneumatic source that operates with lower pressure and larger volumes than conventional high-pressure pneumatic sources). The pressure is a factor of 2 to 4 lower so 600 to 1000 PSI compared to 2000 to 2500 PSI. The volume is two orders of magnitudes larger than the largest conventional pneumatic sources in a typical array. Currently, the TPS is commercial with an up to 26,500 cubic inch configuration and this volume may be increased in the future. A number of design features differentiate the TPS from any other pneumatic source. The acceleration distance, which controls the air flow release, and thus part of the high-frequency noise, is eliminated (as a remark, this distance is reduced on the Bluepulse when compared to conventional sources. Air refill and drainage are done separately into the firing and the operating chambers, rather than via an orifice in the shuttle. This makes the TPS much safer because it eliminates the risk of auto-fire during drainage. The cup-shaped flange and the closed mid chamber avoid expulsion of water as the shuttle is accelerating and opening the ports and reduces cavitation. Figure 10 shows an overview of these TPS features (TPS mark 1, current commercial version being Mark 3).

The larger pressure times volume, about 30 times higher than conventional pneumatic sources, produces lower frequency signals. A large conventional pneumatic source with a volume of 600 cubic inch at a pressure of 2000 PSI, packs 1.2 million lb-inch. A TPS with a volume of 26,500 cubic inches at a pressure of 1000 PSI packs 26.5 million lb-inch. Much more energy is released by the larger TPS, but it is released over a longer period of time resulting in a sound pressure level (SPL) that is lower than a typical array of pneumatic sources and a much lower slope. The slope is how much the pressure changes in a certain time. The slope (Figure 11) is the most important factor for environmental impact because the acceleration associated with acoustic waves is proportional to the slope. The proportion factor is the acoustic impedance of water. For example, if the pressure of an acoustic wave changes by one Bar in one millisecond, the associated acceleration is 6.7 g where g is the earth gravity acceleration. Acceleration (in g) is used to measure the impact on equipment, pilots, passengers, and all marine wildlife great and small.

We tested TPS in a lake and superimposed the signatures in the time (Figure 12) and the frequency (Figure 13) domains of TPS and pneumatic source arrays.

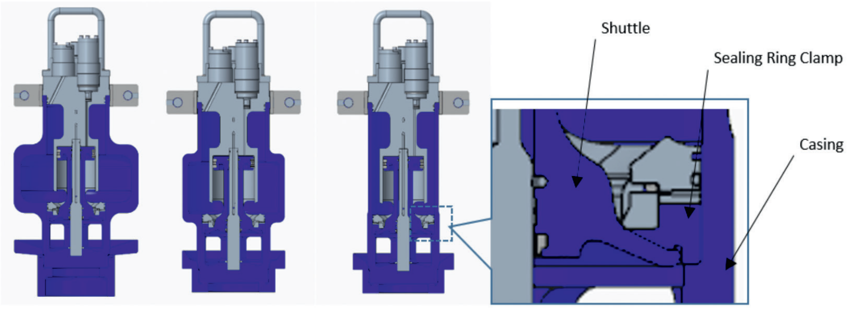

Figure 9 Upgrade kit consisting of three elements: 1. one casing among the available volumes (380/250/150 cu in), 2. Sealing ring clamp (SRC), and 3. Shuttle.

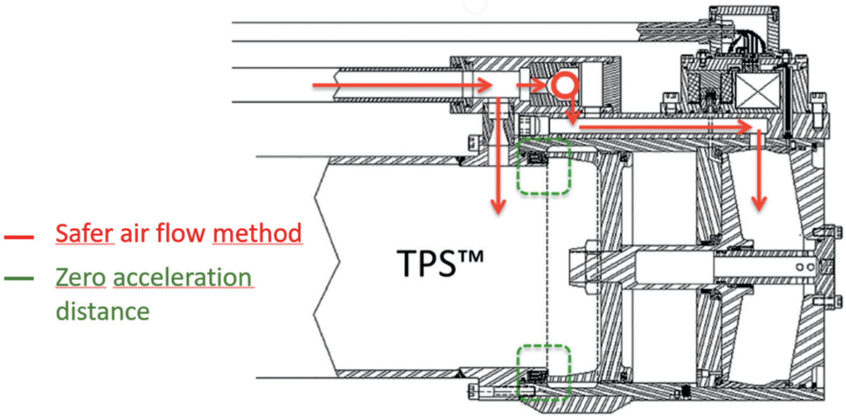

Figure 10 An overview of the internal designs of the TPS source. Of a number of different design features versus conventional pneumatic sources, two are highlighted here: the safer airflow method (in red) and the zero-acceleration distance (in green).

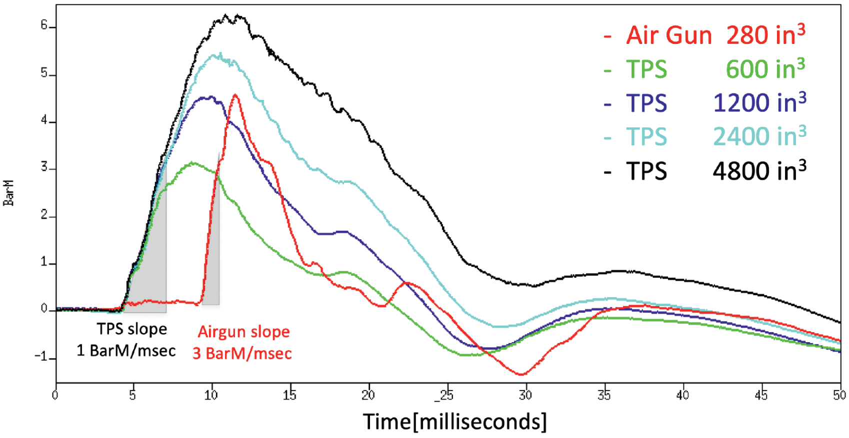

Figure 11 Time domain comparison of a pneumatic source (red, non-Sercel) with TPS for different volumes. The slope of all TPS is < 1 bar.meter per ms, regardless of volume. The slope of the pneumatic source is 3 bar.meter per ms.

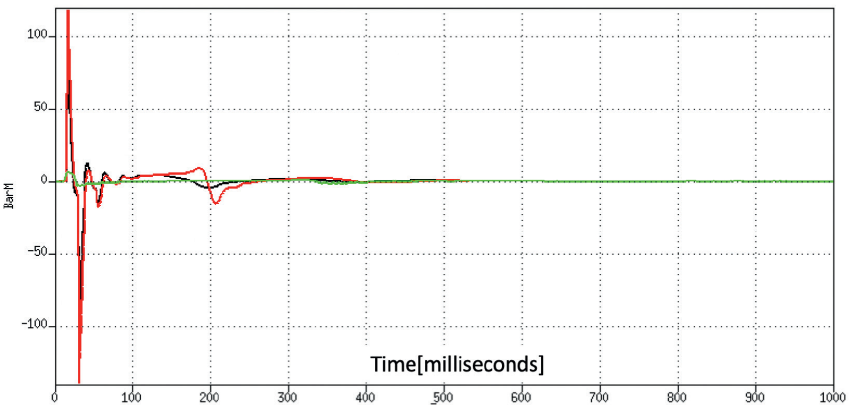

Figure 12 Time domain comparison of TPS (green) to a conventional pneumatic source array (in black) and to an enhanced pneumatic source array (in red). The TPS has lower SPL, lower slope, less sound and ultrasound energy than conventional pneumatic sources.

The 26,500 cubic inch TPS was further tested in the Gulf of Mexico and recorded by ocean bottom nodes. The signature was isolated and is presented in Figure 13. The most significant metric that indicates a low environmental impact is a slope of less than one bar.meter per millisecond. This has to be compared to about 3 bar.meter per millisecond in individual pneumatic sources and 90 bar.m per millisecond vertically under an array of 30 pneumatic sources triggered simultaneously. The geophysical metric that indicates significant added-value in low-frequency signal is the fundamental frequency of the bubble: it is 2.8 Hz for the TPS, to be compared to 7-8 Hz for conventional pneumatic source arrays.

While the direct impact of infrasound on marine wildlife may be an area of biological research, the indirect environmental impact of better seismic data is well known. To the oil industry, increased infrasound provides better seismic data. Better seismic data leads to better information which reduces the environmental impact of the oil industry because it reduces drilling in general and the risk of drilling into formations with unexpected high pressures in particular.

Overlaying the spectra of TPS and pneumatic source shows that the TPS has up to 27 dB stronger signal at 2.8 Hz, 15 dB weaker signal at 40 Hz, and 30 dB weaker noise at 150 Hz (Figure 14).

As a remark, the TPS can and has been deployed either from vessels with booms and rigid floats, or from vessels with a slipway and flexible floats (Figure 15).

Conclusions

There is a pressing need to improve existing marine seismic source technology in order to meet the dual goals of improved low frequency content for imaging more challenging targets and to reduce the high frequency noise to minimize the environmental impact of active seismic surveys. Two new sources have been designed in this regard, with performance in respect of the aforementioned goals maximized through extensive theoretical studies and modelling. A series of field experiments have confirmed the geophysical relevancy of the selected designs, as well as the overall performance of the newly designed sources, including reliability and endurance, and are consequently now fully deemed

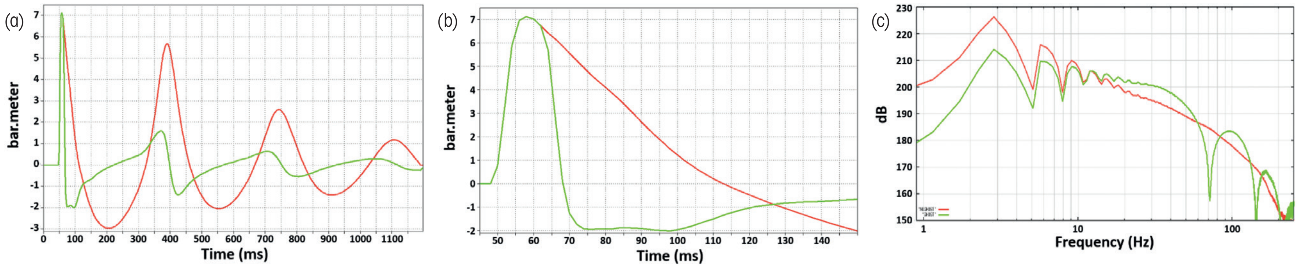

Figure 13 (a) Time domain. Note the bubble period is more than 300 milliseconds. Green: source signature with vertical ghost, red: deghosted signature. (b) Zoom from Figure 13a on the main energy peak in the time domain. Note that the rise time is 8 milliseconds. The peak SPL is 7 bar.meter, so the slope is less than one bar.meter per millisecond. (c) Frequency domain spectra. Note the bubble frequency is 2.8 Hz. Green: source signature with vertical ghost, red: deghosted signature.

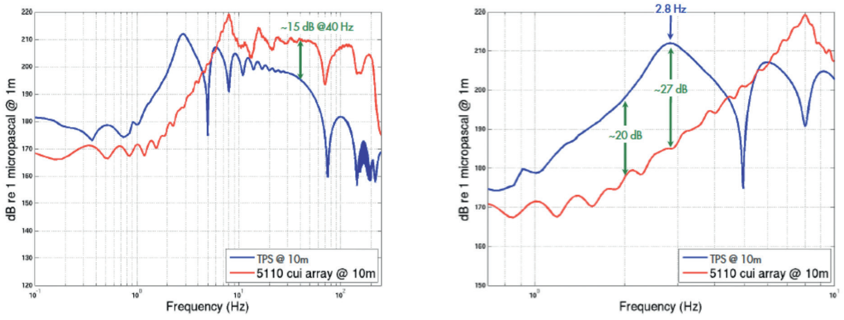

Figure 14 Spectra of TPS compared to conventional pneumatic source exhibit a gain of 27 dB at 2.8 Hz, and a loss of 25 dB at 100 Hz.

Figure 15 (a) TPS deployed with a boom under a rigid float. (b) TPS deployed on a slip-way together with a flexible float.

commercial. Available as a complete source package or as a straightforward upgrade to existing G-Source II inventories, the Bluepulse enables the reduction of the high-frequency output of conventional pneumatic sources. For its part, the TPS provides unprecedented energy at low frequencies, while generating accelerations that are 100 times less than a large array of pneumatic sources. This disruptive technology is intended to operate either as a stand-alone source, or in combination with conventional arrays to obtain unprecedented signal bandwidths.

Acknowledgments

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